COURSE OF TECHNICAL INSTRUCTION

APPLIED ELECTRICITY 2

Engineering Training Section, Headquarters, Postmaster-General's Department, Melbourne C.2.

APPLIED ELECTRICITY 2.

ISSUED 1961

Contents:-

FUNDAMENTALS OF A.C. THEORY

---

1. INTRODUCTION.

1.1 In Applied Electricity I, we studied the nature of electricity and the related terms and laws. We also examined the components which make up electrical circuits, and studied the characteristics of these circuits under D.C. conditions.

However, to understand the operation of telecommunication equipment, a sound knowledge of alternating current theory must be attained, and this paper outlines the behaviour of resistance, inductance and capacitance in A.C. circuits.

1.2 Although this paper briefly revises information given in Applied Electricity I, before proceeding any further, you should revise the paper "Introduction to A.C. Theory" in Applied Electricity I.

2. ALTERNATING CURRENTS IN TELECOMMUNICATION.

2.1 An Alternating Current is one which regularly alters its direction of flow, first flowing in one direction, then reversing and flowing in the opposite direction. Terms commonly used in connection with A.C. are :-

(i) Sine Wave. A graphical representation of the A.C. produced by a conductor rotating at uniform speed in a uniform magnetic field.

(ii) Cycle. One complete reversal of A.C. passing through a complete set of positive and negative values.

(iii) Frequency. The number of cycles per second. Frequencies used in telecom are expressed in :

- cycles per second (c/s).
- kilocycles per second (kc/s), 1 kc/s = 1,000 c/s.
- megacycles per second (Mc/s), 1 Mc/s = 1,000,000 c/s.

2.2 Alternating currents are used in almost every aspect of telecommunication, ranging from the simple magneto telephone to the complex equipment of radio and television.

The ways in which we use A.C. in telecom are as follows :-

(i) Normal Telephone Conversations use A.C. to carry the message from one telephone to the other, over the telephone line.

(ii) Carrier Telephony uses A.C's. produced within the carrier system as "carriers" for a number of telephone conversations which can be transmitted over one line at the same time. The "carrier" currents have different frequencies which allows them to be separated by filters in the receiving equipment.

(iii) Carrier Telegraphy uses A.C. to provide a number of telegraph channels over one telephone line, or over one channel of a telephone carrier system. The telegraph signals are in the form of pulses of A.C., the frequency of which is different for each channel. As with telephone carrier systems, filters separate the signals at the receiving end, and no interference takes place between messages.

(iv) Radio, which embraces broadcasting, radio telephone and telegraph services and television, uses high frequency alternating currents as carriers for the transmission of signals. We often hear radio stations announce their operating frequency.

2.3 In addition to these actual methods of communication, we use A.C. in other ways. Some of these are :

- to ring telephone bells.
- to provide the supervisory tones in automatic exchanges.
- to "direct-dial" over trunk lines.
- to test the performance of amplifiers and other equipment.
- to operate exchange battery charging equipment.
- to heat, light and ventilate buildings.

A.C.'s. used in telecom vary in wave shape and frequency, and come from many different voltage sources. Some have pure sine wave form, but those used for the transmission of speech and music are more complex. The voltages producing these currents range from a few millivolts in the subscriber's telephone to many kilovolts in a radio transmitter. The frequencies used range from 17 c/s for ringing current up to thousands of megacycles per second in the high frequency radio applications.

2.4 Frequencies Used in Telecom. Frequencies are classified according to their use, and are :-

(i) Power frequency. A.C. at 50 c/s is distributed by Electricity Authorities and provides power for all battery charging equipment and for the normal lighting and power circuits in buildings.

(ii) Audio frequencies are those which produce sounds which can be heard by the human ear. They range from 16 c/s to 20 kc/s, but the limits of hearing vary with different persons. Most people can hear sounds from 30 c/s to 15 kc/s.

It is not necessary to transmit the full audio range for satisfactory sound reproduction. In fact, to do so would be both inconvenient and unnecessary. The range of frequencies we normally use for the electrical transmission of sound is :

- 200 c/s to 3 kc/s for telephone conversations.
- 30 c/s to 7.5 kc/s for programme transmission.

Although there are frequencies in both speech and music which are not present after transmission, the frequencies mentioned above are sufficient for normal reproduction.

(iii) Carrier frequencies are those used in carrier systems for transmitting simultaneous telephone messages over one pair of wires. The frequencies used with open wire line systems range from 3 kc/s to 150 kc/s (approx.). However, carrier systems operating over special cable use frequencies in excess of 1 Mc/s.

(iv) Radio frequencies are those which permit electric current to radiate appreciable electromagnetic energy, and are used for all forms of "wireless" transmission.

Radio Frequencies extend from about 30 kc/s upwards.

Frequencies used in telecom in Australia are shown in Fig. 1.

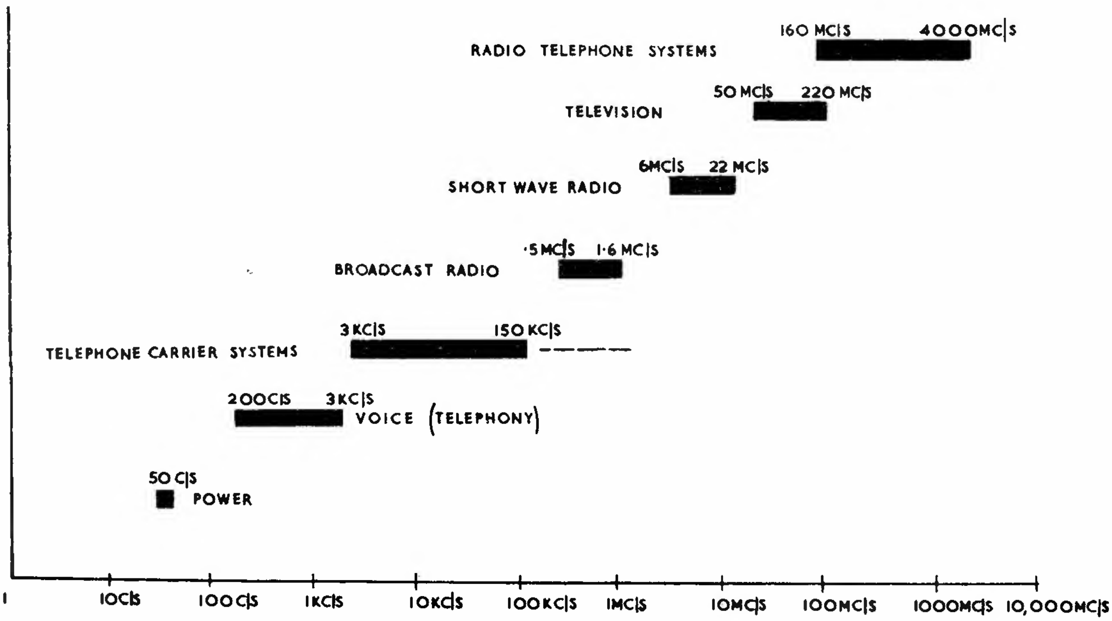


FIG. 1. FREQUENCIES USED IN TELECOM.

3. TRIGONOMETRY AND RIGHT-ANGLE TRIANGLES.

3.1 Trigonometry is a branch of mathematics which deals with the relationships which exist between the sides and angles of triangles.

At this stage it might seem that trigonometry has no connection with A.C., but we will see that currents and voltages in A.C. circuits can be represented by vector diagrams which can be simplified to right-angle triangles. Trigonometry is one of our most useful aids in solving A.C. problems.

3.2 Right-Angle Triangles. We know from earlier studies, the sum of the angles included in a right-angle triangle equals 180°. As one angle is a right-angle, the remaining two angles together contain 90°

The sides of a right-angle triangle are designated with reference to one of these two included angles, as shown in Fig. 2. It is the usual practice to refer to the "reference" angle as "theta", (θ).

FIG. 2. SIDES OF RIGHT-ANGLE TRIANGLES.

The longest side is the hypotenuse.

The side opposite the reference angle is the opposite side.

The side, which, with the hypotenuse, forms the angle is the adjacent side.

3.3 Trigonometrical Ratios. The ratio between the lengths of the sides of right-angle triangles which have similar reference angles, always works out to the same numerical value, irrespective of the size of the triangle, as in Fig. 3.

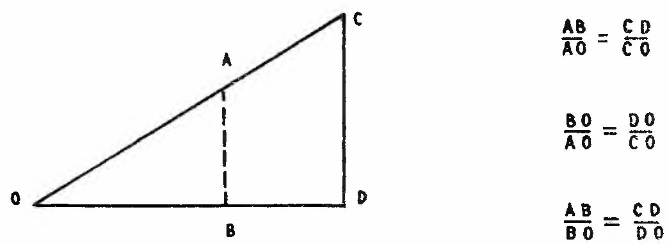


FIG. 3. TRIGONOMETRICAL RATIOS.

These ratios are known as sine, cosine and tangent, and are expressed as follows :-

$$\text{Sin } \theta = \frac{\text{OPPOSITE}}{\text{HYPOTENUSE}}$$

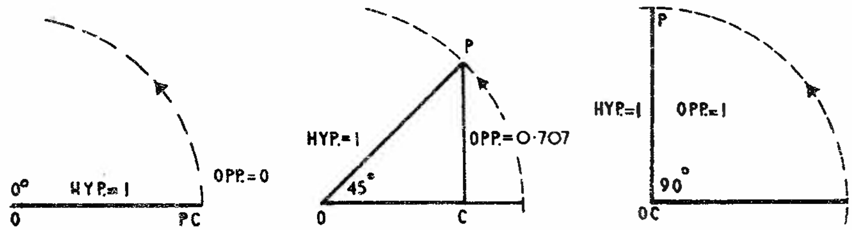
$$\text{Cos. } \theta = \frac{\text{ADJACENT}}{\text{HYPOTENUSE}}$$

$$\text{Tan. } \theta = \frac{\text{OPPOSITE}}{\text{ADJACENT}}$$

3.4 The Numerical Values of sine, cosine and tangent vary according to the magnitude of the reference angle.

For angles between 0° and 90° –

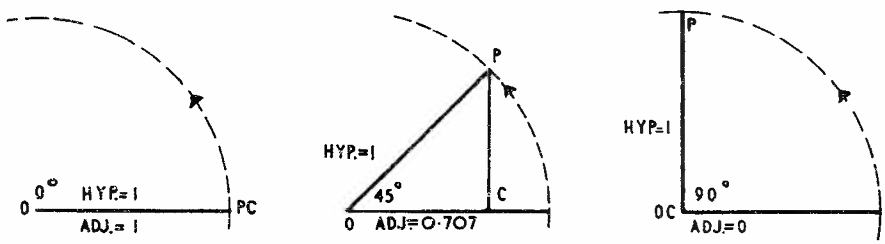
(i) The value of sine changes from zero, at 0°, when the opposite side PC has no length, to unity at 90°, when the opposite side coincides with the hypotenuse, OP. (Figs. 4a, b and c.)



(a) Sine 0° = 0. (b) Sine 45° = 0.707. (c) Sine 90° = 1.

FIG. 4. VALUES FOR SINE.

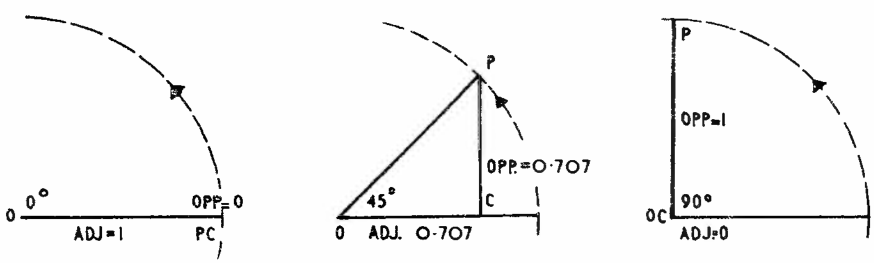
(ii) Cosine has a value of unity at 0° as the adjacent side OC is equal in length to the hypotenuse, OP, but it diminishes in value as the angle θ increases towards 90°. At 90°, cosine is zero as the adjacent side ceases to exist. (Figs. 5a, b and c.)



(a) Cosine 0° = 1. (b) Cosine 45° = 0.707. (c) Cosine 90° = 0.

FIG. 5. VALUES FOR COSINE.

(iii) At 0° tangent has a value of zero, as the opposite side PC has no length. At 45° the opposite side is equal in length to the adjacent side, OC, and tan 45° is unity. After 45° tangent rapidly increases in value until at 90° it is infinite in value, as then the adjacent side has no length. (Figs. 6a, b and c.)



(a) Tangent 0° = 0. (b) Tangent 45° = 1. (c) Tangent 90° = Infinity.

FIG. 6. VALUES FOR TANGENT.

For angles between 90° and 360°, sine, cosine and tangent vary within the same numerical limits as for between 0° and 90°. Whereas sine, cosine and tangent are positive between 0° and 90°, between 90° and 360° there are times when their values are negative.

The familiar sine wave is actually a graph of the variation in values of sine between 0° and 360°.

3.5 Trigonometrical Tables list the numerical values of sine, cosine and tangent for all angles between 0° and 90°. Portion of the "sine" table is shown below.

NATURAL SINES.

		0'	6'	12'	18'	24'	30'	36'	42'	48'	54'	Differences. 1'	2'	3'	4'	5'
	0°	0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
	1	0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
	2	0349	0366	0384	0401	0419	0436	0454	0471	0488	0506	3	6	9	12	15
	3	0523	0541	0558	0576	0593	0610	0628	0645	0663	0680	3	6	9	12	15
	4	0698	0715	0732	0750	0767	0785	0802	0819	0837	0854	3	6	9	12	14
SIN 5°	5	0872	0889	0906	0924	0941	0958	0976	0993	1011	1028	3	6	9	12	14
	6	1045	1063	1080	1097	1115	1132	1149	1167	1184	1201	3	6	9	12	14
	7	1219	1236	1253	1271	1288	1305	1323	1340	1357	1374	3	6	9	12	14
	8	1392	1409	1426	1444	1461	1478	1495	1513	1530	1547	3	6	9	12	14
	9	1564	1582	1599	1616	1633	1650	1668	1685	1702	1719	3	6	9	12	14
SIN 10°24'	10	1736	1754	1771	1788	1805	1822	1840	1857	1874	1891	3	6	9	11	14
	11	1908	1925	1942	1959	1977	1994	2011	2028	2045	2062	3	6	9	11	14
	12	2079	2096	2113	2130	2147	2164	2181	2198	2215	2233	3	6	9	11	14
	13	2250	2267	2284	2300	2317	2334	2351	2368	2385	2402	3	6	8	11	14
	14	2419	2436	2453	2470	2487	2504	2521	2538	2554	2571	3	6	8	11	14
SIN 15°32'	15	2588	2605	2622	2639	2656	2672	2689	2706	2723	2740	3	6	8	11	14
									ADD							
	[illegible]	2756	2773	2790	[illegible]	2823	[illegible]	2857	[illegible]	[illegible]	2907	[illegible]				14

The sine of an angle measured in degrees, or in degrees and certain values of minutes can be read directly from the table of natural sines. For example:-

sin 5° is 0.0872

sin 10° 24' is 0.1805.

To find the sine of an angle which cannot be read directly from the table (for example 15° 32'), the procedure is -

(i) Locate an angle on the table as near as possible to, but less than the required angle, and note its value of sine. (Sin 15° 30' = 0.2672).

(ii) Refer the difference in minutes between the two angles to the "difference" column (2' difference at 15° = 0.0006).

(iii) Add this to the value of sine previously obtained - (0.2672 + 0.0006).

$\therefore$ sin 15° 32' = 0.2678.

To find the angle which corresponds to a known value of sine, (for example 0.2323), the procedure is -

(i) On the table, locate an angle whose sine is nearest to, but less than the known sine value, and note its value (sin 13° 24' = 0.2317).

(ii) Refer the difference to the difference column; (0.0006 difference at 13° = 2').

(iii) Add the corresponding difference in minutes to the angle previously noted - (13° 24' + 2' = 13° 26').

$\therefore$ 0.2323 = sin 13° 26'

Tables for values of tangent are used in exactly the same way as sine tables, as the values for both sine and tangent increase as the magnitude of the angle increases.

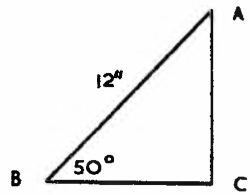
Values of cosine however, decrease as the angle increases, and the numbers shown in the difference column must be subtracted instead of being added.

3.6 Trigonometrical Ratios are used to calculate -

- the remaining two sides of a right-angle triangle when one side and one angle (other than the right angle) are known.
- the included angles of a right-angle triangle when any two sides are known.

Example No.1. In the triangle ABC, calculate -

(i) the length of side BC (ii) the length of side AC.



(i) .... $\cos 50^\circ = \dfrac{\text{adjacent}}{\text{hypotenuse}} = \dfrac{BC}{AB}$

From tables :

$\cos 50^\circ = 0.6428$

$\therefore\ 0.6428 = \dfrac{BC}{12}$

$\therefore\ BC = 0.6428 \times 12$

$= 7.7"$ (approx.)

(ii) .... $\sin 50^\circ = \dfrac{\text{opposite}}{\text{hypotenuse}} = \dfrac{AC}{AB}$

From tables :

$\sin 50^\circ = 0.766$

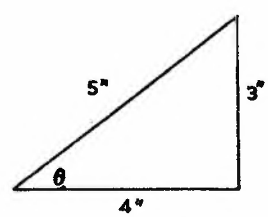
$\therefore\ 0.766 = \dfrac{AC}{12}$

$\therefore\ AC = 0.766 \times 12$

$= 9.2"$ (approx.)

Answer = (i) 7.7" (ii) 9.2".

Example No.2. Calculate the angle θ.



ALTERNATIVE METHODS

$\sin\theta = \dfrac{\text{opposite}}{\text{hypotenuse}}$

$= \dfrac{3}{5}$

$= 0.6$

From tables :

$\sin 36^\circ 52' = 0.6$

$\therefore$ angle $\theta = 36^\circ 52'$

$\cos\theta = \dfrac{\text{adjacent}}{\text{hypotenuse}}$

$= \dfrac{4}{5}$

$= 0.8$

From tables :

$\cos 36^\circ 52' = 0.8$

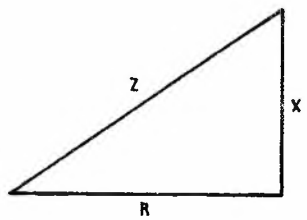
$\therefore$ angle $\theta = 36^\circ 52'$

Answer = $36^\circ 52'$

3.7 There is also a definite relationship between the three sides of a right-angle triangle. This relationship is summarised in Pythagoras' theorem, which states -

> "The square on the hypotenuse of a right-angle triangle equals the sum of the squares on the other two sides."

From this we can develop formulas which enable us to calculate any one side of a right-angle triangle, provided the lengths of the other two sides are known. For example, in Fig. 7.



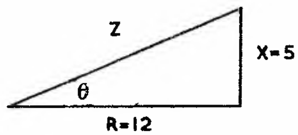
$$Z = \sqrt{R^2 + X^2}$$

$$X = \sqrt{Z^2 - R^2}$$

$$R = \sqrt{Z^2 - X^2}$$

FIG. 7.

Example No.3. In the triangle below, find (i) side Z and (ii) the angle θ.



(i) .... $Z = \sqrt{R^2 + X^2}$

$= \sqrt{12^2 + 5^2}$

$= \sqrt{144 + 25}$

$= \sqrt{169}$

$= \underline{13}$

(ii) ..... $\tan\theta = \frac{\text{Opposite}}{\text{Adjacent}}$

$= \frac{X}{R} = \frac{5}{12}$

$= 0.4166$

From tables =

$\tan 22^\circ 37' = 0.4166$

$\therefore$ Angle $\theta = \underline{22^\circ 37'}$

Answer = (i) 13 units (ii) $22^\circ 37'$.

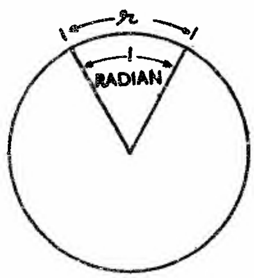
3.8 The calculations involved in Example No.3 are essentially the same as those done when solving A.C. problems. Any one of the three trig. ratios can be used to find the angle, and for practice you should repeat part (ii), using the sin and cos ratios. However, it is the usual practice to use tan in the angle calculation, as the factors involved (X and R) are usually given, or can be calculated with a minimum of working. The factor Z is the denominator in the equations for sin and cos, and as this is nearly always a calculated, and often awkward figure, it is more convenient to use -

$$\textbf{Tan.}\,\theta = \frac{\textbf{OPPOSITE}}{\textbf{ADJACENT}}$$

In the simple aspects of trigonometry dealt with so far, angles have been measured in degrees and minutes. There is another method of angular measurement, called <u>radian measure</u>, which is important in A.C. theory.

3.9 Radian Measure is used to express the angular velocity of, or the angular distance travelled by an object which has rotary motion. When a conductor rotates in a magnetic field to produce sine wave A.C. its rate of rotation can be expressed in terms of radians per second.

A Radian is the angle subtended at the centre of a circle by an arc equal in length to the radius. (Fig. 8).



$$\text{No. of radians in a circle} = \frac{\text{circumference}}{\text{radius}}$$

$$= \frac{2\pi \times \text{radius}}{\text{radius}}$$

$$= 2\pi$$

$$\therefore \text{One radian} = \frac{360}{2\pi}$$

$$= 57.3^{\circ}.$$

FIG. 8. RADIAN MEASURE.

The rotating conductor traverses 2π radians in making one revolution. When "f" is the number of revolutions per second, the conductor has an angular velocity (symbol ω) or rate of rotation of $2\pi f$ radians per second.

Therefore

$$\omega = 2\pi f$$

where

ω = Angular velocity in radians per second.

2π = 6.28.

f = Revolutions per second.

Example No. 4. Calculate the angular velocity of a conductor which rotates in a magnetic field at 3000 revolutions per minute.

$$\text{No. of revolutions per second} = \frac{\text{Revs. per minute}}{60}$$

$$= \frac{3000}{60}$$

$$= 50.$$

$$\text{Angular Velocity } \omega = 2\pi f$$

$$= 2 \times 3.14 \times 50$$

$$= 314 \text{ radians per second}$$

Answer = 314 radians per second.

In A.C. circuits containing inductance or capacitance, the rate of change of current has a direct bearing on the amount of opposition offered by the circuit.

As the rate of rotation of the conductor influences the rate of change of the A.C. produced, we find that wherever the rate of change of current is a factor which governs the behaviour of a circuit, reference is made to the angular velocity of a rotating conductor.

4. VALUES OF ALTERNATING CURRENT AND VOLTAGE.

4.1 As we saw in Applied Electricity I, during each cycle, an A.C. passes through a large range of values. There are several different values associated with A.C. Theory. They are :-

(i) Peak or Maximum Value. This is the maximum value occurring during one cycle. The peak value is not used as a direct indication of the effectiveness of an A.C. as this value is attained at two instants only during each cycle. However we must take peak value into consideration with regard to the insulation of high voltage circuits.

For a sine wave, the relationship between the peak value and effective value is -

PEAK VALUE = 1·414 x EFFECTIVE VALUE

(ii) Instantaneous Value. This is the actual value of an A.C., at a certain instant or rotational degree position during a cycle.

For a sine wave -

INSTANTANEOUS VALUE = PEAK VALUE x sin. θ

where θ = number of degrees from commencement of cycle.

(iii) Effective or R.M.S. Value. This is the value of A.C. which produces the same heating effect as a continuous current of the same amount. An A.C. of 10 amps (effective) has the same heating effect as 10 amps D.C.

The power of an A.C. is used as a basis for determining its effective value. For one cycle, instantaneous values of current (or voltage) are squared to give proportional values of instantaneous power. These are averaged to obtain a mean value of power for the cycle. A value of current (or voltage) which produces the same power is obtained by taking the square root of the mean power.

This value, (the Root of the Mean of the Squares of instantaneous values) is the effective value of the alternating current or voltage under consideration.

For a sine wave -

EFFECTIVE VALUE = 0·707 x PEAK VALUE

Unless definitely stated otherwise, alternating currents and voltages are referred to in terms of effective values. For example, the "240 volt A.C." supply used for home lighting has an effective value of 240 volts. The peak value of this supply is approximately 340 volts. This figure is calculated as follows :-

$$\text{Effective Voltage} = 0.707 \times \text{Peak Voltage.}$$

$$\therefore \quad \text{Peak Voltage} = \frac{\text{Effective Voltage}}{0.707}$$

$$= \text{Effective Voltage} \times 1.414$$

$$= 240 \times 1.414$$

$$= 340 \text{ volts (approx.)}$$

(iv) Average Value. This is the average of all the instantaneous values of the A.C. for one half cycle. Average value is rarely used by technicians, but it has application in electroplating and similar processes.

For a sine wave -

AVERAGE VALUE = 0·637 x PEAK VALUE

4.2 Form Factor. This is a number which indicates the wave form of an A.C. It is found from the ratio of the effective value to the average value. Form Factor is used in calibrating the scale of a moving coil meter to read A.C.

$$\text{FORM FACTOR} = \frac{\text{EFFECTIVE VALUE}}{\text{AVERAGE VALUE}}$$

For a sine wave

$$\text{Form Factor} = \frac{0.707 \times \text{Peak Value}}{0.637 \times \text{Peak Value}} = 1.11.$$

As the wave shape becomes flat topped, the form factor tends towards a value of 1.0. When the wave tends to become peaked, the value rises above 1.11.

5. PHASE.

5.1 When an alternating voltage is applied to a circuit, the resulting current has the same frequency as the applied voltage.

In some circuits, the current and voltage waves reach their peak positive or negative values at the same instant. In such circuits, current and voltage are "in phase" (Fig. 9).

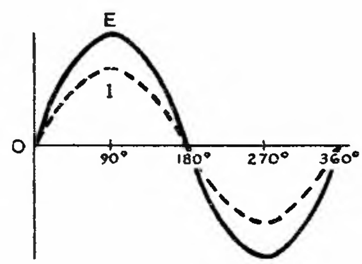
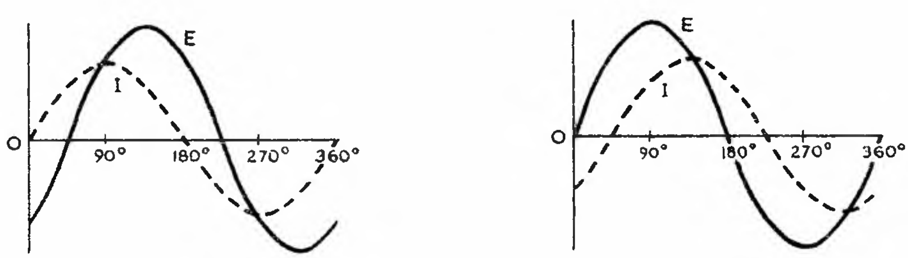


FIG. 9. CURRENT AND VOLTAGE IN PHASE.

In many circuits the current wave reaches its peak value before or after the voltage wave does so. In these cases current and voltage are "out of phase".

5.2 The current in "out of phase" circuits, is said to lead or lag the applied voltage, depending on whether it reaches its maximum positive value before or after the voltage reaches its maximum positive value. (Figs. 10a and b.)



(a) Current Leads Voltage by 45°. (b) Current Lags Voltage by 45°.

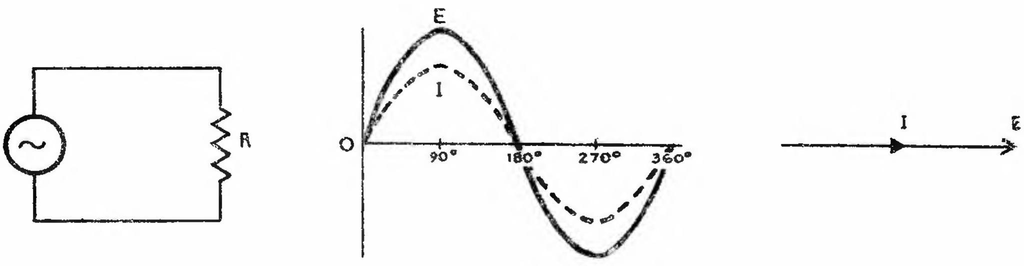
FIG. 10. CURRENT AND VOLTAGE OUT OF PHASE.

The time or fraction of a cycle by which the current leads or lags the voltage in an A.C. circuit at a particular frequency is called the phase difference. Phase difference is often expressed as a phase angle (θ) in electrical degrees.

6. RESISTANCE IN A.C. CIRCUITS.

6.1 The Resistance of a material is the opposition it offers to the passage of current, and it depends upon the nature of the material, and upon its length of cross-sectional area. When an A.C. circuit contains resistance only, the current in the circuit can be calculated directly from Ohm's Law, provided that effective values are used.

6.2 Phase Relationship. In purely resistive circuits, (Fig. 11a) changes in the applied voltage cause corresponding changes in the current, with the result that current and voltage are in phase, as in Figs. 11b and c.



(a) (b) (c)

FIG. 11. RESISTANCE IN A.C. CIRCUITS.

6.3 Effect of Frequency. In some A.C. circuits, the resistance of a conductor is found to be higher than when the conductor is part of a D.C. circuit. This is due to the non-uniform distribution of the current over the cross-section of the conductor when A.C. flows.

The passage of A.C. produces an alternating flux which cuts across the conductor developing in it opposing self induced e.m.fs. which are of a higher value at the centre of the conductor than at the surface.

The result is, that current finds an easier path on the outer surface of the conductor, and as such the effective cross-sectional area is reduced.

The tendency for A.C. to flow in the outer "skin" of the conductor in preference to using the whole cross-sectional area is known as "Skin Effect".

Skin Effect is most noticeable at high frequencies, as the higher the frequency the greater are the self induced e.m.fs. at the centre of the conductor, and it is more noticeable in conductors which have a high permeability, for example, in G.I. line wire. It is kept to a minimum by using low permeability conductors that are tubular or which consist of a number of individually insulated interwoven strands.

6.4 Power in Resistive Circuits. When current flows in a resistive circuit it produces heat, irrespective of its direction. As effective values of A.C. produce the same heating effect as similar values of D.C., the rate of energy transformation, or power in a purely resistive circuit can be calculated from -

$$\text{POWER} = E \times I \; : \; I^2 \times R \; : \; \frac{E^2}{R}$$

where

E = Applied Voltage

I = Current in amperes.

R = Resistance in ohms.

7. INDUCTANCE IN A.C. CIRCUITS.

7.1 An Inductor is a device in which energy is stored in a magnetic field. In the paper "Electromagnetic Induction" of Applied Electricity I, we saw that when the current through an inductor changes, the changing magnetic flux induces an e.m.f. in the circuit, which, according to Lenz's Law, opposes the original change in current.

The ability of a circuit to oppose any change in the current is known as Inductance.

7.2 The Unit of Inductance is the Henry, and a circuit has an inductance of 1 Henry when a current changing at a rate of one ampere per second, induces in it an e.m.f. of one volt.

Whilst the Henry is quite a practical unit, in telecom, we often find it convenient to use submultiple units. They are -

- the millihenry (mH.) which is one thousandth ($\frac{1}{10^3}$ or 10^{-3}) of 1 Henry.
- the microhenry (μH.) which is one millionth ($\frac{1}{10^6}$ or 10^{-6}) of 1 Henry.

All conductors possess inductance; even a straight wire has an e.m.f. induced in it when the magnetic field surrounding it changes. However, almost all practical "inductors" are wound into a coil, the physical properties of which determine the inductance value.

7.3 When A.C. flows in an inductive circuit, the continually changing current produces a continuous opposition or reactance, which is distinct from the normal circuit resistance.

Inductive Reactance (Symbol X_L) is a measure of the opposition to A.C. offered by an inductive circuit. The reactance of a coil is measured in ohms and is determined by -

(i) The Inductance. When the inductance of a coil is increased, the opposition to current change is increased, and so, inductive reactance is increased.

(ii) The Frequency. The magnetic flux, producing the self induced e.m.f. changes at the same rate as the current which produces it. We have seen that the rate of change of current for sine wave A.C. is 2π radians per cycle. When the frequency is increased, the flux changes at a faster rate causing greater opposition.

$$X_L = \omega L$$

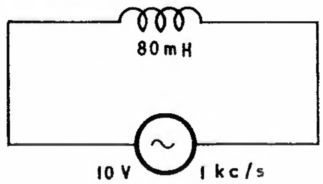
where X_L = Inductive reactance in ohms.
ω = $2\pi f$.
L = Inductance in henries.

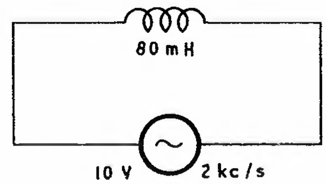
In practice, it is impossible to obtain a purely inductive coil, as its windings and connections must possess some resistance, and when this is large, it must be taken into account when determining the total opposition to current. However, when the resistance is small in comparison with the reactance, it can be ignored in simple calculations.

In the inductive components we use in telecom circuits, there are other factors which influence the opposition to A.C. Generally, the total opposition of a component at a certain frequency is reduced when -

- a steady flux is produced in the magnetic circuit by a D.C. in the winding or by the presence of a permanent magnet. This causes partial saturation of the core and prevents the magnetic field from changing to the same degree as the current.
- copper slugs or short-circuit turns are added. The flux caused by the eddy currents in the slugs opposes the main flux and reduces the magnitude of the self-induced e.m.f.

Example No. 5. Find the value of the current when an alternating voltage of 10 volts at frequencies of (i) 1 kc/s, (ii) 2 kc/s is applied to an 80 mH inductor of negligible resistance.





(i).... $X_L = \omega L$

$= \frac{6.28 \times 1{,}000 \times 80}{1000}$

$=$ 500 ohms (approx.)

$I = \frac{E}{X_L}$

$= \frac{10 \times 1000}{500}$ mA.

$=$ 20 mA.

(ii).... $X_L = \omega L$

$= \frac{6.28 \times 2{,}000 \times 80}{1000}$

$=$ 1000 ohms (approx.)

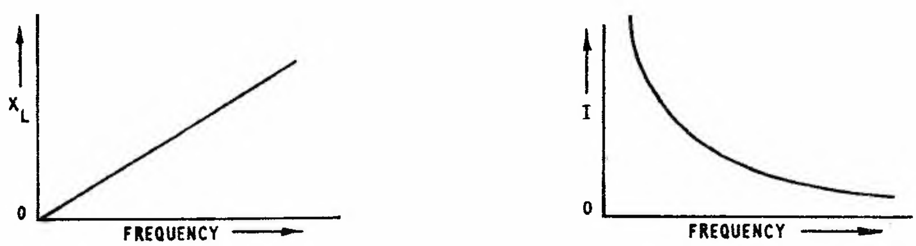
$I = \frac{E}{X_L}$

$= \frac{10 \times 1000}{1000}$ mA.

10 mA.

Answer = (i) 20 mA. (ii) 10 mA.

7.4 Effect of Frequency. As shown in Example No. 5, when the frequency of the A.C. applied to an inductor is increased, the inductive reactance is increased and the current is reduced. The variations which occur in reactance and current in a purely inductive circuit when the frequency is varied are as shown in Fig. 12a and b.



(a) Inductive Reactance Increases as Frequency Increases

(b) Current Decreases as Frequency Increases

FIG. 12. EFFECT OF FREQUENCY ON INDUCTIVE CIRCUIT.

7.5 Inductors Connected in Series. When there is no mutual inductance, the total reactance of a number of inductors connected in series is the sum of the individual reactances.

$$X_L = X_{L1} + X_{L2}$$

7.6 Inductors Connected in Parallel. As more than one current path is provided when inductors are connected in parallel, the joint reactance is determined by the same method as is applied to parallel resistors, provided no mutual inductance exists.

$$\frac{1}{X_L} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}}$$

When there is mutual inductance present between series or parallel connected inductors, factors such as the degree of coupling and the method of connection must be considered before the combined reactance can be found.

7.7 Phase Relationship. There is another characteristic of inductive circuits which is important in the study of A.C. The voltage across an inductor reaches its maximum value when the rate of change of current is greatest. In "sine wave" A.C. circuits containing inductance only, this instant occurs when the current is zero value. In such circuits, current lags the applied voltage by 90°.

Fig. 13a illustrates a circuit containing a "pure" inductance (that is, the resistance is negligible). An alternating sine wave voltage is applied, and the resulting current is as shown in Fig. 13b.

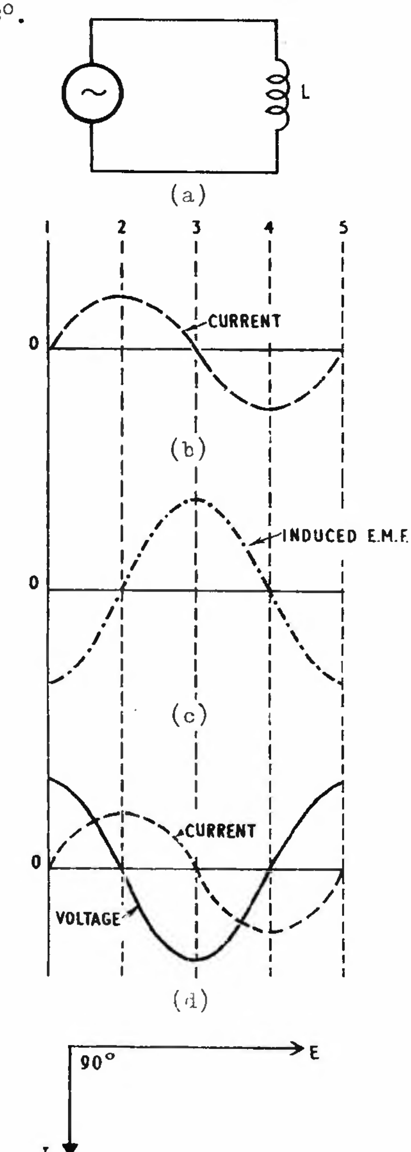
In Fig. 13b we see that at points 2 and 4, the current has reached its maximum value, and as it is momentarily steady, the rate of change of current is zero. Consequently the self induced e.m.f. is zero at these points. (Fig. 13c.)

At points 1, 3 and 5 the current value is zero but here the rate of change of current is the greatest for the cycle. As the magnetic flux has the same rate of change as the current, the rate of change of flux is greatest at these points. The self induced e.m.f. reaches its maximum value when the flux is changing at the maximum rate, that is, at points 1, 3 and 5.

As the self induced e.m.f. opposes the change which produces it, its direction at points 1, 3 and 5 is opposite to the direction of current growth at these instants. At points 1 and 5 the current is changing in a positive direction, therefore the self induced e.m.f. is maximum in the negative direction; at point 3 the current is changing in a negative direction, therefore here, the self induced e.m.f. reaches its maximum positive value. This is shown in Fig. 13c.

By Lenz's Law the direction of the induced e.m.f. is at all times opposite to the change which produces it. Here the change is the applied voltage. The applied voltage is therefore, at all instants, equal in magnitude but opposite in direction to the induced e.m.f.

When we draw this voltage in opposition to the self induced e.m.f. (Fig. 13d), we see that in a purely inductive circuit the current reaches its maximum positive value one quarter of a cycle later than the voltage - or the current lags this voltage by 90°. This is shown vectorially in Fig. 13e.



INDUCTANCE IN A.C. CIRCUITS.
FIG. 13.

The statement "current lags the applied voltage by 90°" is correct only when the inductor has no resistance. In practical inductors, which contain resistance as well as inductive reactance, the applied voltage is distributed partly across the resistance and partly across the reactance. In this case, it is only the reactive component of applied voltage, that is, the P.D. across the inductive reactance which is 90° out of phase with current. As the P.D. across the resistance is in phase with current, the current lags the applied voltage (which is the resultant of the P.D's) by less than 90°. This point is dealt with in the paper "Series A.C. Circuits".

7.8 Power in Inductive Circuits. When A.C. flows in an inductor, a magnetic field builds up and collapses every half cycle. During the first quarter cycle, energy is taken from the source to create the magnetic field. This energy is restored to the supply when the field collapses during the next quarter cycle. Although current flows, no energy is expended in a purely inductive circuit.

7.9 Inductance in Telecom Circuits. The applications of inductance in telecom equipment are many and varied, as shown in the following examples.

(i) A.C. Suppression. Rectifiers alone do not produce a steady D.C., but convert each cycle of input A.C. into two half-cycle unidirectional pulses. This is the equivalent of a steady D.C. with a superimposed A.C. component.

When connected in series with the output (Fig. 14) an inductor called a "choke" coil offers high opposition to the A.C. ripple and reduces its magnitude whilst allowing the D.C. to pass readily.

Inductors used in this application range in value from less than 1 henry to approximately 30 henries.

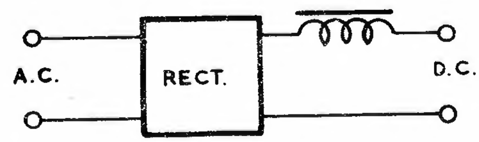


FIG. 14.

Other examples of the application of this characteristic of inductance are found in -

- transmission battery feeds
- C.B. P.M.B.X. alarm (buzzer) circuits,

(ii) Current Control. As the reactance of an inductor is capable of limiting the current in an A.C. circuit without energy loss, variable inductors are employed to control the current in input and output circuits of battery charging equipment.

The reactance of the inductor may be varied in three ways.

- by adjustment of a coil-tapping switch
- by the insertion or withdrawal of a movable portion of the iron core
- by varying the degree of saturation of the magnetic circuit, by varying a D.C. in an auxiliary winding.

This latter method is widely used in modern telecom power plant with automatic output voltage control.

(iii) Loading. In following sections of the paper, dealing with capacitance in A.C. circuits, we will find that the effect of capacitance is opposite to that of inductance, and that one can be used to counter-balance the other.

As the wires in underground cables run side by side, each pair has an appreciable value of capacitance, which adversely affects the transmission performance. By connecting inductors called "loading coils" in series along the cable, the undesirable capacitive effect can be overcome. This process is known as "loading".

Inductance has many other applications in telecom in such items as oscillators, equalizers, filters, aerial coupling units and carrier frequency generators.

These are described in other papers of the course.

8. CAPACITANCE IN A.C. CIRCUITS.

8.1 A Capacitor is a device in which energy is stored in an electric field. In the paper "Capacitance", of Applied Electricity I, we saw that a practical capacitor consists essentially of two conducting plates separated by a thin layer of insulating material, or dielectric.

When an e.m.f. is applied to such a capacitor the electric field produced between the plates distorts the orbits of the outer electrons in the atoms of the dielectric. This limited electron movement in the dielectric, results in a momentary "charging current" in the circuit. When the dielectric is strained in this way, a P.D. is produced across the capacitor which opposes the applied voltage. The charging current ceases when the capacitor counter voltage equals the applied e.m.f. and the capacitor is then said to be "charged".

Should the charging voltage be removed, and the capacitor be connected in a closed circuit, the electrons in the dielectric atoms restore to their normal orbits, and a discharge current, opposite in direction to the charge current, flows in the circuit.

8.2 The Unit of Capacitance is the Farad. A capacitor has a capacitance of one Farad when a charge of one coulomb raises the P.D. across the plates by one volt.

The farad is too large for practical use, and submultiple units are generally used. They are :-

- the microfarad (μF), which is one millionth ($\frac{1}{10^6}$ or 10^{-6}) of one Farad
- the micromicrofarad ($\mu\mu$F) or picofarad (pF), which is one million-millionth ($\frac{1}{10^{12}}$ or 10^{-12}) of one Farad.

8.3 When an alternating e.m.f. is applied to a capacitor, the capacitor alternately charges and discharges. Although no current passes through the dielectric, an A.C. flows in the external circuit. This current is limited by the reactance set up by the capacitor counter voltage.

Capacitive reactance (Symbol X_C) is a measure of the opposition to A.C. offered by a capacitor. The reactance of a capacitor is measured in ohms and is determined by -

(i) The Capacitance. When the capacitance is increased, the quantity of electricity required to charge the capacitor to the same potential is increased, so the current in the circuit must increase also. An increase in current indicates that the capacitive reactance is reduced.

(ii) The Frequency. When the state of charge on the capacitor is changed in any way, current flows in the circuit. When the frequency is increased, the rate of change of charge is increased, which means that the current is correspondingly increased and capacitive reactance is reduced. We have seen, that, for sine wave A.C. the rate of change of current is 2π radians per cycle.

Capacitive reactance can be found from -

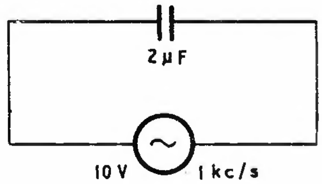
$$X_C = \frac{1}{\omega C}$$

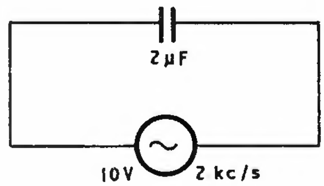
where

X_C = Capacitive reactance in ohms.
ω = $2\pi f$.
C = Capacitance in Farads.

In practice it is not possible to obtain a purely capacitive capacitor, as its plates and connections must contain some D.C. resistance, but this can be ignored in simple calculations.

Example No. 6. Find the current in the circuit when an alternating voltage of 10 volts at a frequency of (i) 1 kc/s (ii) 2 kc/s is applied to a 2μF capacitor of negligible resistance.





(i) .... $X_C = \frac{1}{\omega C}$

$= \frac{1,000,000}{6.28 \times 1,000 \times 2}$

= 80 ohms (approx.)

$I = \frac{E}{X_C}$

$= \frac{10 \times 1,000}{80}$ mA

= 125 mA.

(ii) .... $X_C = \frac{1}{\omega C}$

$= \frac{1,000,000}{6.28 \times 2,000 \times 2}$

= 40 ohms (approx.)

$I = \frac{E}{X_C}$

$= \frac{10 \times 1,000}{40}$ mA.

= 250 mA.

Answer = (i) 125 mA; (ii) 250 mA.

8.4 Effect of Frequency. As shown in Example No. 6, when the frequency of the A.C. applied to a capacitor is increased, the capacitive reactance decreases and the current in the circuit increases correspondingly. The variations in reactance and current in a purely capacitive circuit when the frequency is varied, are as shown in Fig. 15a and b.

(a) Capacitive Reactance Decreases as Frequency Increases

(b) Current Increases as Frequency Increases

FIG. 15. EFFECT OF FREQUENCY ON CAPACITIVE CIRCUIT.

8.5 Capacitors Connected in Series. When capacitors are connected in series, the total reactance is the sum of the reactances of the individual capacitors.

$$X_C = X_{C1} + X_{C2}$$

8.6 Capacitors Connected in Parallel. The joint reactance of capacitors connected in parallel is determined in a similar manner to that employed for parallel resistors.

$$\frac{1}{X_C} = \frac{1}{X_{C1}} + \frac{1}{X_{C2}}$$

8.7 Phase Relationship. We have seen that current flows in a capacitive circuit, only while the capacitor is charging or discharging, or, in other words, when the state of charge is changing. Maximum current flows when the charge is changing at the greatest rate. In A.C. circuits containing capacitance only, this instant occurs when the applied voltage is at zero value. In such circuits, the current leads the applied voltage by 90°.

Fig. 16a illustrates a circuit containing "pure" capacitance. An alternating sine wave voltage is applied and a current flows. The voltage maintained across the capacitor is shown in Fig. 16b.

As the charge on the capacitor is proportional to the voltage maintained across it, $(Q = CE)$, the charge on the capacitor rises and falls in phase with this voltage, as shown in Fig. 16b.

At points 2 and 4 on Fig. 16b, the charge is momentarily steady. As current can flow only when the state of charge is changing, the current at these points is zero.

At points 1, 3 and 5, the charge is changing at the greatest rate, and thus the current is at a maximum value at these instants. At points 1 and 5, the charge is changing in a positive direction, so current at these points reaches its maximum positive value. At point 3, the charge is changing in a negative direction therefore the current attains its maximum negative value. The variations in current are shown in Fig. 16c.

In Fig. 16d the current wave, which, for sine wave applied voltage, is also a sine wave, is referred to the voltage wave. We see that the current reaches its maximum positive value, one quarter of a cycle, or 90° before the voltage wave does so.

In a purely capacitive circuit therefore, the current leads the applied voltage by 90°. This is shown vectorially in Fig. 16e. When the circuit contains resistance as well as capacitance however, the phase difference between current and applied voltage is less than 90° as only portion of the applied voltage is dropped across the capacitive reactance.

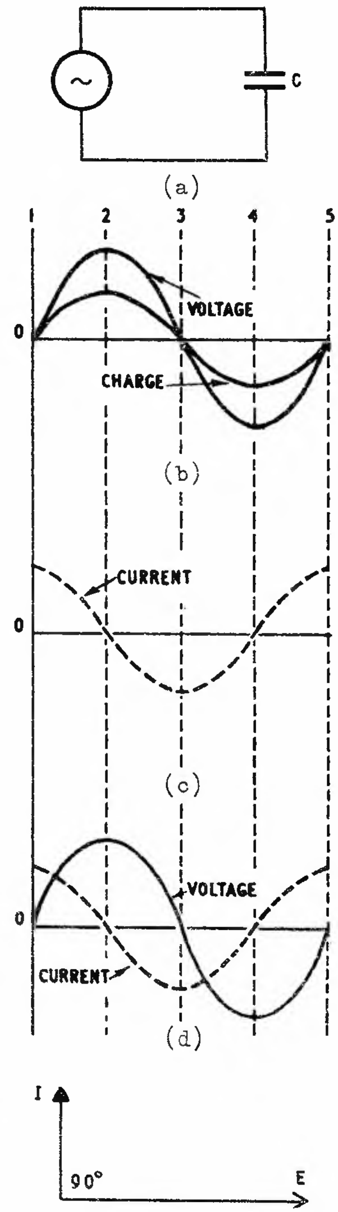


FIG. 16. CAPACITANCE IN A.C. CIRCUIT.

8.8 Power in Capacitive Circuits. A capacitor in an A.C. circuit charges and discharges twice during each cycle. The energy stored when the capacitor charges is returned to the circuit during discharge, and total power dissipation for each half cycle is zero.

In practice, a small amount of energy is converted to heat due to the resistance of the plates but, as this is small, it is often ignored.

8.9 Capacitance in Telecom. Circuits. The capacitor is a very important item in telecom circuits, and it would be a very difficult task to find one item of equipment that does not contain at least one capacitor. Some typical applications of capacitors in telecom are as follows -

(i) Speech Current By-pass Circuit. It is common practice in telecom circuits to include supervisory relays or sometimes non inductive resistors in the transmission circuits of C.B. P.M.B.Xs. and intercom. units. As these relays are inductive, their high opposition to A.C. speech currents could seriously reduce the level of transmission.

By connecting a capacitor (usually 2 μF) in parallel with the relay or resistor, as in Fig. 17, a comparatively low reactance path (40 ohms at 2 kc/s) is provided for speech currents.

FIG. 17. SPEECH CURRENT BY-PASS CIRCUITS.

(ii) Filter Circuits. We have seen that an inductor connected in series with the output of a rectifier smoothes out the pulsating D.C. However, even when the inductor is included, there is still an appreciable A.C. "ripple" present in the output. Should the rectifier be supplying power for the operation of a P.M.B.X. or similar equipment, a "hum" would be heard in every telephone.

This can be almost eliminated by connecting a capacitor across the output of the rectifier as in Fig. 18. The capacitor provides a low reactance path for this A.C. so that it does not pass through the load circuit.

The capacitor used must have a high value of capacitance so that its reactance to the low (power) frequency is small. Capacitors up to 40,000, μF are used in this application.

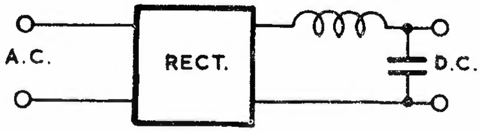


FIG. 18. FILTER CAPACITOR.

(iii) Coupling. Many telecom circuits require one section of the circuit isolated from another section as far as D.C. is concerned, but, at the same time, an A.C. connection must be provided between the two parts. This "coupling" can readily be provided by a capacitor. We find many examples of this in telecom, some of which are -

- the connection of the operators circuit in a C.B. switchboard cord circuit
- the Stone method of transmission feed.

There are many other applications of capacitance in our telecom equipment, but it is not possible to cover them all here. As a matter of interest, items of equipment, in which the capacitor is a vital component include -

amplifiers, oscillators, filters, equalisers, timing circuits, spark quench circuits and voltage doubling rectifiers. These are covered in other papers of the course.

9. ADDITION OF OUT-OF-PHASE VOLTAGES OR CURRENTS.

9.1 In D.C. circuits, the resultant of a number of voltages or currents can be found by simple arithmetic. In A.C. circuits, the same method can be applied to "in phase" voltages and currents, but when currents or voltages are out of phase, they cannot be combined so simply.

There are two basic methods of adding "out of phase" alternating currents or voltages -

(i) the graphical method
(ii) the vectorial method.

9.2 Graphical Addition. Figs. 19 and 20 illustrate the usual method adopted for graphical addition.

Two sine wave voltages "A" and "B", 90° out of phase, each of 70 volts (peak value 100 volts approx.) are to be added. The procedure is -

(i) Draw graphs of the two voltages in their correct phase relationship along a common time axis, as is partly done in Fig. 19a.
(ii) Plot the direction and instantaneous values of one wave at a number of points (Fig. 19b).
(iii) Add these instantaneous values algebraically at corresponding points on the other wave (Fig. 19c).
(iv) Join the ends of these lines to form the graph of the resultant (Fig. 19c).

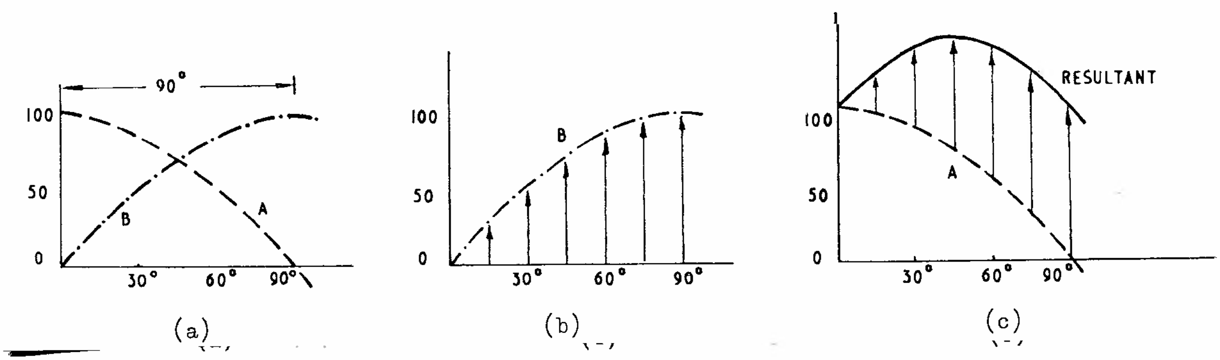


FIG. 19. GRAPHICAL METHOD.

Fig. 20 shows the completed diagram. The resultant has an effective value of approx. 100 volts (peak value 140 volts approx.) and there is a phase difference of 45° between it and each of the original waves.

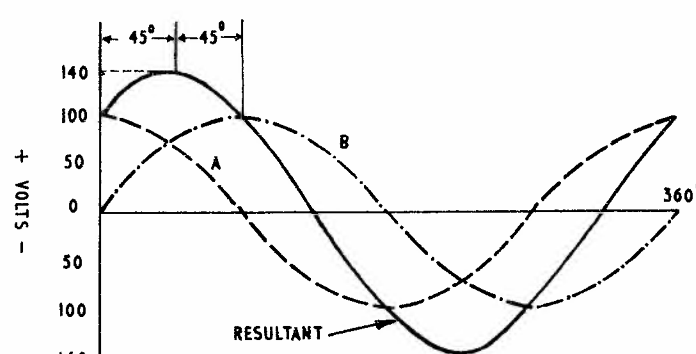


FIG. 20. GRAPHICAL ADDITION.

This method is also applicable to the addition of out of phase currents and is often used to show the wave form of two or more non sine waves.

9.3 Vector Addition. Where the wave form of both waves is the same, the resultant of two out of phase currents or voltages can be found quickly and accurately by using vectors.

A vector is a line whose length and direction represent the magnitude and direction of some physical quantity.

Vectors representing alternating currents and voltages are drawn so that -

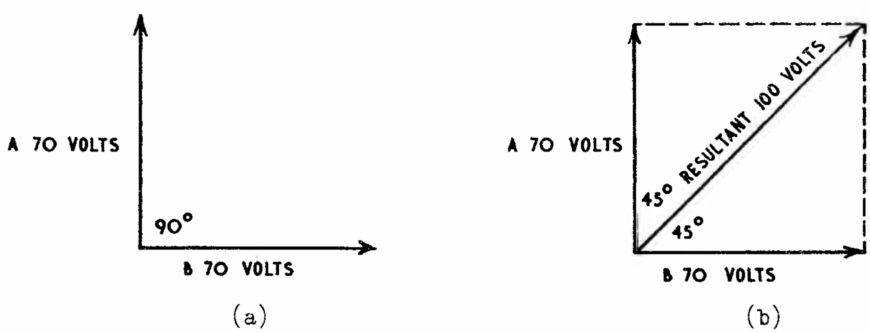
- the length of the vector represents the effective value.
- the angle at which the vectors are drawn to each other or to a reference line indicates the phase angle.
- the direction of rotation (anti-clockwise), indicates leading or lagging phase relationships.

It is customary to use open arrow-heads for voltage vectors and closed arrow-heads for current vectors.

Fig. 21 shows the method of combining the voltages of para. 9.2 by vectors. The procedure is :-

(i) Draw vectors representing the voltages "A" and "B" to scale. As voltage "A" leads voltage "B" by 90°, it is drawn at right angles above the "B" vector, (Fig. 21a).

(ii) Complete the parallelogram on vectors "A" and "B" (Fig. 21b). The length of the diagonal drawn from the point of intersection of the vectors represents the effective value of the resultant. The angle it makes with the original vectors indicates the phase relationship.



VECTOR ADDITION.

FIG. 21.

By measurement on Fig. 21b, the resultant has an effective value of 100 volts (approx.) and there is a 45° phase difference between it and the two original waves.

When a number of currents or voltages in the same circuit are to be added vectorially, it is convenient to show their phase relationship by drawing each in relation to a reference vector.

This reference vector must represent a factor in the circuit common to all the currents or voltages to be combined.

For example -

- voltages in a series circuit are referred to a common current reference vector.
- currents in a parallel circuit are referred to a common voltage reference vector.

It is customary to draw this reference vector horizontally.

9.4 Vector diagrams, similar to Fig. 21 are used extensively to illustrate A.C. circuit conditions and to simplify A.C. problems. Applications of vectors are given in the papers "Series A.C. Circuits" and "Parallel A.C. Circuits".

10. TEST QUESTIONS.

1. What is an alternating current?

2. Frequencies used in telecom are measured in ...., ... or ....

3. Frequencies which produce sounds that can be heard are called ....

4. Radio Frequencies are those which ....

5. In trigonometry sine = ...

   cosine = ...

   tangent = ...

6. From the trigonometry tables,

   sin. $36^{\circ}18'$ = ...; cos $42^{\circ}10'$ = ...; tan $29^{\circ}15'$ = ...

7. From the trigonometry tables,

   sin. ....$^{\circ}$.....' is 0.6372; cos ....$^{\circ}$.....' is 0.7026; tan ....$^{\circ}$.....' is 0.5624.

8. The hypotenuse of a right-angle triangle is 41" long, and one side is 9" long. What is the length of the third side?

9. The angles included in this triangle would be ....$^{\circ}$ and ....$^{\circ}$.

10. What is meant by "Phase angle"?

11. At 30° after the zero point, a sine wave A.C. has an instantaneous value of 5 amps. State -

    (i) The peak value ....

    (ii) The effective value ....

12. Alternating currents and voltages are measured in .... values.

13. What is meant by "form factor"?

14. In a purely resistive circuit, the current leads / lags / is in phase with the applied voltage.

15. At high frequencies, the resistance of a conductor increases / decreases due to ....

16. The opposition to A.C. offered by an inductor is called ....

    This opposition increases / decreases / remains unchanged when the frequency is increased.

17. In purely inductive circuits, current leads / lags / is in phase with voltage by ....$^{\circ}$.

18. In purely capacitive circuits, the current is limited by the .... which increases / decreases / remains unchanged when the frequency is increased.

19. In such circuits, the current leads / lags / is in phase with the applied voltage by ....$^{\circ}$.

20. What is a vector?

END OF PAPER

SERIES A.C. CIRCUITS.

---

1. INTRODUCTION.

1.1 In studying electrical theory, calculations are necessary to illustrate the characteristics of the circuit to be considered. As it is essential to adopt a logical and methodical approach to the solving of all problems, this paper follows the step by step method outlined in the paper "Ohm's Law" of Applied Electricity I, and before proceeding further you should revise these steps to help you in the more involved problems which follow.

1.2 This paper deals with series A.C. circuits, which contain combinations of resistance, inductance and capacitance. Where possible, calculations in this and other papers of Applied Electricity 2 are related to telecom; complex problems with obscure applications are avoided.

1.3 All A.C. calculations involve the factor π. The <u>exact</u> value of π cannot be calculated, and in our work we use 3.14 as π. As the value used for π is approximate, it is quite in order to simplify calculations by using approximate values. For example, the reactance of $1\mu F$ capacitor at 1 kc/s is 159.23 ohms (approx.), using $\pi = 3.14$. The error introduced by stating $X_c = 160$ ohms is about 0.5%, which is negligible. There is, however, a limit to the degree of approximation we can tolerate, and approximations which incur an error of more than 1% should be avoided.

2. SERIES A.C. CIRCUITS.

2.1 Series Circuits. We have seen that the characteristics of any series circuit are -

(i) the current is the same in all parts.

(ii) the sum of the P.D's around the circuit equals the applied voltage.

When we apply these rules to A.C. circuits, it must be remembered that the P.D's across reactive and resistive components are out of phase. Consequently, the addition of these voltages to find the applied voltage must be done vectorially.

2.2 Impedance. In A.C. circuits containing reactance and resistance, the total opposition to current flow is termed the impedance, the symbol for which is Z.

Impedance is measured in ohms, and Ohm's Law as applied to A.C. circuits is as follows -

$$I = \frac{E}{Z}$$

where

I = Current in amperes

E = Applied voltage

Z = Impedance in ohms.

3. RESISTANCE AND INDUCTANCE IN SERIES.

3.1 Fig. 1 shows a circuit containing resistance (R) and inductance (L) connected in series to an alternating voltage. The current (I) produces a P.D. across the resistance (E_R) and a P.D. across the inductance (E_L), the vector sum of which equals the applied voltage (E).

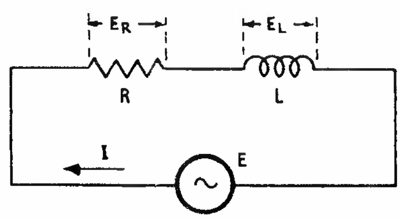


FIG. 1. RESISTANCE AND INDUCTANCE IN SERIES.

3.2 Potential Differences. The P.D's across the components are calculated from Ohm's Law as follows -

$$E_R = I \times R$$

$$E_L = I \times X_L$$

where

E_R = P.D. across the resistance in volts

E_L = P.D. across the inductance in volts

I = Current in amperes

R = Resistance in ohms

X_L = Inductive reactance in ohms.

3.3 Vector Diagram. In Fig. 2, the applied voltage (E) is found from the vector sum of the P.D's E_R and E_L. As each P.D. has a definite phase relationship to the circuit current (I), the phase difference between E_R and E_L can be shown vectorially when vectors representing these P.D's are drawn in relationship to the current vector, which is drawn horizontally.

As the current is in phase with the P.D. across the resistance, the E_R vector is drawn to scale along the horizontal reference vector, I as in Fig. 2a. The current lags the P.D. across the inductance by 90°, therefore the E_L vector is drawn to scale at right angles above I as in Fig. 2a.

When a parallelogram is constructed (Fig. 2b), the length of the diagonal represents the value of the applied voltage, and the circuit phase angle (θ) is shown by the angle the E vector makes with the current (reference) vector.

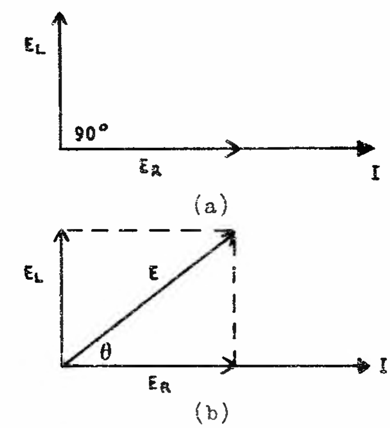


FIG. 2. VECTOR DIAGRAM.

The applied voltage can be calculated by applying Pythagoras' Theorem to Fig. 2b.

$$E = \sqrt{E_R^2 + E_L^2}$$

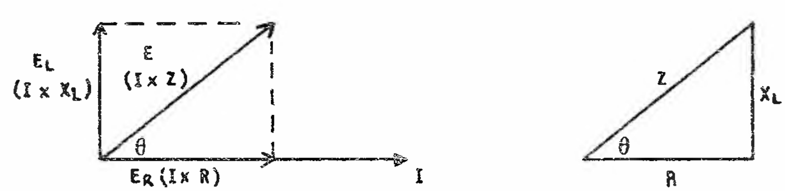
where

E = Applied voltage

E_R = P.D. across resistance in volts

E_L = P.D. across inductance in volts.

3.4 Impedance Formula. As the current is a common factor to voltages E_R, E_L and E, we can represent the circuit by a right-angle triangle, the lengths of the sides of which represent the values of R, X_L and Z. (Fig. 3b.)



(a) Vector Diagram (b) Impedance Diagram

FIG. 3. IMPEDANCE DIAGRAM.

Applying Pythagoras' Theorem to Fig. 3b.

$$Z = \sqrt{R^2 + X_L^2}$$

where

Z = Impedance in ohms

R = Resistance in ohms

X_L = Inductive reactance in ohms.

As inductive reactance varies with frequency, reference must be made to a particular frequency when stating the impedance of such a circuit.

3.5 Phase Angle. Applying trigonometry to Fig. 3b, the angle by which the current lags the applied voltage can be calculated from -

$$\tan.\ \theta = \frac{X_L}{R}$$

where

θ = Phase angle in degrees

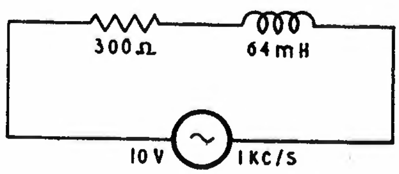
X_L = Inductive reactance in ohms

R = Resistance in ohms.

3.6 Example No. 1. A 64 mH inductor is connected in series with a 300 ohm resistor to a 1 kc/s alternating voltage of 10 volts. Find -

(i) the impedance
(ii) the phase angle
(iii) the current
(iv) the P.D. across the resistor
(v) the P.D. across the inductor.

Include a vector diagram to represent the voltage distribution in the circuit.



$X_L = \omega L$

$= \frac{6.28 \times 1000 \times 64}{1000}$

$=$ 400 ohms (approx.)

(i) ... $Z = \sqrt{R^2 + X_L{}^2}$

$= \sqrt{300^2 + 400^2}$

$= \sqrt{90,000 + 160,000}$

$= \sqrt{250,000}$

$=$ 500 ohms

(ii) $\tan\theta = \frac{X_L}{R}$

$= \frac{400}{300}$

$= 1.3333$

From tables

$\tan 53^\circ 8' = 1.333$

$\therefore$ Angle $\theta = 53^\circ 8'$ lagging.

(iii) ... $I = \frac{E}{Z}$

$= \frac{10 \times 1000}{500}$ mA

$=$ 20 mA

(iv) ... $E_R = I \times R$

$= \frac{20 \times 300}{1000}$

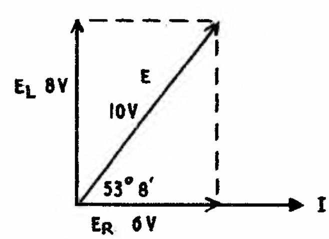
$=$ 6 volts

(v) ... $E_L = I \times X_L$

$= \frac{20 \times 400}{1000}$

$=$ 8 volts

The vector diagram for this circuit is -



Answer = (i) 500 ohms; (ii) 53° 8' lagging; (iii) 20 mA; (iv) 6 volts; (v) 8 volts.

4. RESISTANCE AND CAPACITANCE IN SERIES.

4.1 Fig. 4 shows a series circuit containing resistance (R) and capacitance (C). The applied voltage (E) is found from the vector sum of the P.D. across the resistance (E_R), and the P.D. across the capacitance (E_C).

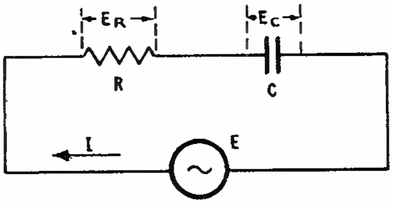


FIG. 4. RESISTANCE AND CAPACITANCE IN SERIES.

4.2 Potential Differences. The potential differences across the resistance and the capacitance in a series circuit are calculated from Ohms Law.

$$E_R = I \times R$$

$$E_C = I \times X_C$$

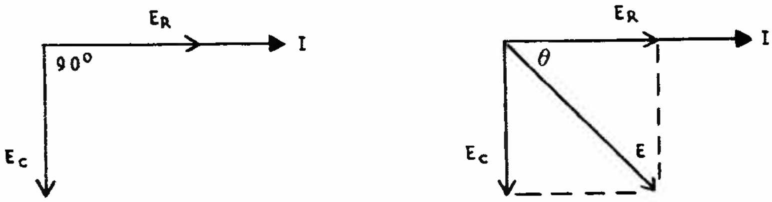
where
E_R = P.D. across the resistance in volts
E_C = P.D. across the capacitance in volts
I = Current in amperes
R = Resistance in ohms
X_C = Capacitive reactance in ohms.

4.3 Vector Diagram. The applied voltage (E) is found from the vector sum of the circuit P.D's. The voltage vector diagram is constructed using the current vector as a reference, in the same way as for series circuits containing resistance and inductance.

The current is in phase with the P.D. across the resistor, therefore, the E_R vector is drawn to scale along the I vector.

As the current leads the capacitor P.D. by 90°, the E_C vector is drawn at right angles below the reference current vector as in Fig. 5a.

When the parallelogram is completed (Fig. 5b), the length of the diagonal represents the value of applied voltage, and the angle made with the reference vector represents the circuit phase angle (θ).



(a) (b)

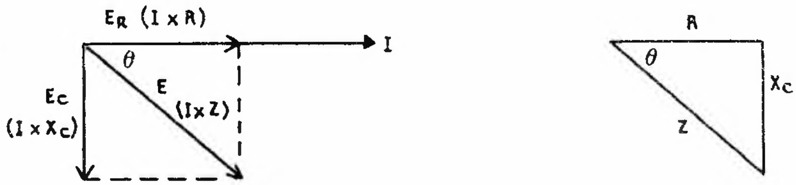
FIG. 5. VECTOR DIAGRAM.

The applied voltage can be found mathematically by applying Phythagoras' Theorem to Fig. 5b, as follows -

$$E = \sqrt{E_R^2 + E_C^2}$$

where
E = Applied voltage
E_R = P.D. across resistance in volts
E_C = P.D. across capacitance in volts.

4.4 Impedance. The current is a common factor to each of the voltages in the circuit, and the voltage vector diagram can be simplified to the Impedance Diagram (Fig. 6b).



(a) Vector Diagram. (b) Impedance Diagram.

FIG. 6. IMPEDANCE DIAGRAM.

From Fig. 6b the impedance of the circuit may be found from -

$$Z = \sqrt{R^2 + X_C^2}$$

where
Z = Impedance in ohms
R = Resistance in ohms
X_C = Capacitive reactance in ohms.

As impedance depends to a large extent on capacitive reactance which varies with frequenc the impedance of such a circuit must be stated as at a particular frequency.

4.5 Phase Angle. In circuits containing resistance and capacitance in series, the current leads the applied voltage by some angle less than 90°.

From Fig. 6b, the phase angle is calculated from -

$$\tan.\ \theta = \frac{X_C}{R}$$

where
θ = Phase angle in degrees
X_C = Capacitive reactance in ohms
R = Resistance in ohms.

4.6 As a matter of interest, it is fairly common in Long Line Equipment practice to state the impedance and phase angle of a circuit or component as a single expression.

For example -

"the characteristic impedance of a telephone line using 100 lb./mile copper conductors, at a frequency of 800 c/s. is given as 804 $\overline{\backslash 20^\circ}$ ohms"

This indicates -

(i) the impedance is 804 ohms.

(ii) the phase angle is 20° leading.

In such expressions the angle sign is drawn as $\overline{\backslash}$ for leading phase angles, (corresponding to θ in Fig. 6b), and as $\angle$ for lagging phase angles (corresponding to θ in Fig. 3b).

4.7 Example No. 2. A 1μF capacitor is connected in series with a circuit of 200 ohms resistance to a 1.6 kc/s alternating voltage of 10 volts. Find -

(i) the impedance

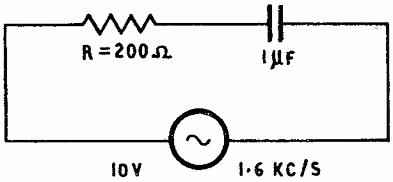
(ii) the phase angle

(iii) the current

(iv) the P.D. across the resistance

(v) the P.D. across the capacitor.

Include a vector diagram to represent the voltage distribution in the circuit.



$X_C = \frac{1}{\omega C}$

$= \frac{1,000,000}{6.28 \times 1600 \times 1}$

$=$ 100 ohms (approx.)

(i) .... $Z = \sqrt{R^2 + X_C^2}$

$= \sqrt{200^2 + 100^2}$

$= \sqrt{40,000 + 10,000}$

$= \sqrt{50,000}$

$=$ 223 ohms (approx.)

(ii) $\tan\theta = \frac{X_C}{R}$

$= \frac{100}{200}$

$= 0.5$

From tables

$\tan 26^\circ 34' = 0.5$

Angle $\theta = 26^\circ 34'$ leading.

(iii) .... $I = \frac{E}{Z}$

$= \frac{10 \times 1000}{223}$ mA

$=$ 45 mA (approx.)

(iv) .... $E_R = I \times R$

$= \frac{45 \times 200}{1000}$

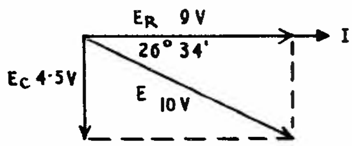
$=$ 9 volts (approx.)

(v) .... $E_C = I \times X_C$

$= \frac{45 \times 100}{1000}$

$=$ 4.5 volts (approx.)

The vector diagram for this circuit is as follows -



Answers - (i) 223 ohms; (ii) 26° 34' leading; (iii) 45 mA; (iv) 9 volts; (v) 4.5 volts.

5. RESISTANCE, INDUCTANCE AND CAPACITANCE IN SERIES.

5.1 Fig. 7 shows a series circuit containing resistance, inductance and capacitance. The current produces P.D.'s across these components, the vector sum of which equals the applied voltage.

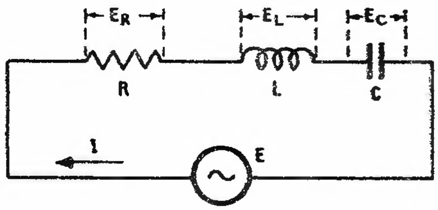


FIG. 7. RESISTANCE, INDUCTANCE AND CAPACITANCE IN SERIES.

5.2 Potential Difference. As in all series circuits, the P.D.'s across the components are calculated from Ohms Law.

$$E_R = I \times R$$

$$E_L = I \times X_L \qquad \text{where}$$

$$E_C = I \times X_C$$

E_R = P.D. across the resistance in volts
E_L = P.D. across the inductance in volts
E_C = P.D. across the capacitance in volts
I = Current in amperes
R = Resistance in ohms
X_L = Inductive reactance in ohms
X_C = Capacitive reactance in ohms

5.3 Vector Diagram. With regard to the P.D.'s in series circuits, we have seen that the current is in phase with E_R, lags E_L by 90°, and leads E_C by 90°.

When we draw a vector diagram for the circuit using the current vector as a reference, we see that E_L and E_C are in opposition (Fig. 8a) and the total reactive P.D. is $(E_L - E_C)$. When the E_R vector is combined with the resultant of E_L and E_C, the length of the resultant indicates the value of the applied voltage, and the angle made with the reference vector is the phase angle (Fig. 8b).

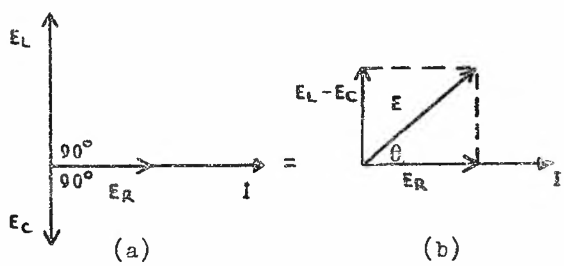


FIG. 8. VECTOR DIAGRAM.

The applied voltage can be calculated mathematically from Fig. 8b by -

$$E = \sqrt{E_R^2 + (E_L - E_C)^2} \qquad \text{where}$$

E = Applied voltage
E_R = P.D. across the resistance in volts
E_L = P.D. across the inductance in volts
E_C = P.D. across the capacitance in volts.

5.4 Impedance. As the current is a common factor to the voltages of Fig. 8b the opposition factors in the circuit can be shown by the Impedance Diagram of Fig. 9b.

(a) Vector Diagram. (b) Impedance Diagram.

FIG. 9. IMPEDANCE DIAGRAM.

From Fig. 9b, the impedance of the circuit can be calculated from -

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

where

Z = Impedance in ohms

R = Resistance in ohms

X_L = Inductive reactance in ohms

X_C = Capacitive reactance in ohms.

In the formula quoted above, it is assumed that X_L is greater than X_C. However the formula still applies when X_C is greater than X_L. In these cases $(X_L - X_C)$ gives a negative result which becomes positive when squared as in Example No. 3.

As the values of X_L and X_C vary with frequency, reference must be made to a particular frequency whenever the impedance of a circuit is stated.

5.5 Phase Angle. In circuits where X_L is greater than X_C, the effect of the capacitance is "swamped" by the greater reactance of the inductance, and the current lags the applied voltage by some angle less than 90°. The degree of "lag" is determined from the ratio of the relative values of $(X_L - X_C)$ and R.

Where X_C is greater than X_L, the resultant circuit reactance is capacitive, and the phase angle is leading, and is found from the ratio of $(X_C - X_L)$ and R.

$$\tan.\theta = \frac{X}{R}$$

where

θ = Phase angle in degrees

X = Resultant reactance of circuit $(X_L - X_C)$ in ohms.

R = Resistance of circuit in ohms.

5.6 Voltage Magnification. In Examples Nos. 1 and 2 of this paper we saw that when resistance and inductance or resistance and capacitance are connected in series, the P.D.'s across the components in the circuit can be comparatively large, but individually they do not exceed the applied voltage.

When inductance and capacitance are connected in series, however, the P.D.'s can be very high, and often can individually be many times greater than the applied voltage.

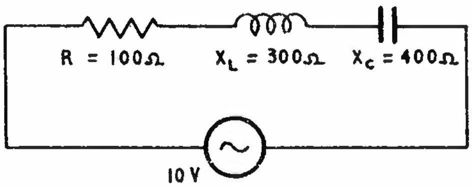
This "voltage magnification" is most noticeable when the inductive reactance and capacitive reactance are approximately equal and are high in comparison with the resistance, as is the case in Example No. 3.

Such circuits are called "resonant circuits" which are widely used in telecommunication and are dealt with in Section 7 of this paper.

5.7 Example No. 3. A series circuit connected to a 10 volt A.C. supply has a resistance 100 ohms, an inductive reactance of 300 ohms and a capacitive reactance of 400 ohms. Find -

(i) the impedance
(ii) the current
(iii) the phase angle
(iv) the P.D. across the resistor
(v) the P.D. across the inductor
(vi) the P.D. across the capacitor.

Include a vector diagram to illustrate the voltage distribution in the circuit.



(i) .... $Z = \sqrt{R^2 + (X_L - X_C)^2}$

$= \sqrt{100^2 + (300 - 400)^2}$

$= \sqrt{100^2 + (-100)^2}$

$= \sqrt{10,000 + 10,000}$

$= \sqrt{20,000}$

= 141 ohms (approx.)

(ii) .... $I = \frac{E}{Z}$

$= \frac{10 \times 1000}{141}$ mA

= 71 mA (approx.)

(iii) $\tan\theta = \frac{X_C - X_L}{R}$

$= \frac{400 - 300}{100}$

$= \frac{100}{100} = 1.$

From tables

$\tan 45^0 = 1$

∴ Angle θ = 45^0 leading.

(iv) .... $E_R = I \times R$

$= \frac{71 \times 100}{1000}$

= 7.1 volts (approx.)

(v) .... $E_L = I \times X_L$

$= \frac{71 \times 300}{1000}$

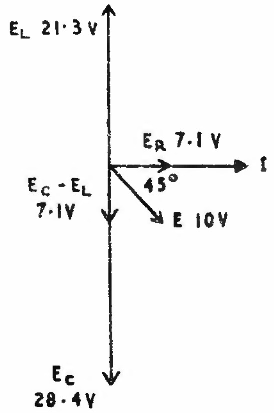
= 21.3 volts (approx.)

(vi) .... $E_C = I \times X_C$

$= \frac{71 \times 400}{1000}$

= 28.4 volts (approx.)

The vector diagram for the circuit is



Answers = (i) 141 ohms; (ii) 71 mA; (iii) 45^0 leading; (iv) 7.1 volts; (v) 21.3 volts; (vi) 28.4 volts.

5.8 In Examples Nos. 1, 2 and 3, the circuit problems have been solved using a nominated value of resistance. It is important to note that when calculations are made on practical A.C. circuits, misleading results may be obtained when the calculations are based on the D.C. or "ohmic" resistance of the circuit.

A.C. circuit calculations must be based on the Effective or A.C. Resistance, which, in most cases, is greater than the D.C. resistance. When figures are quoted for A.C. problems, it is generally assumed that Effective Resistance is meant.

We could define Effective Resistance as that component of impedance, the P.D. across which is in phase with current, and which represents the combined effect of all forms of energy transformation in the circuit.

In a D.C. circuit, all the electrical energy is converted into heat in the D.C. resistance.

In an A.C. circuit, in addition to this, energy is transformed in

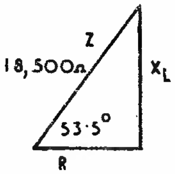
- production of heat in the increased resistance due to "skin effect"
- eddy current and hysteresis losses in inductors
- dielectric losses in capacitors
- induction into neighbouring circuits
- radiation into space.

At very low frequencies, these losses are small, and the Effective Resistance of the circuit is approximately equal to the D.C. resistance.

At higher frequencies, these factors become significantly large, and they must be represented in the circuit by additional resistance of such a value as to cause an equivalent transformation of electrical energy.

There are no set formulae for determining Effective Resistance, but it can be calculated at a particular frequency when the impedance and phase angle have been measured, as in Example No. 4.

Example No. 4. At a frequency of 1 kc/s the impedance of a sample magneto bell is measured at 18,500 ohms, the phase angle being 53.5°. Find the Effective Resistance of the bell at this frequency.



$$\cos 53^\circ\ 30' = \frac{R}{Z}$$

$$\therefore R = Z \times \cos 53^\circ\ 30'$$

$$= 18500 \times 0.5948$$

$$= 11{,}000 \text{ ohms (approx.)}$$

Answer = 11,000 ohms.

We see that the Effective Resistance of the bell at 1 kc/s is very much higher than its 1000 ohms D.C. resistance, but we must remember that the bell is designed to operate at ringing frequency when the power losses would be very much less than at 1 kc/s.

6. POWER IN A.C. CIRCUITS.

6.1 The Power of an electric circuit is the rate at which electrical energy is converted into other forms of energy.

In a purely resistive A.C. circuit, electrical energy is converted into heat at the same rate as in an equivalent D.C. circuit and the power can be calculated from the product of the current and applied voltage.

In purely inductive or purely capacitive A.C. circuits, the electrical energy which is taken to create the electric or magnetic field is restored every alternate quarter cycle when these fields collapse, and the power is zero.

Therefore, in circuits containing both resistance and reactance, electrical energy is converted to heat in the resistive portions only, as no permanent energy transformation occurs due to the reactance. As the applied voltage is distributed partly across the resistance and partly across the reactance, the product of the applied voltage and the current does not give a true indication of the circuit power.

The value obtained from the product of the applied voltage and the current in such circuits is termed the Apparent Power, which is not expressed in watts, but is referred to in terms of Volt-Amp (V.A.) units.

6.2 The True Power of the circuit in watts is the actual rate at which electrical energy is transformed in the resistive portion of the circuit.

The voltage applied to a series circuit containing reactance and resistance can be resolved into two components (Figs. 10a and b).

(i) the P.D. across the resistance (E_R) which is the phase with current

(ii) the P.D. across the reactance (E_L or E_C) which is 90° out of phase with the current.

(a) Inductive Circuit. (b) Capacitive Circuit.

FIG. 10. COMPONENTS OF VOLTAGE.

As the reactive component is ineffective with regard to the power of the circuit, the true power can be found from the product of the resistive component of voltage (E_R) and the current (I).

$$\text{True Power} = I \times E_R$$

$$\text{but } E_R = I \times R$$

$$\therefore \quad \textbf{POWER} = I^2 \times R$$

where I = Current in amperes
R = Resistance of circuit in ohms

The True Power can also be found from -

$$\text{True Power} = I \times E_R$$

From Figs. 10a and b

$$E_R = E \cos\theta$$

$$\therefore \quad \textbf{POWER} = E \times I \times \cos\theta$$

where E = Applied voltage
I = Current in amperes
θ = Phase angle in degrees.

6.3 **Power Factor.** The ratio between the true power in a circuit, and the apparent power is known as **Power Factor**.

$$\text{POWER FACTOR} = \frac{\text{TRUE POWER}}{\text{APPARENT POWER}}$$

$$= \frac{E \times I \times \cos\theta}{E \times I}$$

$$= \cos\theta$$

For a series circuit, $\cos\theta = \frac{R}{Z}$

Therefore -

$$\textbf{POWER FACTOR} = \frac{R}{Z}$$

where θ = Phase angle
R = Resistance in ohms
Z = Impedance in ohms

In purely resistive circuits, the impedance is equal to the resistance.

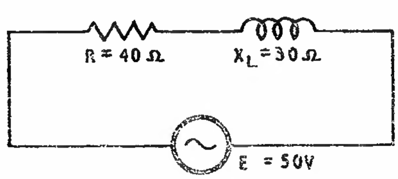
$\therefore$ POWER FACTOR = 1.

As an indication of the nature of the circuit, Power Factor is expressed as "lagging" in inductive circuits, and "leading" in capacitive circuits.

6.4 Example No. 5. In the circuit shown below, find -

(i) the power factor,

(ii) the power in the circuit.



$Z = 50\Omega$
$I = 1$ AMP.
$\theta = 36° 52'$ LAGGING

(i) .... Power Factor $= \frac{R}{Z}$

$= \frac{40}{50}$

$=$ 0.8 lagging (as the circuit is inductive)

(ii) .... ALTERNATIVE METHODS

Power $= I^2R$	Power $= E \times I \times \cos\theta$
$= 1 \times 1 \times 40$	$= 50 \times 1 \times \cos 36^0\ 52'$
$=$ 40 watts.	$= 50 \times 1 \times 0.8$
	$=$ 40 watts.

Answers = (i) 0.8 lagging; (ii) 40 watts.

7. RESONANCE IN SERIES CIRCUITS.

7.1 Up to this point, we have considered the behaviour of series circuits at one or two fixed frequencies. We have seen that both inductive reactance and capacitive reactance vary with frequency, and therefore the characteristics of a series circuit containing inductance, capacitance and resistance must change as the frequency of the applied voltage is changed.

7.2 Series Resonance. When the frequency of the alternating voltage applied to a series circuit containing inductance, capacitance and resistance is increased

- X_L increases as frequency increases.
- X_C decreases as frequency increases.

As X_L and X_C vary, the resultant reactance of the circuit ($X_L - X_C$) changes, the variations for a typical circuit over a range of frequencies being as shown in Fig. 11.

In this diagram (Fig. 11)

X_L and X_C are shown above and below a zero line respectively to indicate their opposing characteristics;

$X_L - X_C$ is shown changing from predominantly capacitive at low frequencies to predominantly inductive at high frequencies.

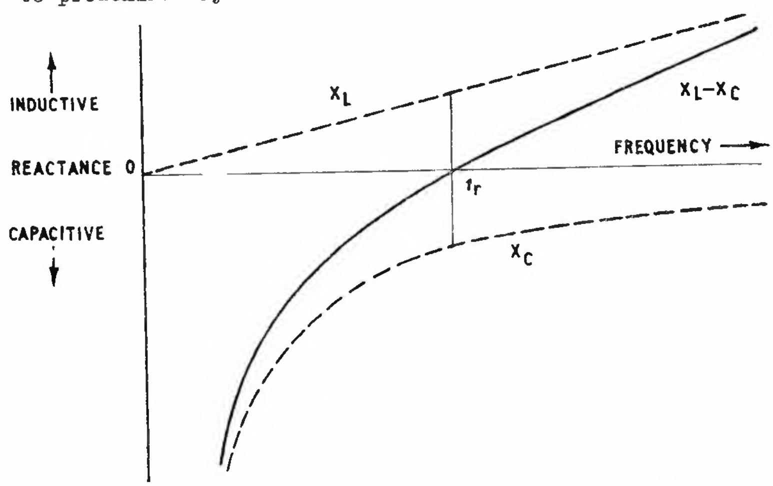


FIG. 11. EFFECT OF FREQUENCY ON REACTANCE.

From Fig. 11 we see that at one particular frequency, the resultant reactance of the circuit is zero.

This frequency is called the Resonant Frequency (f_r), and, in a series circuit, occurs when the inductive reactance equals the capacitive reactance.

Although the reactance of such a circuit is always zero at resonance, all practical circuits contain resistance, and the impedance at resonance must always be a finite val:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

but, at resonance, $(X_L - X_C) = 0.$

∴ At the Resonant Frequency -

$$\mathbf{Z = R}$$

where Z = Impedance of circuit at resonance
R = Resistance of circuit

7.3 Impedance Variations in a Series Resonant Circuit. At low frequencies, the reactance is high since X_C greatly exceeds X_L, (Fig. 11) and therefore the impedance is high.

As the frequency is increased, the reactance decreases, therefore impedance decreases, until, at resonance, the impedance is at a minimum value, and is equal to the resistance.

Beyond the resonant frequency, the reactance increases, as X_L exceeds X_C (Fig. 11), and the impedance increases, rising as the frequency becomes higher.

These variations in impedance are shown in Fig. 12.

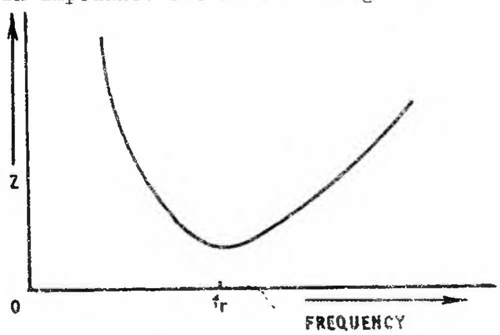


FIG. 12. IMPEDANCE VARIATIONS IN A SERIES RESONANT CIRCUIT.

7.4 Current in a Series Resonant Circuit. The variations in impedance over the frequency range cause corresponding changes in the current in the circuit.

Assuming that the applied voltage remains constant, the current reaches its highest value at the resonant frequency as then the resistance is the only current limiting factor in the circuit. When the resistance is low, the current reaches a high value at resonance, as in Fig. 13.

At frequencies above and below resonance, the impedance is high and the current is correspondingly low.

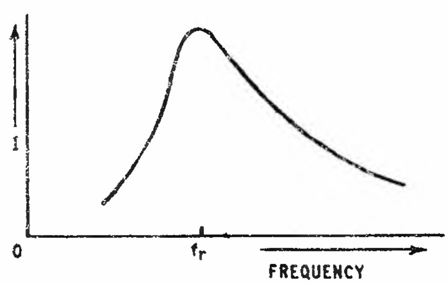


FIG. 13. CURRENT VARIATIONS IN A SERIES RESONANT CIRCUIT.

7.5 Phase Angle. At frequencies below resonance, the circuit is capacitive (Fig. 11) and the current leads the applied voltage.

The angle of lead diminishes as the frequency is increased, until, at the resonant frequency, the circuit is resistive, and current and voltage are in phase.
At frequencies higher than the resonant frequency, the circuit is inductive, (Fig. 11) and the current lags the applied voltage.

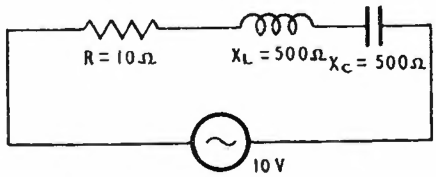
7.6 Voltage Magnification in Series Resonant Circuits. By choosing suitable values of inductance and capacitance, X_L and X_C can be of high value at the resonant frequency.

When the resistance is low, a high value of current flows at resonance, and very high voltage drops are produced across the reactive components. In practice these voltages can be many times greater than the applied voltage as in the following example.

7.7 Example No. 6. A series circuit has a resistance of 10 ohms, and, at the resonant frequency, the inductive reactance is equal to the capacitive reactance at 500 ohms. When 10 volts is applied at the resonant frequency, find -

(i) the P.D. across the inductor

(ii) the P.D. across the capacitor.



As $X_L = X_C$

$Z = R$

$= 10$ ohms

$I = \frac{E}{Z}$

$= \frac{10}{10}$

$= 1$ Amp

(i) .... $E_L = I \times X_L$

$= 1 \times 500$

$= 500$ volts

(ii) .... $E_C = I \times X_C$

$= 1 \times 500$

$= 500$ volts

Answers = (i) 500 volts; (ii) 500 volts.

We must remember, that although these high voltages exist separately across the inductor and the capacitor, their combined total is zero, as they are 180° out of phase.

7.8 Resistance in Resonant Circuits. As the current which causes the voltage magnification at the resonant frequency is limited by the resistance only, the magnitude of the resonant effect depends largely on the value of the resistance in the circuit.

The term resistance implies the "effective resistance", dealt with previously, and includes the total effect of material resistance, skin effect and power losses in the circuit.

When the resistance is low at resonance, the resonant effect is very marked and a high degree of voltage magnification is obtainable.

Should the resistance value be high when compared with the reactance at resonance, the resonant effect is barely noticeable.

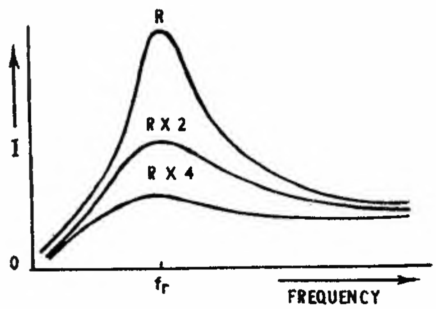


FIG. 14. EFFECT OF RESISTANCE.

7.9 "Q" Factor. In a series resonant circuit, the "Q" or Quality Factor is a number which indicates how many times the P.D's across the reactive components exceed the applied voltage.

For a series circuit -

$$Q = \frac{E_L \text{ OR } E_C}{E}$$

where

Q - Q Factor
E_L - P.D. across inductor at resonance
E_C - P.D. across capacitor at resonance
E - Applied voltage.

The factors which influence Q Factor are -

(i) the reactance at resonance; when X_L and X_C are high, the reactive P.D's are high.

(ii) the resistance at resonance; when resistance is high, the current is low and this reduces the value of the P.D's.

As the windings of the inductor are responsible for the bulk of the resistance, the Q of a resonant circuit can be found from -

$$Q = \frac{X_L}{R}$$

where

Q - Q Factor
X_L - Inductive reactance at the resonant frequency
R - Effective resistance at that frequency.

7.10 Calculation of Resonant Frequency. Resonant frequency has been defined as the frequency at which X_L equals X_C. For any combination of inductance and capacitance, the frequency at which this occurs is calculated from -

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where

f_r - Resonant frequency in c/s
L - Inductance in henries
C - Capacitance in farads.

This formula is derived as follows -

At resonance $X_L = X_C$

$$\therefore \quad 2\pi f_r L = \frac{1}{2\pi f_r C}$$

$$\therefore \quad f_r^2 = \frac{1}{(2\pi)^2 LC}$$

$$\therefore \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

7.11 Example No. 7. Find the frequency at which a circuit containing a 100mH inductor and an 0.4 μF capacitor is resonant.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{\frac{100 \times 4}{10^3 \times 10^7}}} = \frac{10^5}{2\pi\sqrt{100 \times 4}}$$

$$= \frac{100{,}000}{6.28 \times 20} = \underline{800 \text{ c/s (approx.)}}$$

Answer - 800 c/s.

7.12 Series Resonant Circuits in Telecom. The ability of a series resonant circuit to magnify an applied voltage, has wide application in long line equipment and radio work, where small signal voltages generate comparatively high voltages across the components of these "tuned" circuits.

As the impedance of the circuit is much lower at the resonant frequency than at any other frequency, series resonant circuits are often used to separate one frequency from a number of frequencies present in the one circuit.

Examples of the use of series resonant circuits in telecom are found in

- "tuning circuits" in radio receivers.
- "filters" in telephone and long line equipment.
- equalisers in radio broadcast and telephone trunk lines.
- resonant type frequency meters.

These are covered in other papers of the course.

7.13 Summary of Characteristics of Series Resonant Circuits. The principal factors which concern us regarding series resonant circuits are

- resonance occurs at the frequency when X_L equals X_C.
- resonant frequency $(f_r) = \dfrac{1}{2\pi\sqrt{LC}}$
- at resonance, the impedance is a minimum value and equals the effective resistance of the circuit. At all other frequencies, the impedance is higher.
- the current is at the maximum value at the resonant frequency.
- the voltages produced across the inductor and the capacitor are "Q" times the applied voltage and are greater than the applied voltage when the resistance is smaller than the individual reactances.
- at frequencies below resonance, the circuit is capacitive and the circuit current leads the applied voltage.
- at resonance the circuit is resistive and the circuit current is "in phase" with the applied voltage.
- at frequencies above resonance, the circuit is inductive and the circuit current lags the applied voltage.

8. TEST QUESTIONS.

1. The total opposition to current in an A.C. circuit is termed the ....

2. The .... vector is used as a reference in vector diagrams for series circuits.

3. Draw a typical vector diagram for an R.L. series circuit.

4. In series R.L. circuits, current (leads / is in phase with / lags) the applied voltage by an angle calculated from ....

5. When the P.D's across the components in R.L. series circuit are 7 volts and 24 volts respectively, the applied voltage is .... volts.

6. The impedance of an R.C. series circuit is found from the formula ....

7. An R.C. series circuit contains 30 ohms resistance and 50 ohms capacitive reactance. Find (i) the impedance; (ii) the phase angle.

8. When R, L and C are connected in series the impedance is found from the formula ....

9. The P.D's measured across the inductor and capacitor in an R, L, C series circuit are 24 volts and 16 volts respectively. When the applied voltage is 10 volts, the P.D. across the resistance is .... volts.

10. A series circuit has a resistance of 100 ohms, an inductive reactance of 150 ohms and a capacitive reactance of 200 ohms. Find -

(i) the impedance
(ii) the phase angle.

11. The effective resistance of an A.C. circuit is often greater than the D.C. resistance because ....

....

12. In an A.C. circuit the power can be found from the formula ....

13. Resonance occurs in series circuits when ....

14. At the resonant frequency, the impedance of a series circuit is (high / low) and is equal in value to the (resistance / inductive reactance / capacitive reactance)

15. An important property of a series resonant circuit is its ability to magnify ....

16. Q Factor is found from the formula ...., and indicates ....

17. Resonant frequency is found from the formula ....

18. A series combination of 0.1 henry inductor and 0.1 μF capacitor is resonant at a frequency of .... kc/s.

END OF PAPER.

WAVEFORMS, TIMING AND OSCILLATORY CIRCUITS.

---

1. COMPLEX WAVEFORMS.

1.1 The Sine Curve. In the paper "Sound Waves" in Telephony 1 we saw that simple periodic or cyclic motion such as a tuning fork vibrating or a pendulum swinging can be expressed in graphical form by a sine curve or sine wave. The sine curve therefore is the graph which relates the simplest form of natural variation as a function of time. In the paper "Introduction to A.C." it was shown that the basic alternating voltage and current variations related to time are also periodic functions which can be represented by the sine curve.

1.2 Complex A.C. Waveforms. In telecom the intelligence we wish to transmit is converted to electrical signals which do not generally vary in accordance with the simple sine curve. The graphs of such signals may be very complex looking waveforms.

It can be shown that any complex wave (which we must remember is only a graph showing the variation of some quantity in relation to time) can be resolved into a sine curve of the same number of periods or cycles per second (the fundamental frequency) plus a number of additional sine curves occurring at frequencies which are multiples of the fundamental frequency. These multiples are called harmonics; the second harmonic is twice the fundamental frequency, the third harmonic three times and so on.

In studying the composition of A.C. waveforms, those which can be resolved into large numbers of different harmonics extending into high order multiples of the fundamental are regarded as the most "complex". The composite wave containing high order harmonics may not, however, look very complex when drawn as a graph. For example the "sawtooth", "spiked" and square waveforms shown in Fig. 1 look simple rather than complex yet all contain numerous harmonics and a common characteristic which denotes this is the abrupt change accompanying sharp rise and/or decay of the signal. A perfect square wave having instantaneous rise and decay of the voltage or current, theoretically contains harmonics extending to infinitely high frequencies.

A voltage or current rise and fall occupying infinitely small time (no time), cannot be achieved and practical square waves have extremely rapid rise and fall of the waveform with harmonics extending to very high frequencies but not to infinity. Analysed in this way, any waveform which has square corners or sharp points has high order harmonics and its composition is therefore "complex". The waveform in Fig. 1d is typical of a human voice singing a single note (converted to A.C. by a microphone) and although it looks complex it is much less so in its harmonic composition than those depicted in Figs. 1a, b and c.

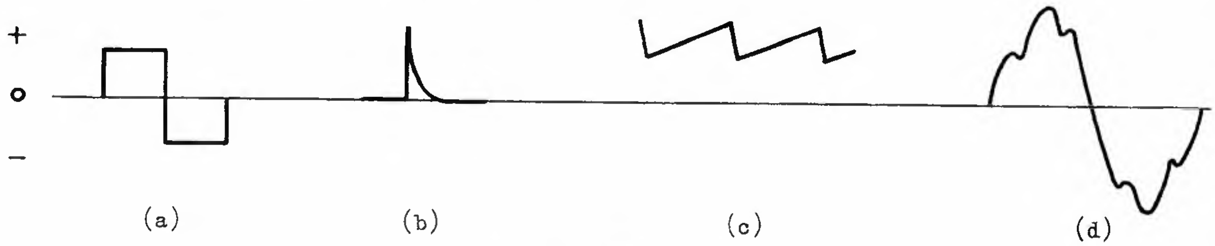


FIG. 1. WAVEFORMS.

1.3 Alternating Voltage or Current. In the operation of most electronic circuits, direct current, varying or pulsating D.C. or A.C. are present in various parts of the circuit. We have seen that varying or pulsating D.C. can be regarded as A.C. superimposed on D.C. and that transformers or capacitors can be readily included in circuits when it is necessary to separate the A.C. component from the D.C. component. In the study of such circuits it is often convenient to ignore the D.C. component and to think of each part of a circuit in terms of its behaviour to A.C. only (reactance, impedance, etc.). D.C. may then be considered theoretically as A.C. of zero c/s and the terms "alternating" and A.C. as including any voltage or current having a changing rate of change; it is not essential for the polarity to change.

Consequently, we encounter terms such as "positive going" half cycle, "negative going" half cycle, positive going "swing" of signal and negative going "swing" of signal which refer to the direction of change but have no reference to polarity change. Fig. 2 shows this graphically. The terms positive swing and negative swing (without the word "going") are used rather loosely in practice and can refer either to direction of change or actual polarity.

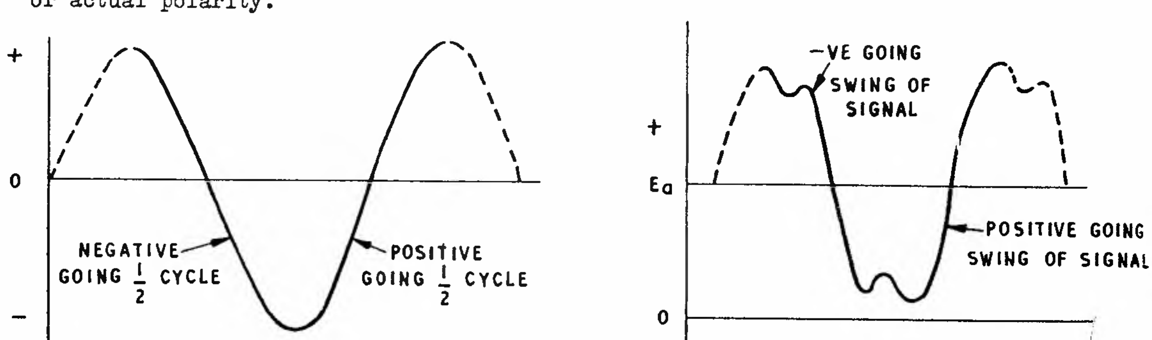


FIG. 2.

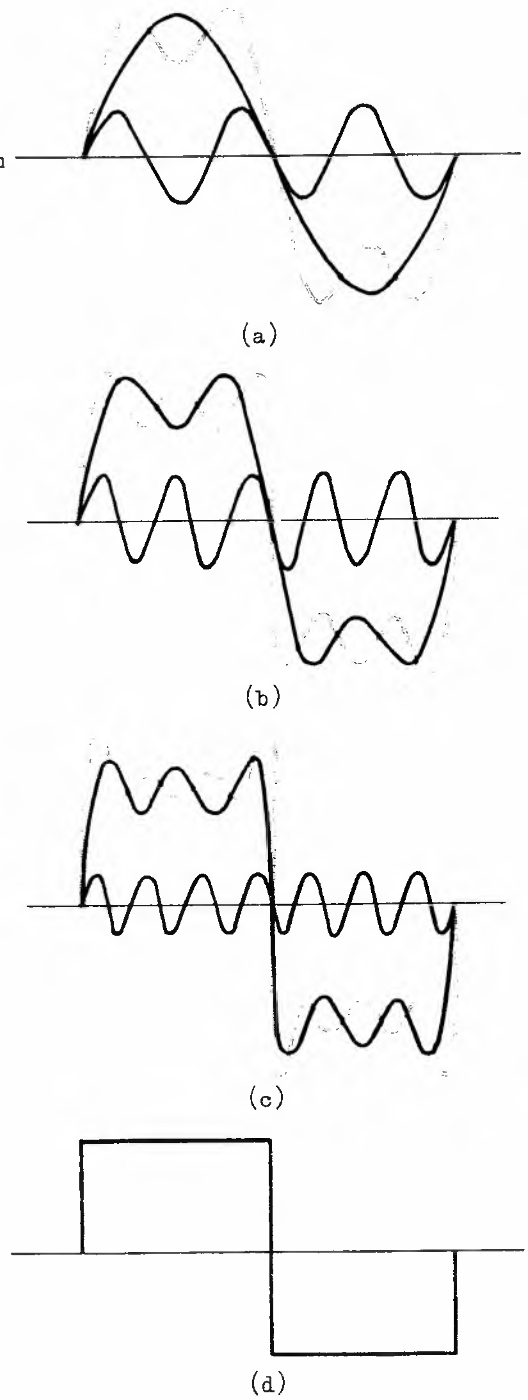
1.4 Square Waveform. It is possible to show graphically that a square wave can be approximated by adding to a sine wave of fundamental frequency a number of odd harmonics.

Fig. 3a shows a sine wave and its third harmonic from which the resultant red waveform is obtainable by algebraic addition.

In Fig. 3b the resultant of Fig. 3a has added to it a fifth harmonic component to obtain the new resultant in red.

In Fig. 3c the resultant of Fig. 3b has a seventh harmonic added and the resultant is shown in red.

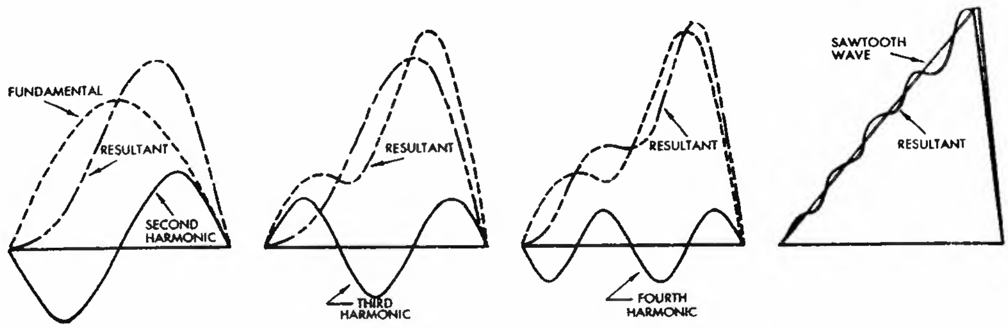
By adding many further odd harmonics having the correct amplitude and phasing, the square waveform of Fig. 3d could be approximated. To do this graphically would be impracticable but Figs. 3a, b and c suffice to show that the tendency is for the wave to become more square as odd harmonics are added.



COMPONENTS OF A SQUARE WAVE.

FIG. 3.

1.5 Sawtooth Waveform. Fig. 4 shows how a sawtooth wave can be simulated by the graphical addition of a fundamental and its odd and even harmonics.



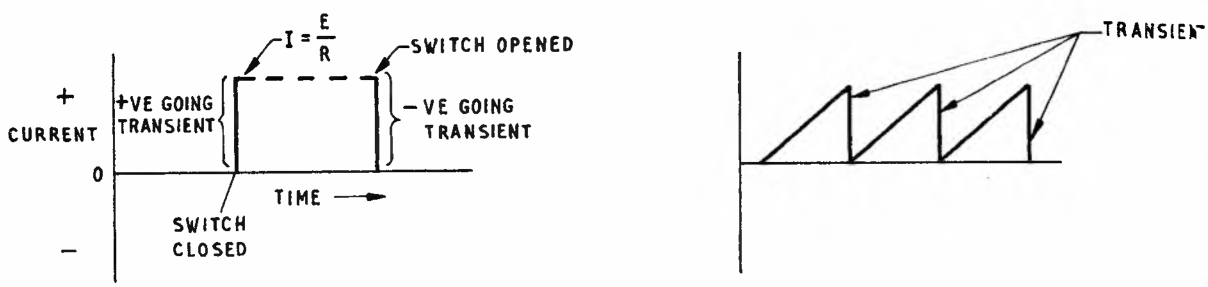
(a) (b) (c) (d)

FIG. 4. COMPONENTS OF A SAWTOOTH WAVE.

1.6 Transients. The word "transient" as an adjective means brief or momentary. In telec through common usage it is used as a noun to designate any momentary surge of voltage or current with a waveform having abrupt change in amplitude or direction.

When a resistive D.C. circuit is switched on, the current rises in the form of a transient and when switched off the current ceases in the form of a transient (Fig. 5 Square waves therefore are actually a series of positive going and negative going transients separated by intervals of no change.

In sawtooth waves (Fig. 5b) the positive going part is gradual, but the negative goi decay of the signal is a transient.



(a) D.C. Resistive Circuit. (b) Sawtooth Generator.

FIG. 5. SOURCES OF TRANSIENTS.

In the transmission, recording and reproduction of sound, transient signals or transients result from sudden sharp sounds which are characteristic of such sources cymbals, bells, triangles and most percussion instruments (or plucked strings) at th instant of being struck.

All transients irrespective of their source have rapid rise or decay in amplitude combined with abrupt change in their rate of change. A transient may be a single r surge which ends abruptly or a series of such changes which develop a more constant amplitude and waveform after a few cycles, or be produced continuously by a device as a special oscillator. The term is somewhat loosely applied to all these situati

All "transients" therefore have the essential characteristics of complex waves and similarly contain A.C. frequency components of a very high order.

In the case of square and sawtooth pulses, etc. (sometimes classified as "D.C. transients"), the component frequencies extend far beyond the pulse repetition rate as we saw in Figs. 3 and 4.

In the case of transients occurring with abrupt origin of sounds (or switching A.C. signals on or off) the additional frequency components cover a wider band extending to both higher and lower frequencies than the subsequent fundamental frequency and its normal harmonics. (Such transients are sometimes distinguished from the pulse type by the term A.C. transients.)

Consequently, circuits designed to transmit or reproduce transients accurately must be capable of handling the necessary range of frequencies (or at least a major percentage of it).

2. CAPACITANCE.

2.1 We saw in the paper "Capacitance" in Applied Electricity 1 that when a capacitor is connected to a D.C. source of e.m.f., current flows until the capacitor charges to a potential equal and opposite to the applied voltage.

When the circuit is opened the charge remains, but when the plates are connected by a conductor the capacitor acts as a source of supply and current flows in the opposite direction to discharge the capacitor.

CAPACITOR CHARGE AND DISCHARGE CURRENTS.

FIG. 6.

The charge or quantity of electricity stored by the capacitor at any instant is calculated from -

$$Q = C \times E$$

where Q = charge in coulombs
C = capacity in farads
E = p.d. across the plates.

Where any two of these quantities are known this formula can be transposed to find the third -

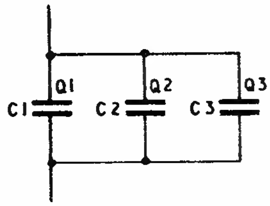
$$C = \frac{Q}{E} \quad \text{AND} \quad E = \frac{Q}{C}$$

The potential difference across the plates of a capacitor at any instant is therefore determined by the quantity of charge (Q) and the capacitance value (C). That is, the larger the capacitance the larger the quantity of electricity (Q) required to charge it to a given voltage.

2.2 Capacitors in Parallel. When capacitors are connected in parallel across a supply source, the plate area is increased and the total capacity is equal to the sum of the individual capacitors:

$$\text{Total } C = C1 + C2 + C3 \text{ etc.}$$

As the same voltage is connected across the capacitors each stores a quantity of electricity (Q) proportional to the individual capacity ($Q = C \times E$). The total charge (Q) is the sum of the charges on the individual capacitors.



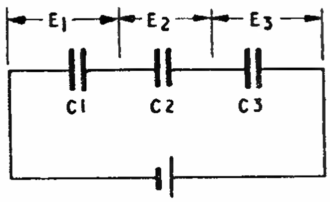
$$Q = Q_1 + Q_2 + Q_3$$

FIG. 7. CAPACITORS IN PARALLEL.

2.3 Capacitors in Series. When capacitors are connected in series the effect is the same as increasing the dielectric thickness and the total capacity is less than the smallest capacity in the combination:

$$\text{Total } C = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}} \text{ etc.}$$

When the combination is connected to a supply source, current in all capacitors continues for the same time and each capacitor stores the same quantity of electricity ($Q = It$). The voltage across each capacitor depends on the quantity stored and its capacity ($E = \frac{Q}{C}$). Thus the largest capacitor in a series combination has the lowest voltage across its plates.



$$Q = Q_1 = Q_2 = Q_3$$

$$E = E_1 + E_2 + E_3$$

FIG. 8. CAPACITORS IN SERIES.

2.4 Energy stored by a Capacitor. When a capacitor charges, energy is transferred from the applied source and stored in the capacitor in the form of an electrostatic field. When the capacitor discharges the same amount of energy is returned to the circuit, providing there are no losses in the capacitor. In practical capacitors however, a small amount of energy is converted to heat due to the resistance of the plates and dielectric losses, but as this is small it is often ignored.

As a matter of interest the amount of energy stored by a capacitor can be calculated from the formula:

$$\text{Energy} = \tfrac{1}{2} C E^2 \text{ (joules)}$$

where C = capacity in farads
E = p.d. across the plates.

3. TIME CONSTANT IN R/C CIRCUITS.

3.1 General. We have seen in studying A.C. circuits that when a sinusoidal voltage is applied across a resistor and capacitor in series the voltages across R and C separately vary sinusoidally but are 90° out of phase. When a D.C. voltage is applied to an R/C series circuit an entirely different set of conditions apply.

It can be shown that if a D.C. energy source were connected across a capacitor, and the entire circuit had no resistance, the capacitor would charge instantaneously by the passage of an infinitely large current for an infinitely short time. In practice however, there is always some resistance to limit the current and the capacitor charges in a finite time which depends on the values of both R and C.

With any combination of R and C however, graphs of voltage and current with respect to time conform to an invariable wave shape and certain laws are deduced which are known as the R/C time constant.

In studying electronics an understanding of time constant is essential. R/C or L/R circuits can be used to introduce intentional time delays, or on the other hand, arrangements of these components for some other function may result in undesired time delays (phase shift) which must be allowed for.

3.2 Capacitor Charging. Fig. 9a shows a capacitor C and a resistor R connected in series across a D.C. source of E volts. E_C and E_R represent the instantaneous voltages across C and R respectively. When switch S1 is connected to contact 1, the resulting current $(I) = \frac{E - E_C}{R}$ at any instant. At the first instant C is uncharged and offers no opposing e.m.f. and is therefore equivalent to a short permitting the initial current to equal $\frac{E}{R}$. The capacitor commences to charge immediately and E_C rises in opposition to the applied voltage E. The current I therefore is reduced from instant to instant as $E - E_C$ becomes less.

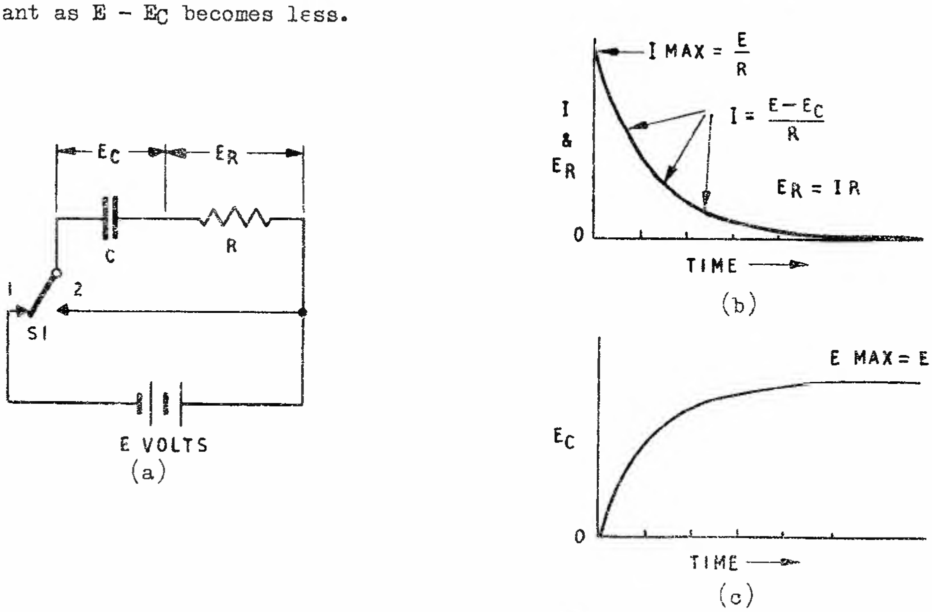


FIG. 9. 'C' CHARGING.

E_R is maximum at the first instant (when $E_R = IR = E$) but becomes progressively less as I is reduced. Being a series circuit $E_R = E - E_C$. When $E_C = E$, current ceases and $E_R = 0$.

Fig. 9b shows the variation of current with time; the graph for E_R with time follows the same shape. Fig. 9c shows the variation of E_C with time.

3.3 Capacitor Discharging (Fig. 10). When C is charged to E volts and S1 switched from contact 1 to contact 2, C commences to discharge. As $E_C = E$, the initial current $(I) = \frac{E}{R}$. E_C is progressively reduced as the energy stored is dissipated in R. At any instant $I = \frac{E_C}{R}$ and the discharge current curve (Fig. 10b) follows the same curvature as the charge curve (Fig. 9b); the direction however is opposite and E_R is of opposite polarity. The variation of E_C with time also follows the same curvature (Fig. 10c).

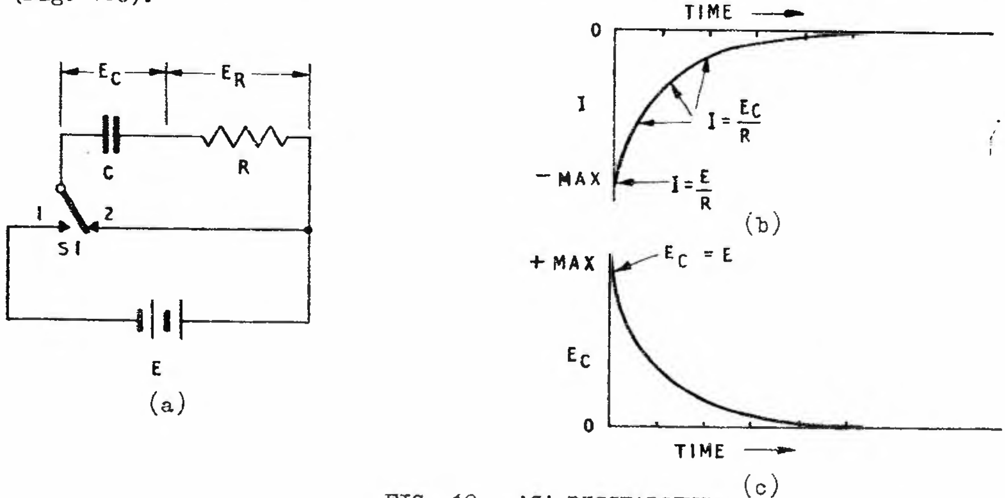


FIG. 10. 'C' DISCHARGING.

The time taken for charge or discharge of C under the conditions shown in Figs. 9 and 10 varies with the value of C and R but is not affected by the value of E. Increasing C increases the time because a greater quantity is needed to raise E_C to E volts; increasing R also increases the time because the current starts off at a lower value.

3.4 Exponential Curve. For any values of C and R the shape of the curve remains the same and it is known as an exponential curve. The mathematics of exponential functions are beyond the scope of this course but are based on a "natural" logarithmic scale (Naperian logs to the base e) and have important applications in many natural phenomena. Theoretically, an exponential curve never reaches maximum (or minimum on discharge) but in practice it is complete enough at 99.9% of maximum.

3.5 Time Constant. Because the C and R values both determine the charge or discharge time and the curve with respect to time always follows the same curvature, a constant percentage of charge is taken on or lost by the capacitor in C X R seconds. CR seconds is called the time constant (C in farads R in ohms). In this time the voltage E_C across C charging will rise to 0.632 (63%) of its maximum value E (Fig. 11) and the charge current will fall by 63% to 37% of its maximum value.

In the second time constant interval of CR seconds the same relationship again applies - in CR seconds E_C increases by 63% of 37% of E, and for each successive interval there is an increase of 63% of the remaining effective E.

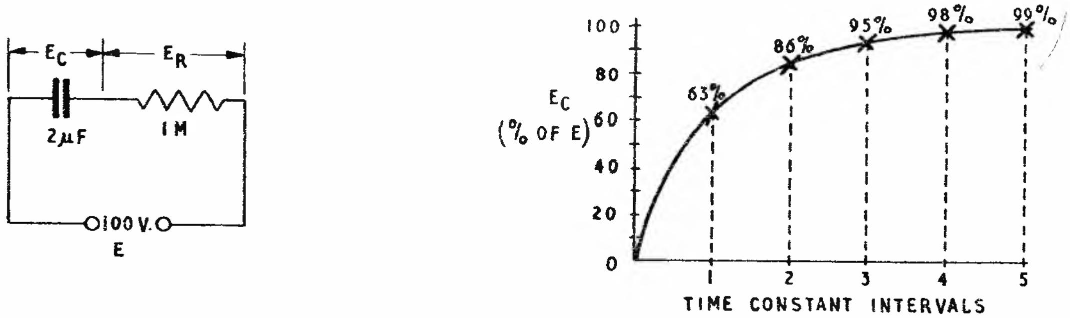


FIG. 11.

Example:

Suppose $C = 2\mu F$ and $R = 1M\Omega$

$$\text{Time Constant} = CR \text{ seconds}$$
$$= \frac{2}{10^6} \times 10^6$$
$$= 2 \text{ seconds.}$$

After 1st CR interval -

$$E_C = 63\% \text{ of } E = \frac{63}{100} \times 100$$
$$= 63V$$
$$\text{Effective e.m.f. } (E - E_C) = 100 - 63$$
$$= 37V.$$

After 2nd CR interval -

$$E_C = 63V + 63\% \text{ of } 37V$$
$$= 63 + 23.3V$$
$$= 86.3V \text{ (approx.).}$$

After 3rd CR interval -

$$E_C = 86.3V + 63\% \text{ of } (100 - 86.3)V$$
$$= 95V \text{ (approx.).}$$

After 4th CR interval -

$$E_C = 95V + 63\% \text{ of } 100 - 95$$
$$= 98V \text{ (approx.).}$$

After 5th CR interval -

$$E_C = 99.3V.$$

E_C is now near enough to E for practical purposes though in theory it can never quite equal E. It is interesting to note also that a capacitor would charge or discharge completely in exactly CR seconds if the current were to maintain its initial value. This can be demonstrated as follows using the CR values chosen for the example above (Fig. 10).

$$\text{Initial } I = \frac{E}{R} = \frac{100}{10^6}$$
$$= 0.0001A.$$
$$Q = CE = \frac{2}{10^6} \times 100$$
$$= 0.0002 \text{ coulombs.}$$
$$Q = It$$
$$\therefore \quad t = \frac{Q}{I} = \frac{0.0002}{0.0001}$$
$$= 2 \text{ seconds}$$
$$= CR.$$

This theoretical relationship between the initial maximum current and CR is sometimes used to formulate a definition of time constant. The mathmatical significance of this for exponential functions has no value for practical circuits and it is better to regard the CR time constant in seconds as the time for the capacitor voltage to attain 63% of maximum on charge and 37% maximum on discharge. The charging current I and the resulting voltage across R fall to 37% of maximum in CR seconds during both charge and discharge.

Time constant is often stated in microseconds and for other occasions in seconds. It is convenient to remember therefore that -

ohms X μF = CR in microseconds

or Megohms X μF = CR in seconds.

For example:

1,000Ω X 0.1μF gives a time constant of 100μsecs.

or 2MΩ X 2μF gives a time constant of 4 secs.

Note also a desired time constant can be obtained by any combination of C and R which give the required product CR. For example a time constant of 4 seconds could be obtained using -

4μF and 1MΩ

or 2μF and 2MΩ

or 1μF and 4MΩ

or 0.5μF and 8MΩ and etc.

It follows that if the time constants are equal the whole charge and discharge curves with respect to time will be equivalent. As the simple product of C and R gives the times for a constant percentage of the charge or discharge, the voltage or current for any other elapsed time can be derived quite simply by applying this to an exponential curve. Examples of this are given in Section 6.

4. INDUCTANCE.

4.1 We saw in the paper "Electromagnetic Induction" in Applied Electricity 1 that when the circuit from a coil to a D.C. source of e.m.f. is closed, current does not rise to its ohms law value immediately. As the current commences magnetic flux around each turn of the coil rises and links all other turns and induces an e.m.f. of self induction (or back e.m.f.). This e.m.f. opposes the applied e.m.f. and the current rises at a rate determined by the instantaneous differences between the applied voltage and the self-induced voltages.

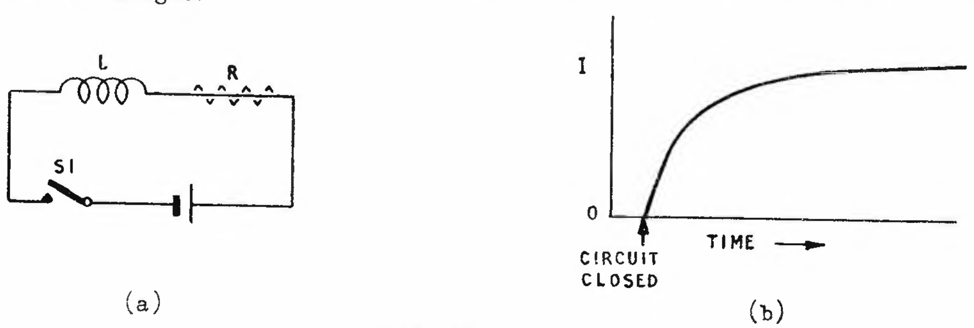


FIG. 12. INDUCTANCE IN A D.C. CIRCUIT.

The value of the self-induced e.m.f. depends on the rate of change of current which is maximum the instant switch S1 is closed (Fig. 12a) and decreases to zero as the $\frac{E}{R}$ current value is reached. As shown in Fig. 12b the current takes a certain time to reach this steady value. When the current does become a constant value the flux in the coil is stationary and the self-induced e.m.f. disappears. Some energy is now stored in the magnetic field while some continues to be dissipated in the circuit resistance (I^2R) which can be considered as a separate series resistance R (although inherent in the coil conductor).

When the circuit is opened current ceases and a self-induced e.m.f. is set up by the collapsing flux, its polarity being such as to tend to keep the current flowing in the same direction. The energy stored in the magnetic field is dissipated in a spark as the contacts open.

4.2 Inductance is the property of a circuit or component (inductor) which offers opposition to any change in current value. Although many coil turns and low reluctance iron cores greatly increase inductance, all conductors possess some inductance and in high frequency circuits this may have to be considered even for straight wires, etc.

Summarising, when current increases, the effect of inductance is to oppose this rise and when it decreases the effect of inductance tends to keep it at its former value.

In coils or inductors the inductance (L) depends mainly on the number of turns, the dimensions and type of winding, and the reluctance of the magnetic circuit (as we have seen the amount of inductance is measured in units called henries). As a matter of interest, in practical iron cored inductors -

$$L \propto \frac{T^2}{S}$$

where

L = inductance in henries

T = turns

S = reluctance of the magnetic circuit

$\propto$ means "is proportional to".

4.3 Energy Stored by an Inductor. With flux maintained by a steady current the energy stored in a magnetic field can be found using the following formula included here as a matter of interest -

$$\text{Energy} = \tfrac{1}{2} L I^2 \text{ (joules)}$$

where

L = inductance in henries

I = current in amperes.

Like the energy stored in a capacitor's electric field this stored energy can also be recovered from the field if, without opening the coil circuit, the D.C. supply is disconnected and replaced by a resistor or short circuit across the inductor (Fig. 13).

As the field collapses the self-induced voltage maintains a diminishing current in the coil while the energy is dissipated as heat in the circuit resistances and by the presence of hysteresis and eddy currents in the core. If the circuit is opened instead of being shunted, the same laws apply. The much more rapid collapse of flux induces a high voltage which ionises the air gap as the contacts open. Any energy not lost in eddy currents and hysteresis is dissipated in the spark gap resistance.

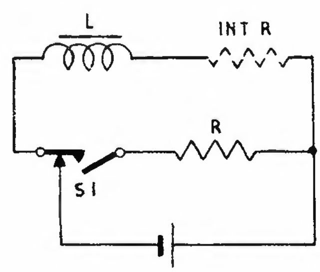


FIG. 13.

4.4 Self-Induction and Mutual-Induction. Inductance is the property possessed by coils, etc., which is expressed as so many henries. Induction is the process or phenomena by which induced e.m.fs. are produced.

Mutual induction exists when two coils are coupled magnetically by sharing wholly or partially a common magnetic field. The amount of coupling can be expressed in henries as mutual inductance.

It is sometimes necessary to make a distinction between magnetically coupled coils and a single coil; the alternative terms self-induction or self-inductance are then applied to the single coil.

4.5 Inductors in Series and Parallel. The joint inductance (L) of series or parallel combinations can be found by the same method adopted for calculating joint R in resistive networks.

That is, with inductors in series

$$\text{Joint L} = L1 + L2 + L3 \text{ etc.}$$

and with inductors in parallel

$$\text{Joint L} = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}} \text{ etc.}$$

These formulae however have very little practical value and if there is any mutual induction between coils they do not apply.

In addition to this, all coils have inherent resistance, and in some inductors this is appreciable. The impedance of an inductor is usually of more importance than the inductance and is dependent on the values of both L and R. As the ratio of L and R varies widely with different coils, the phase angles of voltage and current also vary.

Therefore, when calculating the joint impedance of inductors in parallel or series combinations, it is rarely possible to use simple formulae similar to those quoted for inductance or resistance. Any such additions should be calculated vectorially or if done mathematically the relative phase differences must be allowed for.

5. TIME CONSTANT IN L/R CIRCUITS.

5.1 Suppose a pure inductance (L) (no resistance) is connected in series with a pure resistance R across a D.C. source of E volts (Fig. 14a). E_R represents the instantaneous voltage drop across R and E_L the instantaneous self-induced e.m.f. produced across L.

5.2 "Charge" Curve for Inductance. (Fig. 14b.) The induced e.m.f. E_L (or back e.m.f.) depends on the rate of change of current and is maximum at the instant E is applied. I reaches maximum only after E_L decays to zero.

At any instant

$$E = E_R + E_L$$

$$\text{or } E_L = E - E_R$$

$$\text{or } E_R = E - E_L$$

Theoretically E_L equals E at the initial instant and then is reduced as current rising produces a voltage drop across R, and rate of increase of current becomes less.

As E_L is progressively reduced I increases to a maximum and the relationship of voltage and current with time follows an exponential curve as for R and C in series.

E_L reaches zero as I reaches its maximum $\frac{E}{R}$ value. The now constant current maintains the constant amount of energy stored in the magnetic field (and a power of I^2R watts is being dissipated constantly in R in the form of heat).

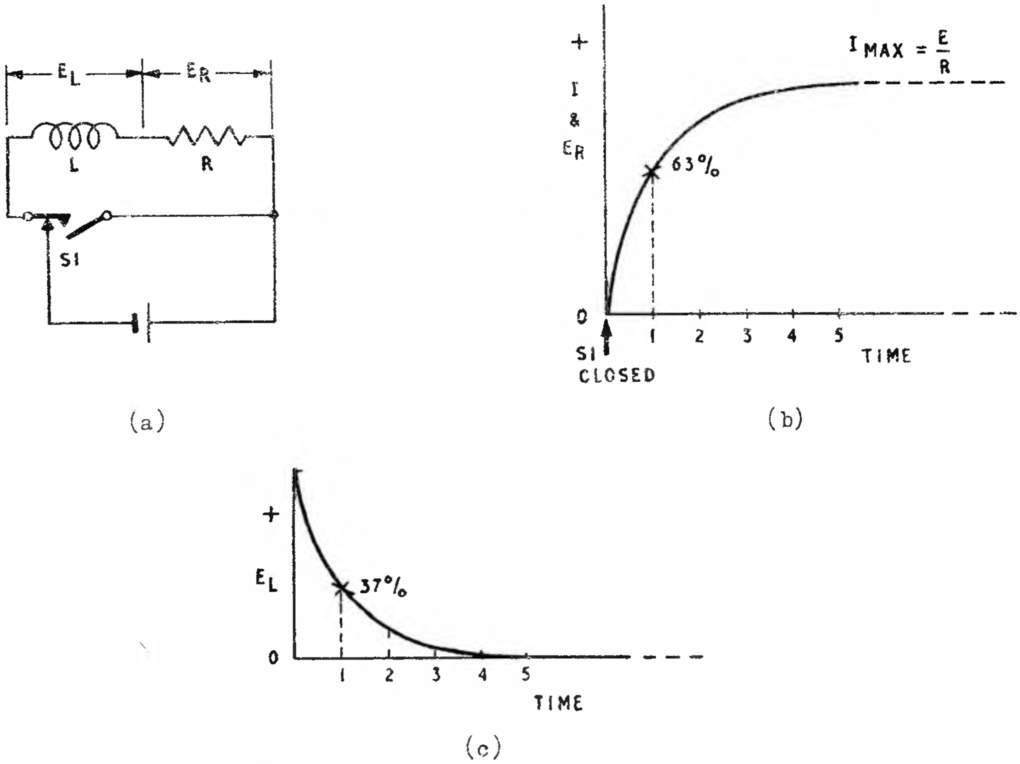


FIG. 14. 'L' CHARGING (FLUX RISING).

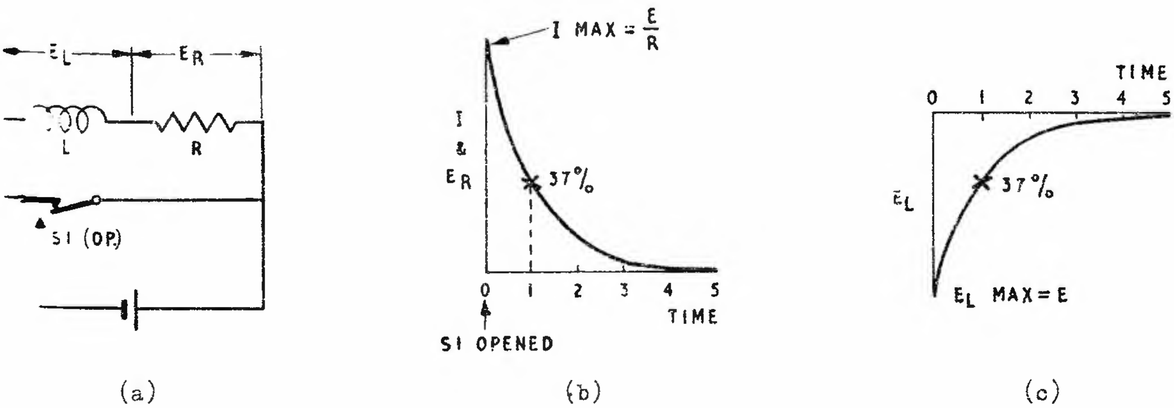


FIG. 15. 'L' DISCHARGING (FLUX COLLAPSING).

5.3 "Discharge" Curve for Inductance. (Fig. 15c.) When switch S1 is switched to short circuit L and R (without break) the magnetic field starts to collapse and the induced voltage opposing the change maintains a current in the same direction. E_L rises abruptly to equal E at the instant S1 is switched but its polarity is opposite that across L, shown in Fig. 14, when the current was rising. E_L, E_R and I all decay exponentially as shown.

5.4 Time Constant for L and R in series is the time taken for the rising current to reach 63% of maximum value or the falling current to reach 37% of the maximum and is equal to $\frac{L}{R}$ seconds. (L in Henries, R in ohms.)

As would be expected large values of L and low values of R give high maximum values of I but considerable time in attaining that maximum - long time constants. Conversely, low values of L and large values of R give short time constants.

Examples -

(i) When L = 30H and R is 60 ohms

$$\text{Time Constant } \frac{L}{R} = \frac{30}{60}$$

$$= \tfrac{1}{2} \text{ second}$$

(ii) When L = 10mH and R is 100 ohms

$$\text{Time Constant } \frac{L}{R} = \frac{10}{1000 \times 100}$$

$$= .0001 \text{ seconds}$$

$$= 100\mu S \text{ or } 0.1 ms$$

(iii) When L = 30H and R is 600 ohms

$$\text{Time Constant } \frac{L}{R} = \frac{30}{600}$$

$$= \frac{1}{20} \text{ sec.}$$

Note that in examples (i) and (iii) inductance is 30H in each case while the time constant is reduced to one tenth its value in example (i) by using a series R ten times as great. The maximum current in example (iii) will of course be only one tenth that in (i) for a given applied voltage. In studying telephone relays we will find these facts important for understanding relay behaviour in the great variety of series circuits encountered in practice. In some circuits for example, reducing relay current with external resistance can reduce its operating time or lag.

6. TIME CONSTANT APPLICATIONS.

6.1 In the design of electric and electronic circuits, the time delay which L, C and R can introduce may need to be considered, especially in high speed or high frequency circuits. Relay operate lag mentioned in para. 5.4 is only one example of this.

6.2 On the other hand, time constant circuits are used intentionally to give time delays ranging from microseconds to several minutes. The usual method of using an R/C circuit for time delay purposes is to connect some marginal device across the capacitor which responds only when the voltage rises to the critical predetermined value.

Time constant circuits are also used for waveshaping such as the production of spiked pulses from square pulses. Examples of this and time delay circuits appear in the paper "Oscillators".

6.3 A Universal Time Constant Chart (Fig. 16) consists of two exponential curves with the Y axis divided into a percentage scale and the X axis a time base divided into units of time constant CR or $\frac{L}{R}$. Regardless of the values of the applied voltage, resistance and capacitance or inductance, the chart can be used to determine the instantaneous current or voltages after any time interval. For example, when the values of the components are known the values of E_C, E_L or E_R at any instant can be obtained by multiplying the percentages from the curves by the applied voltage.

The value of current at any instant can be obtained by multiplying the percentage corresponding to the point on the curve by the maximum current value $(\frac{E}{R})$.

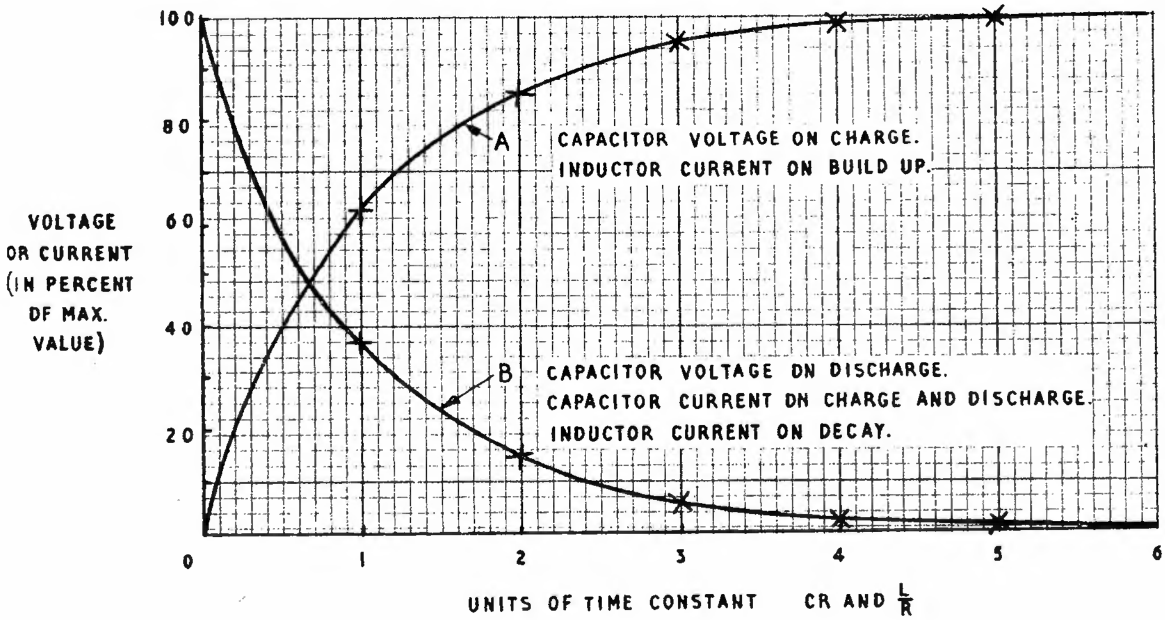


FIG. 16. UNIVERSAL TIME CONSTANT CHART.

Conversely, the chart can be used to determine suitable values for obtaining a desired current or voltage after a specified time interval.

Example:- Calculate the value of R which enables an 0.02µF capacitor to charge to 35 volts in 480 microsecs, when the supply voltage is 50 volts D.C.

$$\text{Percentage of applied E} = \frac{35}{50} \times \frac{100}{1} = 70\%$$

$$\text{From curve A} \quad 70\% = 1.2 \text{ units of time constant}$$

$$1.2 \text{ T.C.} = 480\mu\text{secs (in this example)}$$

$$\therefore \quad 1 \text{ T.C.} = \frac{480}{1.2} = 400\mu\text{secs}$$

$$\text{as} \quad \text{T.C.} = CR$$

$$R = \frac{\text{T.C.}}{C}$$

$$= \frac{400 \times 10^6}{10^6 \times .02}$$

$$= 20{,}000\,\Omega$$

Short time constant circuits are used in many electronic circuits where the applied voltage is not D.C. but A.C. However, where the time constant is much shorter than a half cycle of the A.C. and the A.C. waveform rises or falls as a transient, the time constant circuit can still behave in a similar manner to when it has D.C. applied.

Suppose, for example, an R/C circuit having a time constant of 2µs has an A.C. applied at a frequency of 1,000c/s and the waveform is nearly square; owing to the charging time of C being so much less than the time of 500µs taken by one half cycle, the voltage or current curves can be almost the same as described here for D.C. circuits. Some waveshaping circuits use this principle and examples are given in the paper "Oscillators".

7. L/C OSCILLATORY CIRCUITS.

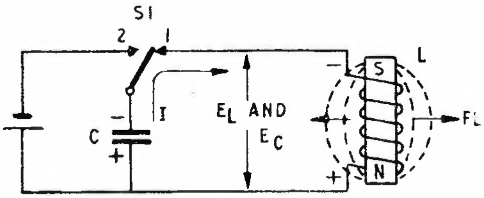
7.1 In Section 3 we saw that when a charged capacitor is connected to a resistor, the discharge current gradually decreases to zero and energy stored in the electric field is dissipated in the resistor as heat.

When a charged capacitor is connected to an inductor having a very low resistance, the energy stored is not dissipated but is nearly all transferred to the magnetic field produced as the capacitor discharges through the coil.

This process will now be examined in detail.

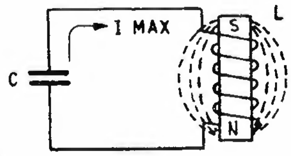
Figs. 17a, b, c, d, e, f, g, h represent the circuit conditions for successive instants throughout the cycle and Fig. 18 shows the relationships graphically with the corresponding instants marked as dotted vertical lines A, B, C, D, E, F, G, H respectively.

Fig. 17a. Fully charged capacitor (C) commences to discharge through the coil. The rising flux induces an e.m.f. of self induction (E_L) which opposes the voltage across the capacitor (E_C) and the current rises gradually (Fig. 18 instant "A").



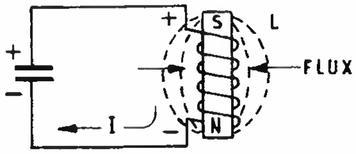
(a)

Fig. 17b. When C has discharged E_L and E_C are zero volts and the current and flux in L momentarily reach a period of zero change at their maximum value (shown as positive peak I in Fig. 18 instant "B"). The energy previously stored in the electric field of the capacitor has been transferred to the magnetic field in the inductor.



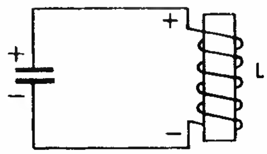
(b)

Fig. 17c. The current value begins to decrease and the collapsing flux in L induces a voltage to maintain a diminishing current in the same direction and charge C to the opposite polarity.



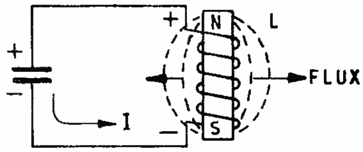
(c)

Fig. 17d. When the current and flux reach zero value they are changing at their maximum rate and C is charged to the maximum induced e.m.f. across L. The energy is again stored in the electrostatic field of the capacitor. (Fig. 18 instant D.)



(d)

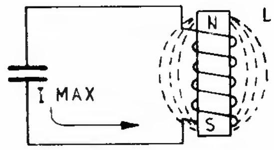
Fig. 17e. The capacitor begins to discharge again through L. The current and flux rise in the reverse direction and maintain the induced e.m.f. (E_L) at the same polarity in opposition to E_C. (As the direction of the flux motion and polarity both reversed at instant "D" the polarity of E_L is unchanged.)



(e)

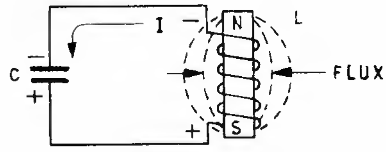
FIG. 17.

Fig. 17f. When C has discharged, the current and flux in L again reach a period of no change at their maximum value (shown as the negative peak I in Fig. 18 instant "F") E_C and E_L are zero. The energy is again stored in the magnetic field of L. (Note opposite polarity to instant "B").



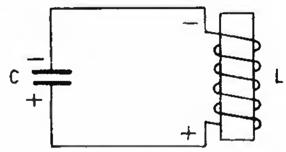
(f)

Fig. 17g. The current value begins to decrease and the flux collapsing induces an e.m.f. to maintain the current in the same direction and recharge the capacitor to its original polarity.



(g)

Fig. 17h. Current and flux reach zero value while changing at the maximum rate. C is charged to the resulting maximum induced voltage. Conditions in the circuit have returned to those existing at the instant the switch closed. The cycle will recommence as described for instant "A".



(h)

FIG. 17.

The designated voltages E_L and E_C and the phase relationships in Fig. 18 should not be confused with those discussed in the preceding A.C. Theory papers. It should be noted that when the capacitor discharges E_C is the applied voltage to the inductor and the current lags this voltage by 90°. When the inductor flux collapses E_L is the applied voltage to the capacitor and the current leads this by 90°.

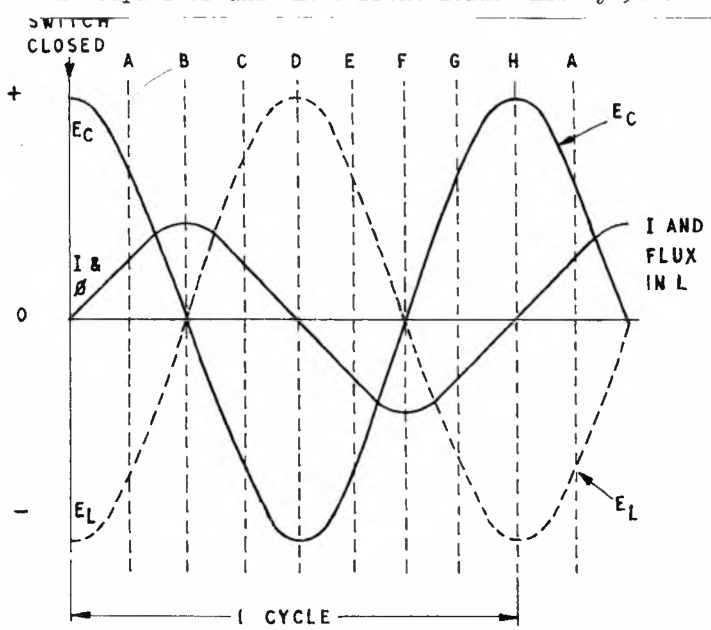


FIG. 18. RELATIONSHIPS BETWEEN E_L, E_C AND I.

The entire process (the discharge of the capacitor and the build up of the magnetic field followed by the charge of the capacitor and the collapse of the field) is repeated at a rate determined by the values of inductance and capacitance. The inductance and the capacitance alternately store and release the energy in their respective fields and the resulting waveform of current in and voltage across the circuit is that of the simplest form of periodic motion - the sine curve.

7.2 As the time taken for energy to transfer from C to L and back again depends on the values of C and L, the number of cycles per second can be found from the formula -

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where f_r = frequency of oscillation or resonance

L = inductance in henries

C = capacitance in farads.

The derivation of this formula is explained in the papers "A.C. Series Circuits" and "A.C. Parallel Circuits".

7.3 Damped Oscillations. If L and C in Fig. 17 contained no resistance or other sources of energy loss, oscillations would continue indefinitely without any decrease in amplitude. The action of the initial energy being transferred from the electric field to the magnetic field and back again in an L/C oscillatory circuit is sometimes described as a "flywheel effect".

A somewhat better mechanical analogy is the timing mechanism of a watch - the capacitance being compared to the elasticity of the hairspring and the inductance to the inertia of the balance wheel.

Resistance is always present in electric circuits like friction in a watch. In each case the amount of energy stored is gradually dissipated as heat and the amplitude of the oscillations becomes less and less until all the energy is expended and the action ceases. This is known as damping. (Fig. 19.)

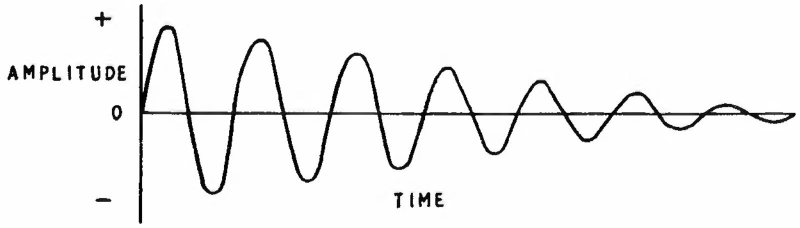


FIG. 19. DAMPED OSCILLATIONS.

The larger the resistance in the circuit the greater is the damping effect and the shorter the time for oscillations to cease. The smaller the resistance the less damping effect and oscillations persist for a longer period. We saw in the papers "Series A.C. Circuits" and "Parallel A.C. Circuits" that the Q of a resonant circuit increases with a decrease in resistance. A high Q circuit will therefore have less damping than a low Q circuit.

Oscillations produced by charging a capacitor and then allowing the oscillations to damp out are rarely of practical use. In most cases, oscillations of constant amplitude are required which can supply some energy to another circuit. Energy must then be applied from an external source at appropriate instants (or, in the correct phasing). This is the principle used in some oscillators which are described in the paper "Oscillators". It should be noted however, the simple oscillatory circuit as in Fig. 17 does not constitute an oscillator which is a device for supplying A.C. continuously to other circuits.

8. TEST QUESTIONS.

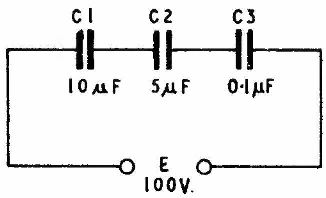
1. A sine curve is the graph relating the variation of .... degrees. A sine curve plotted with the horizontal axis as Time is used to represent a number of natural phenomena such as ....

2. Explain in general terms why some waveforms represented by simple looking graphs are actually quite complex.

3. Show by means of a diagram how an A.C. can have negative going and positive going states without actually changing in direction or polarity.

4. With the aid of diagrams indicate the parts of a square wave and a sawtooth wave which may be called transients. What characteristics distinguish these parts as transients?

5.



Calculate (i) the joint capacitance of the above combination (0.097μF);

(ii) the p.d. across the 0.1μF capacitor (97 volts);

(iii) the charge stored by 10μF capacitor (9.7μ coulombs).

6. Describe the charge and discharge of a capacitor connected to a D.C. supply in series with a resistor in terms of the current and capacitor voltage with respect to time.

7. (i) Describe the setting up of a magnetic field by a coil possessing series resistance in terms of the current and ti

   (ii) Describe the decay of coil current when the applied e.m.f. is replaced by a short circuit.

8. What is meant by the time constant of a series R/C circuit?

9. What is meant by the time constant of a series R/L circuit?

10. Referring to the universal time constant chart Page 15, Fig. 16. alculate the following -

    (i) The approx. time taken for a 2μF capacitor to charge to an applied P.D. of 60V via a 100kΩ resistor. (1 sec.)

    (ii) The approx. capacitance which will charge to 100V in 100 milliseconds from a 250V supply in series with 1MΩ.

    (iii) The approx. inductance of a 200Ω choke in which the current reaches maximum (approx.) in 0.25 secs. after the D.C. potential is switched on. (10H)

11. (i) Describe in general terms and with the aid of diagrams what occurs when a charged capacitor is connected across a low resistance inductor.

    (ii) Explain in terms of fundamental electromagnetic laws why the coil electrical polarity remains the same as the current direction changes from capacitor charging to discharging.

12. Draw the current graph of an L/C oscillatory circuit and indicate on it the states in which energy is stored and the instants at which each state contains maximum energy.

END OF PAPER.

PARALLEL A.C. CIRCUITS.

INTRODUCTION.

.1 In telecom circuits, components are often connected in parallel. In many cases, these are simple by-pass circuits, as were discussed in the paper "Fundamentals of A.C. Theory". However, there are certain instances in modern telephone systems, Long Line Equipment and Radio, where the parallel combination of inductance and capacitance is the most important part of the whole circuit, and to understand the operation of these circuits, we must know the principles of parallel circuits under A.C. conditions.

.2 We found in D.C. circuits that the total opposition of a parallel circuit can be calculated by using a formula based on the conductance values of the branches. Whilst equivalent formulae are available for application to A.C. circuits, the mathematical process is very involved, and at this stage, is beyond the scope of the course.

.3 This paper deals with combinations of resistance, inductance and capacitance connected in parallel in A.C. circuits.

2. PARALLEL A.C. CIRCUITS.

2.1 In D.C. circuits, we saw that the characteristics of a parallel circuit are -

(i) the P.Ds. across parallel branches are equal;

(ii) the total circuit current is the sum of the branch currents.

When these rules are applied to A.C. parallel circuits, we must remember that the currents in resistive and reactive branches are out of phase, and the addition of branch currents must be done by vectors.

2.2 Impedance of a Parallel Circuit. In D.C. circuits, different methods are used to find the total resistance of series and parallel circuits. Similarly, in A.C. circuits, the method used to determine the impedance of a series circuit cannot be applied to parallel circuits. To find the impedance of a parallel A.C. circuit -

(i) calculate the current in each parallel branch from Ohm's Law;

(ii) add these branch currents vectorially to find the circuit current;

(iii) using the circuit current and the applied voltage, calculate the impedance of the circuit from -

$$Z = \frac{E}{I}$$

where Z = Impedance in ohms.
E = Applied voltage.
I = Circuit current in amperes.

3. RESISTANCE AND INDUCTANCE IN PARALLEL.

3.1 Fig. 1 shows a circuit containing inductance and resistance connected in parallel. The branch P.Ds. (E_R and E_L) are equal to the applied voltage (E), and the circuit current (I), is the vector sum of the branch currents (I_R and I_L).

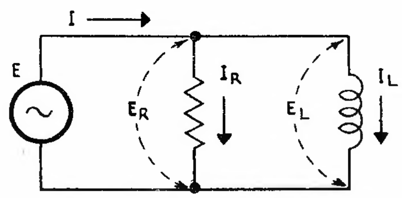


FIG. 1. RESISTANCE AND INDUCTANCE IN PARALLEL.

3.2 Vector Diagram. As the applied voltage is equal to the branch P.Ds. it is a factor common to all the currents in the circuit, and, as such, the E vector is used as a reference vector for the current vector diagram.

In the resistive branch, the current is in phase with the P.D. across the branch, so the I_R vector is drawn to scale along the voltage vector. (Fig. 2a.)

In the inductive branch, the current lags the branch P.D. by 90°, so the I_L vector is drawn to scale below the reference vector, lagging it by 90°. (Fig. 2a.)

When the parallelogram is completed as in Fig. 2b, the length of the diagonal represents the value of the circuit current, and the angle made with the voltage vector is the phase angle.

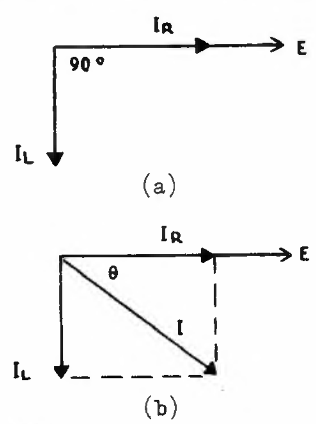


FIG. 2. VECTOR DIAGRAM.

3.3 Circuit Current Formula. In the vector diagram (Fig. 2b), the circuit current is the hypotenuse of a right-angle triangle in which the branch currents are represented by the remaining two sides. From Pythagoras theorem –

$$I = \sqrt{I_R^2 + I_L^2}$$

where

I = Circuit current

I_R = Current in resistive branch

I_L = Current in inductive branch.

3.4 Phase Angle. As inductance is included in the circuit, the circuit current lags the applied voltage. Referring to Fig. 2b, the angle of lag is calculated from –

$$\tan.\theta = \frac{I_L}{I_R}$$

where

θ = Phase angle

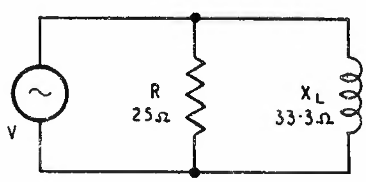
I_L = Current in inductive branch

I_R = Current in resistive branch.

3.5 Example No. 1. A resistance of 25 ohms is connected in parallel with an inductive reactance of 33.3 ohms to a A.C. supply of 10 volts. Find –

(i) the circuit current
(ii) the impedance
(iii) the phase angle.

Include a vector diagram to show the current distribution in the circuit.



$$I_R = \frac{E}{R}$$

$$= \frac{10}{25} = 0.4 \text{ Amps}$$

$$I_L = \frac{E}{X_L}$$

$$= \frac{10}{33.3} = 0.3 \text{ Amps}$$

(i) .... $I = \sqrt{I_R^2 + I_L^2}$

$$= \sqrt{0.4^2 + 0.3^2}$$

$$= \sqrt{0.16 + 0.09}$$

$$= \sqrt{0.25}$$

$= \underline{0.5 \text{ Amps}}$

(ii) .... $Z = \frac{E}{I}$

$$= \frac{10}{0.5} = \underline{20 \text{ ohms}}$$

(iii) ... $\tan\theta = \frac{I_L}{I_R}$

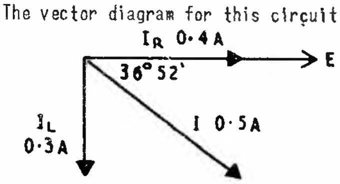
$$= \frac{0.3}{0.4} = 0.75$$

From tables

$\tan 36^\circ 52' = 0.75$

$\therefore \theta = \underline{36^\circ 52' \text{ lagging.}}$

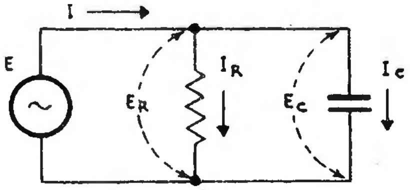
The vector diagram for this circuit is –



Answer = (i) 0.5 Amps; (ii) 20 ohms; (iii) 36° 52' lagging.

4. RESISTANCE AND CAPACITANCE IN PARALLEL.

4.1 Fig. 3 shows a circuit containing resistance in parallel with capacitance. The circuit current (I) is found from the vector sum of the current in the resistive branch (I_R) and the current in the capacitive branch (I_C).



RESISTANCE AND CAPACITANCE IN PARALLEL.

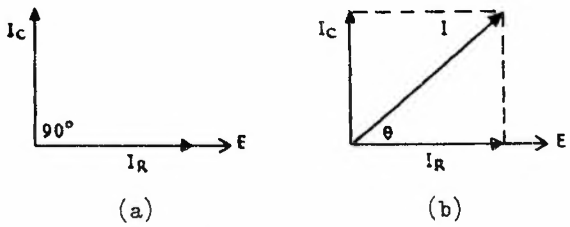
FIG. 3.

4.2 Vector Diagram. As the applied voltage (E) is common to all branches and the branch currents are referred to it, the E vector is the reference vector in the current vector diagram.

In the resistive branch, current and voltage are in phase, so the I_R vector is drawn to scale along the voltage reference vector as in Fig. 4a.

The capacitive branch current leads voltage by 90°, so the I_C vector is drawn to scale above the voltage vector, leading by 90° as in Fig. 4a.

When the parallelogram is completed (Fig. 4b) the length of the diagonal represents the value of the circuit current, and the angle made with the voltage reference vector is the phase angle.



VECTOR DIAGRAM.

FIG. 4.

4.3 Circuit Current Formula. As the currents in the circuit can be represented by the sides of a right-angle triangle, (Fig. 4b) -

$$I = \sqrt{I_R^2 + I_C^2}$$

where
- I = Circuit current
- I_R = Current in resistive branch
- I_C = Current in capacitive branch.

4.4 Phase Angle. Because the circuit is capacitive, the circuit current leads the applied voltage. From Fig. 4b, the phase angle is calculated from -

$$\tan.\theta = \frac{I_C}{I_R}$$

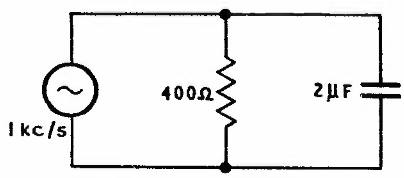
where
- θ = Phase angle
- I_C = Current in capacitive branch
- I_R = Current in resistive branch.

4.5 To find the impedance of a parallel circuit for which no applied voltage is given, for example, a parallel combination of resistance and inductance or resistance and capacitance, a simple method is to assume a value of applied voltage, and work the problem using this assumed value.

The working of the problem can be simplified when we choose a value of voltage which gives "whole number" values of branch currents, and in this regard, a voltage which is proportional to the L.C.M. of branch resistances or reactances is ideal.

Example No. 2. A 2μF capacitor and a 400 ohm resistor are connected in parallel across the relays in the duplex relay set. Find (i) the impedance and (ii) the phase angle of this part of the circuit at a frequency of 1 kc/s. (X_C = 80 ohms.)

Include a vector diagram to show the current distribution in the circuit.



As no voltage value is given, assume that the applied voltage is 4 volts.

$$I_R = \frac{E}{R}$$

$$= \frac{4 \times 1000}{400} \text{ (mA)}$$

$$= 10 \text{ mA.}$$

$$I_C = \frac{E}{X_C}$$

$$= \frac{4 \times 1000}{80} \text{ (mA)}$$

$$= 50 \text{ mA.}$$

$$I = \sqrt{I_R^2 + I_C^2}$$

$$= \sqrt{10^2 + 50^2} \text{ (mA)}$$

$$= \sqrt{100 + 2500} \text{ (mA)}$$

$$= \sqrt{2600} \text{ (mA)}$$

$$= 51 \text{ mA (approx.)}$$

(i) .... $Z = \frac{E}{I}$

$$= \frac{4 \times 1000}{51}$$

$$= 78.4 \text{ ohms.}$$

(ii) ... $\tan\theta = \frac{I_C}{I_R}$

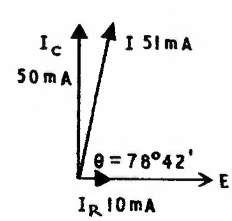
$$= \frac{50}{10} = 5.$$

From tables

$\tan 78^\circ 42'$ = 5 (approx.)

$\therefore \theta$ = $78^\circ 42'$ leading.

The vector diagram for the circuit is -



Answer = (i) 78.4 ohms; (ii) 78° 42' leading.

5. RESISTANCE, INDUCTANCE AND CAPACITANCE IN PARALLEL.

5.1 Fig. 5 shows a circuit in which resistance, inductance and capacitance are connected in parallel.

We have seen that I_R is in phase with voltage, I_L lags voltage by 90° and I_C leads voltage by 90°.

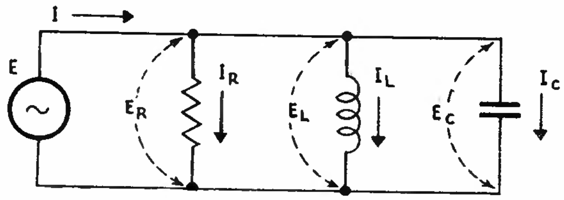


FIG. 5. RESISTANCE, INDUCTANCE AND CAPACITANCE IN PARALLEL.

As in all parallel A.C. circuits, the circuit current is found from the vector sum of the branch currents. The impedance of the circuit is found from the ratio of the value of circuit current and applied voltage.

5.2 Vector Diagram. The applied voltage is common to all currents in the circuit, and the current vector diagram uses the applied voltage vector as a reference. The vector diagram is constructed by drawing:

- the I_R vector to scale along the reference E vector.
- the I_L vector to scale below the reference vector, lagging by 90°
- the I_C vector to scale above the reference vector, leading by 90°

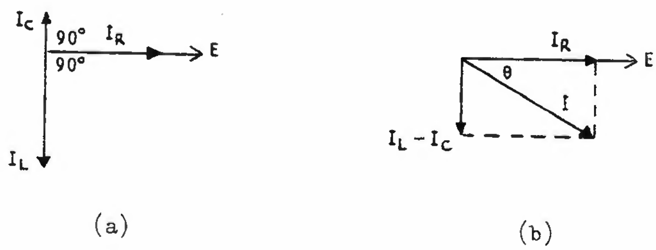


FIG. 6. VECTOR DIAGRAM.

As the currents I_L and I_C are 180° out of phase (Fig. 6a) their vector difference $(I_L - I_C)$ is combined with the I_R vector to give the magnitude and phase relationship of the resultant circuit current (I) as in Fig. 6b.

5.3 Circuit Current Formula. From the vector diagram Fig. 6b, the circuit current is:

$$I = \sqrt{I_R^2 + (I_L - I_C)^2}$$

where

I = Circuit current
I_R = Current in resistive branch
I_L = Current in inductive branch
I_C = Current in capacitive branch.

In the formula quoted above, it is assumed that the current in the inductive branch is greater than that in the capacitive branch.

The formula still applies when the capacitive branch current is the greater, as then, $(I_L - I_C)$ gives a negative result which becomes positive when squared.

5.4 Phase Angle. In circuits where the current in the inductive branch exceeds that in the capacitive branch, the circuit current lags the applied voltage, as in Fig. 6b.

When the capacitive branch has the greater current, the circuit current leads the applied voltage.

The angle of lead or lag is calculated from -

$$\tan\theta = \frac{I_L - I_C}{I_R}$$

where

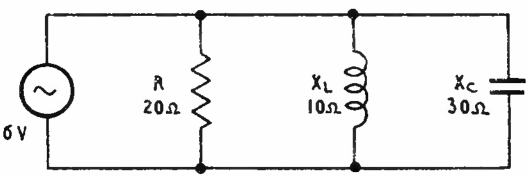
θ = Phase angle
I_L = Current in inductive branch
I_C = Current in capacitive branch
I_R = Current in resistive branch

5.5 Example No. 3. A parallel circuit contains 20 ohms resistance, 10 ohms inductive reactance and 30 ohms capacitive reactance. When an alternating voltage of 6 volts is applied, find -

(i) the impedance

(ii) the phase angle.

Include a vector diagram to show the current distribution in the circuit.



$$I_R = \frac{E}{R} = \frac{6}{20} = 0.3 \text{ Amps}$$

$$I_L = \frac{E}{X_L} = \frac{6}{10} = 0.6 \text{ Amps}$$

$$I_C = \frac{E}{X_C} = \frac{6}{30} = 0.2 \text{ Amps}$$

$$I = \sqrt{I_R^2 + (I_L - I_C)^2}$$

$$= \sqrt{0.3^2 + (0.6 - 0.2)^2}$$

$$= \sqrt{0.3^2 + 0.4^2}$$

$$= \sqrt{0.09 + 0.16}$$

$$= \sqrt{0.25}$$

$$= 0.5 \text{ Amps}$$

(i) .... $Z = \frac{E}{I} = \frac{6}{0.5} = \underline{12 \text{ ohms}}$

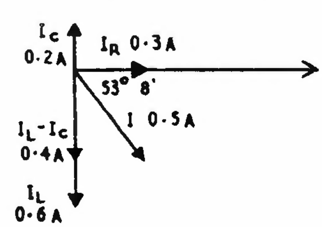
(ii) ... $\tan\theta = \frac{I_L - I_C}{I_R} = \frac{0.6 - 0.2}{0.3} = \frac{0.4}{0.3} = 1.333$

From tables

$\tan 53^0\ 8' = 1.333$

$\therefore \theta = \underline{53^0\ 8' \text{ lagging}}$.

The vector diagram for the circuit is -



Answers = (i) 12 ohms; (ii) 53^0 8' lagging.

6. INDUCTANCE AND CAPACITANCE IN PARALLEL.

6.1 Fig. 7 shows a circuit containing inductance connected in parallel with capacitance. The circuit current (I), is found from the vector sum of the branch currents, I_L and I_C

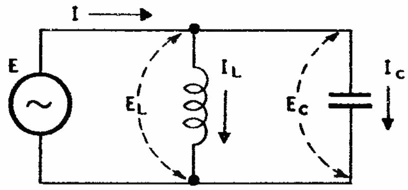


FIG. 7. INDUCTANCE AND CAPACITANCE IN PARALLEL.

6.2 Vector Diagram. The applied voltage is common to all branches, and is used as a reference vector for the current vector diagram.

The current in the inductive branch lags the voltage by 90° so the I_L vector is drawn at right angles below the reference vector (Fig. 8a).

The current in the capacitive branch leads the voltage by 90°, so the I_C vector is drawn at right angles above the reference vector (Fig. 8a).

As the branch currents are 180° out of phase, they are in opposition, and the circuit current is found from the difference in the branch current values (Fig. 8b).

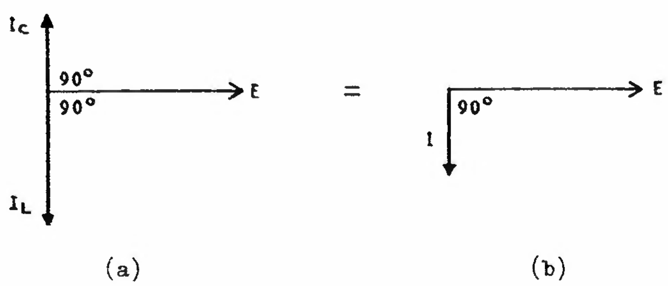


FIG. 8. VECTOR DIAGRAM.

6.3 Circuit Current Formula. As the branch currents are 180° out of phase, the circuit current is found from -

$$I = I_L - I_C$$

where
I = Circuit current
I_L = Current in inductive branch
I_C = Current in capacitive branch.

6.4 Phase Angle. As we are considering the theoretical case of pure inductance in parallel with pure capacitance, the circuit current is 90° out of phase with the applied voltag

When the current in the inductive branch is greater than the current in the capacitive branch, the circuit current lags the applied voltage by 90°.

When the capacitive branch current is the greater, the circuit current leads by 90°.

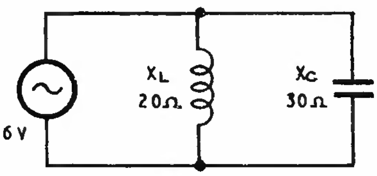
6.5 Example No. 4 illustrates two characteristics of parallel inductance-capacitance circuits. These are :-

(i) the current in the branches may be greater than the circuit current.

(ii) the impedance of the circuit may be much higher than the impedance of either of the branches.

These effects are due to the 180° phase difference between the branch currents, and although they are noticeable at all frequencies, they are most prominent at the frequency at which the branch currents are equal.

Example No. 4. Find (i) the impedance and (ii) the circuit current in a circuit containing 20 ohms inductive reactance connected in parallel with 30 ohms capacitive reactance to an alternating voltage of 6 volts.



$$I_L = \frac{E}{X_L} = \frac{6}{20} = 0.3 \text{ Amps}$$

$$I_C = \frac{E}{X_C} = \frac{6}{30} = 0.2 \text{ Amps}$$

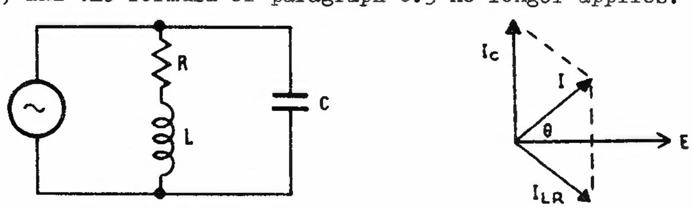
(i) .... $I = I_L - I_C = 0.3 - 0.2 = \underline{0.1 \text{ Amps}}$

(ii) .... $Z = \frac{E}{I} = \frac{6}{0.1} = \underline{60 \text{ ohms}}$

Answers = (i) 0.1 Amps; (ii) 60 ohms.

6.6 Practical Parallel Circuits of this type contain resistance as well as inductance and capacitance and when this resistance is significantly large it must be taken into account when determining the impedance of the circuit.

The resistance is normally due to the windings of the inductor and can be considered as a series resistance in the inductive branch as in Fig. 9a. Because of this resistance, the current in the inductive branch (I_{LR}) lags the voltage by less than 90°, and the formula of paragraph 6.3 no longer applies.



(a) (b)

FIG. 9. PRACTICAL PARALLEL L/C CIRCUIT.

Although the mathematical solution of such problems is beyond the scope of this course, an approximate value of circuit current can be obtained from a vector diagram (Fig. 9b) in which the phase angle of the inductive branch is taken into account.

7. PARALLEL RESONANCE.

7.1 We have seen that in a series circuit containing inductance and capacitance, very significant changes take place in the values of the various circuit quantities at the resonant frequency.

7.2 When a parallel combination of pure inductance and pure capacitance is connected to an alternating voltage, the frequency of which is increased -

- the current in the inductive branch decreases, due to the increasing inductive reactance.

- the current in the capacitive branch increases, due to the decreasing capacitive reactance.

The variations in branch current values over a range of frequencies are shown in Fig. 10. As the branch currents are 180° out of phase, the value of the circuit current is found from the difference in their values. This is also shown on Fig. 10.

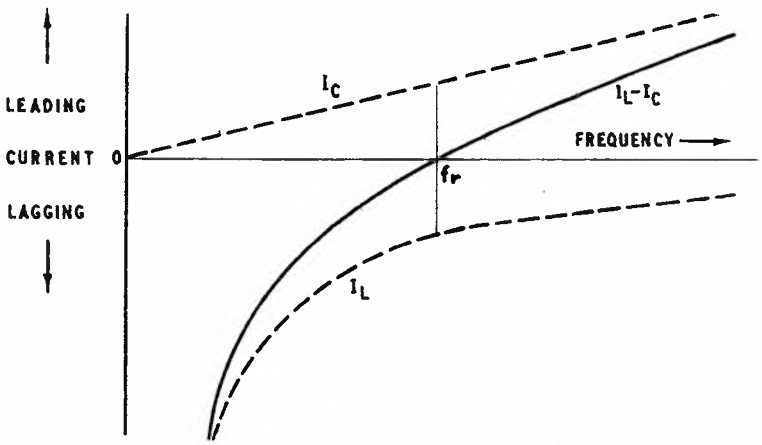
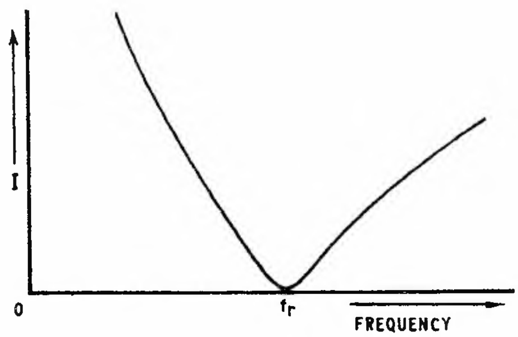


FIG. 10. EFFECT OF FREQUENCY ON CURRENTS.

At one particular frequency, the current in the inductive branch equals the current in the capacitive branch, and consequently the circuit current is zero.

This frequency is the Resonant Frequency, and occurs when the inductive reactance equals the capacitive reactance.

The variations in the circuit current over the frequency range are as shown in Fig. 11



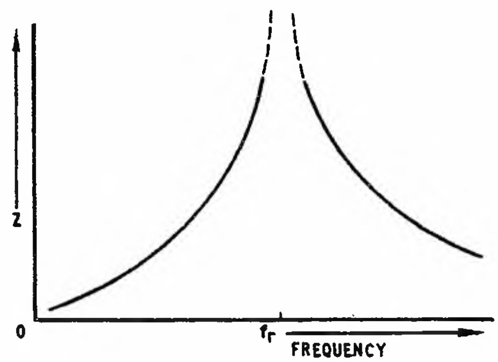
CIRCUIT CURRENT VARIATIONS IN A PARALLEL RESONANT CIRCUIT.

FIG. 11.

7.3 Impedance of a Parallel Resonant Circuit. As changes in frequency cause changes in the value of the circuit current, corresponding variations must be produced in the impedance of the circuit. The impedance of a parallel circuit containing pure inductance and capacitance changes as in Fig. 12.

As the circuit current is high in value at low frequencies, the impedance is small. Approaching the resonant frequency, the current decreases in value, indicating that the impedance increases. At the resonant frequency the impedance is infinite as the circuit current is zero.

Beyond the resonant frequency, the circuit current increases and the impedance decreases, until, at a very high frequency it falls to a very small value.



IMPEDANCE VARIATIONS IN A PARALLEL RESONANT CIRCUIT.

FIG. 12.

7.4 Circulating Currents. Although there is no circuit current at the resonant frequency, current circulates around the branch circuits. This circulating current transfers the storage of energy from the magnetic field to the electric field and back again, as these fields build up and collapse. (Figs. 13a and b.)

(a) Energy Stored in Magnetic Field.

(b) Energy Stored in Electric Field.

OSCILLATORY CIRCUIT.

FIG. 13.

As we are considering the theoretical case of a pure inductance connected in parallel with pure capacitance, no energy is lost in the transfer, and the currents would continue to circulate, even when the applied voltage is disconnected.

In practice however, the components contain resistance, and the stored energy is gradually dissipated, so that if the circulating or "oscillatory" currents are to be maintained, the voltage source must remain in circuit, or be applied in pulses at the correct frequency.

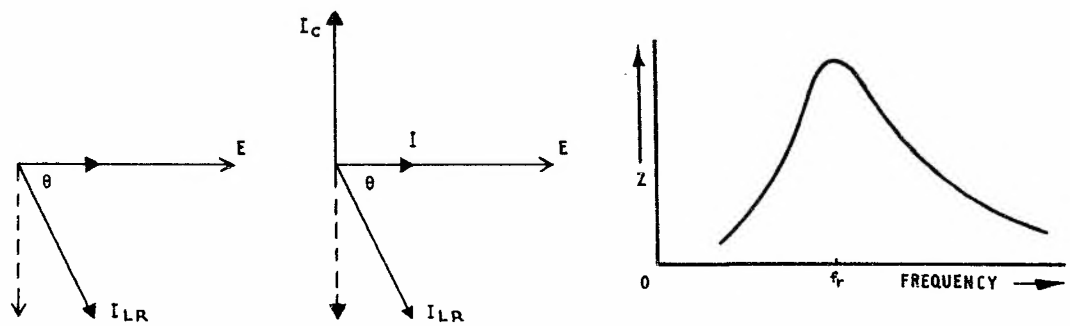
Although currents circulate within the parallel circuit at all frequencies, they attain their highest value at the resonant frequency.

7.5 Effect of Resistance. As the resistance of a capacitor can be made small, the resistance of the circuit is mainly due to the windings of the inductor.

This series resistance causes the current in the inductive branch to lag the voltage by less than 90° as in Fig. 14a. This current, I_{LR} has two components; one in phase with voltage and one which lags voltage by 90°. For the circuit to be resonant this latter 90° component of I_{LR} must be equal to the current in the capacitive branch. (Fig. 14b.)

At the resonant frequency, the branch currents I_C and I_{LR} do not cancel completely, and a small circuit current (in phase with voltage) results. This reduces the impedance of the circuit at resonance to some finite value as in Fig. 14c. The impedance at resonance is often called the Dynamic Resistance.

The small circuit current at resonance is sometimes called a "make up" current as it replaces or makes up for the energy dissipated in the resistance of the circuit thus maintaining the circulating currents.



(a) (b) (c)

RESISTANCE IN PARALLEL RESONANT CIRCUITS.

FIG. 14.

7.6 Current Magnification. In the series circuit, at resonance, we saw that the P.Ds. across the reactive components are magnified, and are "Q" times greater than the applied voltage. In the parallel case at the resonant frequency, current magnification takes place as the circulating branch current is greater than the circuit current.

With pure components, the degree of current magnification is infinite, as the circuit current is zero at resonance. However, in practical circuits, the degree of current magnification is reduced to some finite value, which is indicated by Q Factor.

In a parallel circuit, the Q Factor is a number which indicates how many times the circulating current at resonance is greater than the circuit current.

$$Q = \frac{I_C \text{ OR } I_L}{I}$$

where

Q = Current magnification of circuit

I_C = Current in capacitive branch

i_L = Current in inductive branch

I = Circuit current.

As in series circuits Q can be calculated from the ratio of the values of reactance and resistance at the resonant frequency.

In high "Q" circuits, the reactance of the inductive branch is much greater than the resistance, and the phase angle of the branch is nearly 90^o The capacitive branch has little resistance, and the current in this branch leads by nearly 90^o. As the branch currents are almost 180^o out of phase, the circuit current is small, and the degree of current magnification is large.

In low "Q" circuits, current magnification is small, as the branch currents are much less than 180^o out of phase, and the circuit current is of a comparatively high value.

7.7 Resonant Frequency. For most practical purposes, the resonant frequency of a parallel circuit may be calculated from the formula used for series circuits.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where
f_r = Resonant frequency
L = Inductance in henries
C = Capacitance in farads.

Example No. 5. Find the value of capacitor which must be connected in parallel with an inductor of 160 mH, so that the circuit is resonant at 4 kc/s.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \sqrt{LC} = \frac{1}{2\pi f_r}$$

$$= \frac{1}{\omega}$$

$$\therefore LC = \frac{1}{\omega^2}$$

$$\therefore C = \frac{1}{\omega^2 L}$$

$$\therefore C = \frac{10^6}{\omega^2 L}\ (\mu F)$$

$$\omega = 2\pi f$$

$$= 2 \times 3.14 \times 4000$$

$$= 25{,}000 \text{ (approx.)}$$

$$C = \frac{10^6}{\omega^2 L}\ (\mu F)$$

$$= \frac{10^6}{(25 \times 10^3)^2 \times 0.16}$$

$$= \frac{10^6 \times 10^2}{25 \times 10^3 \times 25 \times 10^3 \times 16}$$

$$= \frac{10^8}{10^{10}}$$

$$= \frac{1}{10^2}$$

$$= 0.01\,\mu F$$

Answer = $0.01\,\mu F$.

7.8 Parallel Resonant Circuits in Telecom. In modern telecom equipment, the "frequency sensitive" parallel resonant circuit finds a wide field of application.

Like the series resonant circuit, it is often used to separate signals having different frequencies, and, in many instances, combinations of series and parallel resonant circuits are used in this regard.

In addition to "filters", of which there are many types, we find parallel resonant circuits in many other telecom applications, such as oscillators, carrier frequency generators, and in many items of measuring and testing equipment.

7.9 Summary of Parallel Resonant Circuits. The main characteristics of parallel resonant circuits are:-

(i) With inductance and capacitance in parallel (theoretical case):

- resonance occurs when X_L equals X_C.
- resonant frequency (f_r) = $\frac{1}{2\pi\sqrt{LC}}$
- the circuit current is zero at the resonant frequency.
- circulating current flows at its maximum value, within the parallel circuit at resonance.
- at frequencies below resonance, the circuit is inductive as the current in the inductive branch is greater than that in the capacitive branch.
- at frequencies above resonance, the circuit is capacitive as the current in the capacitive branch is greater than that in the inductive branch.

(ii) With resistance in series with inductive branch (practical case):

- the circuit current is a minimum value at resonance.
- the circuit current is "in phase" with the applied voltage i.e. the circuit is resistive at resonance.
- at resonance the impedance is a maximum value. At all other frequencies the impedance is lower.
- resistance has the effect of lowering the impedance and increasing the circuit current at resonance.
- circulating current flows at its maximum values within the parallel circuit and is "Q" times the circuit current.
- at frequencies below resonance the circuit is inductive and the circuit current lags the applied voltage.
- at frequencies above resonance the circuit is capacitive and the circuit current leads the applied voltage.

8. TEST QUESTIONS.

1. To find the impedance of a parallel A.C. circuit, the steps are -

   (i) ....

   (ii) ....

   (iii) ....

2. The .... vector is the reference vector for a parallel circuit vector diagram.

3. In an R.L. parallel circuit, the circuit current is found from the formula .... and it leads/lags the ci voltage by an angle calculated from ....

4. An 80mH inductor and 1000 ohm resistor are connected in parallel to a 10 volt 1 kc/s alternating voltage. Find -

   (i) the circuit current

   (ii) the impedance

   (iii) the phase angle.

   Include a vector diagram to show the current distribution in the circuit.

5. When R and C are connected in parallel, the formula for circuit current is ....

6. The branch currents in a parallel circuit with resistive, inductive and capacitive branches are 70 mA, 500 mA and 260 m respectively. What is the circuit current?

7. When L and C are connected in parallel, the branch currents are 90°/180° out of phase, and the circuit current is found fr the formula ....

8. Resonance occurs in a parallel circuit when ....

9. The circuit current is .... in value at resonance in a parallel circuit containing pure L and C.

10. At resonance, parallel circuits are capable of .... magnification.

11. In practical circuits, resistance is present in the .... branch, and its effect is ....
    ....

12. What is the value of the inductor which must be connected in parallel with an 1μF capacitor so that the circuit is resonant at 1.6 kc/s.

END OF PAPER.

TRANSFORMERS AND INDUCTORS

---

1. INTRODUCTION.

1.1 A transformer is a device for transferring electrical energy from one A.C. circuit to another by means of a common magnetic circuit.

1.2 Transformers are used in all branches of electrical engineering but we are concerned only with those used in telecom equipment. These range from very large iron cored units in low frequency power plant, to very small air cored transformers in high frequency radio applications.

Modern transformers are extremely efficient and reliable, and very rarely need replacement. Because of this, their importance is often overlooked, and the reasons for their inclusion in a circuit are not always completely understood.

1.3 The basic theory of transformer operation is outlined in the "Electromagnetic Induction" paper of Applied Electricity 1, and this should be revised before proceeding further.

This paper deals further with the theory of operation of transformers, and gives additional information on their construction and use.

2. TRANSFORMER THEORY.

2.1 In the paper "Electromagnetic Induction" of Applied Electricity 1, we saw that a transformer consists of two insulated windings, called Primary and Secondary, arranged on a core of iron or other suitable material, so that the windings are magnetically coupled.

When an alternating voltage is applied to the primary winding, a flux is set up in the core which changes at the same rate as the primary current. This flux links the turns of both windings and according to Lenz's and Faraday's Laws, produces

- a self induced e.m.f. in the primary winding;
- a mutually induced e.m.f. in the secondary winding.

As both e.m.f's are produced by the same flux, the rate of change of flux is the same for each turn in the primary and secondary windings. Therefore, the induced e.m.f. per turn is the same in each winding.

When both windings have the same number of turns the self induced e.m.f. in the primary winding is equal to the mutually induced e.m.f. in the secondary winding.

When the secondary winding has twice as many turns as the primary winding, the induced e.m.f. in the secondary winding is twice the value of the induced e.m.f. in the primary winding.

As the self induced e.m.f. in the primary winding can be considered to be equal to the applied primary voltage, the ratio of the primary voltage (E_P) to the induced secondary voltage (E_S) is equal to the ratio of the number of primary turns (N_P) to the number of secondary turns (N_S).

That is -

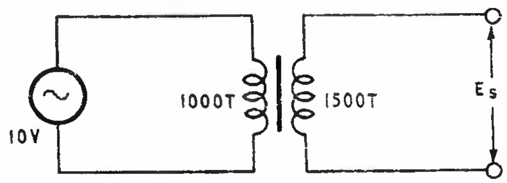
$$\frac{E_P}{E_S} = \frac{N_P}{N_S} \quad \text{or} \quad E_S = E_P \times \frac{N_S}{N_P}$$

As the ratio of secondary turns to primary turns $\left(\frac{N_S}{N_P}\right)$ is the Turns Ratio (T), the secondary voltage can be found from -

$$E_S = T \times E_P$$

where
E_S = Secondary voltage
E_P = Primary voltage
T = Ratio of secondary turns to primary turns.

Example No. 1. A transformer has 1000 turns on the primary winding and 1500 turns on the secondary winding. Find the secondary voltage when an alternating voltage of 10 volts is applied to the primary winding.



$$T = \frac{N_S}{N_P} = \frac{1500}{1000} = \frac{1.5}{1}$$

$$E_S = T \times E_P = \frac{1.5 \times 10}{1} = \underline{15 \text{ volts.}}$$

Answer = 15 volts.

2.2 A transformer is essentially a connecting device by means of which energy is transferred from an energy source to a load circuit.

Within the transformer, voltage transformation may occur, but it must always be remembered that any increase or decrease in the power output from the secondary winding must be accompanied by a corresponding increase or decrease in power input to the primary winding.

The action of transformers can best be shown by vector diagrams which depict the operating conditions in the primary circuit for different types of secondary load circuits.

For our purposes, it is sufficient to consider the action of a perfect transformer, that is, one which has no power losses. Such a device is, of course, only theoretically possible, as in all practical transformers, energy is dissipated in the resistance of the windings and in eddy currents and hysteresis effects in the core. However, as correctly designed transformers can be up to 98% efficient, these losses have only a minor effect on the principles of operation and can be overlooked at this stage.

2.3 No-Load Conditions. When the secondary winding of a transformer is left with an "open" circuit, no transfer of energy can take place between windings, and thus the primary winding is a purely inductive circuit with a comparatively high value of inductance. When an alternating voltage is applied to the primary winding (Fig. 1a), the inductive reactance of the primary winding limits the current to a small value.

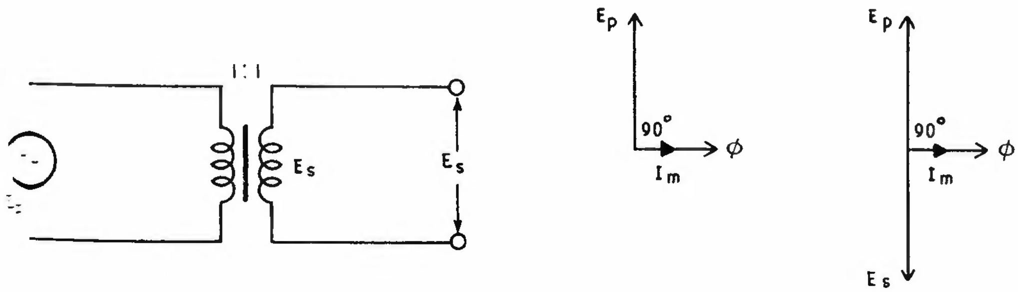
This current is called the magnetising current, as it establishes the flux in the core. Because of the inductance of the primary winding, this current lags the applied primary voltage by 90°.

These "no-load" conditions in the primary circuit are shown vectorially in Fig. 1b, in which

- the flux vector (ϕ) is drawn horizontally as a reference;
- the magnestising current vector (I_m) is drawn in phase with flux;
- the primary voltage (E_p) is drawn so that I_m lags by 90°.

The flux links the turns of the secondary winding, and induces an e.m.f. (E_s) which, according to Lenz's Law, is 180° out of phase with E_p. For simplicity, it is assumed that the transformer has an equal number of turns on each winding and therefore E_s can be drawn equal to, but 180° out of phase with E_p (Fig. 1c).

Under no-load conditions, therefore, an e.m.f. is induced in the secondary winding, but as the power requirements of the secondary circuit are zero, only a small magnetising current flows in the primary winding, lagging the primary voltage by 90°.



(a) (b) (c)

FIG. 1. TRANSFORMER WITH NO SECONDARY LOAD.

2.4 Loaded Conditions. When a load circuit is connected to the secondary winding, energy is transferred from the primary source to the secondary circuit, where it is dissipated in the secondary load.

As the no-load primary current is "wattless", that is, it lags by 90°, additional current must flow in the primary circuit, so that energy is available for transfer to the secondary circuit. This increase in primary current is brought about as follows:-

When current flows in the secondary winding it tends to set up a flux in the core. According to Lenz's Law, this flux opposes that produced by the primary current, and therefore it reduces the flux producing properties, or inductance of the primary winding.

With less inductance, the inductive reactance of the primary winding is reduced and the current in the primary winding increases.

The additional current in the primary winding is called the "Balance current", as it counteracts or balances the demagnetising effect of the secondary current. Irrespective of the type of circuit connected to the secondary winding, the magnetising effect of the balance current is always equal and opposite to the demagnetising effect of the secondary current, or

- balance current (I_b) is always 180° out of phase with secondary current (I_s);
- balance current ampere-turns ($I_b \times N_p$) equals secondary current ampere-turns ($I_s \times N_s$).

Therefore

$$I_b = T \times I_s$$

where

I_b = Primary balance current
I_s = Secondary current
T = Turns Ratio.

2.5 Transformer with Resistive Secondary Load. Fig. 2a shows a transformer which has an equal number of turns on each winding. The action of the transformer when a resistive load is connected to the secondary winding is shown in Figs. 2b, c and d.

Fig. 2b shows the vector diagram for the no-load condition. This is the starting point for all transformer vector diagrams.

As the secondary load is resistive, the secondary current (I_s) is in phase with the secondary voltage. (Fig. 2c.) To overcome the demagnetising effect of I_s, a balance current (I_b) flows in the primary winding, 180° out of phase with I_s. As the windings have an equal number of turns, I_b is equal to I_s (Fig. 2c).

In Fig. 2d, the total primary current (I_p) is found from the vector sum of I_m and I_b. It can be seen that the primary current under load is much greater than the no-load primary current, and that the phase angle of the primary circuit is much less than 90°. This indicates that the energy dissipated in the resistive load circuit is being supplied by the primary voltage source.

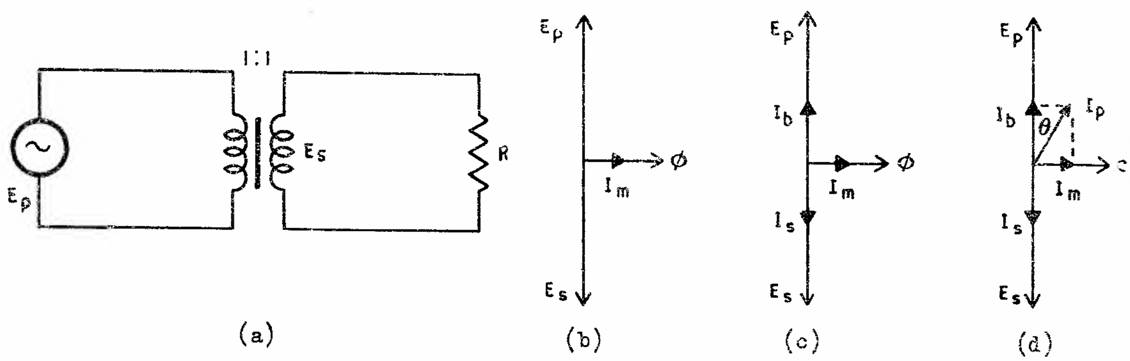


FIG. 2. TRANSFORMER WITH RESISTIVE SECONDARY LOAD.

When the resistance of the secondary load circuit is reduced, the secondary current increases correspondingly. To supply the additional energy, and to counter the demagnetising effect of the increased secondary current, the balance current increases also.

The vector diagrams of Fig. 3 show the effect of applying progressively heavier resistive loads to the secondary winding. When the transformer is fully loaded, (Fig. 3d), the balance current is very much greater than the magnetising current, and, for most practical purposes can be considered as being equal to the total primary current. Under these conditions the primary phase angle is very small, and therefore the primary winding exhibits the resistive characteristics of the secondary load circuit.

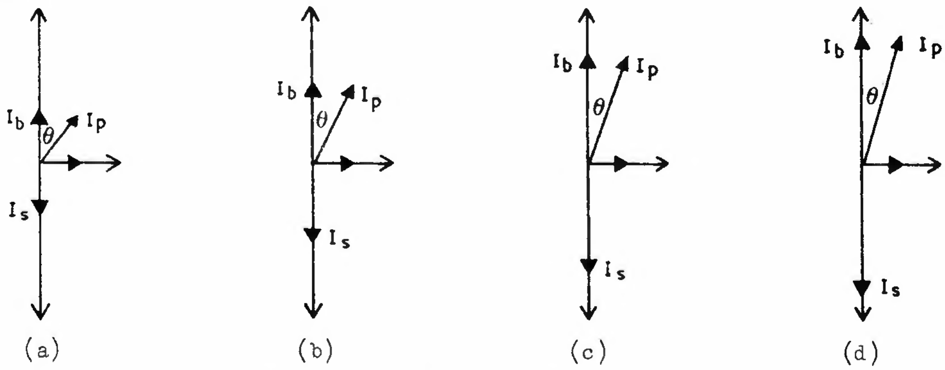
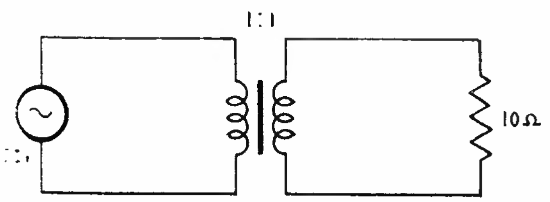
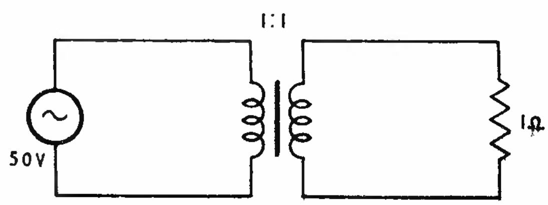


FIG. 3. TRANSFORMER WITH RESISTIVE SECONDARY LOADS.

When the resistance of the load circuit is so low that the maximum rated secondary current value of the transformer is exceeded, the primary current reaches an abnormally high value. In practical transformers, the windings possess some resistance, and under such overloaded conditions, sufficient heat can be produced within the transformer to cause permanent damage.

Example No. 2. A transformer with an equal number of turns on each winding is connected to an alternating voltage supply of 50 volts. Neglecting the effects of losses and the small magnetising current, calculate the primary current when circuits having resistances of (i) 10 ohms and (ii) 1 ohm are connected to the secondary winding.





As $T = 1$

Secondary Voltage = Primary Voltage.

(i).... Secondary Current $= \frac{E_s}{R_s}$

$= \frac{50}{10} = 5$ Amps

Balance Current $= T \times I_s$

$= 1 \times 5$

$=$ 5 Amps

$=$ Primary Current (Approx.)

(ii).... Secondary Current $= \frac{E_s}{R_s}$

$= \frac{50}{1} = 50$ Amps

Balance Current $= T \times I_s$

$= 1 \times 50$

$=$ 50 Amps

$=$ Primary Current (Approx.)

Answers = (i) 5 Amps; (ii) 50 Amps.

2.6 Effect of Turns Ratio. Fig. 4a shows a transformer which has a turns ratio of 2, that is, there are twice as many secondary turns as there are primary turns.

When an alternating voltage is applied to the transformer, a magnetising current flows in the primary winding. This current (I_m) lags the applied voltage (E_p) by 90°. In the secondary winding, the induced voltage (E_s) is 180° out of phase with E_p, but, because of the turns ratio, E_s is twice the value of E_p. This is shown in Fig. 4b, which represents the no-load condition.

As a load circuit is connected to the secondary winding, current flows in the secondary circuit. As the load is resistive, the secondary current (I_s) is in phase with E_s (Fig. 4c).

The balance current in the primary winding (I_b) is 180° out of phase with I_s. As the primary winding has only half as many turns as the secondary winding, I_b needs to be twice the value of I_s to achieve balance (Fig. 4c).

In Fig. 4d, the total primary current (I_p) is found from the vector sum of I_b and I_m. It can be seen that the primary current is approximately twice the value of the secondary current.

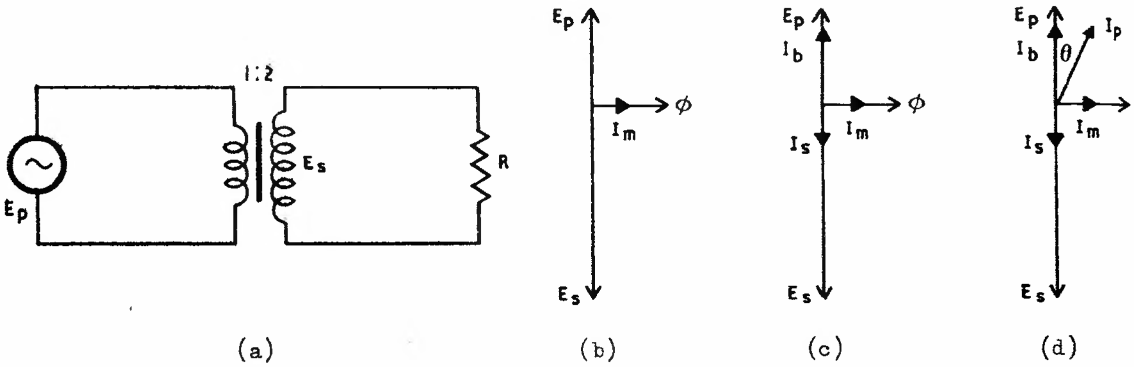
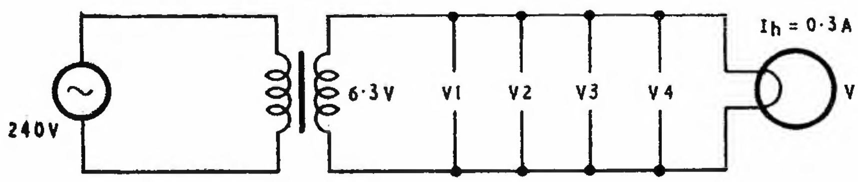


FIG. 4. TRANSFORMER WITH UNEQUAL TURNS RATIO.

Example No. 3. A transformer is used to step down the 240 volt A.C. supply to 6.3 volts for the operation of the heaters of a number of electron tubes, each of which requires a current of 0.3 amps. Neglecting the effects of losses and the magnetising current, find, (i) the turns ratio of the transformer, and (ii) the primary current when five tubes are connected in parallel.



Secondary Current $= I_h \times 5$

$= 0.3 \times 5 = 1.5$ Amps

(i).... $E_s = T \times E_p$

$\therefore T = \frac{E_s}{E_p}$

$= \frac{6.3}{240} = \frac{1}{38}$ (approx.)

(ii).... Balance Current $= T \times I_s$

$= \frac{1}{38} \times 1.5$

$=$ 0.04 Amps.

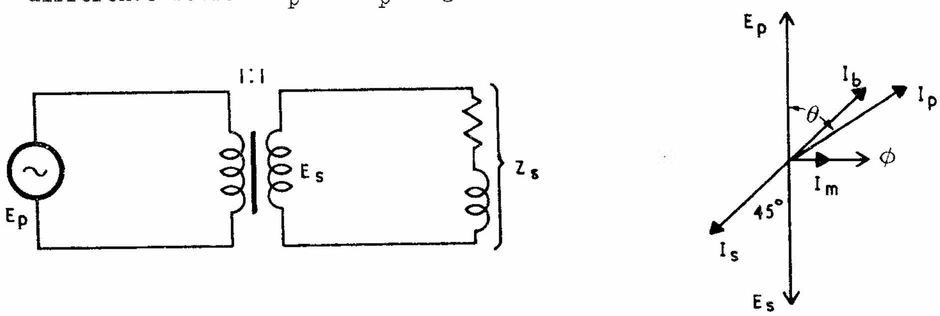
$=$ Primary Current (Approx.

Answers = (i) $\frac{1}{38}$ (ii) 0.04 Amps.

.7 Transformer with Inductive Secondary Load. Fig. 5a shows a transformer having windings with equal numbers of turns, and with an inductive circuit connected to the secondary winding. It is assumed that the characteristics of the load circuit are such that the secondary current (I_s) lags the secondary voltage (E_s) by approximately 45°.

The operating conditions in the primary winding are shown in the vector diagram (Fig. 5b) which is constructed using the same method as in previous diagrams.

Note that the primary balance current (I_b) is again drawn 180° out of phase with I_s, and that because of the lagging effect of the magnetising current (I_m) the phase difference between I_p and E_p is greater than that between I_s and E_s.



(a) (b)

FIG. 5. TRANSFORMER WITH INDUCTIVE LOAD.

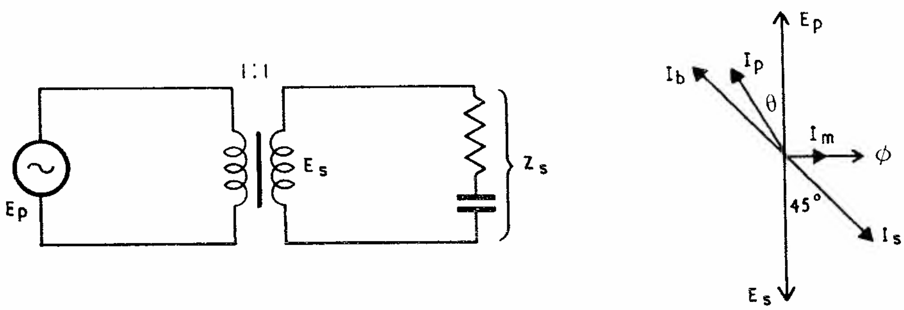
Fig. 5b shows that comparatively large currents flow in the windings, but because the secondary load circuit is inductive only a small amount of energy is consumed in the load.

The efficiency of a practical transformer operated under these conditions is comparatively low, as the winding (I^2R) losses are considerable and out of all proportion to the amount of useful energy transferred.

.8 Transformer with Capacitive Secondary Load. Fig. 6a shows a 1 : 1 transformer with a capacitive load connected to the secondary winding. In the secondary circuit the current (I_s) leads the voltage (E_s) by approximately 45°.

The vector diagram (Fig. 6b) shows that the balance current (I_b) is equal to I_s, and as these currents are 180° out of phase, I_b leads the primary voltage E_p.

The primary current (I_p) is found from the vector sum of I_b and I_m; as I_m lags by 90°, the phase difference in the primary circuit is less than that in the secondary circuit.



(a) (b)

FIG. 6. TRANSFORMER WITH CAPACITIVE LOAD.

In a practical transformer the effect of the losses cause a further reduction in the phase angle in the primary circuit. When the load circuit is only slightly capacitive, the primary current can lag the primary voltage.

Under certain circumstances, the capacitance in the load circuit can combine with the inductance of the transformer to cause a resonant condition, when the secondary voltage under load can exceed the no-load voltage.

2.9 Reflected Impedance. We have seen that when the impedance of the secondary load circuit is changed, the subsequent change in secondary current causes a corresponding change in primary current.

As this change in primary current is fundamentally due to a change in primary impedance, the change in secondary load impedance causes a proportional change in impedance in the primary winding.

This action is commonly called "reflection", and the impedance of the load as "seen" by the energy source through the transformation ratio, is referred to as a reflected impedance.

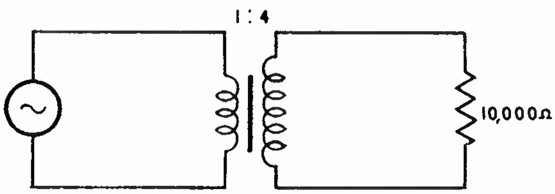
The ratio between the impedance of the load circuit and the reflected primary impedance is called the Impedance Ratio.

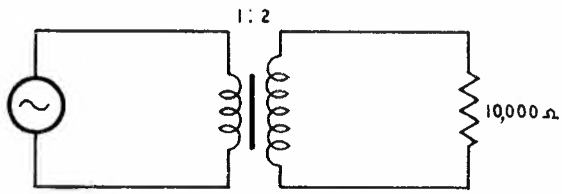
We saw in the paper "Electromagnetic Induction" of Applied Electricity 1, that the impedance ratio of a transformer is equal to the square of the turns ratio, or

$$T^2 = \frac{Z_S}{Z_P}$$

where
T = Turns Ratio
Z_p = Impedance of primary winding
Z_s = Impedance of secondary load circuit.

Example No. 4. Transformers with turns ratios of (i) 4 and (ii) 2 are used in turn to connect a circuit of 10,000 ohms impedance to an alternating voltage source. Neglecting the effects of losses, find the impedance of the transformer primary winding in each case.





(i)....
$$T^2 = \frac{Z_s}{Z_p}$$
$$\therefore \quad Z_p = \frac{Z_s}{T^2} = \frac{10{,}000}{4 \times 4} = \underline{625 \text{ ohms}}$$

(ii)....
$$T^2 = \frac{Z_s}{Z_p}$$
$$\therefore \quad Z_p = \frac{Z_s}{T^2} = \frac{10{,}000}{2 \times 2} = \underline{2{,}500 \text{ ohms}}$$

Answers = (i) 625 ohms; (ii) 2,500 ohms.

In the same way, the transformed impedance of the primary source appears across the secondary winding. However, as we are now "looking" into the transformer in the reverse direction, the turns ratio figure is inverted when calculating the impedance of the secondary winding.

In simple transformer calculations, the effects of the core losses and the resistance of the windings are not considered, and therefore, there is a slight difference between the measured value of impedance and the figure obtained by calculation. However, the discrepancy is not serious and the calculated value is sufficiently accurate for most practical purposes.

2.10 Impedance Matching. In telecom we are concerned with the transmission of A.C.'s over circuits which contain many different items of equipment such as subscribers instruments, lines, amplifiers, etc. As these signal currents are often at very low power levels, electrical energy must be transferred from one circuit to another as efficiently as possible.

We saw in the paper "Electromagnetic Induction" of Applied Electricity 1, that in a D.C. circuit, maximum power transfer takes place when the resistance of the load is equal to the internal resistance of the source. The same conditions apply in resistive A.C. circuits, but where the load and energy source are reactive, maximum power transfer occurs when the resistance of the load equals the resistance of the source, and when the reactances of the load and source are equal in value but opposite in sign. However, these conditions are seldom encountered, and for most practical purposes, the maximum possible power transfer takes place when the impedance of the source equals the impedance of the load.

In telecom very few of the component circuits of a communication channel have equal impedance and, to obtain efficient power transfer, it is necessary to use transformers to connect the various components so that their impedances appear to be equal or are "matched".

2.11 Impedance Matching Using Transformers. We have seen that the impedance of the circuit connected to one winding of a transformer is reflected into the other winding, and that the magnitude of the reflected impedance depends on the turns ratio.

In Example No. 4, a secondary load impedance of 10,000 ohms appears to be 625 ohms when seen from the energy source through a turns ratio of 4. When the turns ratio is 2, the source "sees" the load as an impedance of 2,500 ohms.

Therefore, by using a transformer of suitable turns ratio, it is possible to connect a load to an energy source of unequal impedance, so that

(i) the impedance of the load, as seen by the source, appears equal to the source impedance;

(ii) the impedance of the source, as seen by the load, appears equal to the load impedance.

When this is achieved, the impedances are matched and energy is transferred efficiently from the source to the load.

The turns ratio of a matching transformer can be found from -

$$T^2 = \frac{Z_S}{Z_P}$$

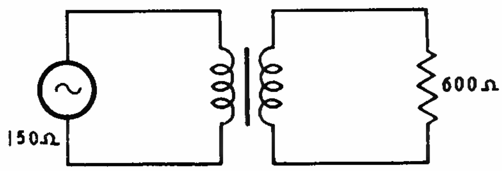
where

T = Turns Ratio

Z_S = Impedance of circuit connected to secondary winding

Z_P = Impedance of circuit connected to primary winding.

Example No. 5. Calculate the turns ratio of a matching transformer suitable for connecting a 600 ohm load circuit to an A.C. source having an internal impedance of 150 ohms.



$$T^2 = \frac{Z_S}{Z_P}.$$

$$\therefore \quad T = \sqrt{\frac{600}{150}} = 2.$$

Answer = 2.

2.12 Transformer Losses. In examining the principles of operation of a transformer, we have considered the transformer as perfect, overlooking the losses which exist in practical transformers.

Briefly these are -

(i) Winding Loss. This is an I^2R loss due to the resistance of the windings. Winding losses increase as the loading increases.

(ii) Eddy Current Loss. This is a power loss caused by the production of eddy currents in the core. This loss remains fairly constant from no-load to full load but it increases rapidly as the frequency of operation rises.

(iii) Hysteresis Loss. This refers to the energy spent in reversing the magnetisation of the core material. Hysteresis losses increase with frequency.

(iv) Magnetic Leakage. This occurs when part of the flux from one winding does not link with the turns of the other winding. Its effect is to add to the inductive reactance of the windings, and so reduce the secondary terminal voltage.

With correct design these losses can be kept to a minimum and modern transformers are very efficient.

As a matter of interest, the efficiency of a transformer is expressed as a percentage and is given by -

$$\text{EFFICIENCY (\%)} = \frac{\text{OUTPUT IN WATTS}}{\text{INPUT IN WATTS}} \times 100$$

2.13 Self-Capacitance. Another factor which has an effect on the operation of a transformer in practice is the self-capacitance which exists across and between its windings. (Fig. 7.)

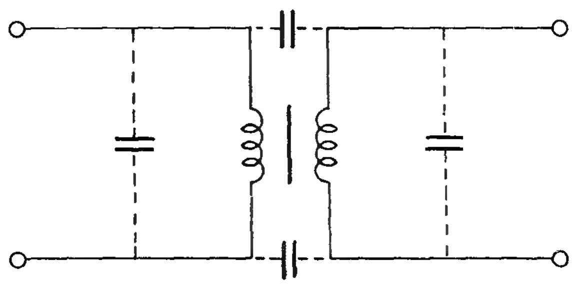


FIG. 7. SELF-CAPACITANCE.

These are due to the combined effects of the minute capacitances between adjacent turns, adjacent layers and adjacent windings.

Although the values of these self-capacitances are comparatively small, they can have a serious shunting effect when the transformer operates at high frequencies. When the transformer operates over a range of frequencies, the self-capacitance can combine with the "leakage reactance" and produce a resonant condition at one frequency within the range. This causes a marked deviation from the normal response of the transformer.

The transformers used in telecom are often required to operate over a range of frequencies, and, as a uniform frequency response is desirable, they must be constructed so that the self-capacitance is kept to a minimum.

TRANSFORMER CONSTRUCTION.

3.1 For efficient operation, a transformer should be constructed so that all the flux set up by the primary winding links with the turns of the secondary winding and vice versa. This ideal cannot be completely achieved but, in a well designed transformer, the percentage leakage flux is very small.

Irrespective of its type, a transformer has three essential sections. These are -

(i) The Core.
(ii) The Windings.
(iii) The Shielding.

3.2 Transformer Cores. The core of the transformer provides the path for the operating flux. It should have minimum reluctance consistent with minimum eddy current and hysteresis losses at the operating frequency. Its shape should be such that the windings can be readily accommodated with maximum flux linkage between windings.

For operation at different frequencies, transformer cores are made from different materials.

At power frequencies, audio frequencies and the lower carrier frequencies (up to about 20 kc/s) laminated cores of silicon steel (stalloy) or nickel iron are used.

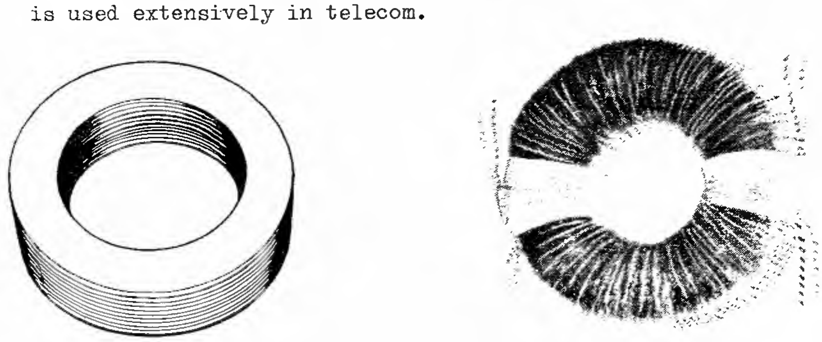
At higher carrier frequencies and radio frequencies, the eddy current losses in a laminated core become excessive and iron dust or "ferrite" cores are used. (Ferrites are a group of ceramic-like magnetic materials in which iron oxide is the major component. These materials have high permeability and extremely high resistivity. As their eddy current losses are negligible, ferrites are suitable for use in solid cores at frequencies up to 100 Mc/s.)

At extremely high radio frequencies efficient operation can only be achieved by using air cores.

Most solid (ferrite) or laminated cores have a closed magnetic circuit, but where the primary current has a D.C. component, an air gap is left in the core to prevent magnetic saturation.

Of the closed magnetic circuit cores, there are three types in general use. They are -

(i) The Toroidal Type. This type of core is in the shape of a closed ring. (Fig. 8.) The circular form of the core enables the windings to be accurately balanced, that is to have identical electrical characteristics. The leakage flux is negligible as the coils are would over the full length of the core. Although the winding procedure is complicated this type of core is used extensively in telecom.



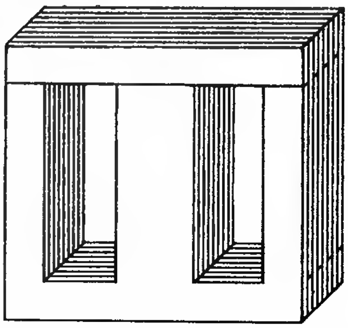
(a) Toroidal Core. (b) Toroidal Core with Winding.

FIG. 8. TOROIDAL TRANSFORMER CORE.

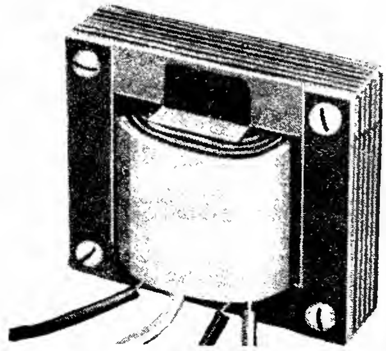
(ii) The Shell Type. In this design, (Fig. 9), the windings are accommodated on the centre limb of the core. The outer limbs form parallel flux paths and therefore have half the cross-sectional area of the centre limb.

The stampings from which a laminated shell core is assembled can be of a variety of shapes, but the "E" and "I" type is the most common. Fig. 9a represents a shell type laminated core in which the joints between the "E" and "I" sections are interleaved to prevent the formation of an air gap.

This type of construction forms an efficient magnetic circuit, and is used extensively in transformer construction.



(a) Shell Core.



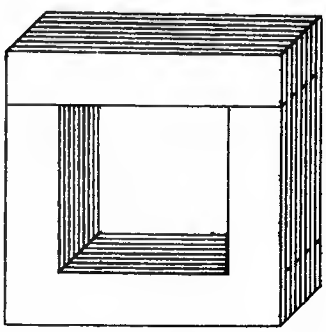
(b) Shell Core with Windings.

FIG. 9. SHELL TYPE TRANSFORMER CORE.

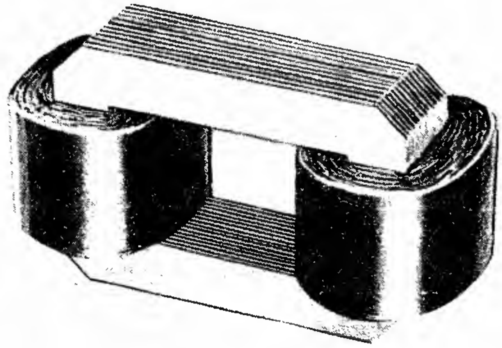
(iii) The Core Type. Fig. 10 shows a transformer core of this design in which the magnetic circuit takes the form of a hollow square. This core is often built up from "U" and "I" type laminations, which can be interleaved as in Fig. 10a.

The windings can be placed on opposite limbs for high voltage isolation, or, the windings can be split with half of each winding placed on each limb. This latter method reduces induction from stray magnetic fields as the interfering e.m.f.'s induced in each half of each winding are in opposition and they neutralise each other when the windings are accurately divided.

The use of this core is generally restricted to transformers in which low noise level is important such as amplifier input transformers, or where high voltages are involved as in T.V. line output transformers.



(a) Core.



(b) Core with Windings.

FIG. 10. CORE TYPE TRANSFORMER CORES.

3.3 Transformer Windings. The number of windings provided is determined by the application of the transformer. Many transformers have two or more secondary windings and each winding may be "tapped" to provide a number of outputs. The number of turns on each winding is influenced by factors such as the operating frequency, the desired voltage or impedance of the windings and the size and composition of the core.

The windings are usually wound on a former and assembled to the core as a unit. They can be layer wound, that is, the turns are wound in layers over the full length of the winding space, or they can be wound in sections or "pies" which are placed side by side along the core. This latter method is used to minimise the self-capacitance of the winding.

3.4 Shielding. In order to reduce interference and noise in communication circuits, transformers must be provided with electromagnetic and electrostatic shields.

Electromagnetic shields are necessary to confine the flux to the transformer and prevent electromagnetic induction into and from neighbouring circuits.

Low frequency transformers are usually enclosed in a cover or case of magnetic material which acts as a magnetic short circuit, preventing the flux from extending beyond the shield.

In high frequency transformers, shielding is achieved by enclosing the transformer in a copper or aluminium can. The flux from the transformer induces eddy currents in the can. The eddy current flux opposes the transformer flux and prevents it from spreading outside the shield.

Electrostatic shields are provided to prevent electrostatic coupling.

Transformers require two types of electrostatic shielding:-

(i) An External shield to prevent the electric field from the transformer from causing interference in neighbouring circuits and vice versa. This form of shielding may be provided by the same earthed metallic can which is used for electromagnetic shielding.

(ii) An Internal shield to reduce the capacitance between windings. Shielding is achieved by separating the windings with an earth connected non-magnetic foil wrapping, usually copper. The joint in the foil must be insulated to prevent the formation of a short-circuited turn (Fig. 11).

By this means, the capacity between windings is replaced by capacity between each winding and earth. In the event of an insulation breakdown in a power transformer the electrostatic shield prevents a direct connection between high voltage and low voltage windings.

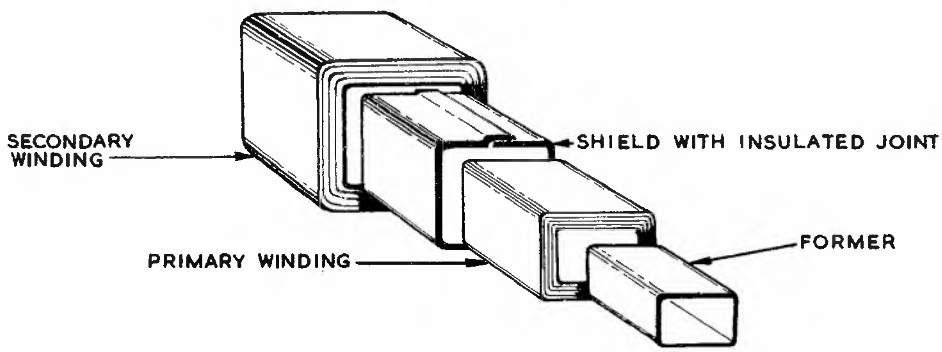


FIG. 11. SHIELDED WINDINGS.

4. TYPES OF TRANSFORMERS.

4.1 The transformers used in telecom equipment vary in size, shape and general construction according to the application of each type, but they can be broadly classified according to their operating frequency as -

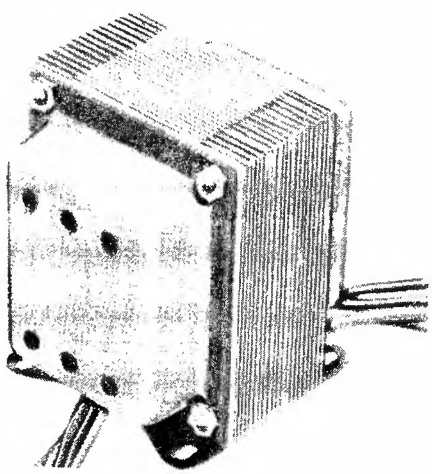
(i) Power transformers.

(ii) Audio frequency transformers.

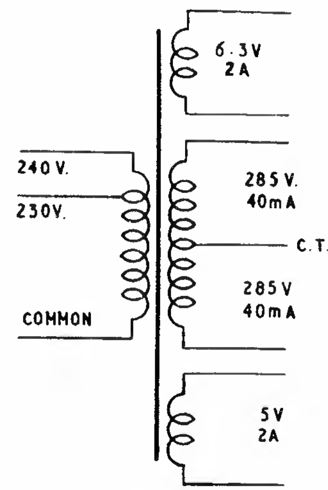
(iii) Radio frequency transformers.

4.2 Power Transformers are designed to operate at the power frequency (50 c/s), and are used to step up or step down the mains supply voltage to a desired value.

The majority of power transformers have closed magnetic circuits employing shell or core type laminated iron cores. Power transformers often have two or more secondary windings each with a different number of turns to provide different voltage outputs. A typical small power transformer as used in mains operated electronic equipment is shown in Fig. 12.



(a) Power Transformer.



(b) Arrangement of Windings.

FIG. 12. POWER TRANSFORMER.

When a power transformer is under load, the secondary terminal voltage is always slightly less than the no-load voltage. This reduction in secondary voltage is mainly due to the voltage drop in the resistance of the windings.

The difference between the no-load voltage and the full load voltage is known as the Regulation of the transformer, and it is usually expressed as a percentage of the no-load voltage.

$$\text{Regulation (\%)} = \frac{\text{No-Load Secondary Voltage} - \text{Full Load Secondary Voltage}}{\text{No-Load Secondary Voltage}} \times 100$$

In a well designed transformer, the regulation does not exceed 5%.

The power output available from a transformer is governed by the cross-sectional area of the core. For example, a transformer with twice the power output of another needs to have a core with a cross-sectional area approximately $\sqrt{2}$ times greater than that of the smaller transformer.

Small radio type power transformers (Fig. 12) are rated in terms of maximum secondary current. A transformer rated at "100 mA" could be permanently damaged if the secondary current exceeded 100 mA for a sustained period.

Larger power transformers are rated in terms of secondary volt-amps. The output is not expressed in watts as the secondary load circuit may not be completely resistive.

..3 Audio Frequency Transformers operate at frequencies in the audio range and are used to transfer or couple a signal from one circuit to another, to electrically isolate two circuits or to match circuits of different impedance.

These transformers usually have laminated iron cores which can be of the open or closed magnetic circuit type. The windings are wound with fine wire, and often special winding methods are used to reduce the self-capacitance to give a uniform or "flat" response over the frequency range.

Audio Frequency transformers require effective shielding to prevent the introduction of noises such as clicks and power hum into the circuit. This is particularly important where the signal current has a low power level.

The transformer shown in Fig. 13 is a matching transformer designed to operate over the frequency range 30 c/s to 12 kc/s.

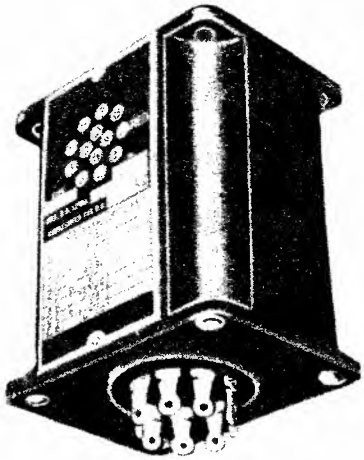


FIG. 13. AUDIO FREQUENCY TRANSFORMER.

..4 Radio Frequency Transformers are used to couple circuits operating at radio frequencies or to step up or step down radio frequency voltages.

In most cases, the windings are loosely coupled magnetically, and ferrite, iron dust or air cores are used. Shielding is achieved by enclosing the unit in a can of aluminium or other low resistance metal.

Many R.F. transformers have a capacitor connected in parallel with one or both windings to form resonant circuits. When signals at different frequencies are applied to the primary winding of such a "tuned" transformer, those signals at or near the resonant frequency predominate in the secondary circuit. A typical tuned radio frequency transformer is shown in Fig. 14.

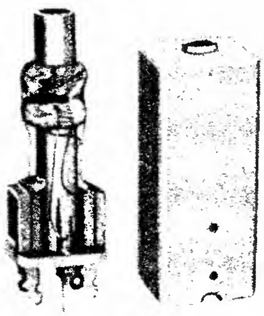


FIG. 14. RADIO FREQUENCY TRANSFORMER.

..5 Because of the wide variety of transformers used in carrier systems, and the extent of the carrier frequency range, no specific reference to "carrier frequency transformers" has been made in this paper. However, these transformers mainly perform the same basic functions of coupling, isolating and impedance matching and are constructed according to the requirements of their operating frequency.

5. INDUCTORS.

5.1 An inductor is a device which has been specifically constructed so that it possesses a certain value of inductance.

In its simplest form an inductor consists of a number of turns of wire. The winding is arranged so that the flux set up by the passage of varying or alternating current links the turns and induces an e.m.f. which opposes the change in current.

5.2 Factors Affecting Inductance. The inductance of an inductor can be expressed in terms of linkages (flux lines x turns) created when the current changes at a certain rate. The factors which determine the inductance are -

(i) The Number of Turns. The number of linkages produced by a certain change in current is proportional to the resultant change in flux and to the number of turns on the coil. But as the change in flux is also proportional to the number of turns, the linkages (and therefore the inductance) is proportional to the number of turns squared.

(ii) The Method of Winding. Inductance is also affected by the method of winding. Factors such as the spacing between turns, the number of layers in the winding, and the type of winding procedure adopted, all influence the coupling between the turns and consequently affect the inductance.

(iii) The Reluctance of the Magnetic Circuit. The reluctance of a magnetic circuit is the opposition it offers to the establishment of a magnetic field. When the current flowing in the winding of an inductor changes, the extent of the resultant change in flux depends on the reluctance of its magnetic circuit.

When two inductors have an equal number of turns and when the magnetic circuit of one has half the reluctance of the other, a certain change in current produces twice as many linkages in the low reluctance inductor than are produced in the inductor having the greater reluctance.

Inductance is therefore inversely proportional to the reluctance of the magnetic circuit, which is the combined effect of -

- the cross-sectional area of the core;
- the length of the core;
- the permeability of the core under working conditions.

With air cored inductors, inductance is independent of current, as the permeability of air is unity and does not change.

With iron cored inductors however, the permeability of the iron varies with the magnitude of the magnetising force produced by the current. All iron cored inductors therefore, are rated as possessing a certain inductance at a specified value of current.

5.3 Construction. Like a transformer, an inductor has three main parts -

(i) The Core.

(ii) The Winding.

(iii) The Shielding.

(i) The Core. Cores used for inductors follow much the same pattern as those used in transformers which operate within the same frequency range.

For different applications, inductor cores can be of the open magnetic circuit type, or of the closed magnetic circuit type with or without an air gap. The material used in the core depends on the operating frequency, but laminated iron, ferrite or air cores are the most common.

Laminated cores can be of the toroidal, shell or core design, but a much wider variety of shapes is available in moulded ferrite cores. These include rods (cylindrical or threaded), tubes, slabs and pot cores. The make-up of one type of pot core is shown in Fig. 15.

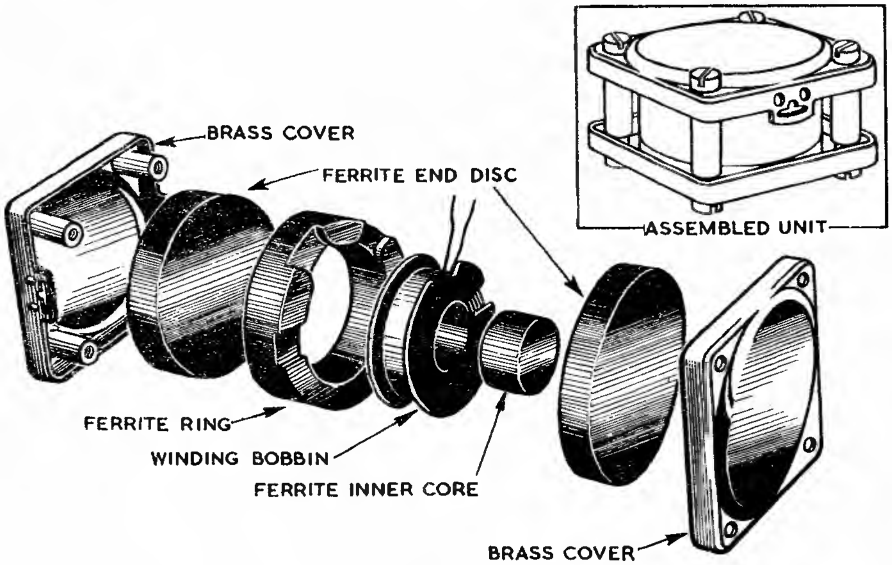


FIG. 15. FERRITE POT CORE INDUCTOR.

(ii) Windings. Inductors operating at low frequencies are usually layer wound over the length of the available winding space. For operation at higher frequencies, the self-capacitance of a layer winding is excessive, and special winding methods are adopted. To reduce skin effect, these inductors are wound with Litzendraht (Litz) wire which consists of a number of individually insulated interwoven stands or, where large current values are involved, the inductor is wound in copper tubing.

(iii) Shielding. Inductors require electromagnetic and electrostatic shields, and these are provided by enclosing the core and winding in an earthed metal case.

When the inductor operates at low frequencies, the case is made from a magnetic material, but for high frequency operation, the unit is enclosed in a case made from a good electrical conductor such as aluminium.

5.4 Types of Inductors. There are many different types of inductors used in telecommunication circuits, and it is not possible to give details of the construction and application of all types at this stage. However, most inductors come within the scope of one of the following classifications.

(i) Power Inductors or choke coils are designed for low frequency operation in association with power equipment. In telecom, they are mainly used in smoothing filters in rectifier power supplies. Most power chokes have laminated iron cores of the shell or core type. In most applications, the greater part of the current is D.C. and an air gap must be left in the magnetic circuit. Most power chokes are rated in inductance with reference to a certain current.

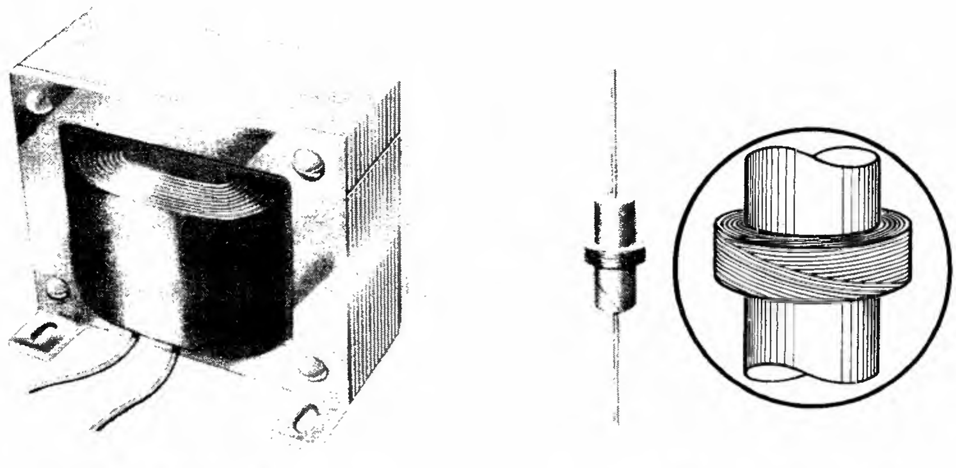
For example, one type of choke is rated at 3 henries when it is carrying its rated current of 300 milliamps (D.C.). When the current is reduced to 200 milliamps, the inductance increases to 4 henries. A typical power choke is shown in Fig. 16a.

(ii) Audio Frequency Inductors are designed to offer high impedance to currents at audio frequencies. They include reactance coils, high impedance relays and coupling chokes which are covered in other sections of the course.

(iii) Radio Frequency Inductors have many applications in telecommunication circuits; these include

- suppression of radio frequency currents in audio frequency circuits;
- coupling in radio frequency amplifiers;
- resonant circuits.

Many R.F. inductors have air cores, but, following the introduction of the ferrite magnetic materials, iron (ferrite) cored inductors are available which can be used at frequencies up to 100 Mc/s. A miniature ferrite cored R.F. inductor is shown in Fig. 16b.



(a) Low Frequency Inductor. (b) Radio Frequency Inductor.

FIG. 16. TELECOMMUNICATION INDUCTORS.

Sometimes an inductor has auxiliary windings or additional features to enable it to perform special functions. As the operation of these types requires an understanding of the equipment with which they are associated, they are described in other papers of the course.

6. TEST QUESTIONS.

1. Briefly describe the principle of operation of a transformer.

2. A transformer has 1200 turns on the primary winding and 3000 turns on the secondary winding. Find the secondary voltage when an alternating voltage of 240 volts is applied to the primary winding.

3. Draw a simple vector diagram to illustrate the no-load condition of a transformer having a turns ratio of 1.

4. When a resistive load circuit is connected to the secondary winding, the primary current rises above / remains the same as / falls below the no-load value, because ....

5. Define Balance current. What relationship exists between balance current and secondary current in terms of magnitude and phase?

6. A transformer is used to operate four 50 volt 100 watt soldering irons from the 240 volt supply. Neglecting losses, fi-:

(i) the turns ratio;
(ii) the secondary current;
(iii) the primary current.

7. What is meant by reflected impedance?

8. A transformer with 600 primary turns and 1,200 secondary turns has a circuit of 800 ohms impedance connected to the secondary winding. Ignoring losses, what would the impedance of the primary winding be under these conditions?

9. What is meant by impedance matching?

10. A 2 ohm loudspeaker is to be connected to an amplifier having an output impedance of approximately 10,000 ohms. What would be the turns ratio of a suitable matching transformer?

11. Describe three types of closed circuit transformer cores in common use.

12. Name three materials used for transformer cores and briefly state where each is used.

13. Why are transformers provided with electromagnetic shields?

14. Transformers often have internal and external electrostatic shields.

(i) The internal shield consists of ....
and its purpose is to ....

(ii) The external shield consists of ....
and its purpose is to ....

15. For what purpose are power transformers used?

16. What is meant by the "regulation" of a power transformer?

17. For what purpose are audio frequency transformers used?

18. Briefly describe the construction of a radio frequency transformer.

19. Name the factors which influence the inductance of an inductor.

20. Why is an air gap left in the core of a power choke?

END OF PAPER.

A.C. MEASUREMENTS.

INTRODUCTION.

.1 From the earliest days of electrical communication, there has been a necessity for suitable electrical measuring instruments. As new and more efficient communication methods were evolved, better measuring instruments were developed, and, at the present time, there are very few electrical quantities or characteristics which cannot be measured or evaluated accurately by specialised instruments.

With such a wide variety of measuring instruments available, a knowledge of the operation of each type is essential, so that the facilities they provide can be put to best use.

.2 The operation and application of D.C. measuring instruments are described in the "D.C. Measurements" paper, Applied Electricity I.

This paper describes general purpose measuring instruments and measuring methods which are used in A.C. circuits. Specialised instruments used in Transmission Measurements are described in other papers of the course.

2. A.C. MEASUREMENTS.

2.1 The basic requirement of an A.C. measuring instrument is that the pointer is deflected in the same direction for each half-cycle of the current or voltage to be measured.

Other desirable characteristics of the ideal A.C. meter for use in telecom. circuits are -

(i) The calibration should be accurate at all frequencies within a wide range, and be independent of waveform.

(ii) The instrument should be capable of adaption for either current or voltage measurements and the scale markings should correspond to effective values.

(iii) The accuracy should not be affected by temperature changes or by the presence of stray magnetic fields.

(iv) The energy requirements of the instrument should be small so that its connection does not unduly upset the circuit under test.

(v) The instrument should be simple to use, and should have an approximately linear scale.

As no one type of meter can completely satisfy all these requirements, several types of meters have been developed. The characteristics and applications of some of the more common types are briefly described in Table 1. All of these meters indicate <u>effective values</u>.

Type	Principle	Characteristics	Application
Rectifier Meter	Moving coil meter in rectifying circuit.	Sensitive; reasonably accurate. Subject to wave form errors. Frequency range 20 c/s to 20 kc/s (approx.) some types to 100 kc/s. Linear scale.	General current and voltage measurements in telecom circuits.
Thermocouple Meter	Moving coil meter with thermocouple.	Less sensitive than rectifier meter. Accurate though sluggish in action. Frequency range 0 to several Mc/s. Non-linear scale. Cannot withstand overload.	Current and voltage measurements in long line and radio equipment.
Moving Iron Meter	Repulsion or attraction between iron vanes.	Insensitive; reasonably accurate; robust. Frequency range 0 to 100 c/s (approx.) Non linear scale.	Current and voltage measurements on some A.C. power control panels.
Electrostatic Voltmeter	Attraction between electrically charged vanes.	Imposes negligible loading on circuit. Frequency range 0 to 1 Mc/s (approx.) Non-linear scale.	Measurement of high voltage only (over 100 volts).
Dynamometer	Interaction between magnetic fields of current carrying coils.	Insensitive; accurate. Frequency range 0 to 100 c/s (approx.) Non-linear scale.	Current and voltage measurements. Principle used in wattmeter.
Vacuum Tube Voltmeter	Moving coil meter with valve amplifier and rectifier.	High input impedance; Very wide frequency range - some types to over 1000 Mc/s. Reasonably accurate. Linear scale.	Measurement of voltage in high impedance, high frequency circuits.

Table 1.

A more detailed description of these instruments is given in Sections 3 to 8 of this paper.

As reliable measurements are essential in telecom, the selection of the most suitable instrument for a particular measurement is of great importance. This is particularly significant with voltmeters, as the parallel connection of a comparatively low resistance voltmeter across a high impedance circuit or circuit component can completely upset the voltage distribution in the circuit, and the results may not be a true indication of its operating conditions.

Fig. 1 illustrates the errors which can be caused by the use of an unsuitable voltmeter. Two resistors, R1 (20,000 ohms) and R2 (40,000 ohms) are connected in series to a D.C. source of 6 volts. The normal working conditions in the circuit have been calculated as :-

Total resistance	=	60,000 ohms.
Circuit current	=	0.1 mA.
P.D. across R1	=	2 Volts.
P.D. across R2	=	4 Volts.

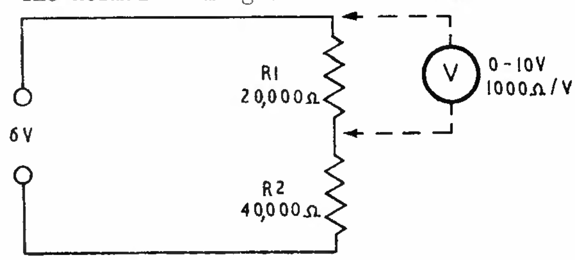


FIG. 1.

When the P.D.'s are measured with a 1000 ohms/volt, 0-10 volt voltmeter (resistance 10,000 ohms) these circuit values are upset and new, false sets of conditions are created.

WITH THE METER ACROSS R1:-

Joint resistance, R1 and Meter	=	6,666 ohms.
Total resistance of circuit	=	46,666 ohms.
Circuit current	=	0.13 mA.
Measured P.D. across R1	=	0.86 Volts.

WITH THE METER ACROSS R2:-

Joint resistance, R2 and Meter	=	8,000 ohms.
Total resistance of circuit	=	28,000 ohms.
Circuit current	=	0.21 mA.
Measured P.D. across R2	=	1.68 Volts.

From the example, it can be seen that a normal 1,000 ohms/voltmeter can give misleading results when used in high impedance circuits, as the current required to operate the meter is sometimes greater than that normally flowing in the circuit.

In general, the resistance of the voltmeter should be many times greater than the impedance of the circuit of circuit component across which it is connected.

Safety Precautions. The "D.C. Measurements" paper of Applied Electricity I lists several precautions to be observed when using measuring instruments. The importance of these precautions cannot be over-stressed as the safety of the meter depends on their observation. Briefly, these points are -

(i) Do not connect a meter in circuits where the values to be measured are likely to exceed its full scale reading. When in doubt, always take the first reading with the meter switched to the highest appropriate range available.

(ii) Do not use ohmmeters in energised circuits.

(iii) Connect ammeters in series; connect voltmeters in parallel.

(iv) Handle all instruments carefully, and store them away from heat and moisture.

In many modern multimeters, silicon diodes are connected in parallel with the meter movement as a precaution against accidental overload. This does not mean that normal safety precautions are unnecessary, as, in most cases, it is only the meter movement that is protected and a heavy overload can cause damage to other vital components.

3. RECTIFIER TYPE MOVING COIL INSTRUMENTS.

3.1 In the "D.C. Measurements" paper of Applied Electricity I, we saw that the moving coil meter is a sentitive and accurate instrument for measuring direct currents and voltages.

Its operation follows the "motor principle" of a current-carrying wire in a magnetic field. The current to be measured passes through the moving coil producing a magnetic field. Interaction between this field and the field of a permanent magnet produces a force which turns the moving coil on its pivots, carrying the pointer across the scale.

The moving coil meter is suitable for D.C. measurements only, as on A.C., each reversal of current reverses the direction of deflection of the pointer. Because of the inertia of the moving system the pointer remains at zero, or at very low frequencies, vibrates about the zero point.

The moving coil meter may, however, be adapted to measure A.C. by associating it with a suitable arrangement of metal rectifiers so that the A.C. is rectified, and passes through the meter in unidirectional pulses.

3.2 Operation. Figs. 2(a) and (b) show a moving coil meter associated with a full-wave bridge arrangement of metal rectifiers and show the direction of each half cycle of current during operation.

For each cycle of A.C., two unidirectional current pulses pass through the meter giving, at frequencies above about 20 c/s, a steady deflection of the pointer. The deflection of the pointer corresponds to the average value of the rectified A.C. but the scale is marked in effective values. (For sine wave A.C. effective values are 1.11 times or 11% higher than average values.) The calibration is correct for sine waves only, and with sharply peaked wave forms, appreciable errors are introduced.

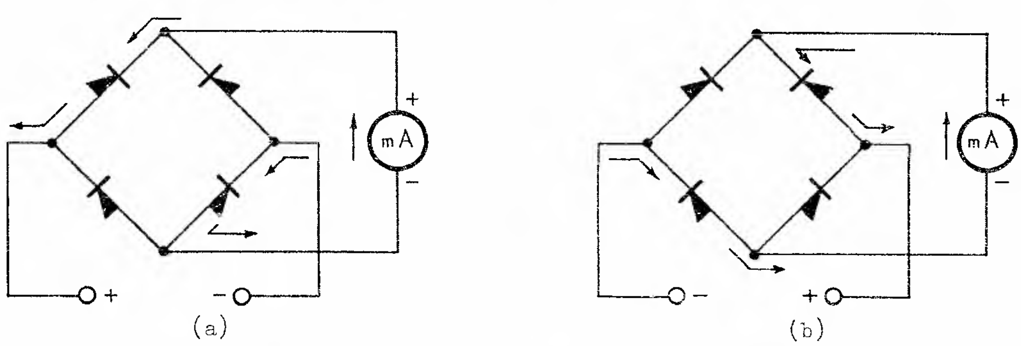


FIG. 2. FULL-WAVE RECTIFIER MILLIAMMETER CIRCUIT.

3.3 The circuit shown in Figs. 3(a) and (b) provides half-wave rectification. With this arrangement each alternate half-cycle is by-passed around the meter as shown in Fig. 3(b). The deflection of the meter pointer corresponds to half the average value of the A.C. being measured but the scale is calibrated in effective values.

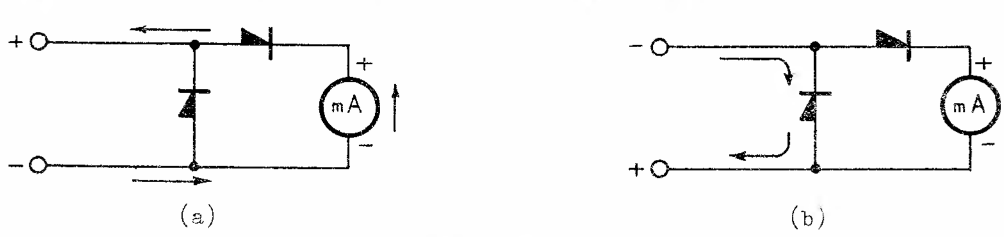


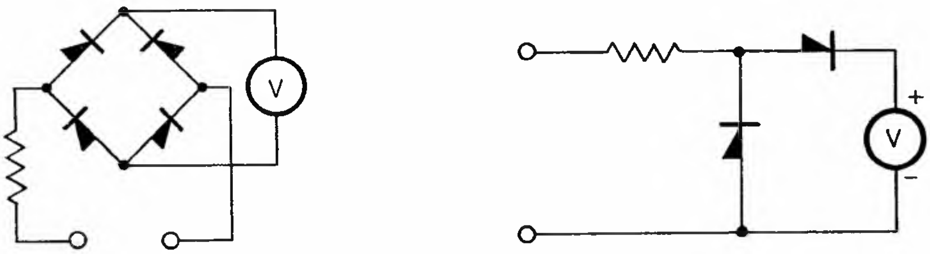
FIG. 3. HALF-WAVE RECTIFIER MILLIAMMETER CIRCUIT.

3.4 Frequency Range. The plates of the rectifier form a small capacitor which, at high frequencies shunts current away from the meter. With good quality rectifiers, accuracy is maintained over the audio frequency range and, by using special low-capacitance rectifiers, some instruments can be used at frequencies up to 100 kc/s.

Rectifier meters can also be used to measure D.C. Because of the scale calibration however the readings with a full wave bridge are 11% high and with a half wave circuit 122% high.

3.5 Rectifier Voltmeters. When a rectifier meter is used as a voltmeter, a suitable resistor is connected in series between the test terminals and the rectifier unit (Figs. 4(a) and (b)).

With some low reading voltmeters, the non-linear resistance characteristics of the rectifier causes a slight cramping of the scale at the lower end. With higher reading instruments however, the variations in rectifier resistance are swamped by the high resistance of the "multiplier", and this scale distortion is not apparent.



(a) (b)

FIG. 4. RECTIFIER VOLTMETER.

3.6 Rectifier Ammeters. Rectifier meters can be used without modification to measure currents up to the full scale deflection value of the meter movement.

When a rectifier meter is used to measure currents in excess of the full scale value, it is necessary to use a current transformer of suitable turns ratio, connected as shown in Fig. 5.

Shunts are not used because the non-linear resistance characteristic of the rectifier makes it difficult to maintain a constant relationship between the resistance of the shunt and the resistance of the meter-rectifier combination over the operating current range of the meter movement.

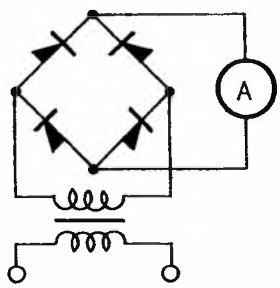


FIG. 5. RECTIFIER AMMETER.

3.7 Application. Rectifier meters are reasonably sensitive, and voltmeters with a sensitivity of several thousand ohms per volt and ammeters capable of reading currents of less than 1 mA are quite common. In telecom, they are used extensively for current and voltage measurements at audio frequencies. Rectifier meters can also be arranged to measure the power level of an A.C. signal, and are used in the specialised "Volume Indicator" which is used to indicate the intensity or volume of an audio frequency signal of complex wave form.

Rectifier meters can be readily adapted so that the one meter provides several current and voltage ranges (A.C. and D.C.) and it is in this "multimeter" form that it finds the widest use. The Multimeter, A.P.O. No. 2 is an instrument of this type.

3.8 Multimeter, A.P.O. No. 3. For many years, the Detector No. 4 was the standard general purpose test meter available to Technicians. This instrument has now been replaced by the more versatile Multimeter No. 3 (Fig. 6a) in which provision is made for measurements over the following ranges.

CURRENT (D.C.)	0–1mA;	0–10mA;	0–100mA;	0–1A;	0–10A.	
VOLTAGE (D.C.)	0–3V;	0–10V;	0–30V;	0–100V;	0–300V;	0–1000V.
CURRENT (A.C.)	0–1mA;	0–10mA;	0–100mA;	0–1A;	0–10A.	
VOLTAGE (A.C.)	0–10V;	0–30V;	0–100V;	0–300V;	0–1000V.	

RESISTANCE - From approximately 1 ohm to 1 megohm in four ranges.

In addition provision is made for testing dry cells.

The meter is designed for use in the "face upwards" position. On all D.C. ranges, the accuracy is better than ± 1% of the full scale value. On the A.C. ranges, the accuracy is better than ± 2%.

The multimeter is self contained and is housed in a bakelite case. The batteries required for resistance measurement are fitted in a moulded recess in the rear of the case, and are accessible via a removable cover.

The operating controls are mounted on the lower part of the front face. A twenty position, rotary switch is used for range changing, and a variable resistor is provided for the "zero ohms" adjustment on resistance measurements. Four test jacks for the connection of test leads are mounted on the front. The test jack (designated "Negative Common") is used for all measurements in conjunction with one of the other three which are designated and used as follows:-

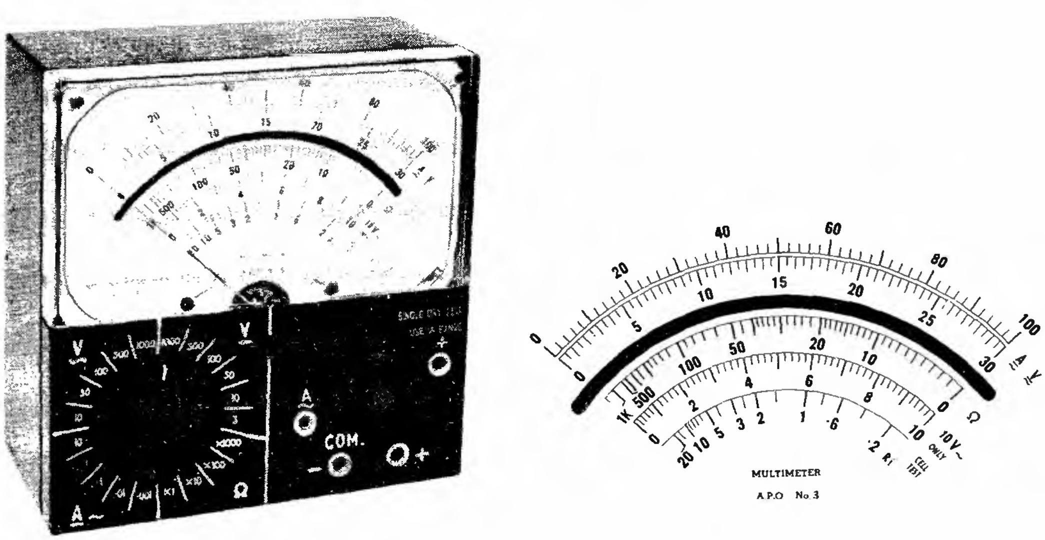
(i) A.C. Amperes ($\overset{A}{\sim}$) for A.C. current measurements.

(ii) Positive (+) jack for resistance, A.C. voltage and all D.C. measurements.

(iii) Cell test (+ cell test) for testing dry cells.

The meter scale (Fig. 6b) has a mirror insert to reduce parallax errors. The main scale is linear and is used on all D.C. and A.C. current ranges and the higher A.C. voltage ranges. Separate non-linear scales are provided for the low (10 volt) A.C. range, resistance measurements and cell testing.

The instrument is supplied complete with flexible test leads and insulated prods to which alligator clips can be attached if desired.



(a) Instrument. (b) Scale.

FIG. 6. MULTIMETER, A.P.O. NO. 3.

3.9 The multimeter incorporates several special features. Some of these are –

(i) The Meter Movement is of the "ruggedised core magnet" moving coil type. In this design, the magnet is mounted in the position normally occupied by the iron core in conventional moving coil meters. This construction renders the meter self shielding. The meter requires 400μA (0.4mA) for full scale deflection and it is compensated for variations in coil resistance due to temperature changes by the inclusion of the thermistor R1 in its circuit. The total resistance of the meter circuit is 250 ohms.

(ii) The Rectifier Unit (D1) for the A.C. ranges consists of a single capsule containing two copper oxide rectifiers, which are arranged in a "half wave" circuit.

(iii) Protection against damage due to an accidental overload is provided by two silicon diodes (D2) connected in parallel with the meter movement. Under normal usage, the P.D. across the diode is less than 0.1 volt. At this potential the forward resistance of the diode is extremely high and its shunting effect is negligible. In the event of an overload, the P.D. across the diode increases to a value at which the forward resistance is very small, and the greater part of the overload current is shunted away from the meter. The action is instantaneous, requires no resetting, and provided the current rating of the diode is not exceeded, has no adverse effect on the diode.

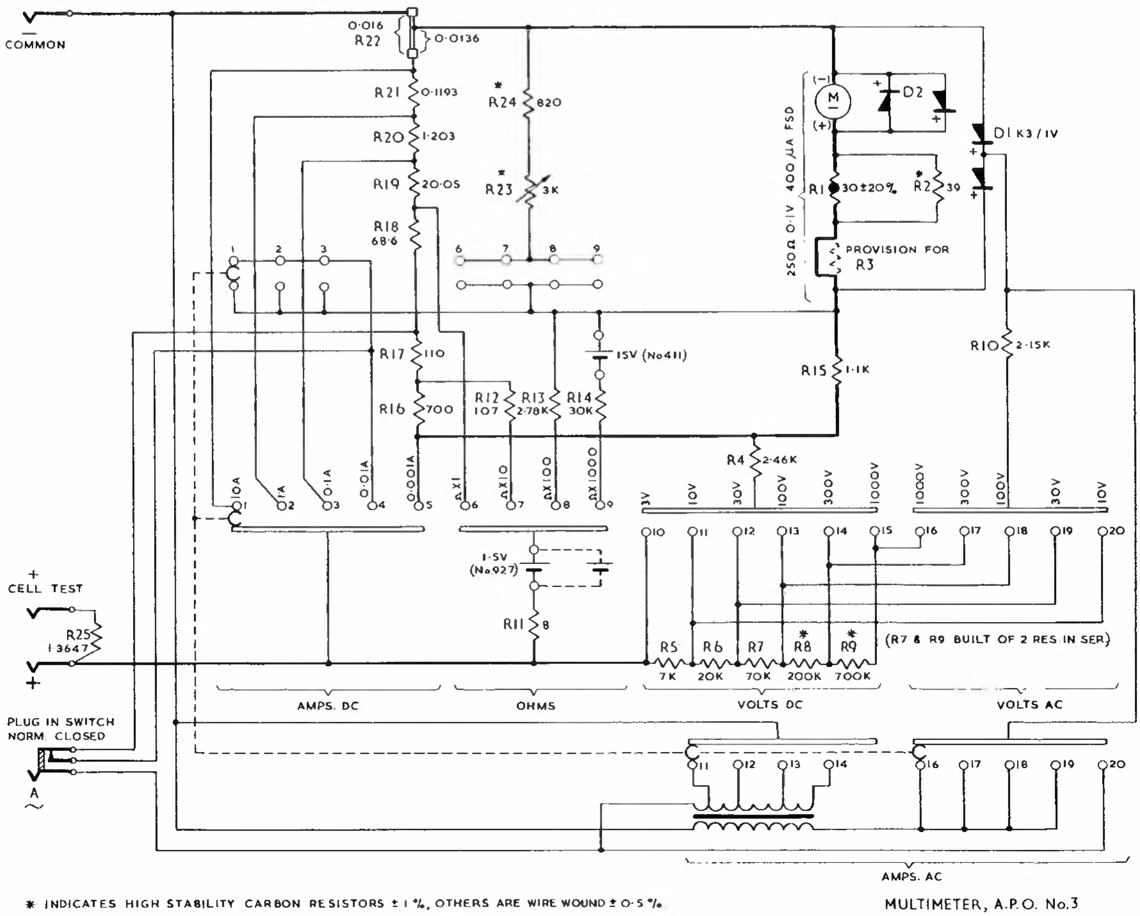


FIG. 7. MULTIMETER CIRCUIT.

(iv) A Printed Circuit is used for the connection of the resistors and other components in the circuit. The printed circuit consists of an insulating board which has specially shaped copper strips deposited on each side. Numbered holes are provided in the board through which the connecting leads of the components are taken and soldered directly to the copper strip on the other side. The strips are arranged so that when all the components are attached, the circuit is correctly connected. The two sides of the printed circuit are shown in Fig. 8.

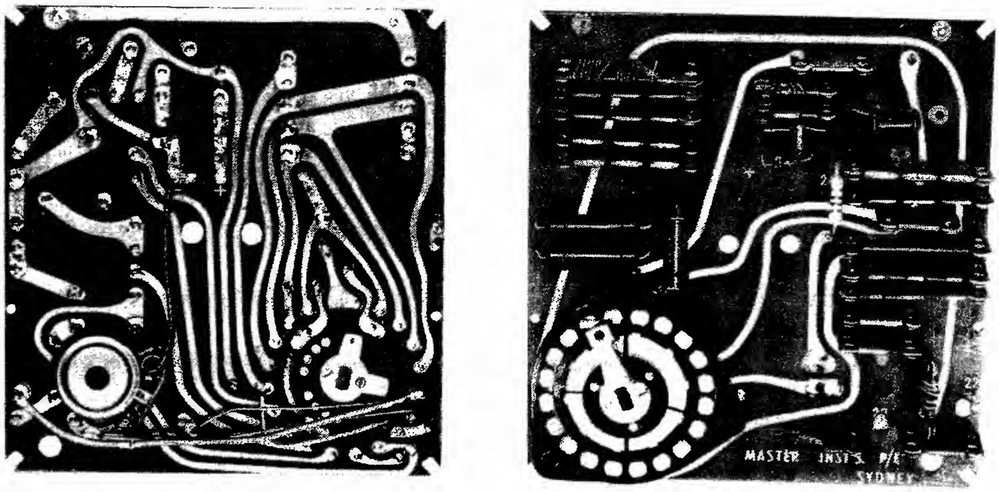


FIG. 8. PRINTED CIRCUIT - MULTIMETER NO. 3.

3.10 The meter is simple to use, and all terminals and switch positions are clearly designated. Important points concerning its use are:-

(i) On the voltage ranges, (A.C. and D.C.), the meter is shunted so that the sensitivity is 1,000 ohms per volt. The main scales are used for all direct voltage measurements, and for alternating voltage measurements over 10 volts. Low alternating voltage readings are made on the 0-10 volt A.C. scale which has been specially marked to compensate for the non-linearity of the rectifiers. For all alternating voltage ranges, the scale markings correspond to effective values.

(ii) Current measurements are made using the upper main scale. On the 0-1mA D.C. range, the resistance of the instrument is approximately 540 ohms. Normally, when currents less than 1mA are being measured, the resistance of the circuit under test is many times greater than 540 ohms, and the connection of the meter has very little effect. Where extreme accuracy is required, however, allowance should be made for the meter resistance. The range of alternating current measurements is extended by using a tapped current transformer.

(iii) When making resistance measurements, the "zero ohms" setting must be readjusted for each range. As the scale becomes very cramped at the "high" end, resistance measurements should be made on the ohms range which gives an indication between the ohms scale markings 5 and 50. To conserve the dry cells, continuity tests should be made on the Ohms X 100 range.

(iv) Single Dry Cell tests are made on the 1 Amp range with the positive test lead connected to the "Cell Test" jack. The meter reading taken after 15 seconds shows the approximate internal resistance of the cell, from which the remaining service life can be estimated.

3.11 Multimeter A.P.O. No. 2. This is an earlier model A.P.O. multimeter which is similar to the Multimeter No. 3 except no provision for A.C. current measurements is provided. Only three test jacks are provided, two of these (+ and -) are used for all current, voltage and resistance measurements; for cell testing the positive (red) lead is placed in the "+ cell test" jack.

-. THERMOCOUPLE INSTRUMENTS.

4.1 A thermocouple consists essentially of two dissimilar metals fastened together to form a junction. When the junction is heated, an e.m.f. proportional to the increase in temperature is developed across the cold ends of the dissimilar metals. This device is used in conjunction with a sensitive moving coil meter in a thermocouple measuring instrument.

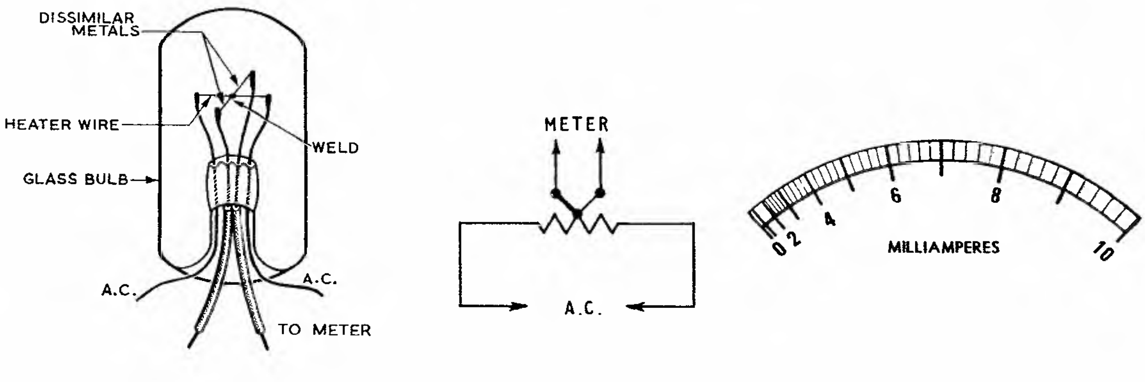
4.2 Construction. Fig. 9a shows the construction of a typical instrument thermocouple. Two fine wires of dissimilar materials (such as eureka and iron) are welded to form a junction. A heater wire is arranged so that it is in thermal contact with the junction, and the unit is sealed in an evacuated glass bulb. The circuit connections of a thermocouple instrument are shown in Fig. 9b.

4.3 Operation. The current to be measured is passed through the heater wire, and the heat developed increases the temperature at the junction. With the increase in temperature, an e.m.f. is produced, and a deflection is obtained on the meter. As the heating effect of an electric current is independant of the direction of flow, thermocouple meters may be used for the measurement of A.C. as well as D.C.

The readings are independant of wave form, and as the deflection is actually a measure of the heating effect of the current, the scale is calibrated in effective values of A.C. Thermocouple meters are inclined to be sluggish in action, due to the thermal lag of the thermocouple. They are reasonably accurate, but are not as sensitive as rectifier instruments.

4.4 Scale. The heat developed at the thermo-junction is proportional to the square of the current to be measured. The deflection is therefore proportional to the current squared and these instruments have a non-linear "square law" scale similar to that shown in Fig. 9c.

4.5 Frequency Range. Because of the extremely small inductance and capacitance of the heater wire, thermocouple meters can be used at high frequencies. Most types can be used at frequencies up to several megacycles/second and some special instruments can be used at 100 Mc/s.



(a) Thermocouple. (b) Circuit. (c) Typical Scale.

FIG. 9. THERMOCOUPLE METER.

4.6 Application. Thermocouple instruments are available as ammeters and voltmeters. In telecom, they are used for measurements at carrier frequencies in some transmission measuring sets, and they are often used to measure high frequency currents in radio apparatus.

4.7 Precautions. When using thermocouple meters, the utmost care must be exercised as a slight overload can burn out the heater wire. Most instruments are calibrated with reference to one particular thermocouple, and should this unit need replacement, the meter usually has to be re-calibrated.

5. MOVING IRON INSTRUMENTS.

5.1 These instruments rely on the forces exerted between iron vanes when they are magnetised.

5.2 Construction. The construction of a typical repulsion type moving iron meter is shown in Fig. 10a; (the attraction type instrument is described in the paper, "D.C. Measurements" of Applied Electricity 1). A curved wedge-shaped iron vane is fixed inside a coil of wire and another iron vane is mounted on a spindle so that it is free to rotate within the arc of the fixed vane. The pointer is attached to the spindle and hair springs are provided to control its movement. On this type of instrument it is usual to damp the movement of the pointer by means of a vane in an air chamber.

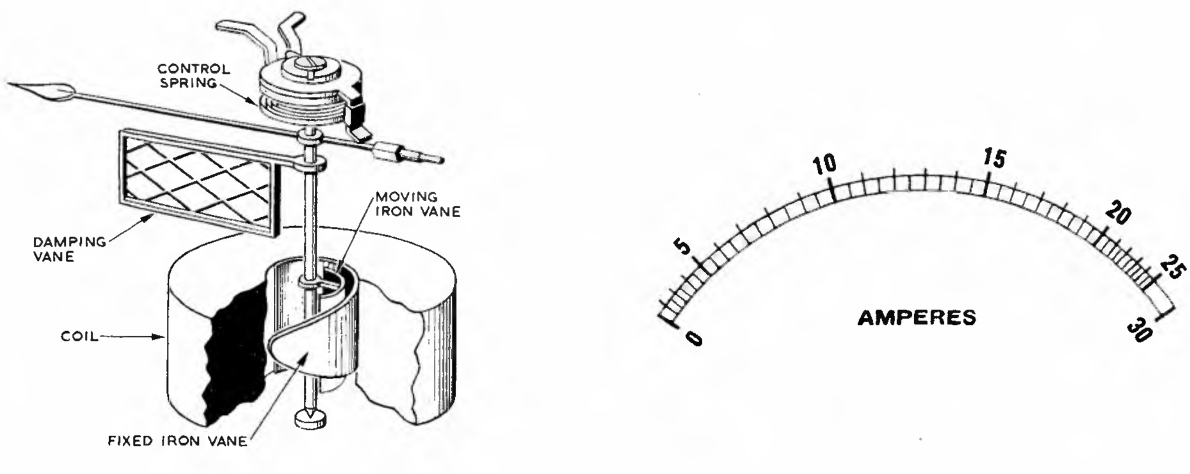
5.3 Operation. The current to be measured is passed through the coil, magnetising both iron vanes in the same direction. The resulting force of repulsion causes the moving vane to rotate on its pivots, carrying the pointer across the scale.

When the current reverses, the magnetic polarity of both vanes reverses, and repulsion is maintained. This meter is therefore suitable for the measurement of A.C. as well as D.C.

On A.C. measurements, the scale markings represent effective values, but the readings are accurate at low (power) frequencies only, due to the inductance of the coil and eddy current effects in the vanes. The meter can also be affected by stray magnetic fields, and it is unsuited to the measurement of A.C.s having complex wave form.

5.4 Scale. The form of the scale is determined by the shape of the vanes. On many instruments, the scale is cramped at the ends with an approximately linear section in between. A typical scale is shown in Fig. 10b.

5.5 Frequency Range. Moving iron meters have a very limited frequency range, the upper limit being in the region of 100 c/s.



(a) Meter movement. (b) Typical scale.

FIG. 10. MOVING IRON METER.

5.6 Application. Moving iron meters are available as both ammeters and voltmeters; they are extremely robust, relatively simple and reasonably accurate at low frequencies, and are often used as panel instruments on A.C. power switchboards. They are, however, not suitable for the measurement of high frequency currents and voltages of small value, and are not used for measurements in telecom circuits.

6. ELECTROSTATIC VOLTMETERS.

6.1 When a capacitor is charged, a force of attraction exists between the oppositely charged plates. This principle is used in the electrostatic voltmeter.

6.2 Construction. Fig. 11a shows the construction of the moving system of a typical electrostatic voltmeter. The pointer is attached to a number of light metal vanes which are mounted on a spindle so that they can move between a number of fixed vanes under the control of a hair spring. The two sets of vanes are insulated from one another and are led out to two terminals. The construction resembles that of a variable capacitor.

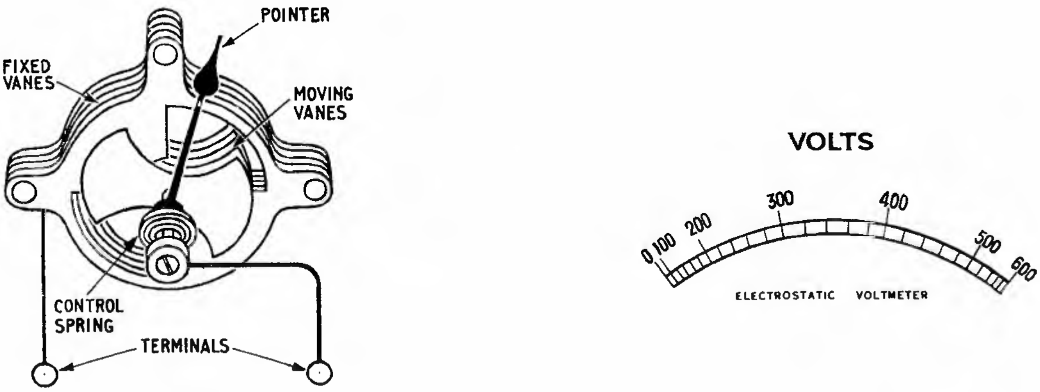
6.3 Operation. When the meter is connected across a P.D., the fixed and moving vanes acquire equal but opposite charges. The resulting force of attraction draws the moving vanes into mesh with the fixed vanes, (as shown in Fig. 11a) and the pointer moves across the scale. The meter can be used for direct and alternating voltage measurements, as the charges on the vanes are always of opposite polarity and the force is always one of attraction.

The force of attraction is proportional to the product of the charges on the vanes. As the charges are equal and proportional to the voltage applied, the deflection is proportional to the square of the voltage to be measured and, on A.C., the meter indicates effective values.

The operating current is zero on D.C. and negligible on all but high frequency A.C.

6.4 Scale. The scale of an electrostatic voltmeter is non-linear and is usually very cramped at the lower end, as is shown in Fig. 11b. The form of the scale is determined by the shape of the vanes, and most meters of this type are designed for readings over the centre part of the scale only.

6.5 Frequency Range. The readings are independant of wave form, temperature, and stray magnetic fields, and are reasonably accurate at frequencies up to approximately 1 Mc/s.



(a) Moving System. (b) Typical Scale.

ELECTROSTATIC VOLTMETER.

FIG. 11.

6.6 Application. Electrostatic voltmeters are suitable for measurement of comparatively high voltages. As they are not suitable for measurements below about 100 volts, and as they cannot be used as ammeters, electrostatic voltmeters have only a limited application in telecom. They are, however, ideal for the measurements of high voltages in circuits where a normal current operated meter is unsuitable.

7. DYNAMOMETER INSTRUMENTS.

7.1 The general principle of this type of instrument is similar to that of the moving coil meter, in that the pointer is attached to a moving coil which is deflected due to the interaction of magnetic fields. It differs from the moving coil meter, as it has no permanent magnet, and the main magnetic field is produced by the passage of current through air or iron cored coils.

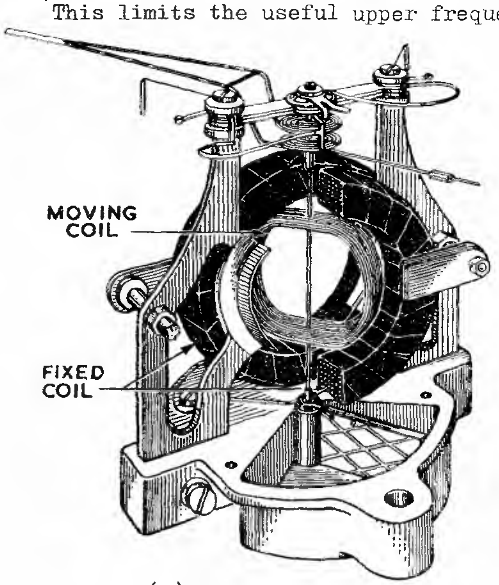
7.2 Construction. The construction of one type of dynamometer is shown in Fig. 12a. The moving coil is mounted inside two fixed air cored coils. Connection is made to the moving coil by hair springs which are also used to restore the pointer. In the meter shown, the movement of the pointer is damped by air vanes attached to the lower end of the moving coil spindle.

7.3 Operation. The current to be measured is passed through both sets of coils. The field set up by the moving coil interacts with the field set up by the fixed coils and a deflection is obtained. Since the directions of both fields reverse when the current reverses, the direction of meter deflection is constant, and the dynamometer is suitable for measuring both A.C. and D.C.

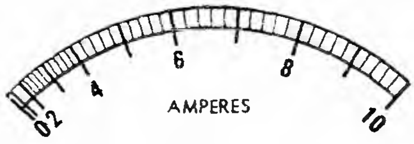
The deflection is proportional to the product of the field strengths of the coils, and, as both fields are produced by the current to be measured, the deflection is proportional to the square of this current. On A.C. measurements, the meter indicates effective values.

7.4 Scale. The scale is non-linear, approximately following the square law form, being cramped at the lower end. A typical dynamometer scale is shown in Fig. 12b.

7.5 Frequency Range. The coils of a dynamometer have an appreciable value of inductance. This limits the useful upper frequency to not much more than 100 c/s.



(a) Dynamometer.



(b) Typical Scale.

FIG. 12. DYNAMOMETER INSTRUMENT.

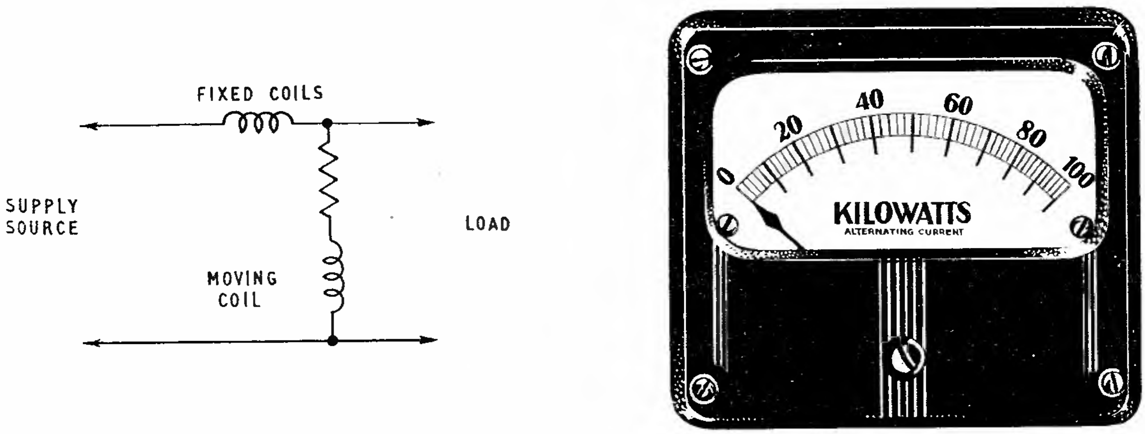
7.6 Application. Dynamometers are available as very accurate ammeters and voltmeters, but, because they are not suited for the measurement of low values, and because of their limited frequency range, they are not often used in telecom. In laboratories, sub-standard dynamometers are used as "transfer instruments", that is for checking A.C. instruments against a D.C. standard. The principle is used in many types of wattmeters.

7.7 Wattmeters. A wattmeter is an instrument which is used to indicate the power or rate of energy transformation in a circuit.

The basic principle of a dynamometer type wattmeter is shown in Fig. 13a. The fixed coils are connected in series with the equipment so that the magnetic field produced by these coils is determined by the current. The moving coil and a high value series resistor are connected in parallel with the equipment under test, so that the current through the moving coil and therefore its magnetic field, is determined by the voltage.

The torque produced by the interaction of the magnetic fields of the fixed and moving coils is proportional to the product of the field strengths. As these are proportional to the current and to the voltage respectively, the resultant deflection is proportional to the power dissipated.

A dynamometer wattmeter (Fig. 13b) has an approximately linear scale, and instruments of this type are available for measuring power up to 1 megawatt.



(a) Circuit Principle. (b) Kilowatt Meter.

FIG. 13. WATTMETER.

In A.C. circuits, dynamometer wattmeters indicate the true power, that is, the effect of any phase difference between current and voltage is automatically compensated for.

For example, when current and voltage are in phase, the fields produced by the moving and fixed coils reverse at the same instants, and so the direction of the torque produced does not change. The deflection is proportional to the product of the current and the voltage, which in an "in phase" circuit, is equal to the true power.

When current and voltage are out of phase, the fields reverse at different instants and the torque is no longer unidirectional. Under these conditions, the deflection is less than would be obtained when the current and voltage are in phase, and it corresponds to the true power ($E \times I \times \cos \theta$) in the circuit.

Wattmeters indicate the average of the instantaneous powers throughout a cycle. They do not record the total energy dissipated over a period of time. This function is performed by the "Watt-hour meter" which, although mechanically different, operates on a similar principle.

8. VACUUM TUBE VOLTMETERS.

8.1 A vacuum tube voltmeter or V.T.V.M. (sometimes called a Thermionic Valve Voltmeter) consists essentially of a sensitive moving coil meter associated with a rectifying and amplifying circuit which contains one or more electron tubes. Vacuum tube voltmeters (Fig. 14) can be used for the measurement of both direct and alternating voltages. Compared with other types of voltmeters, the advantages of a V.T.V.M. are -

(i) The connection of the instrument imposes a negligible loading on the circuit under test as the operating current for the meter is supplied from an internal power supply.

(ii) The frequency range of a V.T.V.M. is much greater than that of a normal voltmeter because of the use of a electron tube as the rectifying device.

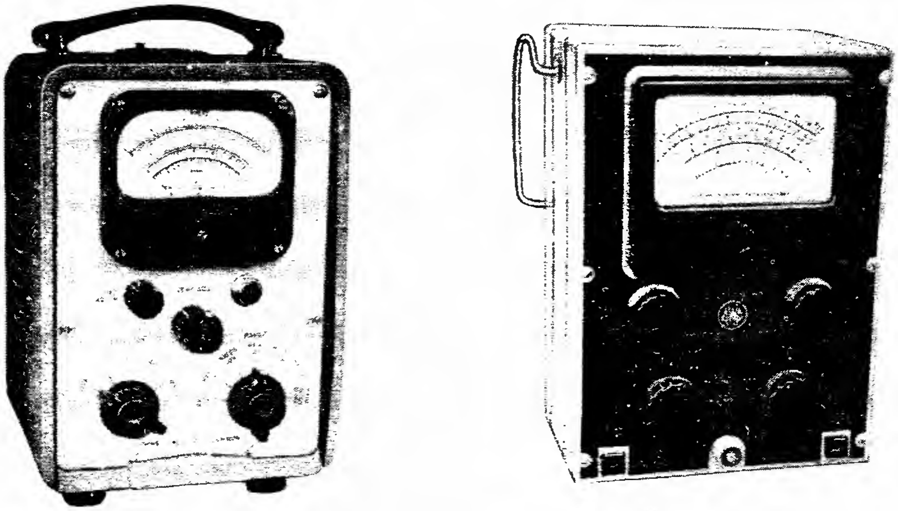


FIG. 14. VACUUM TUBE VOLTMETERS.

8.2 Frequency Range. Vacuum tube voltmeters retain their rated accuracy (which is approximately ± 5% of full scale values) over a very extensive frequency range which extends from about 20 c/s to about 5 Mc/s. The useful frequency range can be extended to over 100 Mc/s (in some special instruments to over 1000 Mc/s) by using special test probes.

8.3 Input Conditions. One of the most favourable features of a V.T.V.M. is its high impedance, which on the D.C. ranges, is of the order of 10 megohms.

On the A.C. ranges, the input impedance is usually less than this figure because of stray capacitance and dielectric losses. The input impedance becomes less as progressively higher frequency measurements are made, and at frequencies of several hundred megacycles/second, the impedance may be as low as 100 ohms.

8.4 Resistance Measurements. Vacuum tube voltmeters can be adapted to serve as very versatile ohmmeters, reading, on different ranges, from about 0.1 ohms to 1000 megohms. This feature is incorporated in most instruments.

8.5 Application. These instruments are not used for general measurements of direct and alternating voltage up to carrier frequencies as rectifier instruments which are simpler to use and less costly are quite adequate. In the high impedance, high frequency circuits of radio telephone and television however, the V.T.V.M. has an extensive field of application.

3.6 Principle of operation - direct voltage measurements. Fig. 15 shows a simple circuit which is used in many modern vacuum tube voltmeters. A sensitive moving coil meter is connected between the cathodes of two identical triodes. The anodes are connected to a positive voltage source and the cathodes are connected to a source of negative voltage via the resistors R1 and R2. The input terminals lead to a high impedance voltage divider network, one end of which is earthed. A tapping on the voltage divider is taken to the grid of V1 and the grid of V2 is earthed.

Basically, the circuit is that of a Wheatstone bridge. V1 and V2 are two of the arms, and the cathode resistors R1 and R2 comprise the other arms. In the absence of a P.D. across the input terminals the grids are at the same potential and both triodes conduct to the same extent. As equal currents flow through R1 and R2, both cathodes are at the same potential and, in this balanced condition, no current flows through the meter.

When a P.D. is connected across the input terminals, the grid-cathode potential of V1 changes causing a change in current in this arm of the bridge. With unequal currents, the cathodes are no longer at the same potential and current flows through the meter. As the magnitude of the meter current is determined by the value of the voltage applied to the input terminals, the meter scale can be calibrated to indicate the value of the applied P.D.

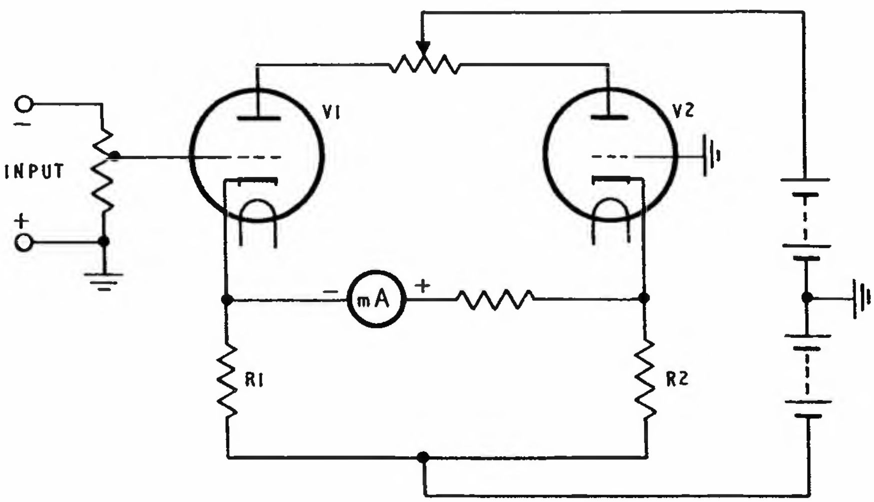


FIG. 15. ELEMENTS OF VACUUM TUBE VOLTMETER CIRCUIT.

The potentiometer is provided to compensate for differences in the characteristics of the tubes so that the initial balance or "zero volts" condition is obtainable.

Other refinements (not shown on Fig. 15) found on a practical V.T.V.M. include:-

(i) additional tappings on the voltage divider network to enable more than one voltage range to be covered;

(ii) a means of reversing the polarity of the instrument so that positive or negative voltages can be measured;

(iii) a D.C. amplifying stage between the voltage divider and bridge circuits to increase the sensitivity.

8.7 Principle of operation - alternating voltage measurements. For A.C. measurements, a rectifying circuit containing a diode tube (or semiconductor diode) is added to the bridge voltmeter circuit. The basic circuit is shown in Fig. 16.

When an alternating voltage is applied across the input terminals, the diode conducts only when the anode is positive with respect to the cathode. During the first of these conducting half-cycles, a direct voltage, equal to the peak value of the applied alternating P.D., appears across the capacitor C1 as it charges via the diode.

The capacitor discharges via R3 and the voltage divider in series, and a unidirectional P.D. is produced across the voltage divider. This unbalances the bridge circuit, and causes a deflection on the meter which is proportional to the voltage being measured.

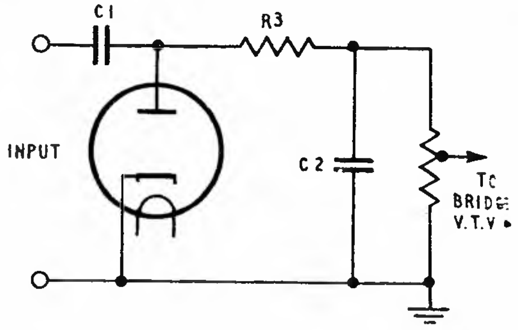


FIG. 16. V.T.V.M. DIODE RECTIFIER.

Because of the extremely high resistance of the discharge path (approximately 15 megohms) only a small amount of charge leaks away between cycles, and consequently the diode needs to conduct for only a very short period during each subsequent positive voltage peak to maintain the full peak voltage across C1. Any slight variations in the P.D. across C1 as it charges and discharges, are bypassed away from the voltmeter circuit by the shunt capacitor C2.

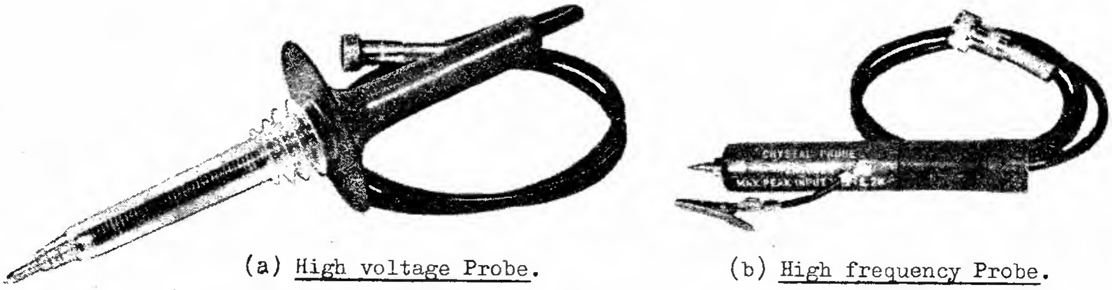
When the V.T.V.M. is intended for high frequency measurements, the rectifier section is housed in the test probe. This is done to keep the connecting leads between the rectifier and the circuit under test as short as possible, as the inductance and capacitance of these leads introduce serious errors at high frequencies.

On most V.T.V.M.'s the scales are marked to indicate effective values on the assumption that the unknown P.D. is sinusoidal. Some instruments have additional scale markings to indicate peak to peak (twice peak) values.

8.8 Probes. A probe is a special test prod which is designed specifically for one type of measurement. There are two main types of probes used with V.T.V.M.'s. They are :-

(i) High Voltage (D.C.) Probes. (Fig. 17a). These are used to extend the range of the instrument so that extremely high values of voltage (up to 30,000 volts) can be measured. They contain the necessary multiplier and are heavily insulated for protection.

(ii) High Frequency (A.C.) Probes. (Fig. 17b). These are used to extend the frequency range of the V.T.V.M. They contain a complete rectifying circuit which can be of the thermionic valve or semiconductor diode type. Valve type probes can be used to measure R.F. voltages up to 1000 volts but semiconductor or crystal probes are limited to the measurement of much smaller values, usually less than 30 volts.



(a) High voltage Probe. (b) High frequency Probe.

FIG. 17. PROBES FOR V.T.V.M.

:.9 Using the V.T.V.M. A vacuum tube voltmeter is a sensitive instrument which can be damaged if it is subjected to rough handling. In addition to the normal precautions observed when using meters, the following procedures must be followed when using instruments of this type.

(i) Warm Up. Before attempting to take measurements, allow sufficient time for the tubes and other components to warm up and stabilise.

(ii) Zero Setting. Most vacuum tube voltmeters incorporate an electrical zero adjustment which must be correctly set before measurements are made. Zero adjustments are usually made by means of a potentiometer control when the input terminals are short circuited. Check the zero adjustment occasionally during use, and always reset whenever the range is changed.

Do not use the zero adjuster on the meter movement for this purpose.

(iii) Connections. Vacuum tube voltmeters are usually designed for measurements of voltage with respect to earth potential, and they are provided with one or more "active" terminals (for various ranges) and one common earth terminal. Connect the "active" test lead to the desired measuring point and the "earth" lead to the test circuit earth.

Do not reverse these connections, as the connection of an earthed test lead at an unearthed high impedance test point can completely upset the voltage distribution and the results obtained under these conditions are meaningless.

Voltage measurements between two high impedance test points can be made by reading the P.D. between each point and earth and noting the difference. The use of this method is limited to cases where there is no change in wave form or phase between the two test points.

(iv) High Frequency Measurements. An R.F. probe should be used when the frequency is higher than approximately 50 kc/s. Connect the probe at the exact point where the measurement is to be made, and make the earth connection for the probe as close as possible to this point.

Remember that crystal probes are not suited for the measurement of high voltages.

(v) High Voltage Measurement. When direct voltages greater than 1000 volts are to be measured, a high voltage probe must be used. Hold the probe behind the guard (where provided) or near the rear of the handle.

This reduces the electric shock hazard and decreases the capacitive effects of the hand on the test circuit.

Other safety precautions to be observed when taking high voltage measurements are

- Locate all high voltage test points with the power off.
- Make sure no part of the body touches earthed objects.

In all cases the manufacturer's instruction book should be consulted as to any specialised procedures necessary with a particular instrument. As these manuals contain information concerning input impedances, accuracy, maximum input ratings, etc. they should be kept in a safe place where they are not likely to be mislaid.

9. THE CATHODE RAY OSCILLOSCOPE.

9.1 The Cathode Ray Oscilloscope (sometimes called the cathode ray oscillograph or C.R.O.) is an electronic device by means of which variations in electrical quantities are depicted graphically on the screen of a cathode ray tube.

A cathode ray tube (C.R.T.) is a special type of electron tube in which the electrons emitted from the cathode are formed into a narrow beam and directed at a fluorescent screen. The screen glows when bombarded by electrons and a spot of light is produced, which moves as the electron beam is deflected by the application of voltages to deflection plates within the tube.

In an oscilloscope, the electron beam is deflected vertically by a voltage which varies in accordance with the electrical quantity under test at the same time as it is deflected horizontally at a uniform rate by a voltage generated within the instrument. In this way, the movement of the spot traces out the variations in amplitude of the test voltage in relation to a linear time base. As the screen continues to glow for a short period after the energising electron beam has moved on, and as the beam is deflected horizontally many times a second, a fully illuminated graph is displayed on the screen.

9.2 Components. A cathode ray oscilloscope consists of a cathode ray tube, a sweep generator, amplifiers and a power supply, arranged as shown in the simple block diagram of Fig. 18.

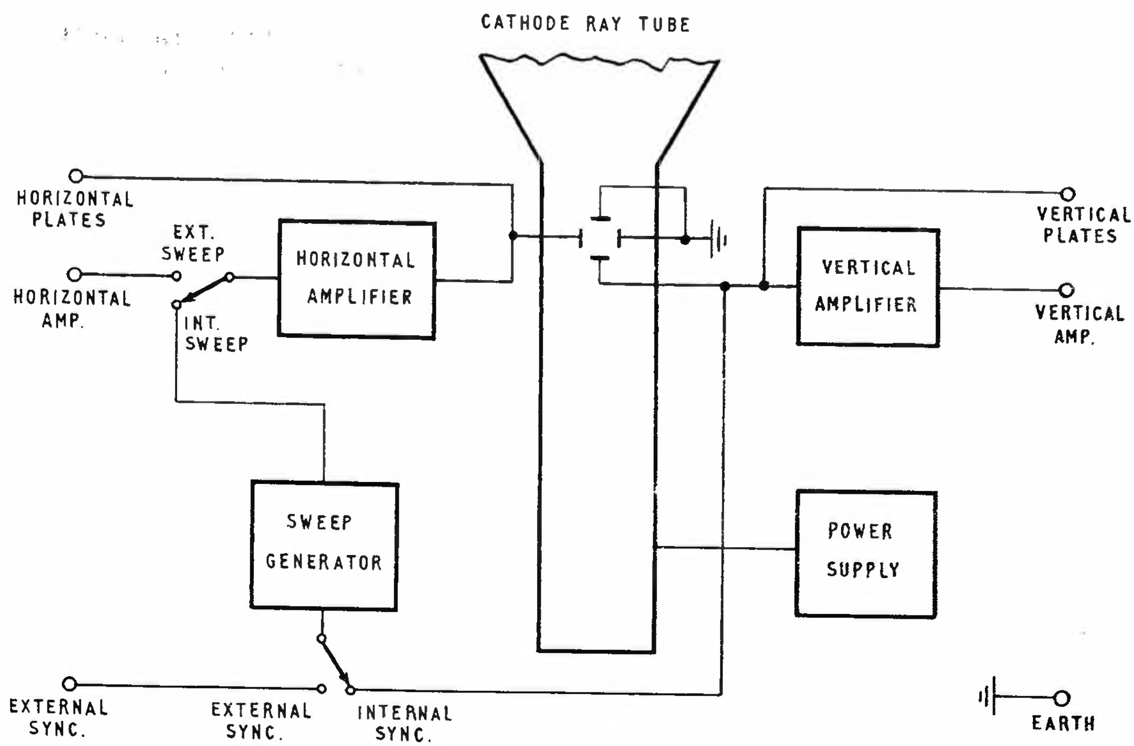


FIG. 18. BLOCK DIAGRAM OF AN OSCILLOSCOPE.

The major components are -

(i) The Cathode Ray Tube. The construction and operation of this tube is described in the paper "Electron Tubes". Associated with the tube is the power supply which provides the high voltages necessary for the formation and focussing of the electron beam.

(ii) The Sweep Generator. This is a variable frequency oscillator from which the "sweep voltage" for the horizontal deflection of the electron beam is derived. (Oscillators of this type are described in the paper "Oscillators".)

The sweep voltage has a "saw tooth" wave form (Fig. 19) so that the electron beam is swept across the screen at a uniform speed, corresponding to the linear time base of a graph. At the end of each sweep, the spot is returned to its starting point and a new sweep is started. The number of sweeps which occur each second is called the Sweep Frequency.

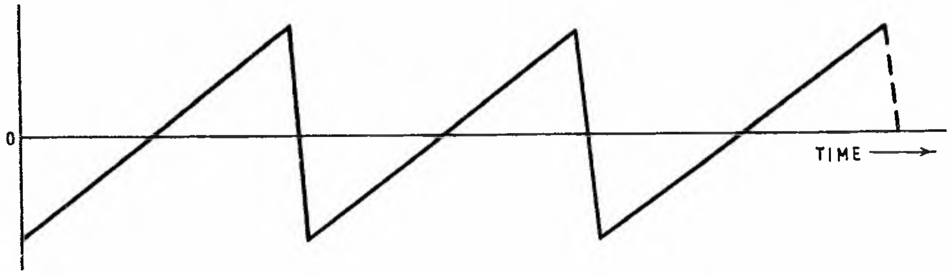


FIG. 19. SAW TOOTH VOLTAGE.

To obtain a steady pattern on the screen, the sweep frequency must be the same as, or a submultiple of, the frequency of the voltage applied to the vertical deflection plates. The sweep generator is therefore provided with coarse and fine frequency controls which enable this adjustment to be made.

In practice, it is very difficult to set the sweep generator controls to produce the exact sweep frequency required to obtain a completely stationary pattern, and it is necessary to synchronise the sweep generator with the frequency of the voltage applied to the vertical plates. The synchronising signal may be obtained from an external source, or part of the vertical deflecting voltage may be fed back to control the sweep generator.

(iii) Horizontal or "X" Amplifier. This amplifies the voltage to be applied to the horizontal deflecting plates of the C.R.T. to a value sufficiently high to deflect the spot across the full width of the screen. The horizontal amplifier is provided with a gain control so that the extent of the horizontal deflection can be adjusted.

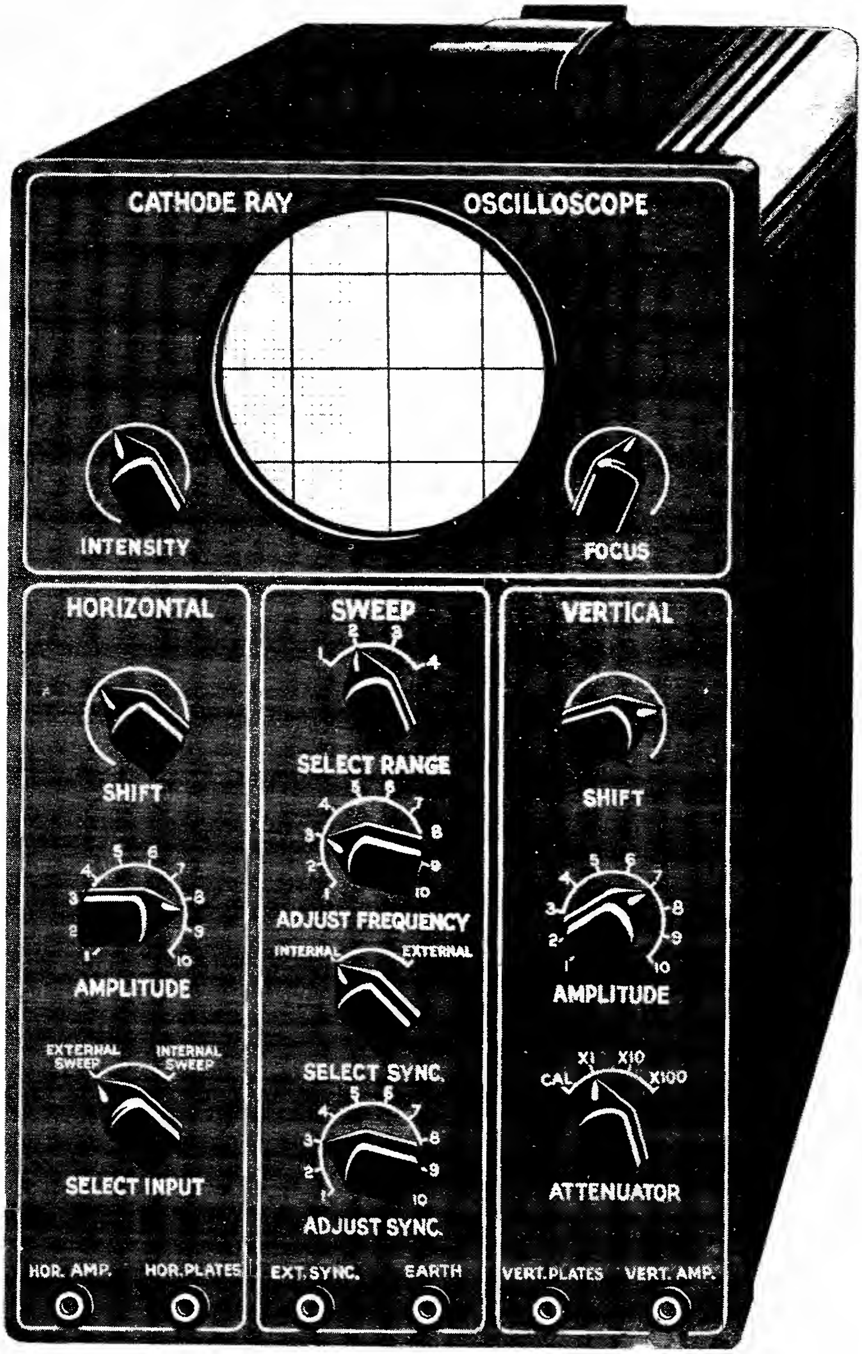
For wave form examination, the output of the sweep generator is amplified to provide the horizontal deflecting voltage, but for other applications this voltage may be obtained from an external source.

(iv) Vertical or "Y" Amplifier. This amplifies the voltage to be applied to the vertical deflecting plates to a value sufficient to obtain the desired vertical deflection of the electron beam.

Since the test voltage can be of a high value in some applications and of a very low value in others, the gain of the vertical amplifier must be controllable over a very wide range. In many oscilloscopes, this is accomplished by means of a stepped "coarse" control in conjunction with a continuously variable "fine" gain control. The coarse control is usually a stepped attenuator by means of which the sensitivity of the vertical amplifier is changed by a convenient factor at each step.

When the voltages to be examined are of a sufficiently high value, the vertical and horizontal amplifiers need not be used, and some C.R.O.'s provide terminals or some switching device which enables external voltages to be applied direct to the deflection plates of the cathode ray tube.

9.3 Controls. The operating controls associated with the various component circuits of an oscilloscope are grouped on the front face of the instrument. The appearance of a typical general purpose oscilloscope is shown in Fig. 20.



CATHODE RAY OSCILLOSCOPE.

FIG. 20.

At present there is no uniformity in the designation, location and number of controls provided for oscilloscopes, as they vary according to the manufacturer. However all instruments are provided with certain essential controls, and the designations and functions of the typical controls shown in Fig. 20 are -

(i) FOCUS. A potentiometer control which is used to adjust the sharpness of the pattern.

(ii) INTENSITY. A potentiometer control which is used to adjust the brightness of the pattern.

(iii) HORIZONTAL OR "X" SHIFT. A potentiometer control which is used to adjust the horizontal position of the pattern.

(iv) VERTICAL OR "Y" SHIFT. A potentiometer control which is used to adjust the vertical position of the pattern.

(v) HORIZONTAL OR "X" AMPLITUDE. A potentiometer control which is used to adjust the width of the pattern.

(vi) VERTICAL OR "Y" AMPLITUDE. A potentiometer control which provides a fine adjustment of the height of the pattern.

(vii) VERTICAL OR "Y" ATTENUATOR. A multi-position rotary switch which provides a coarse adjustment of the height of the pattern.

(viii) HORIZONTAL OR "X" INPUT SELECTOR. A rotary switch with two or more positions which is used to select the source (that is, internal or external) of the horizontal deflecting voltage.

(ix) SWEEP RANGE SELECTOR. A multi-position rotary switch which is used to select the required frequency range of the internal sweep generator.

(x) SWEEP FREQUENCY ADJUST. A potentiometer control which provides a fine adjustment of the sweep frequency.

(xi) SYNCHRONISING SELECTOR. A rotary switch which selects the source (that is, internal or external) of the signal which synchronises the sweep frequency with the frequency of the voltage applied to the vertical deflection plates.

(xii) SYNCHRONISING ADJUST. A potentiometer control which adjusts the amplitude of the synchronising signal.

On some oscilloscopes the control designations differ from those listed above, but, in most cases the designations used have essentially the same meaning.

Terminals. The terminals for the connection of external voltages are also mounted on the front face. The number of terminals provided and their designations vary, but the functions of those shown in Fig. 20 are:-

(i) HORIZONTAL OR "X" AMP. Allows an externally generated voltage to be connected to the horizontal deflection plates of the C.R.T. via the horizontal amplifier.

(ii) HORIZONTAL OR "X" PLATES. Provides a direct connection to the C.R.T. horizontal deflection plates.

(iii) VERTICAL OR "Y" AMP. The normal connection point for the voltage to be examined. It connects to the vertical deflection plates of the C.R.T. via the vertical amplifier.

(iv) VERTICAL OR "Y" PLATES. Provides a direct connection to the C.R.T. vertical deflection plates.

(v) EXTERNAL SYNC. Allows the connection of an externally generated synchronising signal.

(vi) EARTH. The common earthed input terminal.

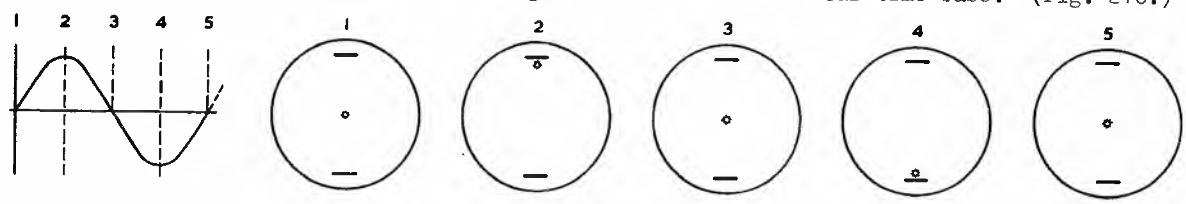
On some instruments the horizontal and vertical plate connections are located behind a removable panel at the rear of the case. This position is chosen to minimise the length of the connecting leads to the deflection plates so that R.F. voltages can be examined.

9.5 Application. The C.R.O. is a very versatile instrument with an ever-expanding field of application. In telecom its main uses are:-

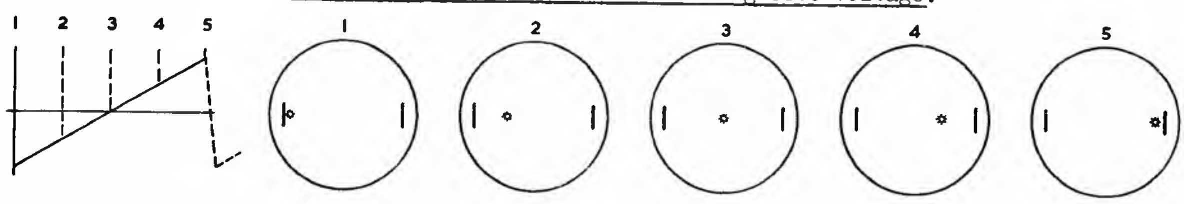
(i) Waveform Examination. This is the most common application of the oscilloscope. The alternating voltage to be examined is connected to the vertical deflection plates of the C.R.T. (via the vertical amplifier) and the internally generated sweep voltage is applied to the horizontal deflection plates.

The operation of the instrument under these conditions is shown in Fig. 21. As the electron beam is deflected vertically by the alternating test voltage, the vertical movement of the spot traces out the variations in amplitude, and changes in direction which are a characteristic of this voltage. Instantaneous positions of the spot which correspond to a number of instantaneous values of test voltage are shown in Fig. 21a.

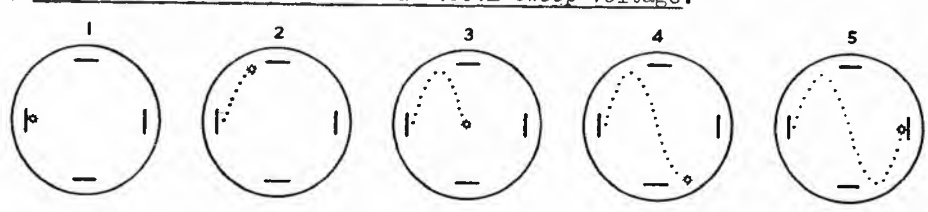
With the saw-tooth sweep voltage applied to the horizontal deflection plates, the electron beam is deflected horizontally at a uniform rate. Instantaneous positions of the spot at corresponding instantaneous values of sweep voltage are shown in Fig. 21b. As both voltages are applied simultaneously, the spot moves vertically at the same time as it moves horizontally, tracing out the waveform of the test voltage in relation to a linear time base. (Fig. 21c.)



(a) Vertical Movement due to Alternating Test Voltage.



(b) Horizontal Movement due to Saw-tooth Sweep Voltage.



(c) Simultaneous Vertical and Horizontal Movement.

FIG. 21. WAVEFORM EXAMINATION WITH LINEAR TIME BASE.

When the sweep frequency is the same as the frequency of the test voltage (Fig. 21), one complete cycle of test voltage waveform is displayed. To display more than one cycle, the sweep frequency is reduced to a submultiple of the frequency of the test voltage. For example, when the sweep frequency is one quarter of the test voltage frequency, the spot moves vertically through four complete sets of positive and negative values in the time taken for one horizontal sweep and four complete cycles are displayed on the screen.

(ii) Frequency Measurement. In conjunction with a calibrated oscillator, the C.R.O. is often used to determine the frequency of an A.C. signal. This is described in Section 10.5 of this paper.

(iii) Voltage measurement. The C.R.O. can be used to determine the peak-to-peak value of an unknown alternating voltage. The magnitude of the unknown voltage is indicated by the length of the vertical line traced on the screen when the unknown voltage is applied to the vertical deflection plates. A horizontal sweep voltage is unnecessary in this application but a high frequency sweep is often used to "spread" the pattern. This makes measurements easier, and also prevents damage to the screen.

On most oscilloscopes the unknown voltage is connected to the deflection plates via the vertical amplifier. This allows the measurement of comparatively small voltages (less than 5 volts). As the gain of the amplifier is adjustable, the C.R.O. can be calibrated against a known reference voltage, so that a convenient pattern height represents a certain value of voltage.

On these instruments the vertical amplifier "coarse" control is usually arranged so that each position of the control changes the sensitivity of the amplifier by a factor of 10 or other convenient figure. In this way, the coarse control can be used as a range changing switch and a wide range of voltages can be measured.

It must be remembered that a C.R.O. measures peak-to-peak values which, for sine waves, are 2.82 times greater than effective values.

(iv) Response curves. In conjunction with an external sweep generator (a frequency modulated oscillator) the oscilloscope can be used to examine the response characteristics of a circuit which operates over a range of frequencies.

The oscillator generates a constant voltage test signal, the frequency of which varies over the frequency range of the test circuit many times a second. This signal is applied to the circuit under test, where it is either amplified or attenuated. The rectified output of the test circuit is then applied to the vertical deflection plates of the C.R.T. Any variations in response of the test circuit over the frequency range of the test signal cause a change in the voltage applied to the vertical plates and are therefore traced out by the vertical movement of the spot of light on the screen.

Horizontal deflection of the electron beam is accomplished by a voltage which changes in value at the same rate as the frequency changes take place in output of the sweep generator. Since the frequency variations in most sweep generators occur at power frequency, that is, 50 frequency "sweeps" per second and the frequency variations during each sweep take place sinusoidally, a 50c/s sine wave voltage is usually used to provide horizontal deflection.

With the vertical deflection of the spot corresponding to the variations in the response of the circuit, and the horizontal deflection corresponding to the frequency range over which these variations occur, the pattern on the screen portrays accurately a response/frequency graph of the circuit under test.

Some other applications of the C.R.O. are -

- Adjustment of telegraph relays.
- Simultaneous examination of two signals using a "double-beam" instrument.
- Measurement of time using a sweep generator calibrated in time units (micro-seconds)
- Plotting characteristic curves of electron tubes and transistors.
- Examining hysteresis effects in magnetic materials.
- Visual location of trunk line faults.

Also, on many instruments provision is made for attaching a camera, so that the nature of transient (non-recurring) phenomena can be recorded on film. These instruments are, generally, only used in research laboratories.

9.6 Frequency Range. When the amplifiers are not used, the cathode ray oscilloscope is capable of operating at extremely high frequencies. When the amplifiers are used, however, the frequency range of the instrument is limited to the frequency range over which the response of the amplifiers is uniform. Most general purpose instruments perform satisfactorily within the range 10 c/s to 500 kc/s, and some special laboratory instruments can be used at frequencies up to 50 Mc/s.

9.7 Using an Oscilloscope. When using an oscilloscope certain precautions are necessary to ensure the reliability of the results. These are -

(i) Synchronising. When the C.R.O. is used for waveform examination, set the synchronising control to zero, and adjust the controls of the sweep generator until as near as possible to a stationary pattern is obtained. Then advance the synchronising control to eliminate the slight horizontal drift.

In any case do not adjust the synchronising control to more than about one third of its range, as the waveform of the sweep voltage may be distorted, and the resultant pattern would be misleading.

(ii) Amplifier Overloading. When the signal to be examined is connected via the vertical amplifier, care is necessary in setting the gain controls to avoid distortion of the signal waveform due to overloading in the amplifier.

This is particularly important where the vertical amplifier has a "coarse" stepped control in addition to a continuously variable "fine" control, and where the range of the latter is sufficient to reduce the overall gain of the amplifier to zero.

With such an arrangement, it is possible to adjust the pattern to the desired height by means of the fine control, whilst an excessively high voltage is applied to the amplifier input via an incorrect setting of the coarse control. In this way, the input stage of the amplifier is overloaded, and a distorted signal is applied to the deflection plates of the C.R.T.

To avoid this, set the fine control to near the centre of its range and adjust the coarse control so that the approximate pattern height is obtained. Final adjustments can then be made by resetting the fine control.

(iii) Connections. All general purpose oscilloscopes use unbalanced input circuits, that is, connection to amplifiers, etc. is made by via one "input" or "active" terminal and an "earth" terminal.

When the C.R.O. is used in a high impedance circuit, connect the "active" terminal at the high impedance point, and connect the oscilloscope "earth" terminal to the test circuit earth, or to a point which has a low impedance to earth.

Should these connections be reversed, the C.R.O. may seriously upset the operation of the circuit under test and in many cases the pattern will be confused by extraneous power frequency deflections so that the results are meaningless.

To prevent damage to the instrument, never exceed the maximum permissible input voltage as specified by the manufacturer, and never allow the electron beam to bombard the one spot on the screen for any length of time.

FREQUENCY MEASUREMENTS.

.1 The measurement of frequency is very important in telecom, as many communication systems rely on frequency controlled alternating currents for their operation.

Because of the wide range of frequencies encountered in telecom. several different measurement methods are in use. Briefly, these are:-

(i) Mechanical Resonance methods which are used at power frequencies.

(ii) Comparison methods which are used mainly at audio frequencies.

(iii) Electrical Resonance methods which are mainly used at radio frequencies.

In all cases, the accuracy of the method employed depends upon the accuracy of the reference frequency used for comparison or calibration. In this regard some precise frequency measuring devices achieve an accuracy of $\pm$ 1 part in 100 million. However, this standard of accuracy is not attainable - nor is it necessary, for routine frequency measurements in the field.

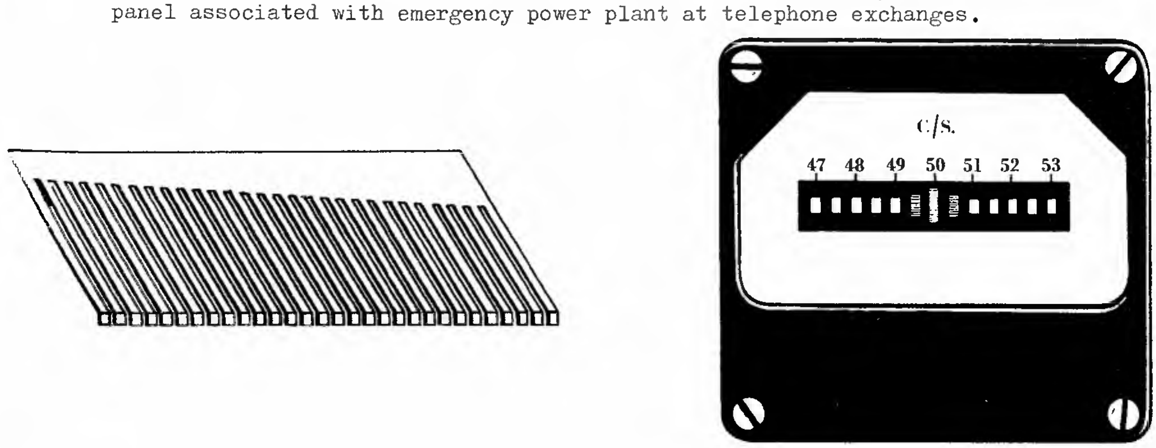
.2 Vibrating Reed Frequency Indicator. This is a direct reading instrument which operates on the mechanical resonance principle. It is used to indicate the frequency of the mains power supply.

It consists of a number of steel reeds which are assembled into a comb (Fig. 22a) and placed in proximity to an electromagnet. Each reed has a different length so that each has a different natural frequency of vibration. The free ends of the reeds are usually painted white, and the whole unit is assembled so that the painted ends of the reeds are visible under a scale which is marked off in cycles per second.

The current the frequency of which is to be measured is passed through the electromagnet and the resulting alternating flux causes the reeds to vibrate. The reed which has a period of vibration which corresponds to the rate of fluctuation of the magnetic field vibrates with the greatest amplitude and when viewed from the front, the movement of its painted end creates the illusion of a vertical line.

The frequency is read by noting the scale marking which is associated with the reed which has the greatest amplitude of vibration. The instrument shown in Fig. 22b is indicating a frequency of 50 c/s.

Vibrating reed frequency indicators of this type are usually mounted on the control panel associated with emergency power plant at telephone exchanges.



(a) Reed Assembly. (b) Vibrating Reed Indicator.

FIG. 22. VIBRATING REED FREQUENCY INDICATOR.

10.3 The Stroboscope. The stroboscope is a device for checking the speed of a rotating shaft.

As some items of telecom equipment rely on rotating machines for the generation of A.C. at a definite frequency, the stroboscope provides a very convenient means of checking the speed (and therefore the frequency of the generated A.C.) of the machine.

A stroboscope usually consists of a disc or drum, the surface of which is divided int: a number of equal sectors which are painted in contrasting colours. The stroboscope is attached to the shaft of the machine and, as it rotates, it is illuminated by a flashing light. When the machine is running at the correct speed, the sectors of the stroboscope appear to be stationary when viewed under the interrupted illumination.

Fig. 23 shows the action of a 4 sector stroboscope, which, in conjunction with a lamp operating from a 50 c/s supply, is suitable for checking machines which rotate at 3000 r.p.m.

As the lamp operates on A.C., it flashes twice every cycle, and therefore 100 flashes occur each second.

Assuming that the machine speed is correct, the disc rotates at 3000 r.p.m., or, 50 times each second.

Therefore, the disc is illuminated twice during the time it takes for each revolution.

Fig. 23 shows that in the period between flashes, (0.01 seconds), the disc travels a half revolution, and the relative position of black and white sectors at each instant of illumination is the same. The eye registers these fleeting glimpses of the illuminated disc, and, as they occur at the rate of 100 a second, the sectors appear to be stationary.

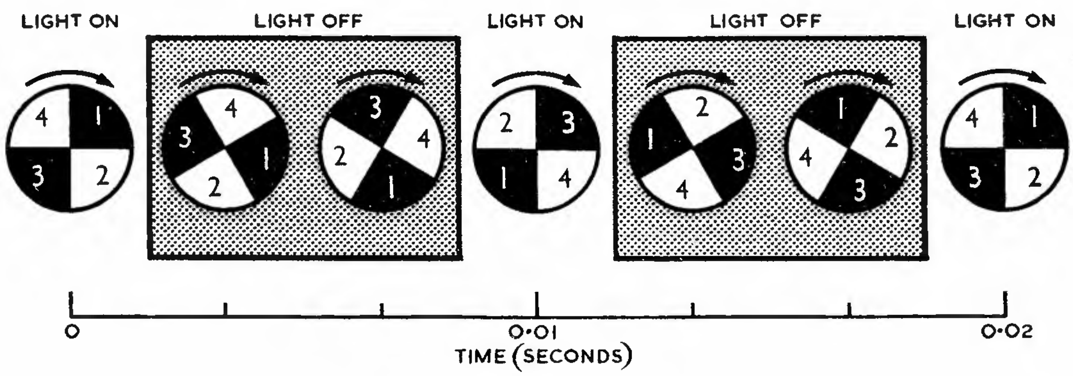


FIG. 23. STROBOSCOPE ACTION.

When the machine is running faster than normal speed, the disc completes slightly more than half a revolution between flashes, and therefore at each successive instant of illumination, the black and white sectors are displaced forward of their previous position, and the sectors appear to rotate in the direction of rotation of the machine.

When the machine is running at less than its normal speed, the disc does not complete a half revolution between flashes and the sectors appear to rotate in the opposite direction.

Stroboscopes used in telecom usually have a large number of sectors and often, special equipment is used to produce the interrupted illumination. The multi-frequency generator associated with voice frequency telegraph carrier systems rotates at 3600 r.p.m. This speed is checked and adjusted by viewing a 68 sector stroboscope (34 black sectors and 34 white sectors) when it is illuminated by a neon lamp operated from a 1020 c/s oscillator.

Beat Frequency Method. When two alternating currents having different frequencies are combined over a period of time, they aid one another at some instants and oppose one another at others. The resultant current varies in amplitude at a rate equal to the difference in frequency.

This effect is shown graphically in Fig. 24 where two sine wave A.C.s of 10 c/s and 8 c/s respectively are combined over a period of one second. The resultant complex wave has approximately the same frequency as the originals but it goes through two distinct "cycles" of amplitude variation over the period of one second. Each cycle of amplitude variation is called a "beat", and the "beat frequency" is equal to the difference in frequency between the currents which are combined.

In Fig. 24 where a 10 c/s signal is combined with an 8 c/s signal, the beat frequency is 2 c/s. In the same way, a beat frequency of 5 c/s results when a signal at 1000 c/s is combined with a signal at 995 c/s. When the two signals at the same frequency are combined, these variations in amplitude do not occur, and the beat frequency is zero.

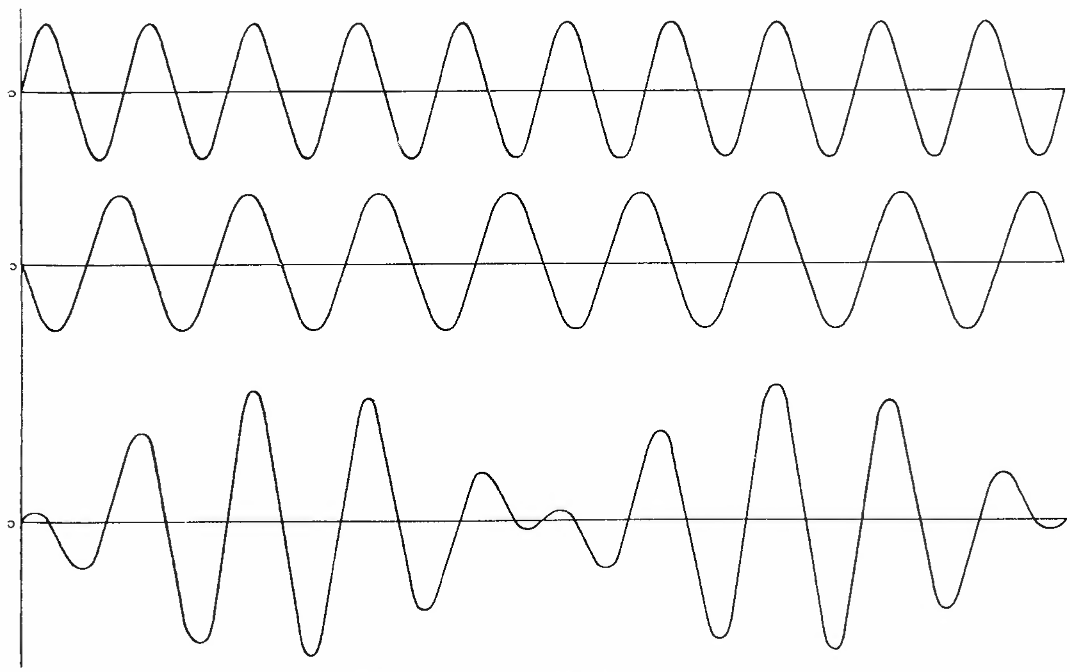


FIG. 24. PRODUCTION OF BEATS.

This principle can be used to determine the frequency of an unknown signal by "beating" it with a known frequency obtained from a calibrated variable frequency oscillator. In this method, the known and unknown signals are applied together to some form of indicating device such as a telephone head receiver, and the frequency of the variable oscillator is adjusted until a beat frequency is detected. This is indicated by variations in the loudness of the tone heard in the receiver.

The variable oscillator is further adjusted to reduce the frequency of the beat to zero, or as close as possible to this "zero beat" condition. At this point, the two frequencies are equal and the unknown frequency can be read from the dial of the calibrated instrument. An A.C. meter can be used in place of the head receiver, in which case, the beat is indicated by variations in the deflection of the pointer. Zero beat is indicated when these variations cease completely.

This method is commonly used to measure frequencies in the audio range, and the principle is used in the hetrodyne frequency meter, which is capable of measurements at radio frequencies.

10.5 Frequency Measurements Using an Oscilloscope. The C.R.O. can be used to determine an unknown frequency by comparison with a known standard frequency. The internally generated sweep voltage is not used in this application of the C.R.O. as the electron beam is deflected by the voltage of the known and unknown frequency sources.

10.6 Lissajous Figures. When sine wave alternating voltages of approximately equal values are applied simultaneously to both sets of deflection plates of a cathode ray tube, a series of patterns called "Lissajous Figures" is traced on the screen.

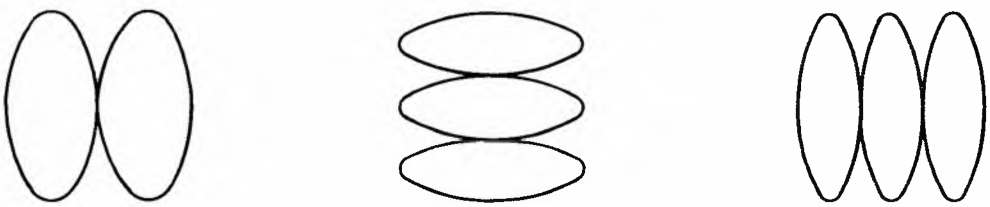
When the deflecting voltages have the same frequency, the electron beam is deflected vertically and horizontally at the same rate, and, depending on the phase relationship between the voltages, a diagonal straight line, an elipse or a circle is displayed on the screen. (Fig. 25.)

(a) Phase Difference = 0°. (b) Phase Difference = 45°. (c) Phase Difference = 90°.

FIG. 25. LISSAJOUS FIGURES WITH EQUAL FREQUENCIES.

When the deflecting voltages do not have the same frequency, the rate of vertical deflection is different from the rate at which the electron beam is deflected horizontally, and the pattern consists of a number of intersecting loops. Fig. 26 shows typical patterns obtained when the deflecting voltages have different frequencies.

These patterns vary slightly for various phase relationships, and they appear to rotate when the frequency ratio is not precisely a simple fraction. However, in all cases, the ratio of the frequency of the vertical deflecting voltage (f_y) to the frequency of the horizontal deflecting voltage (f_x) is the same as the ratio of the number of vertical deflections to the number of horizontal deflections contained in the pattern.



$f_y : f_x :: 2:1$ $f_y : f_x :: 1:3$ $f_y : f_x :: 3:1$

FIG. 26. LISSAJOUS FIGURES WITH UNEQUAL FREQUENCIES.

To measure frequency using this method, the unknown frequency is usually applied to the vertical deflection plates, and a known frequency is applied to the horizontal deflection plates. When a stationary pattern is obtained, the unknown frequency can be calculated from -

$$\frac{\text{Frequency of Vertical Deflecting Voltage } (f_y)}{\text{Frequency of Horizontal Deflecting Voltage } (f_x)} = \frac{\text{No. of Vertical Deflections}}{\text{No. of Horizontal Deflections}}.$$

With odd frequency combinations, some patterns can be quite involved, and to simplify counting the number of vertical and horizontal deflections, the pattern is enclosed in an imaginary rectangle. Then

Number of Vertical deflections = Number of loops touching horizontal side.

Number of Horizontal deflections = Number of loops touching vertical side.

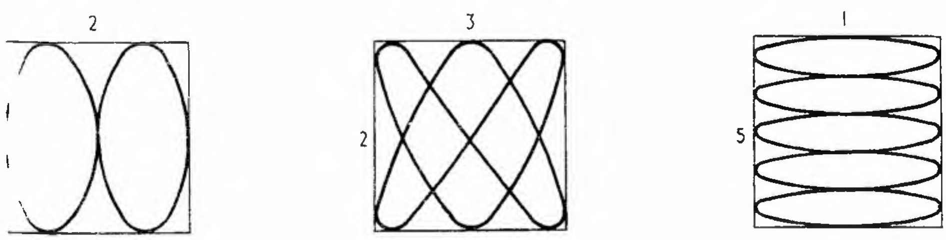
Therefore $$\frac{f_y}{f_x} = \frac{\text{NUMBER OF LOOPS TOUCHING HORIZONTAL SIDE}}{\text{NUMBER OF LOOPS TOUCHING VERTICAL SIDE}}$$

where

f_y = Frequency of vertical deflecting voltage

f_x = Frequency of horizontal deflecting voltage.

Examples of the use of this method are shown in Fig. 27 where a known frequency of 1 kc/s is applied to the horizontal deflection plates.



$\frac{f_y}{f_x} = \frac{2}{1}$ $\qquad$ $\frac{f_y}{f_x} = \frac{3}{2}$ $\qquad$ $\frac{f_y}{f_x} = \frac{1}{5}$

$f_y = 2 \times 1000$ $\qquad$ $\therefore f_y = \frac{3 \times 1000}{2}$ $\qquad$ $\therefore f_y = \frac{1 \times 1000}{5}$

= 2000 c/s $\qquad$ = 1500 c/s $\qquad$ = 200 c/s

FIG. 27. FREQUENCY CALCULATIONS.

This method of counting applies in all cases where the pattern contains open loops as, for example, in Figs. 25b and 25c. When the phase difference is such that the forward and return traces coincide, and the pattern consists of a single line (Fig. 25a), this method cannot be used. In practice, however, this condition is comparatively rare, as the slightest variation in the frequency of either voltage is sufficient to cause the pattern to open up, when the loops are clearly visible.

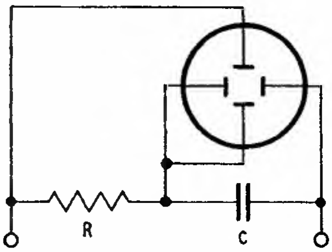
Lissajous Figures can be used for frequency measurements up to radio frequencies. The method has the advantage that the range of measurement is not limited to the frequency range of the known source, as frequency ratios of up to 1:10 or 10:1 can be detected.

It is also used to check the calibration of an oscillator against a standard fixed frequency. For example, 25 different spot checks at frequencies between 30 c/s and 3 kc/s are possible by comparison with a fixed 1 kc/s source, without having to count patterns more complex than 11:4.

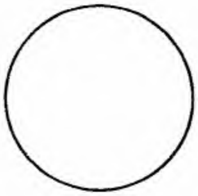
When the ratio between the known and unknown frequencies is a large value, the interpretation of the Lissajous Figures becomes difficult owing to the complexity of the pattern. In these cases the frequency ratio can be determined from the "spot wheel" or "gear wheel" patterns obtained by using a circular time base.

10.7 Frequency Comparison Using a Circular Time Base. This method makes use of a circular time base which has a repetition rate equal to the lower of the two frequencies to be compared.

The circular time base is derived by applying the low frequency voltage to a resistance-capacitance phase splitter, and using the potential drops across the resistor and capacitor as the deflecting voltages for the C.R.T. (Fig. 28a). As these voltages are 90° out of phase and as they are at the same frequency, the resultant pattern is a circle (Fig. 28b).



(a) Phase Splitting Circuit.



(b) Circular Trace.

FIG. 28. CIRCULAR TIME BASE.

The high frequency voltage is applied to one of the electrodes of the C.R.T. electron gun, so that the electron beam is modulated at the higher frequency. This produces irregularities in the circular trace, the number of which corresponds to the number of times the higher frequency is greater than the lower frequency.

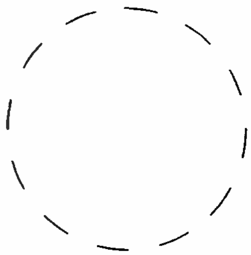
Two types of patterns can be produced by this method.

(i) The Spot-Wheel Pattern. This consists of alternate dark and light streaks on the circular trace (Fig. 29a). It is produced by varying the intensity of the electron beam by applying the high frequency voltage to the intensity grid of the C.R.T.

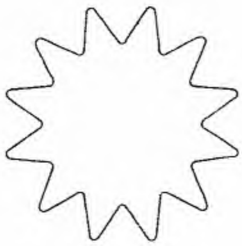
(ii) The Gear Wheel Pattern. This takes the form of a number of equally spaced "gear teeth" around the circular trace (Fig. 29b). It is produced by varying the deflection sensitivity of the C.R.T. by applying the high frequency voltage to the accelerating electrode.

The number of irregularities (streaks or teeth) on the pattern depends on the ratio between the frequencies being compared. For example, when the frequency ratio is 25:1 the electron beam undergoes 25 complete changes in intensity, or alternatively the deflection sensitivity of the C.R.T. changes 25 times in the time taken for one complete circular sweep, and 25 streaks or teeth are produced.

The patterns shown in Fig. 29 correspond to frequency ratios of 12:1.



(a) Spot Wheel Pattern.



(b) Gear Wheel Pattern.

FIG. 29. FREQUENCY COMPARISON USING C.R.O.

With this method, ratios up to 50:1 can be determined. When the higher frequency is not an exact multiple of the lower frequency, the pattern rotates, and the direction of rotation indicates whether the higher frequency is above or below an exact multiple of the lower frequency.

.8 Resonance Frequency Meters. In the paper "Series A.C. Circuits" we saw that the impedance of a series circuit containing inductance and capacitance is at a minimum value at the resonant frequency. This principle is used in "Wavemeters" which are used for frequency measurements in the R.F. range.

A wavemeter usually consists of an externally mounted inductor, a variable capacitor and a sensitive A.C. meter connected as in Fig. 30.

To measure an unknown radio frequency, the wavemeter is placed so that the inductor comes under the influence of a magnetic field produced by the current whose frequency is to be measured. An e.m.f. is induced across its turns, and a current at the unknown frequency flows in the wavemeter circuit.

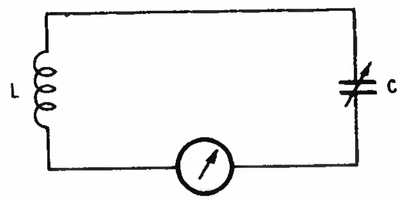


FIG. 30. WAVEMETER CIRCUIT.

The capacitor is adjusted until the current reaches a maximum value as indicated on the meter. At this setting of the capacitor, the wavemeter is resonant at the unknown frequency, which can then be read from the calibrated dial of the variable capacitor. It is important that the magnetic coupling between the wavemeter and the circuit under test is as loose as possible, as otherwise, the loading imposed by the tuned wavemeter could upset its operation.

Frequency meters of this type are suitable for use at frequencies up to approximately 300 Mc/s. Other types operating on the resonance principle can be used up to 30,000 Mc/s.

IMPEDANCE BRIDGES.

.1 In the paper, D.C. measurements (Applied Electricity 1) we saw that the Wheatstone Bridge provides a most convenient and very accurate means of resistance measurement. The same principle is applied in the Impedance Bridge which is used for the measurement of impedance in A.C. circuits.

.2 Basic Impedance Bridge. The circuit of a basic impedance bridge is shown in Fig. 31. The network is energised from an A.C. source and a head receiver is used as a detector. The balance condition of equal potential between points B and D is indicated when no tone is heard in the receiver.

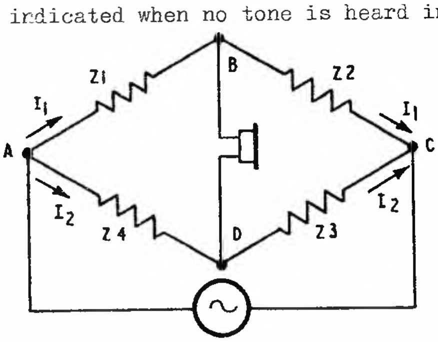


FIG. 31. IMPEDANCE BRIDGE.

AT BALANCE:-

$$I_1 \times Z_1 = I_2 \times Z_4$$

and $$I_1 \times Z_2 = I_2 \times Z_3$$

$$\therefore \frac{Z_1}{Z_2} = \frac{Z_4}{Z_3}$$

When the bridge is balanced, and when the values and phase angles of the impedances comprising three of the arms are known, the value and phase angle of the unknown impedance comprising the fourth arm can be calculated. In practice two of the arms (ratio arms) contain known, non-reactive resistors; the third arm contains a calibrated variable resistance connected in series or in parallel with a calibrated variable reactance.

.3 There are many adaptations of the basic bridge in use, capable of accurate measurement of either capacitive or inductive impedances. Impedance bridges used in telecom are described in other papers of the course.

12. TEST QUESTIONS.

1. Draw a simple circuit showing how a moving coil meter can be adapted to read A.C.

2. The frequency range of a normal rectifier meter is from approximately .... c/s to approximately .... c/s

3. Draw simple circuits showing the circuits of (i) a rectifier voltmeter, and (ii) a rectifier ammeter.

4. On the Multimeter, A.P.O. No. 2, protection against accidental overload is provided by the connection of .... in series / in parallel with the meter movement.

5. The sensitivity of the Multimeter No. 2 on the voltage ranges is .... ohms/volt. This means that the resistance of the instrument on the 30 volt D.C. range is .... ohms.

6. What is a thermoccuple?

7. Briefly explain the principle of operation of a thermocouple meter.

8. What is the effect of overloading a thermocouple meter?

9. Moving iron meters are suitable for use at power / audio / radio frequencies.

10. Electrostatic meters are used to measure currents / voltages of low / high values.

11. Briefly describe the principle of operation of a dynamometer.

12. In an A.C. circuit a dynamometer wattmeter indicates true / apparent power.

13. Compared with normal voltmeters, the advantages of a vacuum tube voltmeter are -

(i) ....

(ii) ....

14. Why is it necessary to use a probe when measuring high frequency voltages with a V.T.V.M.?

15. Draw a simple block diagram of a cathode ray oscilloscope.

16. The functions of the following oscilloscope controls are -

(i) Intensity ....

(ii) Vertical Shift ....

(iii) Horizontal Amplitude ....

17. A C.R.O. is calibrated so that 10 volts peak-to-peak corresponds to a line one inch long. What is the length of line traced when a sinusoidal voltage of 7 volts (effective) is measured?

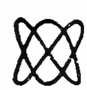
18. Vibrating reed frequency meters are suitable for measurements at power / audio / radio frequencies.

19. Briefly describe how an unknown frequency is measured by the beat frequency method.

20. When a standard frequency of 1 kc/s is applied to the horizontal deflection plates of a C.R.T. and unknown frequencies are applied in turn to the vertical deflection plates, the following patterns are obtained. What is the frequency in each case?

(i)  .... c/s.

(ii)  .... c/s.

(iii)  .... c/s.

END OF PAPER.

GENERATORS AND MOTORS.

INTRODUCTION.

.1 Generators and motors have always been part of the essential equipment at communication centres and large motor generator sets and motor driven ringers are familiar sights at many telephone exchanges.

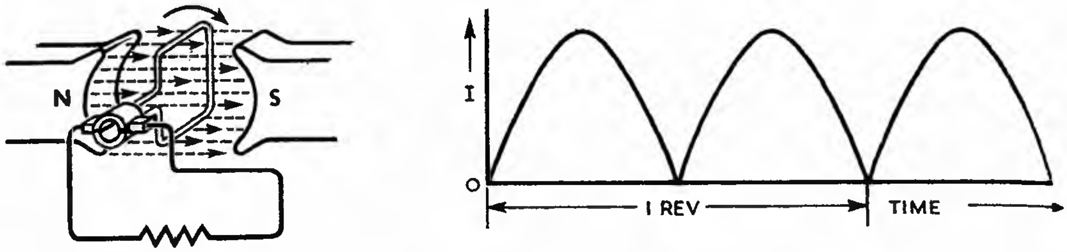
The use of motors and generators is not strictly limited to battery charging power plant. Small motor driven A.C. generators (alternators) provide the supervisory tones in telephone exchanges and also generate the voice frequency carrier currents which allow several motor driven telegraph machines to operate simultaneously over one pair of wires.

.2 A telecom Technician must have a sound knowledge of the basic construction and theory of operation of electric machines to enable him to operate them correctly, interpret their behaviour, and know when to call in a specialist to repair and overhaul them.

.3 This paper deals with the most common types of motors and generators which have application in telecom. Basic principles are revised briefly; a full description of these principles is given in the paper "Electromagnetic Induction" of Applied Electricity 1.

2. D.C. GENERATORS.

2.1 We saw in the paper "Electromagnetic Induction" (Applied Electricity 1) that when a coil of wire is rotated in a magnetic field an alternating e.m.f. is induced across its ends. When the ends of the coil are terminated on the segments of a commutator (Fig. 1a), each time the direction of the induced e.m.f. reverses, the connections of the coil to the external circuit reverse and a pulsating D.C. flows in the external circuit.



(a) Generator Principle. (b) Pulsating Current.

FIG. 1. SIMPLE D.C. GENERATOR.

A D.C. generator with a single coil winding (as in Fig. 1a) has little or no practical use because of the pulsating nature of its output. In practical machines, the variation in D.C. output is reduced to a slight "ripple" by using a large number of generating coils, connected to a corresponding number of commutator segments. The efficiency of the machine is further improved by -

(i) Winding the coils on a soft iron armature to reduce the reluctance of the magnetic circuit.

(ii) Using D.C. excited electromagnets to increase the intensity of the magnetic field.

2.2 D.C. Generator Construction. A practical D.C. generator has three main sections. These are -

(i) The Field Assembly, (Fig. 2) which consists of the outer frame or yoke, the field poles and the field winding. The field windings are placed around the field poles, and, when energised by D.C., they establish the magnetic field in which the generating winding rotates. The yoke completes the magnetic circuit between the field poles. Small generators usually have only two field poles, but large machines may have four or more poles. Regardless of the number of poles, however, adjacent field poles are always of the opposite polarity.

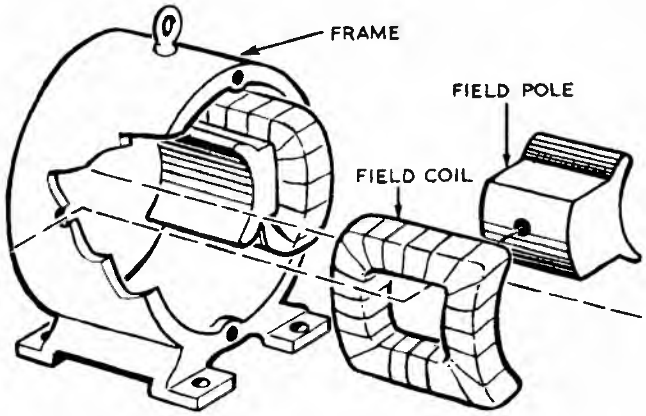
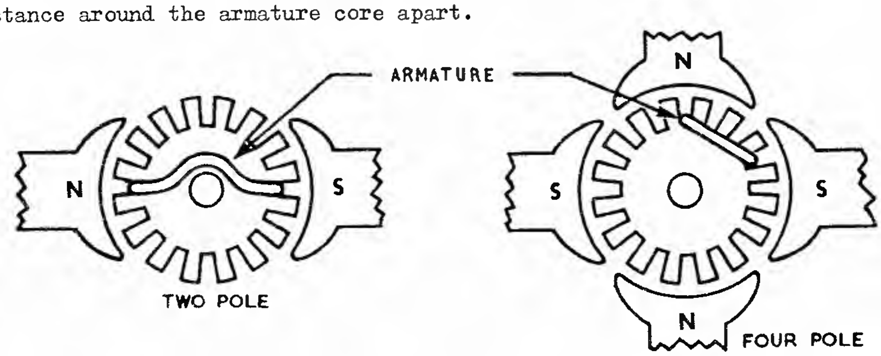


FIG. 2. FIELD ASSEMBLY.

(ii) The Armature Assembly consists of the main shaft, the armature core, the armature winding and the commutator. The armature core is assembled from soft iron laminations, and it is slotted to accommodate the coils which comprise the armature winding. The armature coils terminate on the commutator, which consists of a number of individually insulated copper segments, built up into a cylinder and fixed to the armature shaft. Generally there are as many commutator segments as there are armature coils.

(iii) The Brush Assembly consists of the carbon brushes which bear on the commutator, and their associated holders and tensioning springs. Small generators usually have only two brushes, one for the positive connection and one for the negative connection. However in larger machines with wide commutators each "brush unit" may contain several brushes placed side by side, and in large multi-pole generators two or more brush units are connected in parallel to form each "brush".

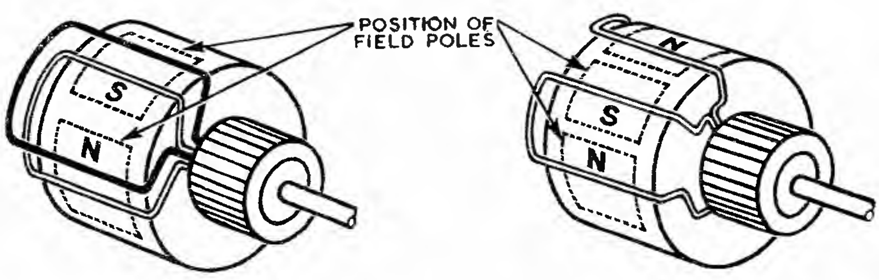
2.3 Armature Windings. Most modern generators use a "closed circuit" winding, that is the coils forming the winding are interconnected at the commutator segments and form a closed circuit. The coils are arranged in the armature slots so that opposite sides of each coil come under the influence of unlike field poles, and the e.m.fs induced in each side of each coil are additive. With a two pole machine (Fig. 3a) each coil spans approximately half the armature core; with a four pole machine (Fig. 3b), the coils are placed in slots approximately one quarter of the distance around the armature core apart.



(a) Two Pole Generator. (b) Four Pole Generator.

FIG. 3. PLACEMENT OF ARMATURE COILS.

As a matter of interest, there are two winding methods in common use. With the "lap" winding (shown in simplified form in Fig. 4a) there are as many parallel current paths as there are field poles, and this method is used in generators which have a high current output at a comparatively low voltage. With a "wave" windings, (Fig. 4b) there are only two current paths irrespective of the number of field poles; this winding is used mainly in high voltage generators.



(a) Lap Winding. (b) Wave Winding.

FIG. 4. ARMATURE WINDINGS.

2.4 Commutation. In a simple D.C. generator, the commutator brushes short-circuit the armature coil for a brief period, each time the connections to the coil are reversed. This action is shown in Fig. 5, in which the brushes are positioned so that the short-circuit occurs when the plane of the coil is at right-angles to the magnetic field.

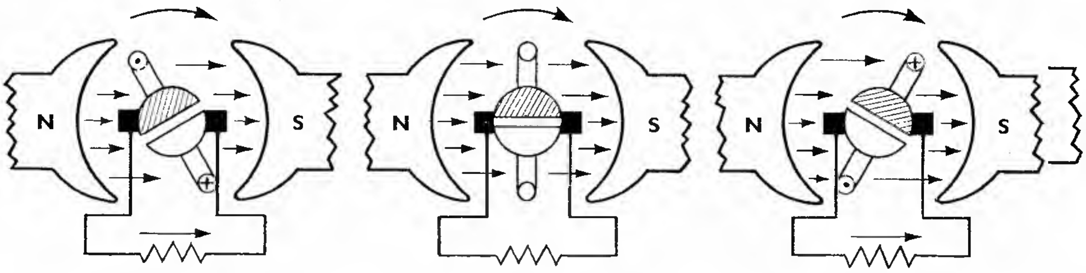


FIG. 5. COMMUTATION IN A SIMPLE GENERATOR.

With the brushes in this position, the coil is short-circuited when its conductors are moving parallel to the field, and the induced e.m.f. is zero. Should the brushes be rotated a few degrees from this position, they short-circuit the coil when its conductors are moving across the field. As a result, an e.m.f. is induced in the short-circuited coil, and the resultant current causes sparking at the brushes.

The same conditions apply in practical generators in which the armature winding consists of a large number of coils. Whenever the brushes bridge two commutator segments a coil is short-circuited. To prevent sparking, the brushes must be positioned so that the e.m.f. in the short-circuited coil is zero at this instant.

2.5 Armature Reaction. When a generator is in operation, current in the armature winding sets up a magnetic field which distorts the main field. Fig. 6 shows the field distortion due to armature flux in a simple two pole generator.

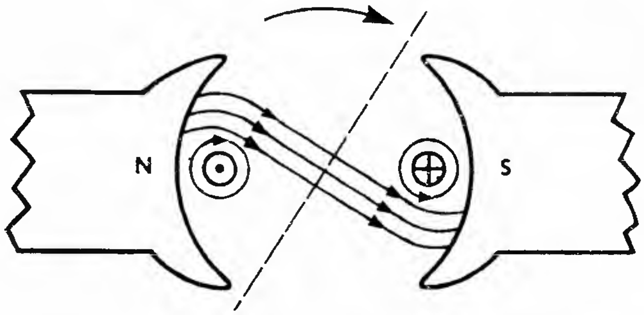


FIG. 6. FIELD DISTORTION DUE TO ARMATURE FLUX.

This "armature reaction" affects the positioning of the brushes, as they must be moved in the direction of rotation a few degrees so that the short circuit is applied when the plane of the coil is at right angles to the distorted field.

In practice, it is very difficult to position the brushes correctly, as the armature flux, and therefore the extent of the field distortion, varies with changes in the value of armature current. To overcome this difficulty, large generators are usually provided with auxiliary field poles called "interpoles".

1.6 Interpoles. Interpoles which are auxiliary field poles situated between the main field poles of a generator cancel the effect of armature reaction. The interpole windings are connected in series with the armature winding and their polarity is the same as that of the adjacent main pole ahead. When the interpole windings have the correct number of turns, their magnetic field (which is proportional to armature current) cancels the field distortion due to the armature flux (also proportional to armature current) and improves commutation under all conditions of load.

Fig. 7 shows the field assembly of four pole generator which is fitted with interpoles.

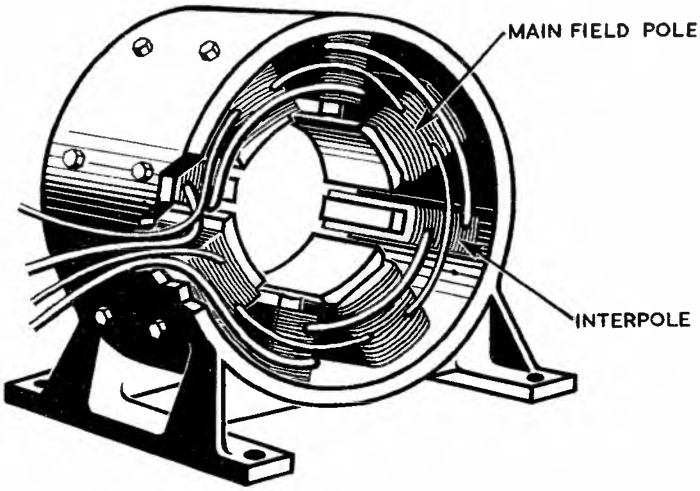


FIG. 7. D.C. GENERATOR WITH INTERPOLES.

1.7 Types of Generators. D.C. generators are classified according to the manner in which the field windings are energised. There are two basic types -

(i) Separately Excited Generators, in which the field current is supplied from an external D.C. source.

(ii) Self-Excited Generators, in which the field current is supplied by the machine itself.

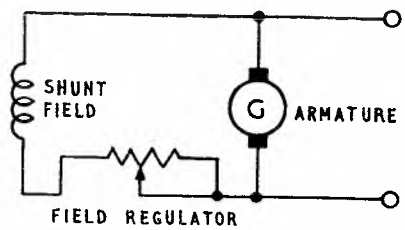
Most generators in common use are of the self-excited type which rely on the residual magnetism of the field system for their initial operation. When the generator is first started, a small e.m.f. is induced in the armature winding as it moves in the weak residual field. This induced e.m.f. causes a small current to flow in the field winding, and this creates a stronger magnetic field resulting in an increase in the value of induced e.m.f. This "build-up" action continues until the field system is fully fluxed when the induced e.m.f. attains its rated value.

It is important to note, that the connections to the field windings of a self-excited generator must never be reversed, as under these conditions, the initial passage of field current cancels the residual magnetism of the field poles. With no field flux the generator cannot build up, and the field windings must be "flashed", that is connected momentarily across a D.C. supply, to restore the residual field.

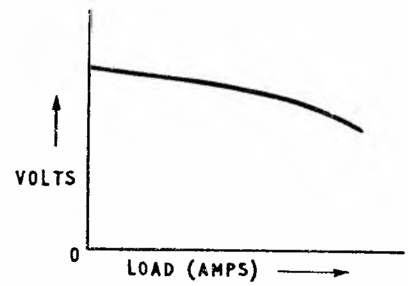
Self-excited generators can be divided into three types, shunt, series and compound, which derive their different characteristics from the method of connecting the field and armature windings.

2.8 Shunt Generators. A shunt generator has its field winding connected in parallel with the armature winding as shown in Fig. 8a. Provided the generator is driven at a constant speed, the value of the e.m.f. developed in the armature winding depends on the strength of the magnetic field, which is in turn determined by the magnitude of the field current. With the shunt connection, the voltage applied to the field winding is the same as the terminal voltage of the generator, which is equal to the armature e.m.f. less the P.D. across the internal resistance of the armature winding.

When the generator is connected to a load circuit the drop of potential across the resistance of the armature causes a slight reduction in terminal voltage, which is magnified by the decrease in field strength due to the lower voltage applied to the field winding. As the loading is increased, the terminal voltage decreases as shown in the typical voltage/loading curve (Fig. 8b).



(a) Circuit.



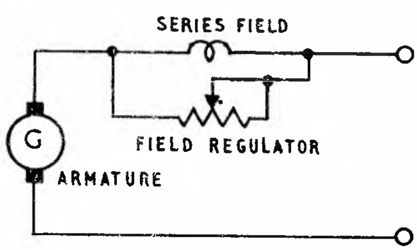
(b) Characteristics.

FIG. 8. SHUNT GENERATOR.

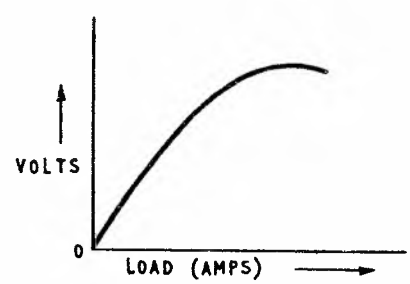
Most shunt generators are provided with a field regulator (Fig. 8a) by means of which the field current can be varied to provide a means of controlling the output voltage. When it is necessary to maintain a constant output voltage under varying load conditions, automatic regulators are employed. These are described in Telephony 5 (Power Plant Components).

2.9 Series Generators. In a series generator, the armature, the field winding and the load circuit are connected in series (Fig. 9a) so that all or a definite part of the output current is used to establish the magnetic field.

Under no-load conditions, the terminal voltage is minimum, as the field winding is unenergised. When a load circuit is applied the terminal voltage increases (Fig. 9b), becoming greater as increases in output current increase the strength of the magnetic field. The output voltage can be adjusted by a variable resistance shunted across the series field.



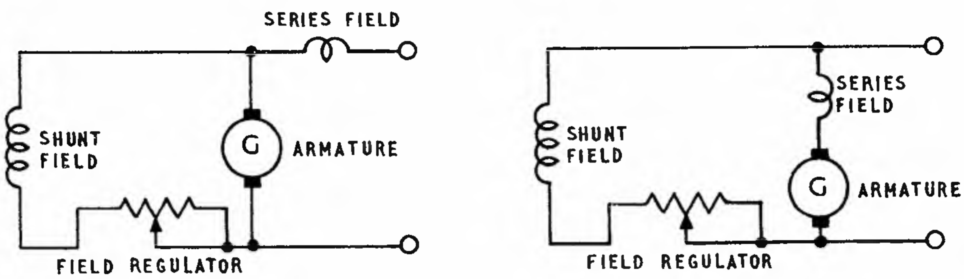
(a) Circuit.



(b) Characteristics.

FIG. 9. SERIES GENERATOR.

Compound Generators. A compound generator is a combination of the shunt and series types, as the field winding consists of shunt and series connected coils. When the shunt winding is connected between the series winding and the armature (Fig. 10a) the generator is referred to as a "short shunt" machine; when the shunt field is connected between the series field and the output terminals, (Fig. 10b), the generator is called a "long shunt" machine.



(a) Short Shunt Generator. (b) Long Shunt Generator.

FIG. 10. COMPOUND GENERATORS.

With either connection, a compound generator combines the decreasing voltage characteristic of a shunt generator with the increasing voltage characteristic of a series machine. For different applications, a generator may be -

(i) Flat-compounded when the series winding is so proportioned that the voltage remains substantially constant from no-load to full load.

(ii) Over-compounded when the series winding has sufficient turns to cause the voltage to increase slightly from no-load to full load.

(iii) Under-compounded when the voltage decreases slightly when the load is increased.

The characteristics of the various types are shown in Fig. 11.

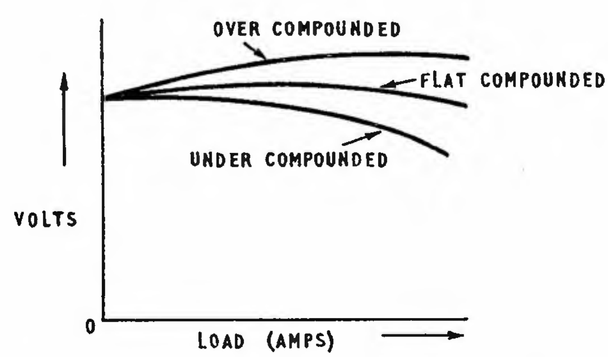


FIG. 11. COMPOUND GENERATOR CHARACTERISTICS.

.11 Application. In telecom, motor driven generators are used for battery charging at many telephone exchanges. These machines are always of the shunt field type, since a series field generator has a less stable output and may run as a motor at dangerously high speeds if accidentally connected across the battery. In some cases, the machines are compounded to improve commutation and give a constant voltage output under varying load conditions. Further details of motor-generators and of their associated equipment is given in the papers "Power Plant Components" and "Power Plant, Telephone and Long Line Stations" in Telephony 5.

3. D.C. MOTORS.

3.1 We saw in the paper "Electromagnetic Induction" (Applied Electricity 1) that in a simple D.C. motor, a coil of wire is mounted so that it is free to rotate between the poles of a permanent magnet. The ends of the coil terminate on the segments of a commutator, and carbon brushes complete the circuit to an external D.C. supply.

3.2 Principle of Operation. Figs. 12a, b and c show that when current flows in the coil, the magnetic field surrounding its conductors interacts with the field of the magnet and the resulting force causes the coil to rotate. After the coil reaches the vertical position the commutator reverses the direction of current. The direction of the forces acting on the conductors are similarly reversed and the coil continues to rotate in the same direction as before.

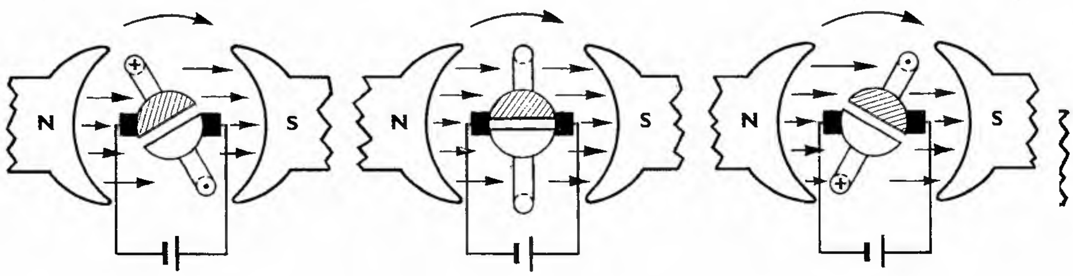


FIG. 12. SIMPLE MOTOR.

Practical D.C. motors have the same general construction as D.C. generators. The use of a large number of armature coils connected to an equal number of commutator segments results in the production of smooth continuous torque. The magnetic field is created by D.C. excited field windings, which are connected in series or in parallel with the armature winding.

3.3 Armature Back e.m.f. and Motor Speed. When a motor armature rotates in a magnetic field an e.m.f. is induced across its winding. This induced e.m.f. opposes the applied voltage, according to Lenz's law, and limits the armature current. The value of the back e.m.f. depends on the strength of the magnetic field and the motor speed.

When the motor is unloaded, the back e.m.f. rises as the speed increases from zero until the motor reaches a speed that the back e.m.f. is almost equal to the applied voltage. The motor settles down at this speed; a small value of current is drawn from the source to supply the small amount of energy required to overcome friction, windage and resistance losses to keep the armature in motion.

When a mechanical load is applied to the motor, the speed of rotation is reduced and the back e.m.f. decreases. The armature current increases until sufficient torque is developed to handle the increased load. The motor then settles down at a steady reduced speed.

Decreasing the mechanical load has the opposite effect. When the load is reduced the motor accelerates. The back e.m.f. rises and the armature current decreases, thus reducing the torque to the necessary value for the reduced load.

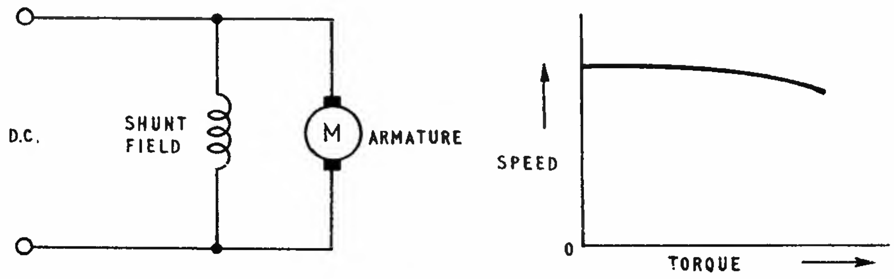
The fundamental relationships which apply to all motors are:-

(i) Motor speed depends on back e.m.f.
(ii) Motor torque depends on the armature current.

In all motors the running speed decreases as the load increases. The extent of the speed variation from no load to full load varies with the different types of motors mainly because of the manner in which the windings are energised. However, reducing the field strength decreases torque but increases the speed as the machine runs faster to produce the necessary balancing back e.m.f.

Shunt Motors. In a shunt motor, the field winding is connected in parallel with the armature winding as shown in Fig. 13a. With this arrangement, field current is independent of variations in armature current due to load changes, and the resulting constant magnetic field keeps the speed fairly constant from no-load to full load.

The characteristics of a typical shunt motor are shown in Fig. 13b in which the motor speed is plotted against the torque requirements of the load. As the speed variation from no-load to full load is only about 10% of the no-load speed, shunt motors are considered to be "constant speed" motors. In telecom, they are used to drive ringing machines in some telephone exchanges and in more modern exchanges the motor sections of the larger ring and tone dynamotors are usually shunt connected.

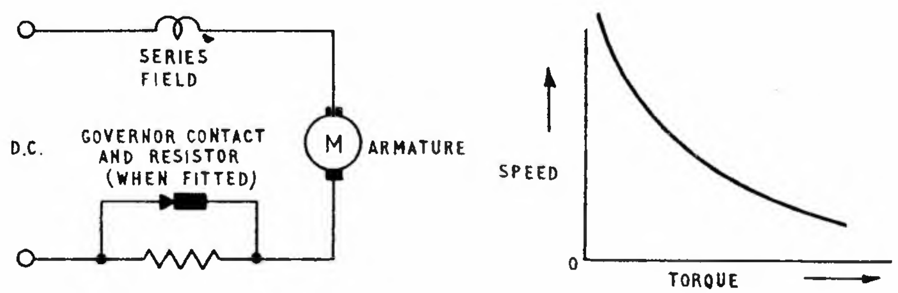


(a) Connections. (b) Characteristics.

FIG. 13. D.C. SHUNT MOTORS.

Series Motors. Fig. 14a shows the basic circuit of a series motor, in which the field winding, the armature winding and the supply source are connected in series. As the field winding is energised by armature current, the field strength of a series motor is not constant, and under different conditions of load, the speed can vary over a wide range as shown in Fig. 14b.

Unloaded, the weak field due to the low value of armature current causes the motor to race, and possibly run to destruction. The speed decreases rapidly as the load is applied, and under heavy loads the motor runs comparatively slowly. A feature of series motors is their tremendous starting torque which far exceeds that of any other type of electric motor.



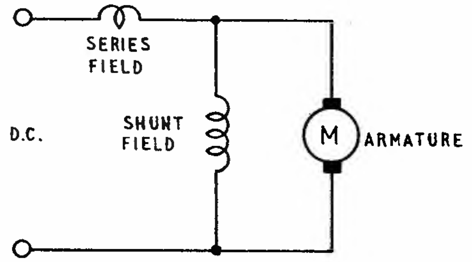
(a) Connections. (b) Characteristics.

FIG. 14. D.C. SERIES MOTOR.

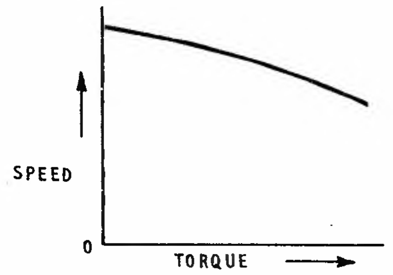
In small motors, the speed can be controlled within close limits by the use of a centrifugal governor attached to the motor shaft. The governor contains contacts which intermittently short-circuit a series field resistor. In telecom, small governor controlled D.C. series motors are used in impulse machines in 2000 type telephone exchanges, and they are also used to drive the multi-frequency tone generators associated with voice frequency telegraph carrier systems.

3.6 Compound Motors. A compound motor has a field winding which contains both series and shunt coils, as shown in Fig. 15a. The series field enables the motor to gain speed quickly under load, and the shunt field enables it to maintain a near constant speed when the load is removed or varied.

They are designed for applications requiring constant speed with quick changes from no load to full load, and in telecom, they are used in "no break" standby power plant.



(a) Typical Connections.



(b) Typical Characteristics.

FIG. 15. D.C. COMPOUND MOTOR.

3.7 Position of Brushes. We have seen that armature reaction in a D.C. generator distorts the main magnetic field and affects the positioning of the brushes. Similar field distortion occurs in a D.C. motor, but the direction of distortion is opposite to that in a generator, that is, armature reaction in a motor shifts the neutral commutating plane against the direction of rotation, as shown in Fig. 16.

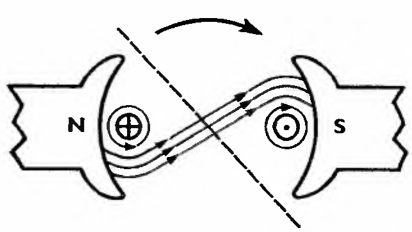


FIG. 16. FIELD DISTORTION - D.C. MOTOR.

To compensate for armature reaction, the brushes are moved backwards until sparking is at a minimum. No single setting can give sparkless commutation under all conditions of load, but on small motors the brushes are set by the maker in a position which gives good average results.

In large motors armature reaction is corrected by means of compensating windings and inter-poles which function in the same way as those provided in large generators.

3.8 Starting D.C. Motors. When a D.C. motor is running, the armature current is limited by the armature back e.m.f. However, when the machine is at rest, this back e.m.f. is not present, and the only factor which opposes the passage of armature current is the low resistance of the armature winding.

When a large motor is stationary, the application of the full supply voltage, would result in a starting current at least 20 times greater than the normal running current. As this current surge could damage the motor, a resistor is connected in series with the armature winding during the starting process. The value of the resistor is reduced as the motor gains speed and, when full speed is reached, the resistor is short circuited.

The complete starting assembly for a D.C. motor usually includes equipment which protects the motor in the event of overload, and which restores the starter to the "start" position if the supply voltage fails.

D.C. starters are rarely encountered in telecom, as most of the small motors used can be started without special equipment. However, the principle is applied in starters for large A.C. motors, which are used extensively at telecom stations.

ERNATORS.

Alternators. An alternator is a rotary generator, generally provided with D.C. excited field windings, which, when driven at the appropriate speed, develops an alternating voltage at a particular frequency.

Regardless of their size or application, all alternators operate on the principle of electromagnetic induction as a result of relative motion between an electrical conductor and a magnetic field. The relative motion can be brought about in three ways -

(i) By moving conductors through a stationary magnetic field, as in the rotating armature alternator.

(ii) By moving a magnetic field across stationary conductors as in the rotating field alternator.

(iii) By varying the intensity of the magnetic field surrounding stationary conductors as in the inductor alternator.

The Rotating Armature Alternator. The rotating armature alternator is similar to a D.C. generator, in that the generating winding is placed on the rotating part of the machine. The principle of operation is shown in Fig. 17.

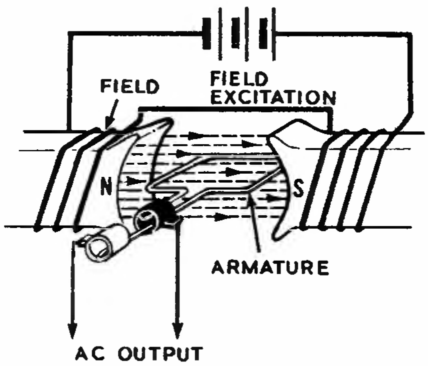


FIG. 17. PRINCIPLE OF ROTATING ARMATURE ALTERNATOR.

The Stator or stationary frame is similar in construction to the field assembly of a D.C. generator. The field coils are wound on specially shaped pole pieces and they are energised from an external D.C. source. The field system may have four or more poles, but most of the rotating armature alternators used in telecom have only two field poles.

The Rotor or rotating portion is laminated and it accommodates the generating winding in slots in its outer surface. The winding terminates on insulated slip rings, and carbon brushes which rub on the slip rings complete the circuit to the external load.

The principle of operation is exactly the same as that of the simple A.C. generator, described in the paper "Electromagnetic Induction", of Applied Electricity 1. The frequency of the A.C. depends on the speed at which the machine is driven and on the number of field poles. Frequency can be calculated from -

$$\text{FREQUENCY (c/s)} = \frac{\text{SPEED (r.p.m.)}}{60} \times \frac{\text{NUMBER OF POLES}}{2}$$

Rotating armature alternators are suitable for low voltage, low power applications, and motor driven machines of this type are used in some telephone exchanges to produce ringing current. As the D.C. excited field system is the same as that used in a D.C. machine, it is possible to combine a D.C. motor and a rotating armature alternator in one unit called a "dynamotor". In these machines, the rotating portion carries a D.C. motor winding and commutator as well as an alternator winding and slip rings, with both windings served by a common field. Dynamotors are in common use as "ringing machines" in telephone exchanges.

4.3 The Rotating Field Alternator. When electrical energy is generated at high voltages, insulation problems are introduced which would be very difficult to overcome at the exposed slip rings of a rotating armature alternator. This difficulty is not encountered in a rotating field alternator, as, in this type of machine, the field system rotates and the stationary generating winding can be connected directly to the load.

The principle of a basic rotating field alternator is shown in Fig. 18. In practice, the turns of the generating winding are embedded in slots in the laminated stator and the field winding is placed on the rotor. The rotor windings are energised by D.C. connected via slip rings and carbon brushes. The basic machine shown in Fig. 18 has four field poles but this number varies in alternators designed for different applications.

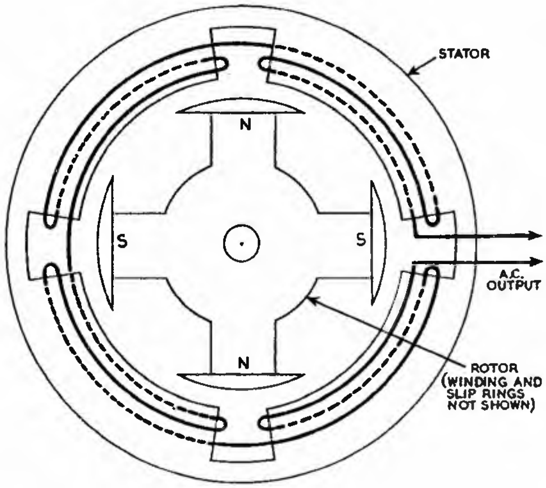


FIG. 18. PRINCIPLE OF ROTATING FIELD ALTERNATOR.

With a D.C. in the rotor winding, a magnetic field with alternate north and south poles is produced. When the rotor is set in motion the rotor flux links the turns of the stator winding and an alternating e.m.f. is generated. The frequency of the output voltage is determined by the speed of the machine, and the number of field (rotor) poles. With a four pole machine, the magnetic field linking each turn of the generating winding goes through two complete changes in polarity with each revolution, and two cycles of A.C. are produced. When this alternator is driven at 1,500 r.p.m. (25 revolutions per second) the output voltage has a frequency of 50 c/s.
The frequency can be calculated from -

$$\text{FREQUENCY (c/s)} = \frac{\text{SPEED (r.p.m.)}}{60} \times \frac{\text{NUMBER OF POLES}}{2}$$

In large machines the D.C. required for the excitation of the rotor winding is derived from a small shunt or compound wound D.C. generator. This "exciter" generator is mounted on the alternator and is driven from the rotor shaft.

Rotating field alternators are used in practically all applications where electrical energy is generated commercially. These machines have three separate generating windings on the stator and produce three voltages which are 120° out of phase.

At important telecom stations, it is current practice to provide a diesel driven "three-phase" alternator which is brought into operation in the event of a failure in the commercial power supply. The value and frequency of the output voltage of these machines is the same as that of the commercial supply, and their operation allows power plant and other essential services to function normally for the duration of the power failure. A detailed description of the facilities offered by "standby" alternators is given in Telephony 5.

1.4 The Inductor Alternator. In the rotating armature and rotating field alternators the rotor has a current-carrying winding requiring the use of slip rings and brushes. In the inductor alternator, however, slip rings and brushes are not necessary as both the generating and exciting windings are stationary.

A simple inductor alternator is shown in Fig. 19a. It consists essentially of a specially shaped, laminated, soft iron rotor which revolves in the magnetic field of a D.C. (or permanent magnet) excited laminated stator. The rotor is unwound and both generating and exciting windings are accommodated on the stator.

When the exciting winding is energised, a magnetic field is established across the air gap between stator and rotor. The intensity of this field depends on the position of the rotor. For example, when the projections or "teeth" on the rotor are opposite the stator poles (Fig. 19b), the air gap is of minimum length, and the low reluctance of the magnetic circuit allows maximum flux across the air gap. When the rotor teeth are away from the stator poles (Fig. 19c) the reluctance is greatest, and the flux is considerably reduced.

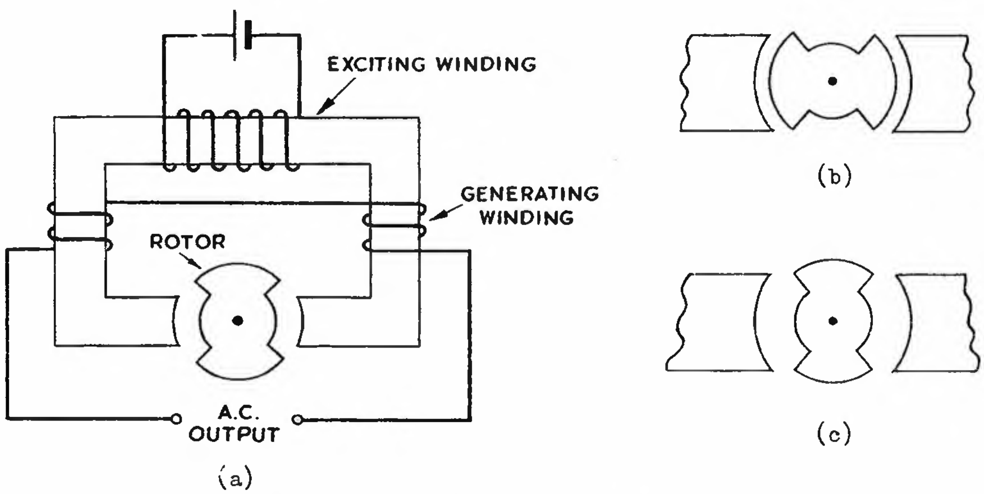


FIG. 19. SIMPLE INDUCTOR ALTERNATOR.

With the rotor in motion, the changing reluctance of the magnetic circuit causes corresponding changes in the flux linking the turns of the generating winding. As each rotor tooth passes a stator pole, the flux goes through one complete change in values, from minimum to maximum and back to minimum, inducing one cycle of alternating e.m.f. across the turns of the generating winding.

The simple machine shown in Fig. 19 has two rotor teeth and therefore two cycles are produced each time the rotor makes one revolution. In the same way, a machine with four rotor teeth develops four cycles per revolution. The frequency of the output voltage can be calculated from -

$$\text{FREQUENCY (c/s)} = \frac{\text{SPEED (r.p.m.)} \times \text{NUMBER OF ROTOR TEETH}}{60}$$

In practice, the rotor often has a large number of teeth and the generating winding is placed on projections on the inner periphery of the stator. Inductor alternators are capable of producing voltages at voice frequencies and machines equipped with several multi-toothed rotors and a number of multipole stators can generate several different frequencies simultaneously.

In telecom, inductor alternators are used to generate the supervisory tones in automatic telephone exchanges, and they are also used to produce the voice frequency carrier currents for telegraph carrier systems. Details of the construction and operation of these machines are given in Telephony 5 and Long Line Equipment 2.

5. THE COMMERCIAL ELECTRICITY SUPPLY.

5.1 In Australia, electric power is generated in power stations and distributed by a complex system of high voltage power lines. Although knowledge of the details of the generating and distributing equipment are not necessary, we must have some appreciation of the nature of this supply, as all power plant in telephone exchanges, long line equipment stations and other major communication centres operates from the commercial power mains.

5.2 The Three Phase System. In most electricity supply areas, alternating current at a frequency of 50 c/s is generated and distributed by means of the three phase system. In this system, the generating machines have three generating windings which are constructed and positioned in the machine so that the voltage developed in any one winding is equal to, but 120° out of phase with, the other two voltages. The relationship between the three voltages is shown graphically in Fig. 20.

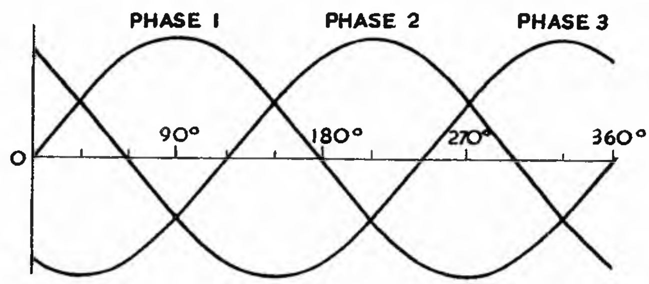


FIG. 20. THREE PHASE VOLTAGE.

The three phase system offers several advantages in usage and distribution when compared with the single phase system. It delivers a uniform power output throughout each cycle and therefore facilitates the use of physically smaller, more efficient, and smoother running machines of simple design. It also allows the outputs of the three generator windings to be distributed to three balanced load circuits using three conductors only, as against six for three equivalent single phase supplies.

To appreciate the three wire distribution system, let us consider that the three "phases" are connected to three resistive load circuits, each of which has the same resistance.

Because of the nature of the load circuits, the three currents are of equal value, and as each is in phase with voltage, the currents are 120° out of phase (Fig. 21). For convenience, assume that the current in each circuit reaches a peak value of 10 amps.

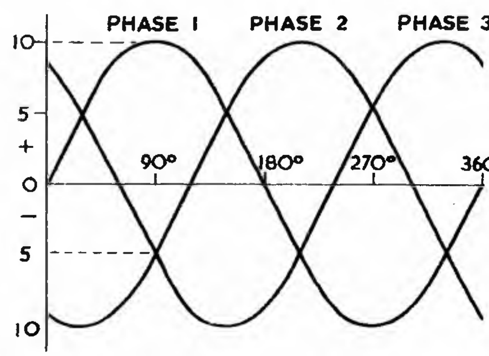


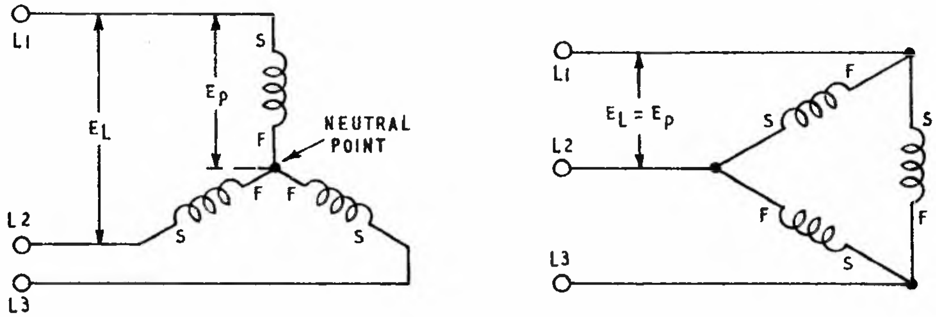
FIG. 21. THREE-PHASE CURRENTS.

At any instant in Fig. 21, the value of the current in any one phase is equal in value but opposite in direction to the algebraic sum of the currents in the two remaining phases. For example, at 90°, the instantaneous value of the current in phase 1 is 10 amps in a positive direction; at this instant the currents in phases 2 and 3 are both 5 amps in the negative direction. As similar conditions exist at all instants throughout the cycle, it is possible to connect the three generating windings to the three load circuits using three wires only, as the return path for each phase is provided by the conductors connecting the two remaining phases.

Three Phase Connections. There are two methods of connecting the generating windings so that a three wire circuit can be used. These are -

(i) The Star Connection. In this method, (Fig. 22a), corresponding ends (either starting ends or finishing ends) of the three windings are connected together to form a "neutral point", and the line wires are connected to the other ends of the windings. With a star-connected alternator, the "line voltage" (E_L) or voltage between lines is 1.732 times greater than the "phase voltage" (E_p) or voltage across one winding.

(ii) The Delta Connection. In the delta connection, (Fig. 22b), the windings are connected in series to form a closed circuit and the line wires are connected at the junction points. A neutral point is not available in this connection. With a delta-connected alternator, the line voltage is equal to the phase voltage.



(a) Star Connection. (b) Delta Connection.

FIG. 22. THREE-PHASE CONNECTIONS.

In the same way, the load circuits can be connected in star or delta. It is not essential to use the same connection for the load circuit as is used at the alternator.

Usually, the commercial power supply is derived from star-connected alternators, and a four-wire circuit is used in its final distribution. The fourth or "neutral" wire connects to the neutral point at the source, and it allows unbalanced loads to be connected, as the out-of-balance currents return via the neutral wire. With this arrangement, single-phase supplies are readily obtainable.

Single-Phase and Three-Phase Supplies. Most domestic supplies are single-phase, derived by connecting between one "line" and the neutral wire at the distribution pole. However, with large buildings such as telephone exchanges, a three-phase supply is usually provided for the operation of large motors, rectifiers, etc. Single-phase circuits for lighting, etc., are derived at the main switchboard.

The nominal voltages of single and three-phase supplies are -

Single-phase	-	240 volts (between one line and neutral).
Three-phase	-	415 volts (between any two lines).

Nearly all three-phase operated equipment used in telecom is permanently wired. However, many single-phase appliances, such as hand drills, soldering irons, etc., are portable and can be operated from single-phase power outlets. In most cases, portable appliances are connected via a three-way cord, in which the third (green) conductor serves to earth the appliance frame. This is a vital safety feature and periodic inspection of these appliances must be carried out as outlined in E.I. WORKSHOPS Plant X 0002 "Testing Single Phase Appliances".

6. A.C. MOTORS.

6.1 In a D.C. motor both the armature and field system contain insulated windings, and when these are energised by D.C. the interaction of their magnetic fields produces torque.

Similarly, torque is developed in an A.C. motor as the result of interaction between two magnetic fields. However, in most A.C. motors, only the stator windings are connected to the A.C. supply, as the magnetic field of the rotor is established by induced currents. Motors operating on this principle are called Induction Motors.

6.2 Induction Motors. Induction motors are available in either single-phase or three-phase types. They are simple and rugged in construction, reliable in operation and have practically a constant speed characteristic.

An induction motor consists of two parts. The Stator or stationary frame, consists of an assembly of ring-shaped soft iron stampings which contains insulated windings in slots around its inner surface. An outer carcase is sometimes provided as a mechanical protection for the stampings and windings, but this does not form part of the magnetic circuit, as does the outer frame or yoke of a D.C. motor.

The Rotor or rotating member consists of another set of soft iron stampings which are rivetted together and fixed to the main shaft.

In most induction motors the rotor winding consists of a number of bars of copper or aluminium which have been embedded or cast in slots around the surface of the rotor and short circuited at their ends by end rings of the same material.

The rotor-bar assembly resembles a tread-mill or squirrel-cage, and rotors using this construction are often referred to as "squirrel-cage rotors". Fig. 23 shows how the rotor-bar assembly of a large induction motor would appear if removed from the rotor and reassembled. The copper bars are often angled for smoother running of the rotor.

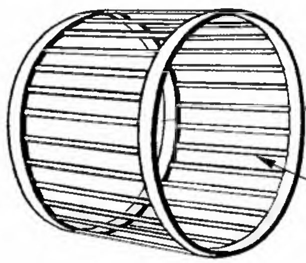


FIG. 23. ROTOR-BAR ASSEMBLY.

6.3 Principle of Operation. When the stator windings are energised by A.C., a rotating magnetic field is produced, similar to that of a rotating horse-shoe magnet. This field cuts across the rotor, and the induced e.m.f. causes current to circulate in the short-circuited rotor bars.

The induced currents in the rotor create a magnetic field, which, in accordance with Lenz's Law opposes the motion producing them. The rotor flux therefore interacts with the rotating magnetic field of the stator, and the resulting force turns the rotor in the same direction as the direction of the rotating stator field.

To maintain the currents producing the rotor flux and keep the motor running there must always be relative motion between the rotating rotor bars and the rotating stator flux. Therefore the speed of the rotor can never be equal to the "Synchronous Speed", or, speed at which the stator field rotates. When the mechanical loading on the motor is increased, the rotor slows down slightly, increasing the relative motion between rotor and field. This results in an increase in the magnitude of the induced current and a greater torque is developed.

The difference between the speed of the rotor and the speed of the field is termed the "slip", and it is usually expressed as a percentage of the synchronous speed. The slip varies with different types of machines but, on full load, it is in the vicinity of 5%.

Production of a Rotating Stator Flux. The means by which a rotating magnetic field is produced varies slightly with different types of induction motors, but, in general, the stator requires at least two windings, and these must be energised by out of phase A.C.'s.

Fig. 24a shows the stator of a simple "two-phase" induction motor which has two windings, A and B, each of which is arranged to produce two magnetic poles of opposite polarity. The windings are placed so that the pole axes are at right angles, and they are energised by two A.C.'s of the same frequency which are 90° out of phase, that is from a "two-phase" supply. The relative direction of the stator flux at a number of instants is shown in Fig. 24b.

At 0°, current in winding A is zero, and current in winding B is at a maximum positive value. Therefore poles A and A1 are unmagnetised, but a field exists across B and B1, with a north pole at B.

At 90° current in winding A has risen to a maximum value in the positive direction, and current in winding B has fallen to zero. The field between B and B1, no longer exists but a field is established between A and A1, with a north pole at A. Therefore the axis of the stator magnetic field has turned through 90°.

At 180° and 270°, the currents in the windings are of the same value, but in the opposite direction to those at 0° and 90°. The magnetic fields at 180° and 270° are therefore opposite in direction to those at 0° and 90°, representing a further angular displacement of 90° at each position. At 360°, the same conditions apply as at 0°, and therefore, over the cycle, the axis of the stator flux has turned through 360°. This action continues as long as the windings are energised, and a continuously rotating stator flux is produced.

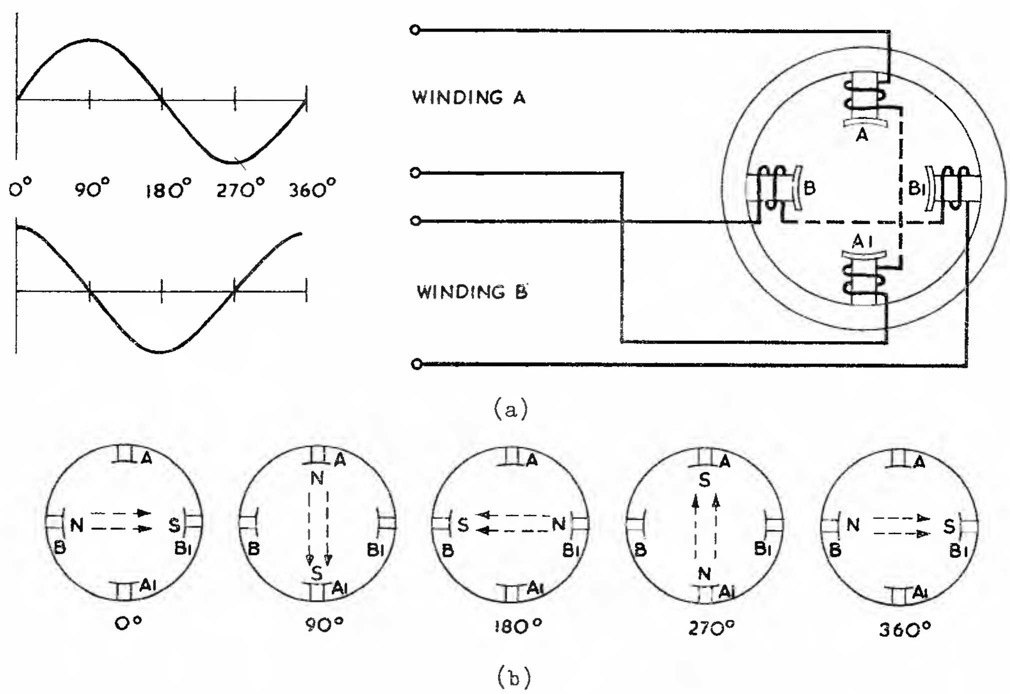


FIG. 24. PRODUCTION OF A ROTATING STATOR FLUX.

In the same way a rotating magnetic field is established when a three-phase supply is applied to a stator with three-windings, spaced 120° apart. However, the number of stator windings does not affect the synchronous speed, and this is determined by the frequency of the A.C. supply and the number of poles produced by each winding. For example, when a two pole stator (Fig. 24a) is energised from a 50 c/s supply, the magnetic field rotates once per cycle, or at 3,000 r.p.m. With a four pole stator, synchronous speed at 50 c/s is 1,500 r.p.m.

6.5 Single-Phase Induction Motors. A single-phase supply provides only one voltage. When an induction motor stator is energised from such a supply, the magnetic field rever- but it does not rotate. Although a reversing stator flux is sufficient to keep the rotor turning once it has been started, it is not capable of starting the rotor from a stationary position.

Most induction motors operated from a single-phase supply are, in fact, two-phase motors, as they have two separate windings, and incorporate a phase-splitting arrangement so that the windings are energised by currents which are out of phase. The most commonly used single-phase motors are briefly described in following paragraphs.

6.6 The Split-Phase Motor. This is a squirrel cage motor which has two separate stator windings, called the "running" winding and the "starting" winding. Both are wound to produce the same number of poles, and they are arranged so that the poles of one winding are situated mid-way between adjacent poles of the other winding. The running winding is wound with many turns of heavy wire, and has a higher inductance and lower resistance than the starting winding, which is wound with fewer turns of finer wire.

The windings are connected in parallel to the single phase supply. As the ratio of inductive reactance to resistance in the running winding is greater than in the starting winding the currents energising them are out of phase, and as the windings are displaced around the stator a rotating magnetic field is set up in the stator. This cuts across the short-circuited bars in the rotor and sets it in motion. The starting torque is comparatively low, as the phase difference between the currents is much less than the required 90°, and a uniform rotating field is not established.

When the rotor speed is approximately 75% of the normal speed, the starting winding is disconnected and the motor runs on the running winding alone. In most cases, this is done automatically by a switch actuated by a centrifugal mechanism attached to the rotor shaft. The major components of a split-phase motor are shown in Fig. 25.

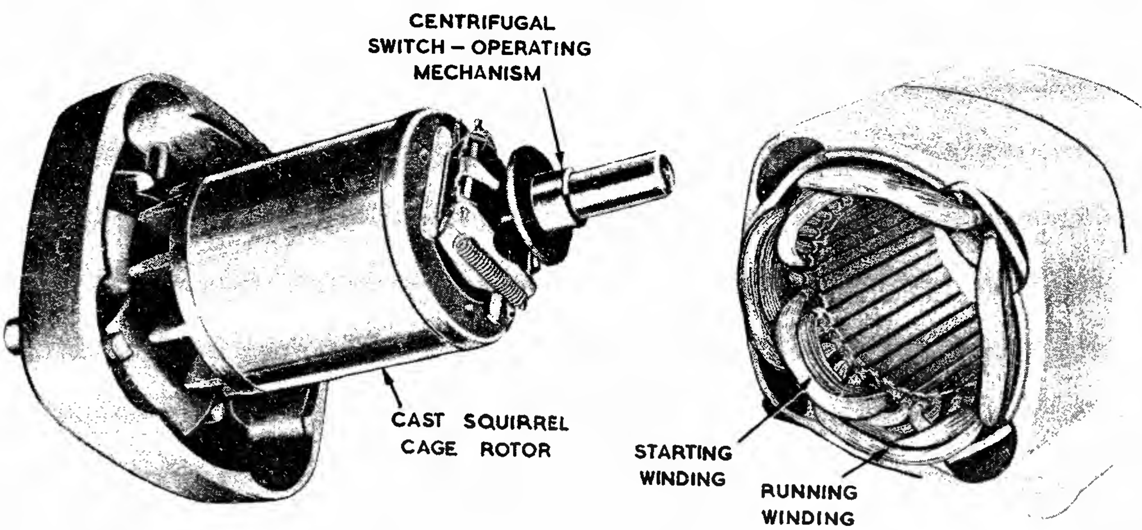


FIG. 25. MAJOR COMPONENTS, 4 POLE SPLIT-PHASE MOTOR.

Split-phase motors are mainly used where heavy starting loads are not encountered, as, for example in bench grinders, circular saws and air circulators. They cannot withstand a prolonged severe overload, as this causes the rotor speed to fall to a point where the centrifugal switch restores, and the motor runs with the starting winding energised continuously. Under these low speed conditions, excessive current flows in both windings and the heat generated is often sufficient to burn out the starting winding.

Capacitor Motors. A capacitor motor is a form of split-phase motor in which a capacitor is connected in series with the starting winding (Fig. 26).

The inclusion of the capacitor causes the current in the starting winding to lead the supply voltage. As the inductance of the running winding causes the current in this winding to lag the supply voltage, a full 90° phase difference can be obtained and a uniform "two-phase" rotating stator field is established.

Capacitor motors have a greater starting torque and require a smaller starting current than the normal split-phase motors. They can be started under load and are used in refrigerators, air compressors and similar applications.

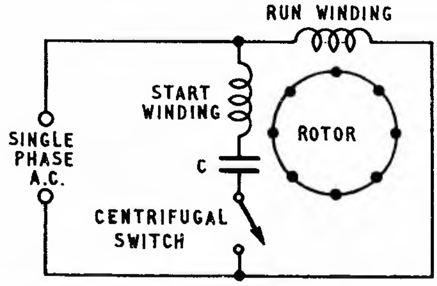


FIG. 26. CAPACITOR MOTOR.

In most machines, the starting winding is disconnected by a centrifugal switch when running speed is reached, and the rotor continues to turn under the influence of the reversing magnetic field of the running winding. Machines of this type are called "capacitor-start" induction motors. In some special machines, the starting winding is left in circuit, but the value of the series capacitor is reduced when the rotor attains normal speed. These "capacitor-start, capacitor-run" motors operate continuously as two-phase machines, and generally are more efficient, quieter running and have a greater overload capacity than other single-phase induction motors.

Shaded Pole Motors. This type of induction motor has only one insulated stator winding, and this is placed on projecting pole pieces which are similar to those used in D.C. machines. Starting torque is developed by the provision of a short-circuited "shading" winding (usually a single turn of copper strip) around one of the tips of each pole piece.

The effects of the shading winding is shown in Fig. 27. When the current in the main winding is increasing from zero, the magnetic effect of the induced current in the shading windings opposes the build-up of flux in the shaded pole tips, and tends to divert the main field to the unshaded pole tips (Fig. 27a). At the instant when the current is at its maximum value, the shading winding has no effect and the main field is evenly distributed over the pole pieces (Fig. 27b).

When the current is decreasing to zero, current again circulates in the shading winding and its effect is to prolong the decay of the main field. The main field is now concentrated in the shaded pole tips (Fig. 27c).

Although the stator flux does not actually rotate, its axis is tilted slightly before and after each reversal, and this is sufficient to set the rotor in motion.

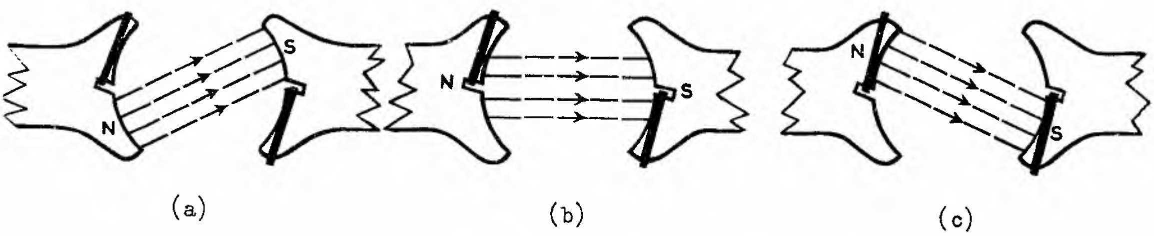


FIG. 27. EFFECT OF POLE SHADING.

Shaded pole motors have low starting torque, and because of the presence of the short-circuited shading windings, they are relatively inefficient. They are made in small sizes only and are used extensively in electric fans.

6.9 Three-Phase Induction Motors. Induction motors operated from the three-phase supply have three separate stator windings, arranged so that corresponding poles are spaced by 120°. As the windings are energised by currents which are 120° out of phase, a rotating magnetic field is established which sets the rotor in motion.

The rotor can be of the squirrel cage type, or, in some cases, a wound rotor is used. Both types produce good starting torque without auxiliary stator windings but, a wound rotor machine requires a lower starting current. The wound rotor type has the advantage that its speed is variable, but the simpler squirrel cage motors are more common.

In telecom three phase induction motors drive the large D.C. generators used for battery charging at telephone exchanges. Although a great number of these "motor generator" sets are still in use, they have been superseded by static rectifiers. A typical motor-generator installation is shown in Fig. 28.

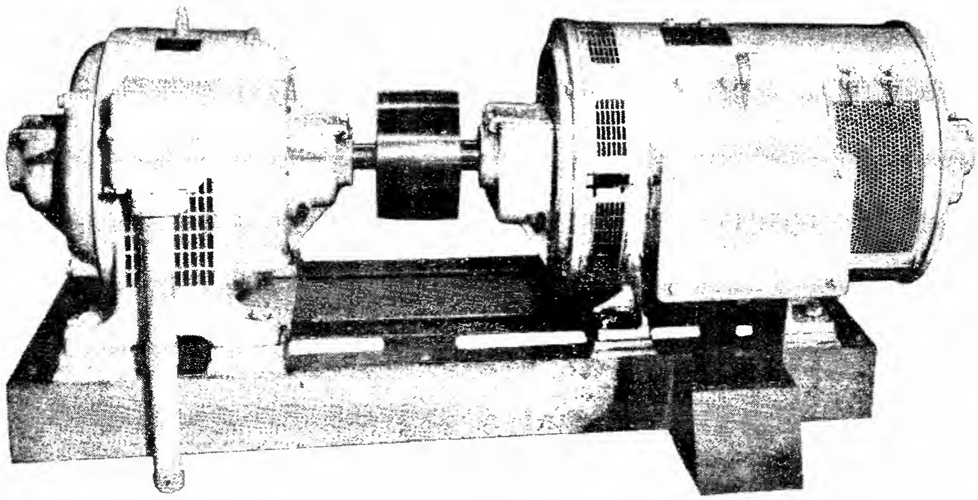


FIG. 28. MOTOR GENERATOR.

6.10 Synchronous Motors. As its name implies, a synchronous motor is one which rotates at the synchronous speed, that is, in step with the rotating magnetic field of the stat

Large synchronous motors have the same construction as alternators. The stator win are energised by A.C. to establish a rotating magnetic field; the rotor winding is excited from a D.C. source, creating a magnetic field similar to that of a permanent magnet. When the motor is run up to synchronous speed, the magnetic field of the ro "locks in" with the rotating field of the stator, and the rotor continues to rotate. following the stator flux in the same way as a compass needle follows a moving magne

Unless it is specially adapted, a synchronous motor is not self-starting, and a mechanical overload can cause the rotor to drop out of synchronism and come to a st still. Their principal feature is their constant speed, which, at all times is the same as the speed of the rotating stator flux, and therefore dependent on the freque of the supply voltage.

Small single phase A.C. motors with synchronous characteristics are used extensively where a known, constant speed is essential.

These small units often have specially shaped iron rotors which are permanent magne are magnetised by induction from the stator flux. Some types can be made self-star and they can be arranged to run at comparatively slow speeds.

Typical applications of these synchronous type motors are in electric clocks and in s types of tape recorders and gramophone turn-tables.

A.C. Commutator Motors. In a commutator motor, the rotor is similar to the armature of a D.C. machine in that it has an insulated winding and is fitted with a commutator.

There are two main types of commutator motors:-

(i) Series Motors. In a series motor, (Fig. 29), the armature (rotor) and field (stator) are connected in series as in a series D.C. motor. When A.C. is applied, the magnetic fields of both armature and field windings reverse each time the current reverses and a unidirectional torque is produced.

A.C. series motors have the same high speed and high starting torque characteristics as series D.C. machines. Small series motors with laminated fields are frequently designed to operate from either A.C. or D.C. supplies.

These machines are called "universal motors", and they are used in electric hand tools.

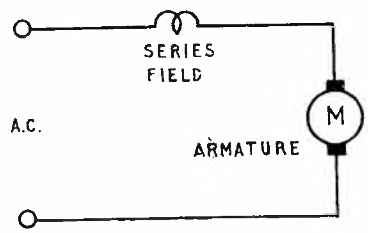


FIG. 29. SERIES MOTOR.

In telecom, A.C. operated universal motors fitted with centrifugal governors, are used extensively in telegraph machines.

(ii) Repulsion Motors. A repulsion motor is a form of induction motor in that the rotor flux is created by induced currents. However, it does not employ a rotating magnetic field to develop starting torque as this results from the force of repulsion exerted between like magnetic poles.

In a repulsion motor the A.C. supply is applied to the stator winding only; the rotor winding is short-circuited at the brushes (Fig. 30). When the stator winding is energised, a reversing magnetic field cuts across the short-circuited rotor winding and the induced current sets up a magnetic field about the rotor.

This rotor field has poles of the same polarity as the magnetic poles produced by the energised stator winding, and their mutual repulsion produces torque.

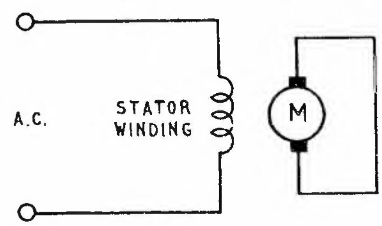


FIG. 30. REPULSION MOTOR.

In this type of motor, the angle at which the brushes are placed with respect to the axis of the stator poles is most important, as torque is produced in certain brush positions only.

The most common type of repulsion motor is the "repulsion start, induction run" variety. This type of machine starts as a repulsion motor, but when it has attained speed, a centrifugal mechanism lifts the brushes and applies a short circuit to all the commutator segments, after which the machine runs as a normal induction motor.

These machines are notable for their high starting torque, but they are superseded to some extent by capacitor motors.

6.12 Starting A.C. Motors. Normally, fractional horse-power single phase motors can be started without the use of special equipment. With large three-phase motors however. it is necessary to provide some form of starter which limits the current during the starting process.

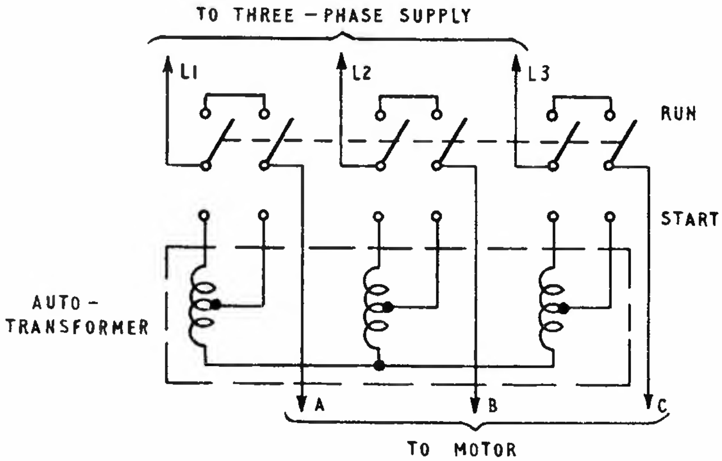
Starters for wound rotor motors connect resistance in series with the rotor winding during starting. As the motor gains speed, the value of the starting resistance is reduced and when the motor attains normal speed, the rotor winding is short-circuited.

Squirrel cage motors are generally provided with a starter which reduces the applied voltage during starting. There are two general types of starters for three-phase squirrel cage motors. -

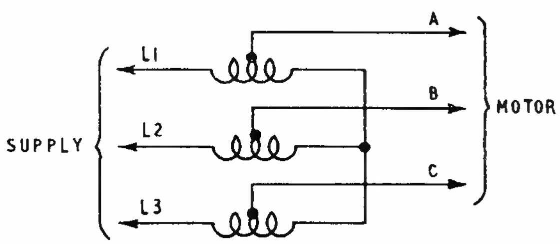
(i) Auto-transformer Starters in which an auto-transformer is used to reduce the value of the supply mains voltage during the starting process. The starter consists essentially of a multi-pole, two-position switch and a step-down, three-phase, auto-transformer connected as shown in Fig. 31a.

When the switch is operated to the "start" position, the auto-transformer is brought into circuit (Fig. 31b) and the voltage applied to the motor windings is about half the normal value of the supply mains. This reduced voltage is sufficient to start the motor and allow it to gain speed.

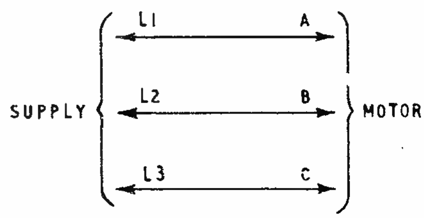
When the normal speed is attained, the starter is operated to the "run" position. This disconnects the auto-transformer, and the supply mains are applied direct to the motor (Fig. 31c.)



(a) Starter Circuit.



(b) Starting Condition.

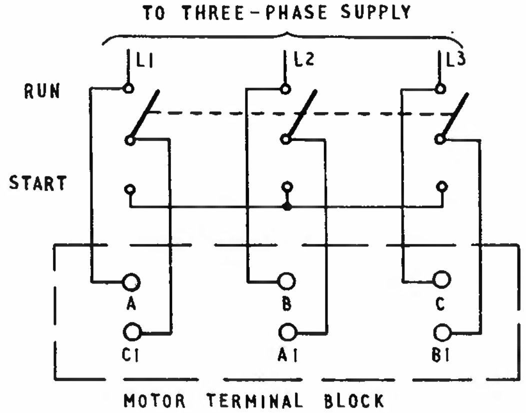


(c) Running Condition.

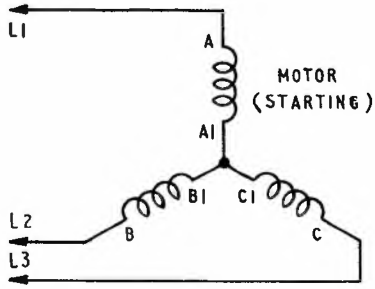
FIG. 31. ELEMENTS OF AUTO-TRANSFORMER STARTER.

(ii) Star-Delta Starters by means of which the motor windings are connected in "star" for starting and "delta" for running. The starter consists of a multi-pole, two-position switch to which each of the three motor windings is connected as shown in Fig. 32a.

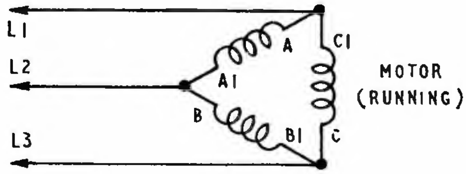
With the star connection (Fig. 32b) the voltage applied to each winding of the motor is $\frac{1}{1.732}$ of the line voltage (240 volts in a 415 volt system) and the starting current is reduced. With the delta connection (Fig. 32c) the full line voltage is applied to each winding and the motor is capable of turning its rated load.



(a) Starter Circuit.



(b) Starting Condition.



(c) Running Condition.

FIG. 32. ELEMENTS OF A STAR-DELTA STARTER.

With either method, the starter usually incorporates protective devices which operate in the event of an overload, and a mechanical latch ensures that the "start-run" sequence of operation is carried out.

7. TEST QUESTIONS.

1. Briefly explain the principle of operation of a D.C. generator.

2. How is sparkless commutation achieved in a D.C. generator?

3. Name the three basic types of self-excited D.C. generators.

4. Briefly explain the principle of operation of a D.C. motor.

5. Draw simple graphs which show how the speed of (i) a shunt motor, and (ii) a series motor, is affected by loading.

6. Alternators operate on the principle of electromagnetic induction as a result of relative motion between a conductor and a magnetic field. How is this achieved in:-

   (i) a rotating armature alternator?

   (ii) a rotating field alternator?

   (iii) an inductor alternator?

7. What is a dynamotor?

8. When a two pole, rotating field alternator is driven at 3000 r.p.m., the frequency of the output voltage is..........

9. With the aid of simple diagrams, describe the operation of a basic inductor alternator.

10. Show graphically the relationship between the voltages in a three-phase supply.

11. In the commercial electricity supply, the nominal voltages are:-

   (i) single-phase.................... volts.

   (ii) three-phase.................... volts.

12. Briefly describe the construction of a "squirrel cage" induction motor rotor.

13. What is meant by the term "slip" as applied to induction motors?

14. How is a rotating magnetic field established in:-

   (i) a split-phase induction motor,

   (ii) a capacitor type induction motor.

15. What is the principal application of three-phase induction motors in telecom?

16. What is the most important characteristic of a synchronous motor?

17. Briefly explain the principle of operation of a "star-delta" starter for a large three phase induction motor.

END OF PAPER.

DIODES AND RECTIFIERS

INTRODUCTION.

1.1 This and other papers in this book present important aspects of the subject known as Electronics, which is defined as the "science that deals with the behaviour of free electrons". "Free electrons" originally implied those which left the surface of a conductor as in the emission from an electron tube cathode. During the nineteen twenties however, "dry plate" or "metal" diodes began to take their place as rectifiers beside the electron tube diodes. These "solid state" materials are now classified as semiconductors.

Since about 1950, newly developed semiconductors such as crystal diodes, transistors and other semiconductor devices have been performing most of the functions previously served by electron tubes or valves.

Electronics as a study now includes semiconductor devices, and many electronic circuits use both electron tubes and semiconductors.

However, although the design, application, and use of semiconductor devices is increasing rapidly, electron tubes are at present more efficient in certain applications.

1.2 The subject of electronics deals with alternating voltages and currents over a wide frequency spectrum, and considerations of reactance, phase change, resonance etc., are fundamental to the understanding of most electronic circuits. This paper assumes that you have a thorough understanding of the basic theories involved; before proceeding any further you should revise "Basic Electronics" in Applied Electricity 1, and the A.C. papers in this book.

2. ELECTRON TUBE DIODES.

2.1 General. The principles of electron emission and diode construction are explained in the paper "Basic Electronics" in Applied Electricity 1. Cathodes may be directly heated and this arrangement is generally called the "filament" (Fig. 1a). Indirectly heated cathodes have a separate insulated "heater" (Fig. 1b).

(a) Directly Heated. (b) Indirectly Heated.

FIG. 1. DIODE SYMBOLS.

All types of electron tubes are subdivided into two general classes -

(i) High-vacuum tubes;

(ii) Gas filled tubes or gas tubes.

High-vacuum tubes are those from which as much air as possible has been removed. With modern techniques of manufacture this results in internal gas pressure of no more than one hundred-millionth ($\frac{1}{10^8}$) of atmospheric pressure. Even so, many millions of gas atoms remain but they occupy a negligible part of the space and nearly all electrons in the operating current stream pass between electrodes unimpeded. For most practical purposes the effects of residual gas are neglected.

Gas-filled tubes are first highly evacuated and some inert gas is then introduced at low pressure to modify the characteristics in some desired manner. Gases commonly used are xenon, argon, neon, mercury vapour and sometimes helium. Gas tubes are classed as vacuum tubes however because the gas pressure is generally less than $\frac{1}{20,000}$ of atmospheric pressure.

High-vacuum tubes are sometimes called "hard" and gas tubes are commonly called "soft". Hard tubes sometimes become faulty by developing a leak and turning soft or "gassy".

2.2 Factors Affecting Anode Current. We have seen that when two plates or electrodes are at different potentials with respect to each other an electric field is established between them (see the paper "Capacitance" in A.E.1). The behaviour of electrons (negative charges) in vacuum tubes can be explained with reference to the electrostatic fields produced between the various electrodes.

We have also learned that the anode current in high-vacuum electron tube diodes may be controlled by varying either -

(i) cathode temperature, or

(ii) anode voltage with respect to cathode.

In practice, the cathode temperature is kept constant by operating the filament or heater at the voltage specified by the makers. At this temperature the specially treated surface of the cathode is capable of emitting several times the required maximum anode current but the emission is automatically limited to meet the average demand of the anode current. This limitation is brought about by the "cloud" of electrons or space charge which forms around the cathode as represented in Fig. 2a. As it consists of free electrons the space charge exhibits a negative electrostatic potential which exerts a strong repelling force on further electrons being emitted from the cathode surface. Also, the cathode has an electron deficiency which leaves it electrostatically positive and this makes it more difficult for electrons to escape from its surface.

When no voltage is applied to the anode (Fig. 2a) the cathode therefore reaches a state of equilibrium where as many electrons return to the cathode as are emitted.

Space Charge Limitation. When a small voltage is applied to make the anode positive with respect to cathode only a few of the electrons farthest from the cathode are attracted across to the anode and constitute the anode current (Fig. 2b). The emission is still limited by the space charge as a small positive potential or charge between anode and cathode can only partly overcome the strong negative potential between the space charge and cathode.

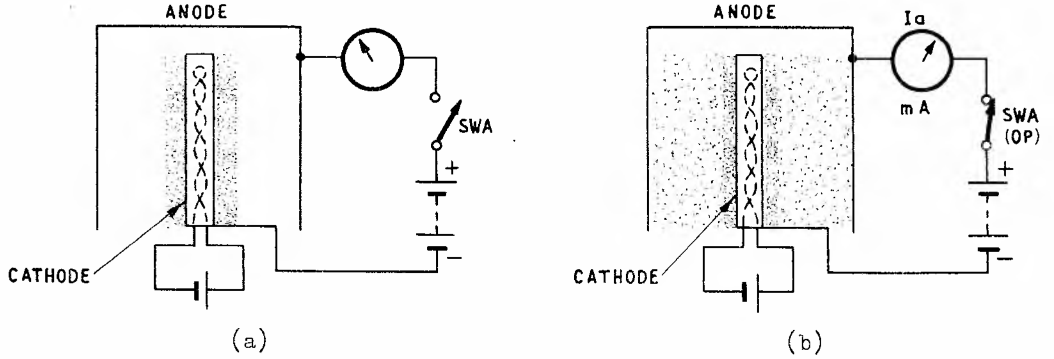


FIG. 2.

When the anode voltage is increased, anode current increases progressively as the space charge is further cancelled by the greater positive charge on the anode.

Fig. 3a shows graphically the relationship between anode voltage (E_a) and anode current (I_a) for a typical diode. Note that the anode current rises progressively with an increase of anode voltage until a point is reached where further increases in E_a have little effect on I_a. Up to this point (marked P) anode current depends on the extent the positive anode charge overcomes the negative space charge and from points O to P anode current is said to be "space charge limited".

Saturation. Above point P, anode voltage is high enough to completely cancel the negative space charge and electrons are attracted to the anode at the maximum rate of emission (for that particular cathode temperature). This condition is called "voltage saturation" or simply "saturation" and above point P anode current is said to be "saturation limited". Actually, most diodes give a slight increase in I_a as E_a is increased beyond saturation point. This is because increasing positive anode charge stimulates emission from pockets in the cathode which are not effective emitting surfaces when space charge is present.

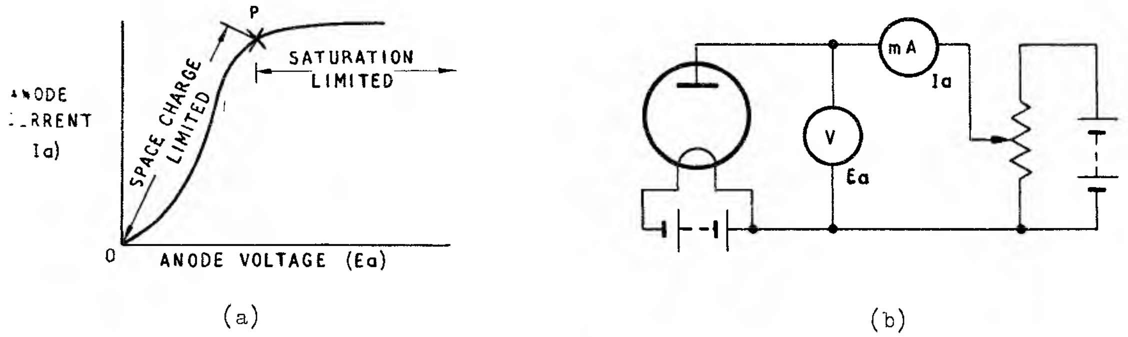


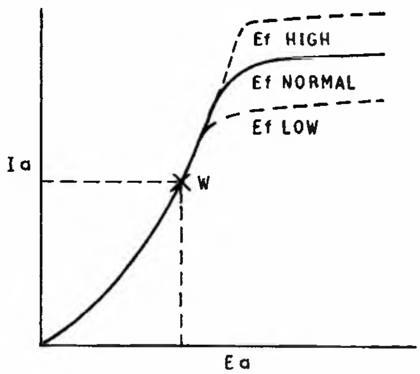
FIG. 3. DIODE CHARACTERISTICS.

Fig. 3a is called a diode characteristic curve or simply diode characteristic. Triodes and other multi-element thermionic tubes all have cathode and anode as emitter and collector of electrons and their relationship is the same as described here for diodes.

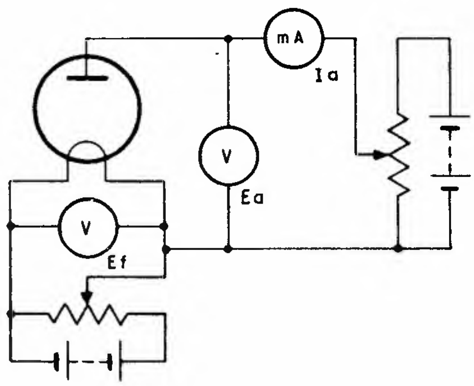
2.3 Operating Range. Tubes of all types are normally operated well below saturation point with maximum I_a in the relative vicinity of point W on Fig. 4a. The filament or heater voltage specified by the manufacturer is designed to provide ample emission (and space charge) combined with long service life. One dotted curve shows how saturation occurs at lower I_a and E_a values when cathode temperature and emission are reduced by lowering filament voltage E_f. A falling off in emission during the working life of a tube results from gradual deterioration of the cathode surface so that even with normal E_f the point at which saturation would occur is gradually lowered and gives the same effect as lowered cathode temperature in a new tube. As Fig. 4a shows a considerable drop can occur before performance is affected.

Operating tubes well below saturation point prolongs their working life in another important way. As explained in para. 2.1 the residual gas atoms remaining in high vacuum tubes are too few to effect operation as practically all electrons pass to the anode unimpeded. A few electrons colliding with gas atoms knock off an electron leaving positive gas ions. This is "ionization by collision". The positive ions are comparatively heavy and if there were no space charge surrounding the cathode they would strike the cathode with enough force to damage its emissive coating and greatly reduce its life. The space charge provides a free electron to neutralise the ion before it strikes the cathode.

The upper dotted curve in Fig. 4a shows that a higher value of E_f raises the saturation point. Increased cathode activity would accelerate the surface deterioration and increase the risk of the filament or heater failing prematurely by "burning out" or fusing. We see therefore that heaters and filaments should be operated at the rated voltages.



(a)



(b)

FIG. 4.

2.4 Electrode voltages of electron tubes are always given with respect to the cathode unless otherwise stated. For example, an anode voltage E_a of +200V means that the anode is at a positive potential of 200V with respect to the cathode. The anode supply voltage is A.C., for diode rectifiers; at other times a separate D.C. supply is used to keep the anode positive with respect to cathode and this supply is designated by various symbols in different text books. Anode supplies used in telecom range from about 50V in telephone exchanges up to several thousand volts in radio transmitters. The terms E_B or HT (high tension) will be used in this course. (It is worth noting however that many makers use the term E_{bb} in their published data.) Throughout the study of tube theory it is important not to confuse the anode voltage E_a with the anode supply voltage or HT. They may be equal in a few test circuits and under certain conditions in others but in most cases E_a varies and is less than the HT which is kept constant.

2.5 Gas tubes are of two main types -

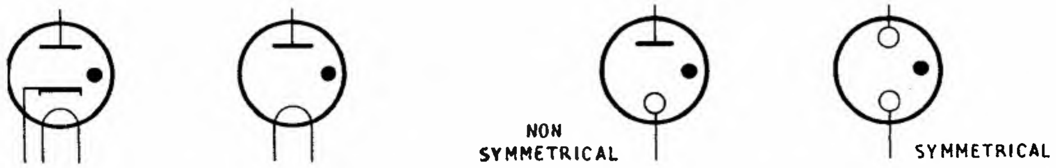
(i) Hot cathode tubes.

(ii) Cold cathode tubes.

With the hot cathode tubes the anode current is derived almost wholly from the electron emission of the heated cathode. The presence of the gas greatly lowers the internal resistance of the cathode to anode path and wider electrode spacing may be used to permit high voltage operation.

Cold cathode tubes conduct by means of a phenomena known as "gas discharge" which was demonstrated many years before the discovery of thermionic emission and the diode.

Fig. 5a shows the symbols for hot cathode gas diodes and Fig. 5b two commonly used symbols for cold cathode diodes. Cold cathode tubes may have symmetrical electrodes to conduct in either direction or non-symmetrical electrodes corresponding to cathode and anode and conduct much better in one direction than the other. The black dot indicates a gas filled tube.



(a) Hot Cathode. (b) Cold Cathode.

FIG. 5. GAS DIODE SYMBOLS.

2.6 Hot Cathode Gas Diodes. Some of the electrons passing to the anode collide with gas atoms and cause ionization by releasing an electron from the gas atoms to join those flowing to the anode; the positive ions return to the cathode. As the ions are much heavier and move more slowly than the electrons, large numbers collect in the region of the electron cloud around the cathode, and by completely neutralising the negative space charge they remove its limiting effect on the anode current. When the external circuit resistance permits, the current may rise to the full emission of the cathode without appreciable increase in the anode voltage; that is, the internal resistance decreases as current rises. Fig. 6 shows a typical gas diode characteristic compared to portion of a high vacuum diode characteristic.

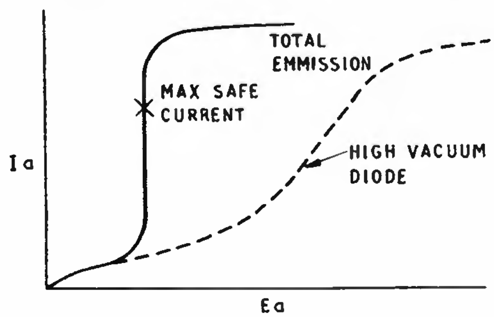


FIG. 6. GAS DIODE CHARACTERISTIC.

Mercury Vapour rectifier diodes operate on this principle and are used where high voltages and output currents are required as in radio transmitter power supplies. The mercury is introduced as a liquid during manufacture and when the air is evacuated from the bulb some of it evaporates. At the normal working temperature, the residual pool of liquid mercury remaining within the bulb evaporates further to achieve the optimum gas pressure.

The quantity of mercury vapour which ionises contributes only a very small proportion of the anode current but the effect of the positive ions cancelling the space charge keeps the internal voltage drop to about 15V irrespective of the anode current. Mercury vapour rectifiers are made having current capacities of up to several hundred amperes whereas the high internal voltage drop (and therefore heat dissipation) of high-vacuum rectifiers limits their practical output to about 1A maximum and in most cases a good deal less than this.

The low voltage between cathode and anode maintained in the operation of gas diodes ensures that the ions do not strike the cathode with sufficient velocity to damage its emissive coating. They must not be overloaded beyond their maximum current, however, as the sharp rise in voltage accompanying saturation will impart greater energy to the comparatively heavy ions and they will rapidly damage the cathode. A feature which makes mercury vapour tubes more critical to use than high vacuum diodes and some other gas diodes, is the need to fully heat the cathode before applying anode potential. Otherwise the high voltage across the tube in the absence of full emission will give the initially formed ions enough energy to damage the cathode (high ionising potentials can knock two electrons from gas atoms to give twice the normal charge). Section 4 contains some further information on gas diode applications.

2.7 Cold Cathode Gas Diodes. Gas at atmospheric pressure is commonly regarded as an insulator. However, in any gas including air, there are always a few ions and free electrons present owing to the bombardment by solar radiation in the form of ultra violet and cosmic rays. In this form of ionization the few free electrons do not have far to travel before colliding with other gas atoms and unless the charge is very high they do not attain sufficient velocity to ionize additional atoms. Raising the voltage and/or reducing the spacing between electrodes will eventually raise the charge to a point where these electrons have enough energy to ionize other atoms and the gap conducts a visible spark followed by an arc when the circuit can maintain the current.

When two cold electrodes are surrounded by gas at a low pressure the few free electrons and ions can move freely and some current will flow with quite low potentials. Fig. 7 shows the characteristic curve of a typical cold cathode diode together with the test circuit used in plotting the curve.

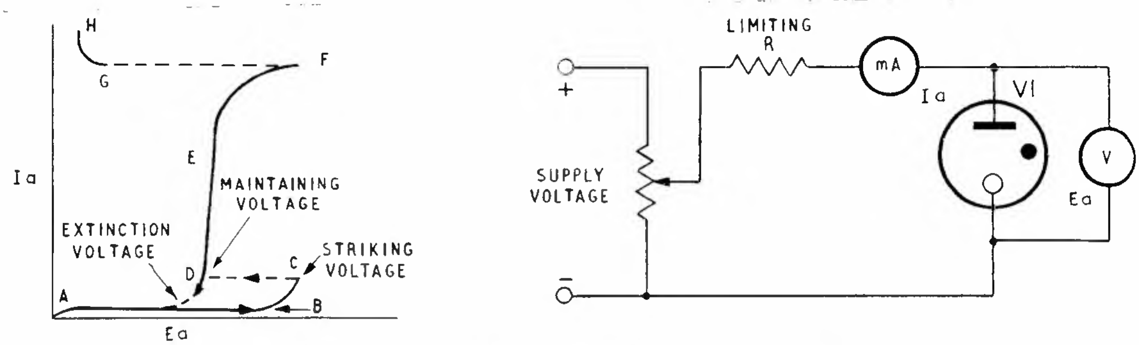


FIG. 7. COLD CATHODE DIODE CHARACTERISTIC.

Glow Discharge. As the supply voltage is increased, the voltage across the tube (E_a) increases (A to B on the characteristic) and a very small current (about 1μA) flows. Although ionization increases with voltage, the ions are neutralised quickly and the current remains almost constant over this region.

At a potential near B, the velocity of the charged particles is sufficient to start greater ionization of the gas and current rises sharply to point C. At this point (known as the "striking voltage") the increased ionization decreases the internal resistance of the tube and the voltage across the tube decreases abruptly (C to D). The current through the tube is limited by the external resistance (R_1).

When the supply voltage is increased further, the current increases and causes a further decrease in the resistance of the tube. The voltage across the tube therefore remains almost constant.

Arc Discharge. If the voltage is further increased, ionization becomes more intense. The positive ions bombard the cathode and heat it so that it emits thermionically and at point F this is enough to promote an "arc discharge" similar to the conduction in a hot cathode gas diode. The internal resistance and voltage across the tube drop sharply once more and a low voltage will maintain a high current in the region GH. This is a damaging current, unless the tube is designed to operate in this region. A few rectifier tubes use cold cathode arc discharge and are sometimes referred to as "ionically heated".

Applications. Cold cathode tubes operating in the glow discharge region DE (Fig. 7) have several uses - voltage stabilisers or regulators, intermittent light sources for stroboscopes, surge protectors or voltage limiters, relaxation oscillators and switching devices. Their dull glow and low energy requirements make them ideal pilot and warning lights. Many miniature types are made especially for this purpose and are called glow tubes.

Cold cathode tubes have three important potentials or voltages as marked on Fig. 7 and these vary with design and intended use. Point C is the striking or firing voltage necessary to start the glow discharge. The lower voltage at D is necessary to maintain it and is the maintaining voltage. Below this voltage, current drops rapidly and the glow discharge stops; this is the extinction voltage. Maintaining voltages are generally in the region of about 60V to 150V.

Gas discharge in both hot and cold cathode tubes may be controlled by additional electrodes but only up to the striking point after which they behave like diodes rather than triodes. Triode gas tubes are described in the paper "Electron Tubes".

Photo Tubes, photodiodes or photoelectric "cells" are in three general classes :-

(i) Photoemissive tubes.
(ii) Photoconductive cells.
(iii) Photovoltaic cells.

In photoemissive tubes light falling on the cathode surface causes it to emit electrons.

In photoconductive cells the resistance varies with the intensity of light.

Photovoltaic cells generate an e.m.f. on being exposed to light.

Photoemissive tubes are constructed as shown in Fig. 8. The relatively large cathode area is coated with a photosensitive material such as caesium and caesium oxide. The anode is a thin rod or wire which is adequate for the very small emitted current, and being small in diameter does not shade the cathode from the light source.

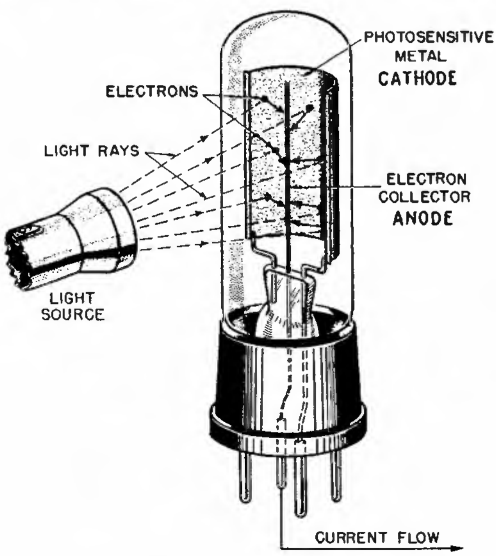


FIG. 8. PHOTOEMISSIVE TUBE - TYPICAL CONSTRUCTION.

The region D to E is called the "glow discharge" and is the normal operating region of most cold cathode tubes. The tube glows fairly dimly and the colour of the light depends on the gas used.

Photoemissive tubes may be either high-vacuum or gas filled. Cathode emission in either type rarely exceeds 10µA with a maximum anode voltage of 90V.

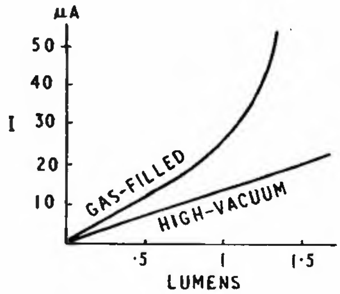


FIG. 9.

Ionization in the gas types increases anode current and thus increases overall sensitivity. The maximum anode current may be up to about 10 times that due to the photoemission alone. Fig. 9 shows characteristics for typical phototubes.

Gas filled tubes do not respond as well to rapid light variations above about 5kc/s, and as the curve shows, they are not as linear in their response as the high vacuum tubes.

"Dark current" is the small current which flows when the cathode is not illuminated; that is, there is always a residual anode current imposed on that due to light signal. With high-vacuum tubes this is extremely small and of the order of 0.001µA but with gas filled tubes may be up to 0.1µA. This may seem negligible but represents a considerable proportion of a typical maximum output of 5-10µA.

A typical photoelectric (P.E.) cell circuit is shown in Fig. 10. To make use of the minute current changes to operate a voltage operated device such as a triode, a load resistance is used (R_L), and this is usually a very high resistance of the order of 10MΩ or higher.

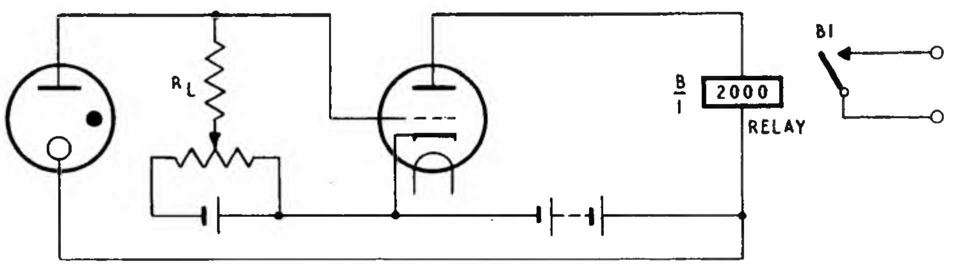
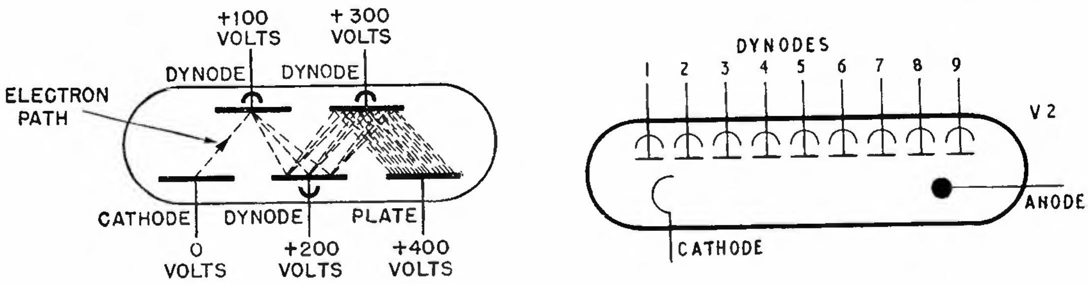


FIG. 10. P.E. CELL, TYPICAL CIRCUIT.

Multiplier photoemissive tubes. When the light levels are very low, phototubes incorporating an electron multiplier give better performance than an ordinary photodiode plus amplifier. Figs. 11a and b show the principle of operation and symbol of a multiplier phototube. Before reaching the anode the emitted current from the cathode is attracted to a series of additional electrodes called dynodes which have progressively higher voltages until the anode is reached. The dynodes have a surface coating to facilitate secondary emission; that is, each primary electron from the cathode or previous dynode releases several secondary electrons which are attracted to the next more positive dynode and so on. In this way the weak current due to the light signal may be increased up to several million times with much less noise and distortion than by using an external amplifier.

High voltage, low current power supply is needed, as voltage between successive dynodes is from 100 to 400 volts and 9 or more dynodes are commonly used.

One Telecom application of multiplier phototubes is facsimile picture transmission via long line or radio.



(a) Principle of operation.

(b) Symbol.

FIG. 11. TYPICAL MULTIPLIER PHOTOTUBE.

Photoconductive Cells generally consist of a photosensitive resistance element of cadmium sulphide mounted in a vacuum tube. When unilluminated the resistance is very high but becomes lower with increasing levels of illumination. With a polarising voltage of 100V or more, some photoconductive cells have sufficient sensitivity and output to operate a relay directly without an amplifier. The evacuated envelope is not essential for the operation, but ensures stable characteristics by preventing contamination of the photosensitive material by the air and water vapour.

Fig. 12 shows the symbol for a photoconductive cell in a typical application.

Semiconductor "junction", photoconductive devices are a more recent development in this field and their principles are described in the paper "Transistors and Other Semiconductor Devices".

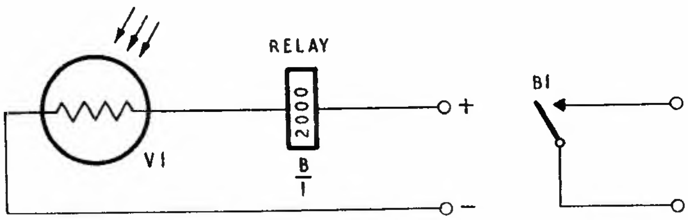


FIG. 12. PHOTOCONDUCTIVE CELL - TYPICAL APPLICATION.

2 Photovoltaic Cells are the basis of most photographic exposure meters and other forms of light intensity meters. They have the advantage of small size and relatively high output which requires no external energy supply as in the case of all other photoelectric cells. Sensitive meters and even relays may be operated directly without the need of an amplifier. Common materials for the electrodes are iron and iron-selenide; selenium is also used.

3 The Solar Converter or solar battery is a recently developed semiconductor "junction" device which uses solar energy directly to produce useful amounts of electric energy.

The basic unit of a solar converter is a silicon junction diode "cell" having a flat surface of about one square inch and with the upper electrode thin enough for light to penetrate to the junction. Cells are connected together to produce a battery of the desired rating. In operation the cells are both photoconductive and photovoltaic showing reduced resistance and increased voltage with increase in illumination. A typical output is about 20-30 milliwatts per cell.

The output and possibilities of solar converters will undoubtedly increase with development but their use for telecom is being tested overseas for such applications as power supply for remote line repeaters (amplifiers) carrier systems and small R.A.Xs. Continuity of service is achieved by having the solar converter charge a battery during the hours of sunlight.

3. SEMICONDUCTOR DIODES.

3.1 General. In 1925 in Great Britain a static rectifier was introduced which required n: heated cathode or evacuated envelope. It consisted essentially of stacks of copper discs, each disc having a coating of cuprous oxide on one side. Such an arrangement is known as a "metal" rectifier or "dry plate" rectifier or simply a copper oxide rectifier. A similar metal rectifier was introduced by Germany in the early ninetee thirties which used steel discs treated with selenium. Both types developed rapidly and soon superseded tube rectifiers in most high current/low voltage and high voltage low current applications. (High voltage/high current requirements of traction syste (trams and trains) are met by mercury arc or ignitron rectifiers.)

Metal rectifiers possess high conductivity in one direction and low conductivity in the other, a phenomena classified as assymetrical or unilateral conductivity. The exact reason for this has never been fully explained.

Much research into semiconductors led in 1950 to the American invention of the germanium junction diode and junction transistor.

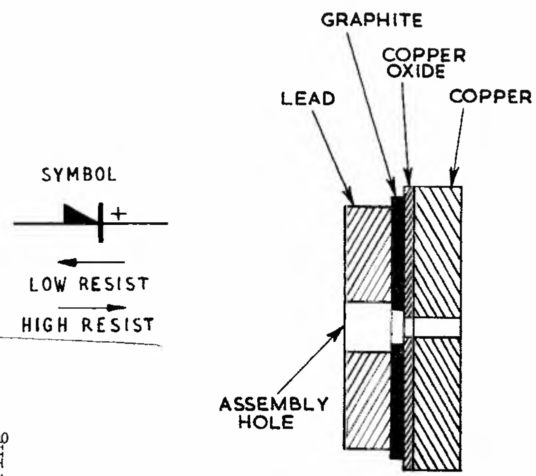
Metal rectifiers are thought to function in a somewhat similar fashion to germanium diodes and silicon diodes and are now classified together with these more recent developments as semiconductor diodes. Substances having conductivity (or resistivity between that of metals and insulators are called semiconductors.

The construction and operation of germanium and silicon "crystal" diodes is describe in the paper "Transistors and Other Semiconductor Devices". Although the term "diode" was defined originally as "a two-element vacuum tube......" it now includes, through common usage, all devices possessing unilateral conductivity.

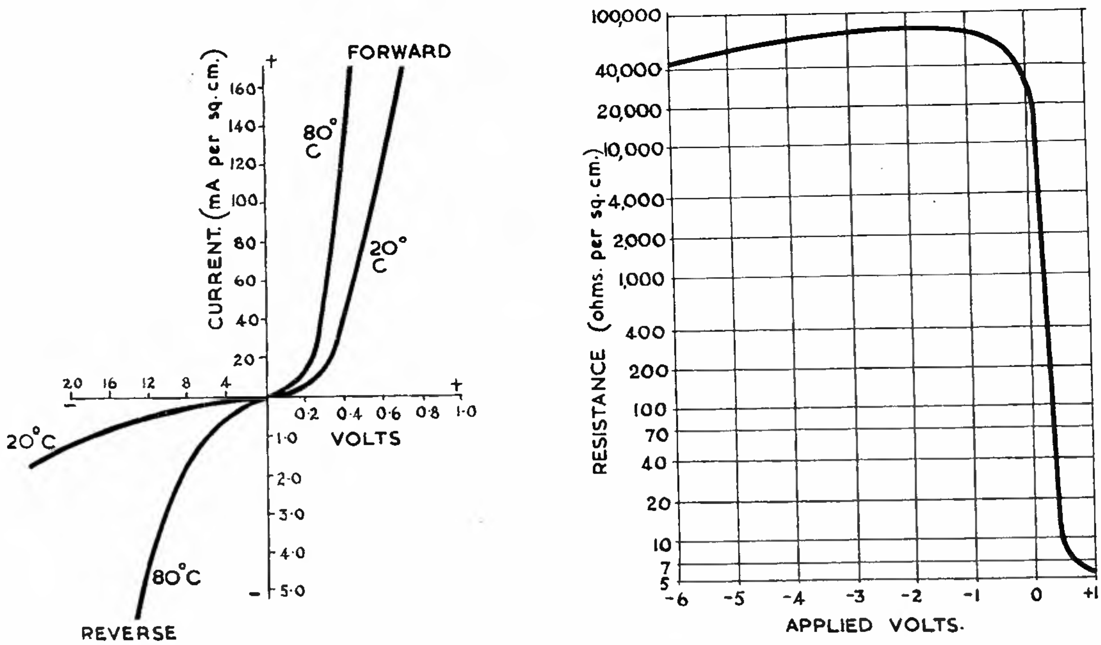
3.2 Copper Oxide Rectifiers. Fig. 13 shows the principle of construction of a copper oxide rectifier element. Each element consists of a disc of pure copper on one side of which a thin film of cuprous oxide is formed by a process of heat treatment. Current flows readily from copper to oxide but meets a high resistance to flow from oxide to copper (current being regarded as electron movement from the negative to the positive pole of the supply).

To make good electrical contact with the somewhat irregular surface of the oxide it is generally sprayed with graphite, and a lead disc pressed against its surface is soft enough to make intimate contact. In the figure the various layers are exaggerated in thickness for clarity, especially the oxide and graphite. Individual elements are assembled in series under high pressure by clamping on an insulated bolt.

The number of series elements depends on the voltage rating; this is dealt with in para. 3.4. Fig. 14a shows characteristic curves for a copper oxide rectifier tested at two temperatures. In Fig. 14b the 20°C curve is plotted as voltage versus resistance. Notice the very high resistance in the non-conducting or reverse direction. In the conducting or forward direction the current is low (and resistance high) until the applied voltage reaches about 0.25V. With further increase in voltage, but before 1V is reached, the resistance drops rapidly to a few ohms.



EMENT OF COPPER OXIDE RECTIFIER.



(a) Voltage/Current Graph.

(b) Variation of Rectifier Resistance with Applied Voltage.

FIG. 14. GRAPHS FOR COPPER OXIDE RECTIFIER.

Selenium Rectifiers. Each element consists of a steel disc on which is sprayed a thin layer of very pure selenium. A tin or lead soft alloy sprayed on the selenium provides the second or counter electrode. Fig. 15 shows the construction but with thicknesses exaggerated for clarity. The conducting direction is from selenium to steel (electron current). The low forward resistance and high reverse resistance occurs in metal rectifiers at the junction of the two electrodes - oxide and copper or selenium and steel.

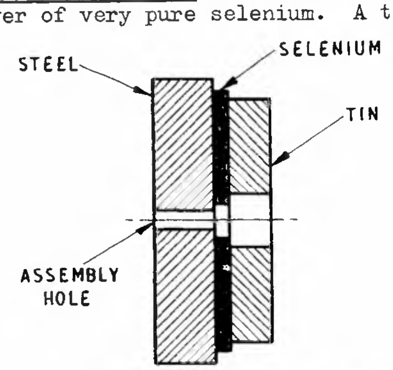


FIG. 15. SELENIUM RECTIFIER ELEMENT.

The voltage/current characteristic of selenium rectifiers is similar to that of the copper oxide type. Higher temperatures lower both the forward and reverse resistance as with copper oxide, and forward resistance remains high below about 0.5V.

Selenium rectifiers are "formed" during manufacture by the passage of current in the forward direction. If allowed to stand idle for long periods or used only in the reverse direction for D.C. blocking they may become unformed and lose their rectifying property. Copper oxide is not affected in this way.

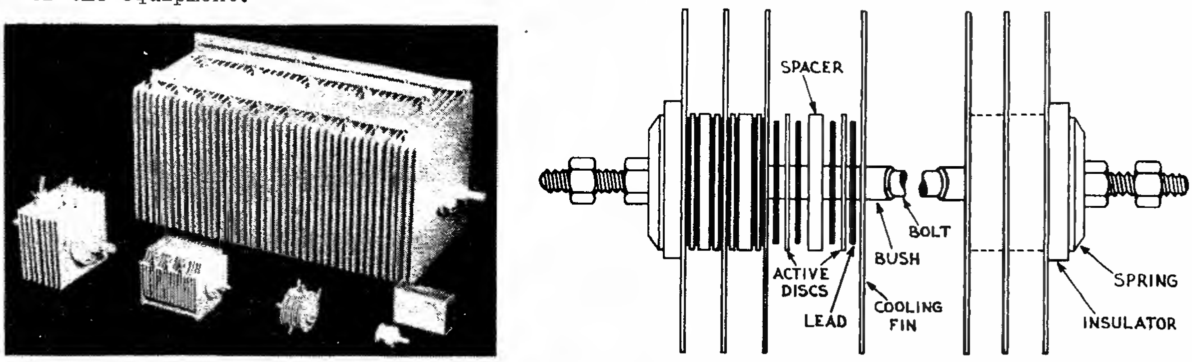
.4 Voltage Rating of Metal Rectifiers. Single elements can only be used at low voltages, and discs are assembled in series to safely withstand higher reverse voltages. The reverse or inverse voltage is specified in the rating because in the non-conducting direction the full voltage appears across the rectifier. In the conducting direction the voltage drop in the rectifier is small, the greater part of it being dropped across the load.

The voltage ratings of both copper oxide and selenium rectifiers have been steadily improved over the years, copper oxide increasing from about 6V to about 20V per element and selenium from about 12V to 30V or even higher in some cases. By variations in the manufacturing processes selenium discs are made with several voltage ratings.

3.5 Current Rating of Metal Rectifiers. The current rating depends on the rectifying area of a disc and the method of cooling. Temperature rise during operation must be kept below a specified maximum or the elements may become permanently damaged by developing lower reverse resistance. To minimise the generation of heat within the rectifier the forward resistance should be as low as possible and reverse resistance as high as possible. Maximum temperatures are about 55°C for copper oxide and about 75°C for selenium.

Power rectifiers are assembled with cooling fins between the discs and spacing washers to allow airspace between fins (Fig. 16). In some applications, ratings are further increased by the use of a forced draft of air or oil bath cooling. Free air flow through vertically-mounted fins is the most general form of cooling in A.P.O. telecom power supplies.

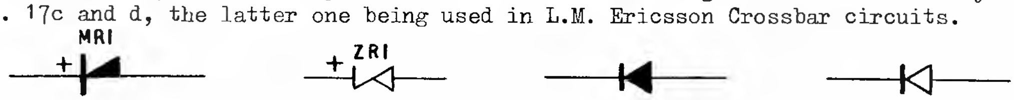
In a rectifier unit or "stack" the number of elements in series determine the inverse voltage rating. In power supply rectifiers complete units are interconnected in series to achieve still higher voltage ratings and in parallel to increase the current capacity of the equipment.



(a) Photo. (b) Typical Assembly.

FIG. 16. ASSEMBLY OF POWER RECTIFIERS.

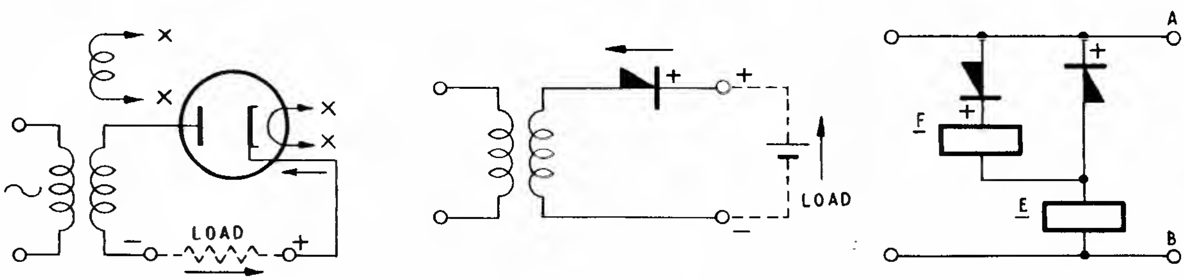
3.6 Diode Symbol. Figs. 17a and b show the A.P.O. symbols for semiconductor diodes (general), and zener diodes, respectively. Manufacturers circuit diagrams often use the symbols in Figs. 17c and d, the latter one being used in L.M. Ericsson Crossbar circuits.



(a) General (A.P.O.) (b) Zener (A.P.O.) (c) (d)

FIG. 17. DIODE SYMBOLS.

The positive end of a unit is generally marked; a red terminal or red end being one common method of identification. The marked end corresponds to the cathode of an electron tube and is called the positive end because when used as a rectifier of A.C. the cathode is the positive output terminal for connection to the D.C. load. Fig. 18 compares an electron tube and semiconductor diode when each is connected as a half-wave rectifier. It is important to note however, that when the unit is conducting, the end marked positive is actually negative with respect to the other end.



(a) (b) (c)

FIG. 18.

In the case of the tube it can be seen, that for connection to the load the + output terminal is the cathode even though the cathode is negative with respect to the anode. Similarly the arrow head side of the diode symbol in Fig. 18b is positive (anodic) with respect to the stroke side of the symbol which is therefore equivalent to the cathode. This side is marked for connection to the positive pole of the load. The load may be either resistive as in Fig. 18a or a battery undergoing charge as in Fig. 18b. The arrows indicate electron flow, not conventional current.

Rectification of A.C. is only one of a great many applications of diodes. In other applications it must be remembered that the diode conducts when the terminal marked positive is negative to the other terminal. For example, Fig. 18c shows a circuit having two relays bridged across a line, the polarity of which can be reversed. Relay F operates only when line A is positive to line B; relay E remains operated with either line polarity.

Small diodes (not intended for use as power rectifiers) are to be found in numerous telecom circuits. Copper oxide units were first in this field for such tasks as polarising ordinary relays (Fig. 18c shows a typical example) and in Long Line Equipment modulators. More compact selenium units were a later development and more recently still germanium diodes have appeared.

The term "signal diodes" is sometimes applied to these small diodes used in audio frequency, radio frequency and switching circuits to distinguish them from "power diodes" which handle appreciable power. Both categories are also applied at times to electron tube diodes.

The copper oxide and selenium diodes used in many Telephony circuits use discs of $\frac{3}{4}$" diameter arranged in units of from 2 to 12 discs. Assembly is on spindles as in Fig. 16 but without cooling fins.

In another form of construction the discs are contained in insulating tubes with metal end caps serving as the terminals.

Selenium diodes have not completely replaced copper oxide diodes because of the tendency of selenium units to become unformed in the absence of polarising voltage.

Coding. In circuit diagrams (mainly A.P.O. and B.P.O.) these diodes are coded as follows:- 1/12A, 1/6A, 2/6A, 2/2A etc. The prefix 1 indicates a single rectifier unit, the figure after the bar indicates the number of copper oxide discs, (12 to withstand 50 to 60V and 6 or 2 to withstand lower inverse voltages) and the A indicates the $\frac{3}{4}$" diam. disc. Fig. 19 shows typical coding as used in circuit diagrams.

The prefix 2 indicates two separate units on the same spindle with a common terminal. The common terminal may be the positive electrode of one unit and the negative of the other. Alternatively the intermediate terminal (or terminals for more than 2 units in one) may connect to either two positive or two negative electrodes.

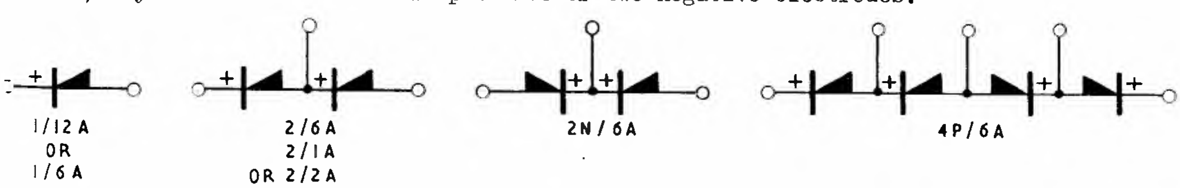


FIG. 19. TYPICAL CODING OF DIODES IN TELEPHONY.

When the two internal electrodes are negative the two ends are therefore positive and the prefix 2P/ is used. Similarly 2N/ indicates that the two ends are the negative electrodes.

Selenium discs are used in similar assemblies to serve the same purposes but because of their higher inverse voltage rating equivalent units contain half as many discs. The coding however has become firmly associated with the voltage rating rather than the number of discs. Therefore a selenium unit used for the same purpose as say a 1/12A copper oxide rectifier is still designated 1/12A even though it has only 6 size A discs.

Different makers use their own forms of coding. For example L.M. Ericsson Crossbar equipment uses many copper oxide and selenium diodes, but their coding differs and the discs are generally of a smaller diameter. Crossbar equipment also incorporates crystal diodes.

4. RECTIFIERS.

4.1 General. In providing D.C. power from A.C. mains, selenium and silicon rectifiers have almost superseded all the earlier conversion methods. These have proved to be both more reliable and efficient than earlier methods except where high currents at high voltage are involved - for example, high power broadcasting, telecasting and traction systems.

In 1950, motor generator sets and copper oxide rectifier sets were commonly used in telecom equipment but there have been no new installations of either for some years.

The term "rectifier set" is used to describe a complete power supply unit including rectifier elements plus any associated equipment within the unit such as mains transformer, filtering apparatus, switchgear and manual or automatic output control equipment. "Rectifier equipment" also implies the complete rectifier set. Very large sets may have two adjacent cubicles with separate framework and front panelling. Fig. 20 shows typical rectifier sets as used in many branch telephone exchanges. Rectifier sets are commonly referred to as rectifiers.

Rectifier sets are available ranging from a few watts up to about 60kW, this limit being imposed only by the need to maintain a convenient size. Single sets may be operated in parallel, this being an economical method of operation where the load varies throughout the day. One of the largest units used by the A.P.O. has a maximum output of 800A at about 50V. Much larger units are used overseas for Telecom power supplies.

Descriptions of rectifier sets are given in the paper "Power Plant Components" in Telephony 5.

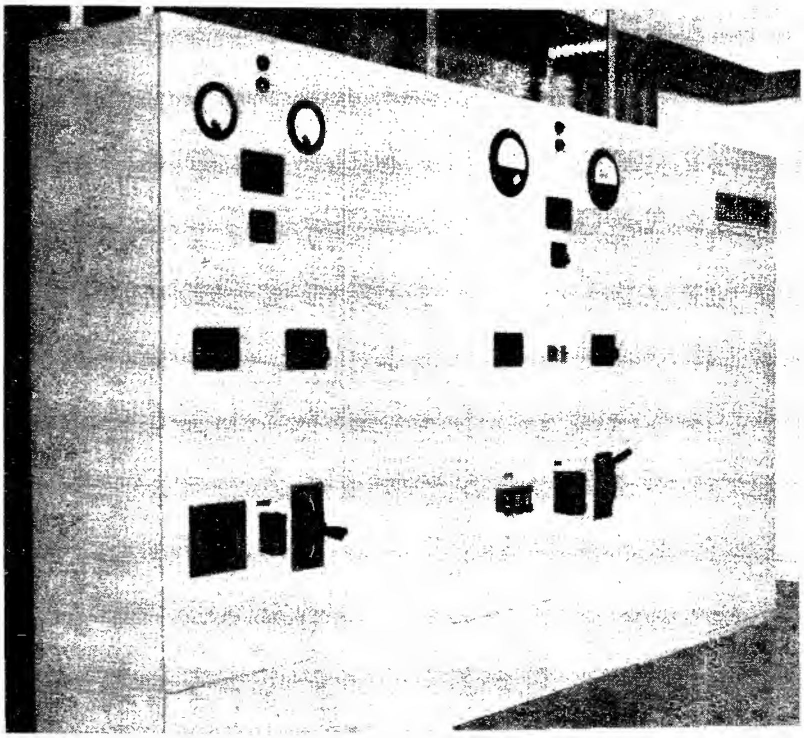


FIG. 20. TYPICAL RECTIFIER SETS.

In the early rectifier sets most of the space was taken up by the diode elements and their large cooling fins. The gradual improvement in temperature and voltage rating of selenium discs has gradually reduced the space taken by the rectifying elements to a point where most of the space is now occupied by the input transformer and auxiliary gear.

The use of silicon diodes commenced in Australia in 1960. As a single silicon element has inverse voltage and maximum temperature ratings many times that of a selenium disc, the space needed for a given output has been further reduced. Fig. 21 shows a typical silicon power diode actual size. Diodes of these small dimensions are made in various ratings ranging from 50 to 600V peak inverse voltage and will handle maximum continuous rectified D.C. of from 70 to 250A depending on the cooling arrangements. Typical figures are 200A at 100°C base temperature, and 100A at 120°C. A 7" X 7" cooling fin and forced air draft are needed to achieve such high output but even allowing for this, silicon power rectifiers are both smaller and more efficient than selenium rectifiers of comparable output. Note also that much higher working temperatures are permissible (maximum for selenium is about 75°C).

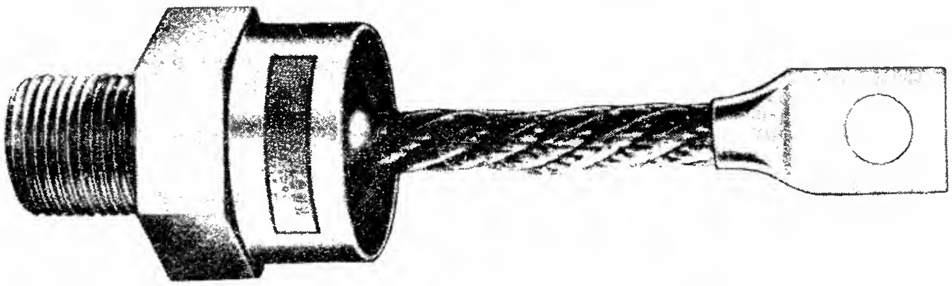


FIG. 21. TYPICAL SILICON POWER DIODE.

Rectifier Arrangements. A.C. - D.C. conversion plant operates from single-phase and three-phase supplies. The supply to the rectifier is normally connected via a transformer single-phase or three-phase. This provides the correct input voltage or a readily adjustable voltage using a tapped transformer. Outputs up to about 3kW are generally catered for by single-phase rectifiers and above that by three-phase units. Three-phase transformers are more costly than single-phase transformers but three-phase rectification is more economical at the higher outputs.

Half-wave rectifiers are suitable only for small powers and where the pulsating nature of the output is not a disadvantage, such as in small battery chargers, etc.

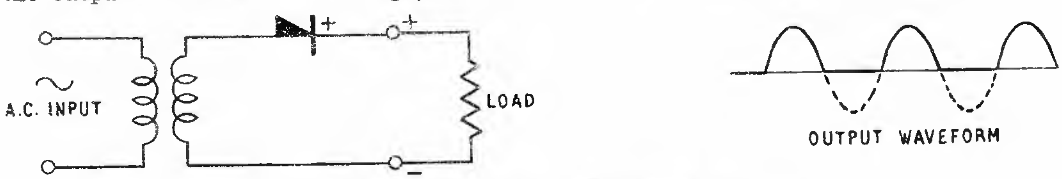


FIG. 22. HALF-WAVE RECTIFIER.

.4 Single-phase full-wave push-pull rectification is provided by two diode units and a centre tapped transformer (Fig. 23). One diode conducts for each alternate half cycle. The black and red arrows indicate the relative current paths (- to +).

The alternating voltage across each winding of the transformer must be sufficient to provide the required D.C. output voltage. The inverse voltage across the non-conducting rectifier each half cycle however, is the total voltage induced across both secondary transformer windings in series.

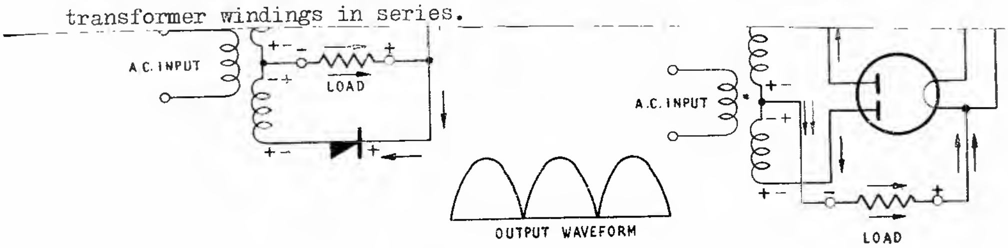


FIG. 23. FULL-WAVE PUSH-PULL RECTIFICATION.

The push-pull arrangement is little used ~~with selenium rectifiers~~ because the same result is obtainable from the same number of plates using bridge connection which does not require a centre tapped transformer. The arrangement is widely used with duo-diode tubes in the power supply of radio and T.V. receivers, test gear, etc., where load current rarely exceeds 200mA. Silicon diodes are beginning to supersede tubes in these applications.

4.5 Single-phase bridge rectifiers use four diode units and give full-wave rectification. Fig. 24a shows that opposite pairs conduct together with one pair handling each alternate half cycle. The black and red arrows indicate the relative current paths for each half cycle (- to +).

With a bridge rectifier the inverse voltage is applied across the two non-conducting diodes in parallel. The inverse voltage across each unit is equal to the supply voltage and the total number of plates of the four units need be no more than that used for two units in the push-pull arrangement of Fig. 23a. Figs. 24b and c show alternative schematic arrangements commonly used in circuit drawings; these are electrically identical to Fig. 24a.

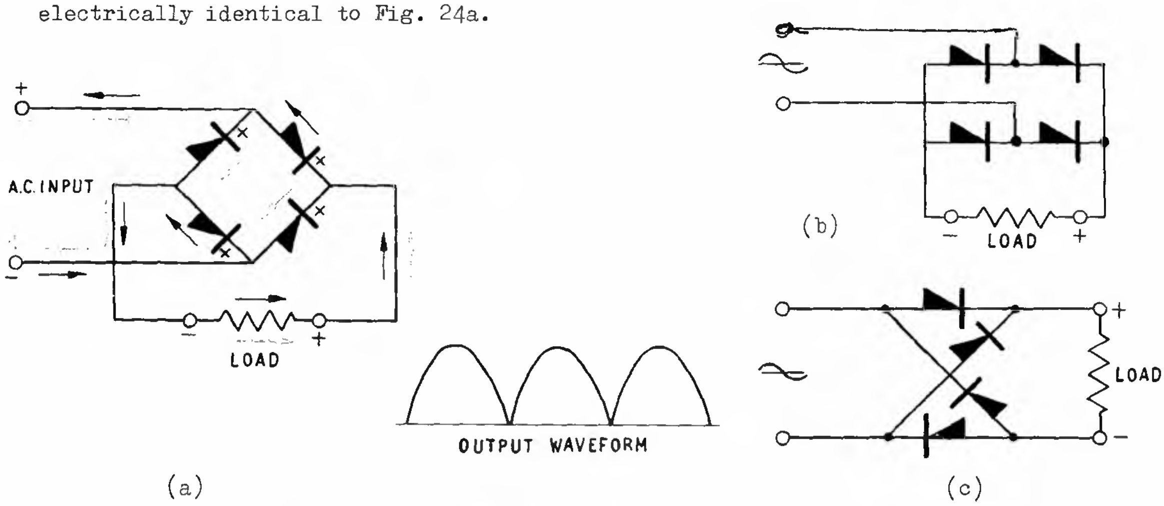


FIG. 24. SINGLE PHASE BRIDGE RECTIFIER.

4.6 Three-phase half-wave rectifiers have three diode units arranged as shown in Fig. 25. One half cycle from each phase is suppressed but because the three voltages overlap in time the output does not have periods of zero voltage as with single-phase half-wave circuits (Fig. 22).

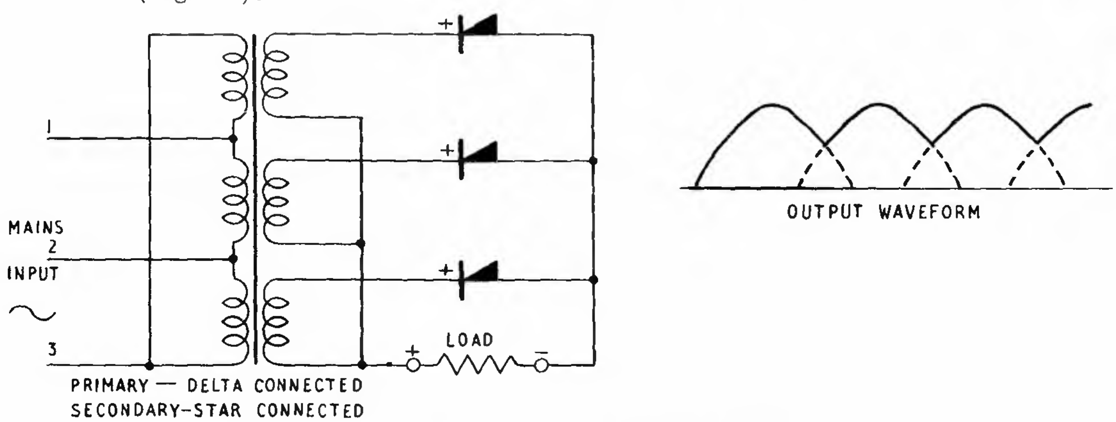


FIG. 25. THREE-PHASE HALF-WAVE RECTIFIER.

4.7 Three-phase bridge rectifiers require six diode units arranged as shown in Fig. 26 which also shows how the half cycle pulses are partly superimposed to give D.C. output of higher voltage with smaller variation than either single-phase full-wave or half-wave three-phase rectifiers.

There are several configurations of diodes and transformer which permit three-phase full-wave rectification, including a push-pull arrangement. They were developed originally for use with gas diodes and some arrangements had advantages for particular types of service. With metal rectifiers the three-phase bridge shown in Fig. 26 is suitable for practically all high power applications; the single-phase bridge (Fig. 24) is used for most lower power applications up to 2-3kW.

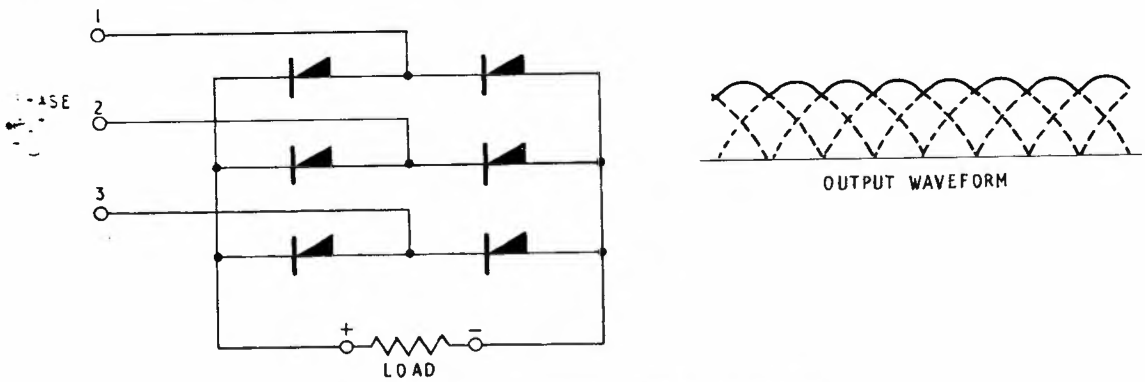


FIG. 26. THREE-PHASE BRIDGE RECTIFIER.

Gas diodes connected in a three-phase bridge circuit are used for high tension supply in modern radio and T.V. transmitters where selenium rectifiers would be more bulky and less efficient at the very high voltages used (6kV being typical). A typical circuit is shown in Fig. 27. The diode connections are electrically equivalent to that of Fig. 26 but the cathodes are directly heated filaments and in three of the six tubes they are supplied by separate and well insulated transformers because of the high voltage difference between them. The cathodes of the other three tubes are commoned and may be supplied by one transformer of higher rating but in many cases separate transformers are again used; a single spare transformer of the same rating can then be used in the event of failure to replace any one of the working six.

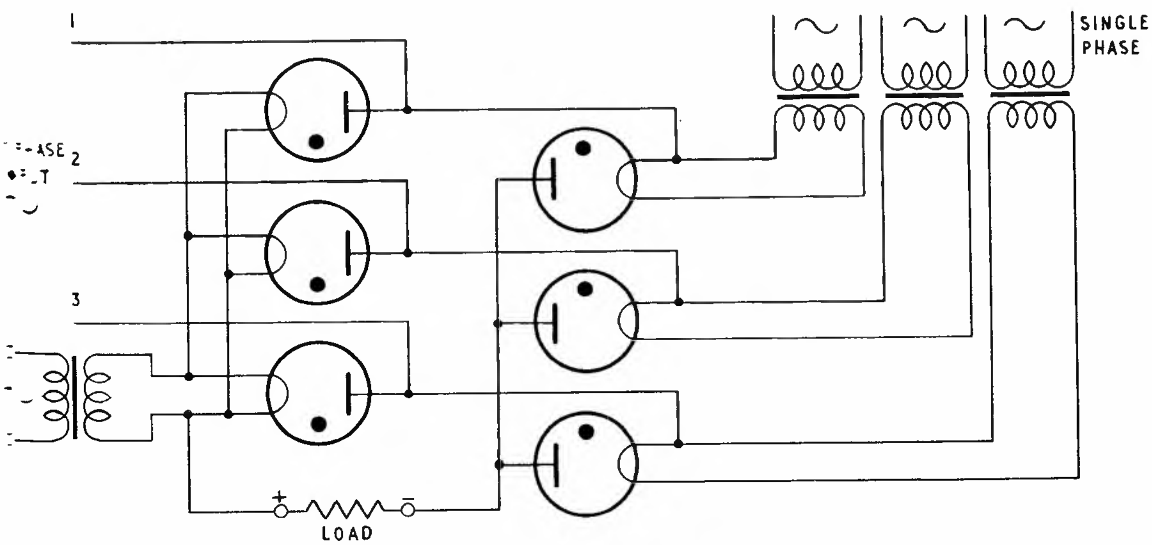


FIG. 27. THREE-PHASE HIGH VOLTAGE POWER SUPPLY.

For many years mercury vapour tubes have been used extensively for this class of service, but it is necessary to observe some special precautions with them because the cathodes can be damaged if the filaments and tubes are not allowed to warm up before the anode voltage is applied. Automatic switching is generally provided to ensure this; a time delay before the anode voltage is applied allows the residual mercury to vapourise and produce the correct gas pressure. Continuing operation within correct temperature limits is also important.

Recent development of xenon gas diodes have made them equally suitable for high voltage power supplies having a moderate current drain. Time delay switching is not necessary as anode and filament voltages can be applied together. Xenon diodes are finding general use for this class of service.

4.8 Voltage Doublers are rectifier circuits sometimes used to provide relatively high voltages with low power outputs. Fig. 28 shows a typical full-wave voltage doubler circuit. The name is derived from the fact that D.C. output voltage on open circuit is approximately twice that of the A.C. peak input voltage.

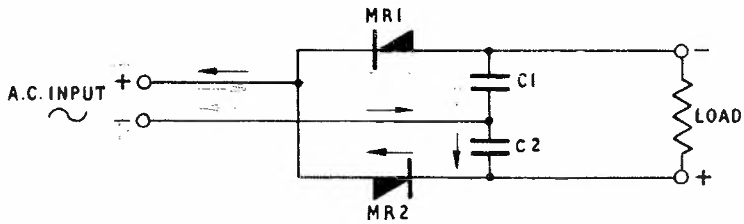


FIG. 28. VOLTAGE DOUBLER (FULL-WAVE).

One half cycle of input charges capacitor C1 to the peak A.C. voltage via diode MR1 as indicated by red arrows. The other half cycle charges C2 via MR2. The load connects across the two charged capacitors in series so that the output voltage is twice the peak input voltage. With large capacitors and light load current the output voltage on load is maintained, but heavy load currents or the use of small capacitors which hold only a small charge will result in output voltage being much less than twice the peak input value. A varying load will result in varying output voltage.

Because of these disadvantages voltage doublers have, in the past, found only limited application. Recent developments in electrolytic capacitors and silicon diodes have made the voltage doubler principle of practical use over a much wider field and many items of electronic equipment are now using this form of conversion (radio and T.V. receivers, test gear, etc.).

The circuit of Fig. 28 is only one of several circuits which give rectification and voltage multiplication. Using more elaborate arrangements of diodes and series capacitors, it is possible to have voltage tripling and voltage quadrupling rectifiers and such circuits are used occasionally to derive medium voltage, very low current outputs from low voltage A.C. Higher multiplying factors are quite possible but not generally practicable.

4.9 Regulation. Power supplies which supply varying load current are required to have what is known as "good regulation". As explained in relation to power transformers in the paper "Transformers and Inductors", regulation is a measure of the output voltage variation from no-load to full-load and is usually expressed as a percentage of the no-load voltage.

In power supplies the overall regulation is the voltage variation with load variation resulting from the losses in every component of the A.C. to D.C. conversion path - transformer, diodes and filter.

Expressed as a percentage, regulation is :-

$$\frac{\text{No-load voltage} - \text{full-load voltage}}{\text{No-load voltage}} \times 100$$

Where output drain is constant, regulation is not of prime importance. As long as output voltage on load is sufficiently high a considerable terminal voltage drop when the load is applied will not affect operation, except that poor regulation also indicates a power supply which is wasting energy in its relatively high internal resistance. When a rectifier supplies several separate circuits low internal supply impedance is desirable to avoid interference or the need for extensive decoupling filters.

The resistance of the diode elements accounts for most of the voltage drop in rectifiers although cheap filters used in some low current circuits give a considerable voltage drop

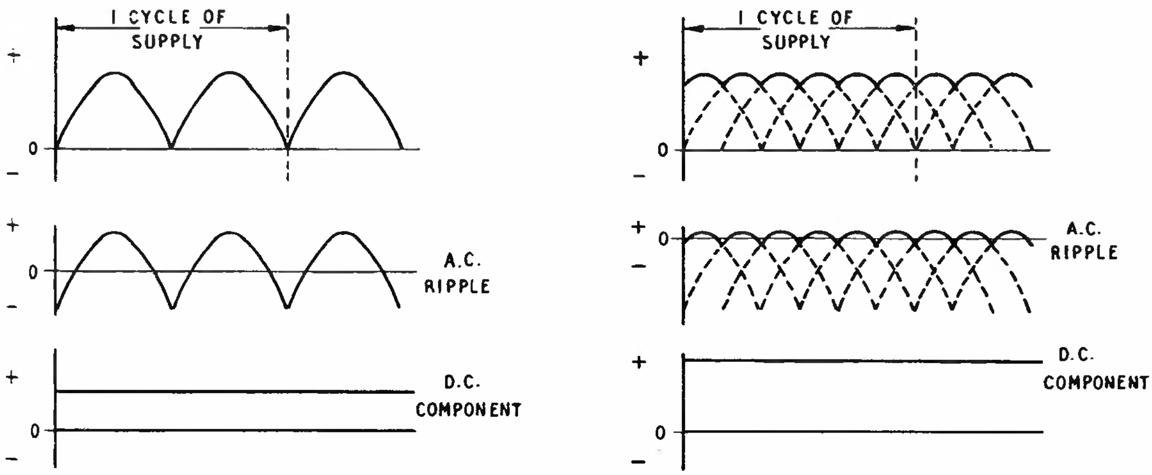
̶̶TERING IN POWER SUPPLIES.

Ripple. The output from any rectifier is varying D.C. as we saw from the waveforms shown in Figs. 22 to 26. Any varying or pulsating D.C. may be regarded as comprising two components; a steady D.C. having an A.C. component superimposed upon it. The A.C. component is called the ripple and it is the function of the smoothing equipment or filter to eliminate it or transfer its energy into steady D.C. output.

Ripple Frequency. The frequency of the A.C. ripple depends on the rectifier arrangement used. The following table lists the ripple frequency for the various arrangements.

Rectifier Arrangement	Ripple Frequency	Ripple Frequency with 50c/s Supply
Single-phase, half-wave	Supply frequency	50c/s
Single-phase, full-wave (bridge, push-pull or voltage doubler)	Supply frequency X 2	100c/s
Three-phase, half-wave	Supply frequency X 3	150c/s
Three-phase, full-wave	Supply frequency X 6	300c/s

Fig. 29 shows the output waveform of a single-phase and three-phase, full-wave rectifiers divided into their two separate components.



(a) Single-phase, full-wave.

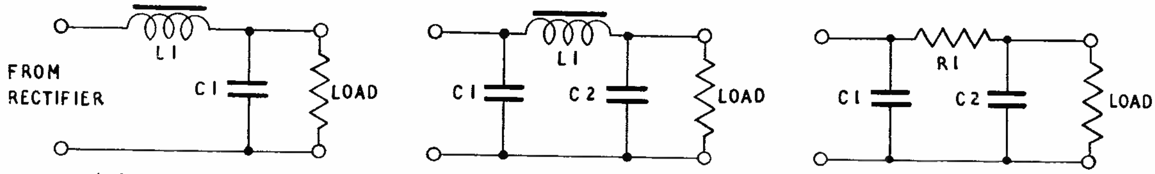
(b) Three-phase, full-wave.

FIG. 29. RECTIFIER OUTPUT COMPONENTS.

Notice that the A.C. ripple is not of sine waveform and that in Fig. 29a two positive going and two negative going peaks occur in the time of one cycle of the supply. This explains how the fundamental ripple frequency is twice that of the supply; in addition, the non-sinusoidal waveform indicates the presence of higher order harmonics.

Fig. 29b shows that the A.C. ripple on the three-phase full-wave output is six times the supply frequency and compared to Fig. 29a has a much lower proportion of ripple to D.C. component. These factors make the smoothing much easier especially with large output currents.

5.2 Ripple Filters. Ripple filters usually consist of series inductance and shunt capacitance although series resistance may also be used in low power circuits. The inductors and capacitors can be connected in two main ways resulting in filters being classed as either "choke input" (inductance input) or "capacitor input". (Fig. 30.) In general terms, filters eliminate the A.C. by offering to the ripple a high series impedance and a low shunt impedance. In effect they constitute a low pass filter with cut-off frequency less than the ripple frequency. (Low pass, high pass and band pass filters are explained in "Long Line Equipment 1".)



(a) Choke Input. (b) Capacitor Input. (c) Resistance-capacity.

FIG. 30. BASIC FILTERS.

5.3 Filter Chokes. The choke offers an impedance to ripple which depends on the inductance and the frequency ($X_L = 2\pi fL$). The D.C. also flows in the choke and in high current circuits a low resistance is imperative to avoid wasteful I^2R power loss and excessive heating of the choke. Very low resistance necessitates very heavy winding; this limits the number of turns and consequently the amount of inductance which can be obtained in a choke of reasonable size.

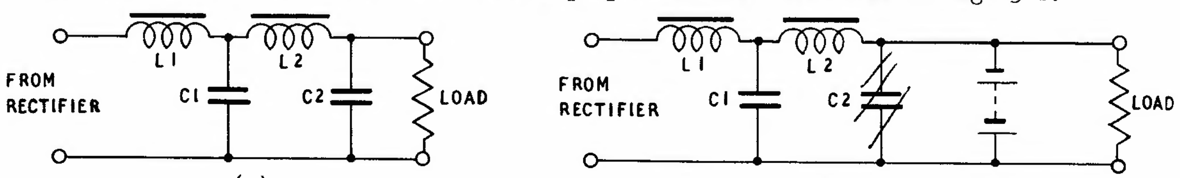
A choke with a closed magnetic circuit will readily saturate on a low value of load current with a consequent loss of inductance. Filter chokes therefore have an air gap in the magnetic circuit to prevent saturation. Even so, the inductance value is less than a similar choke which does not have to pass D.C. The inductance of a choke or inductor carrying D.C. is less than that for A.C. only.

Rectifiers having outputs of 100A or more have chokes with a low inductance in the region of one henry or less, whereas small equipment power supplies giving less than, say ½A have chokes ranging up to about 30 henries.

Filter capacitors are nearly always the electrolytic type which have the necessary high capacity in a reasonable space. Long life is achieved by special sealing techniques which prevent drying out. Capacities range from 8 or 16µF in low current filters up to as high as 40,000µF in high current filters although this is achieved with ten or more capacitors in parallel. Large capacitors are always connected via a fuse to protect the equipment in the event of a short circuit.

5.4 Choke-input filters are used in high current circuits, and in low current circuits requiring good regulation. Theoretically the A.C. component flows via the choke and the capacitor but not in the load, the ripple voltage being dropped across L which has relatively high impedance and not across C which has low impedance. However, as the impedance of L is not infinite and that of C is not zero at the ripple frequency, some ripple voltage will be developed across C, and therefore across the load also, which is in parallel. Where a very high degree of smoothing is required a second filter section may be used (Fig. 31a) and even a third in some cases.

Where the load incorporates a "floating" secondary battery the smoothing is greatly improved by the very low impedance of the battery which acts as an effective short circuit to the A.C. component and shunts any remaining ripple from the load. A capacitor across the output would serve no useful purpose and is omitted as in Fig. 31b.



(a) (b)

FIG. 31. TWO SECTION FILTER.

Capacitor - input filters (Fig. 30b) are suitable only in fairly low current circuits and only where the transformer, rectifier combination contains sufficient resistance to limit the peak charging current of the input capacitor to a safe value. Large capacitors have very low impedance to current change and a very low impedance source would result in very large peak charging currents of short duration which could adversely affect the diode element.

The charged capacitor across the output of the rectifiers prevents current flow from them until the voltage reaches that across the capacitor terminals. The rectifier therefore supplies its energy in pulses of short duration and the design of transformers for high output with this type of loading is not practicable. The capacitor C1 discharges to the load between the charging pulses from the rectifier and the voltage across it varies as shown in Fig. 32.

VOLTAGE ACROSS INPUT CAPACITOR.

FIG. 32.

When load current is small the input capacitor charges to the peak value of the A.C. input so that output voltage is higher than that of a choke input filter on the same rectifier. With heavier load current the peak voltage cannot be maintained and output voltage drops; regulation therefore is not as good as obtainable with choke input filters. The choke and second capacitor of input filters attenuate the remaining ripple in the same manner as described for choke-input filters.

Capacitor-input filtering enables a higher degree of filtering from one section than choke-input filtering because the input capacitor greatly reduces the ripple voltage which the following L/C network has to handle.

The use of capacitor-input filters is mainly limited to power supplies for P.M.B.Xs., radio receivers, test gear, etc., where load variation is small and a high degree of filtering is required in a small space. The supply impedance necessary to limit the charging current of C1 is inherent in high vacuum diodes. With semi-conductor diodes some series resistance may be used but the resistance in small transformers is generally sufficient to limit peak currents.

R/C Filters (Fig. 30c) are used in some low current circuits because of their cheapness and because the space taken by a choke is saved. Capacitor input is used and a resistor takes the place of the choke. After the input capacitor has reduced the ripple voltage as described above, the remainder flows through the second capacitor and drops most of its voltage in R. The D.C. voltage drop in R is allowed for in the design so that the output voltage is sufficient on load. R is usually a wirewound vitreous resistor mounted so that there is sufficient ventilation to dissipate the heat.

Graded Filters. Two or three section filters are used in high quality audio amplifier power supplies. Such filters are often "graded" so that part of the output receives one stage of filtering, another part two stages, and only the circuits highly susceptible to "hum" pick-up receive the full three stages of filtering. (The first stage of an amplifier handles signal voltages which may be less than 1mV and noise such as A.C. hum must be low in proportion.) This makes smaller components adequate in the second and third sections as the full output is filtered by the first section only (Fig. 33).

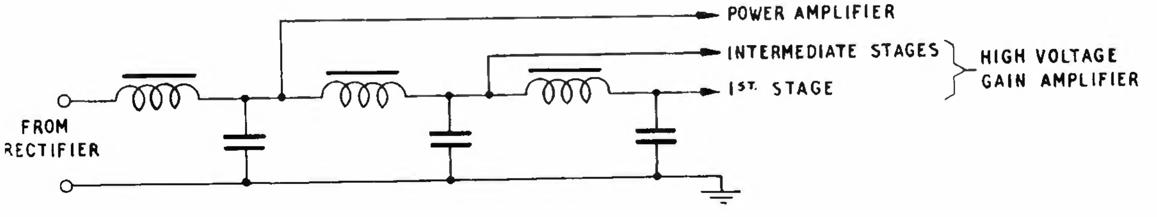


FIG. 33. GRADED OUTPUT THREE SECTION FILTER (Choke Input).

6. RECTIFIER OUTPUT CONTROL.

6.1 General. In most rectifier sets provision is made to control the output current to suit the load demand.

Supply sources having negligible internal resistance such as large alternators and secondary batteries will of course supply a wide range of current values to varying loads at a practically constant output voltage. Rectifier sets however have some resistance in the diode elements, transformer, and filter, and without control can only supply increased output current at a reduced terminal voltage. In the majority of cases this is undesirable as the supply voltage for modern telecom equipment must be maintained within narrow limits.

For example, a telephone exchange having a typical load variation of from say 10A to 400A requires a supply maintained between about 46V and 52V. For most economical operation of the power plant (batteries, rectifiers, etc.) even closer limits are necessary and modern rectifier sets are able to maintain the busbar voltage within ± 0.5V of an optimum value.

Modern circuits and devices provide sensitive automatic control and are the result of many years of development. Fig. 34 shows the operating conditions of most large telecom rectifiers where the load is supplied directly from the rectifier with the battery "floating" across the terminals and being maintained in a fully charged state. This arrangement is universal for automatic telephone exchanges although many P.M.B.Xs. and much long line equipment have no battery supply.

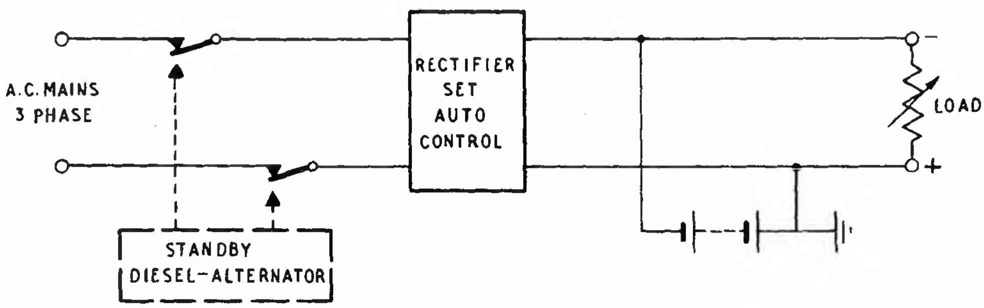


FIG. 34. TYPICAL APPLICATION OF RECTIFIER SET.

6.2 Manual Control is affected generally by varying the A.C. input to the rectifying elements as shown in Fig. 35.

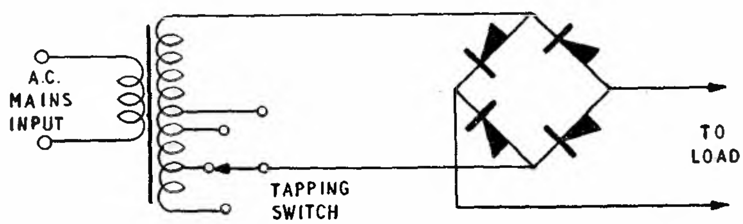


FIG. 35. MANUAL CONTROL.

Manual control (or no control with preset output) is suitable for very light loads such as C.B. P.M.B.Xs., constant loads, or non-critical loads such as batteries being charged while off load.

Voltage stabiliser or voltage regulator (V.R.) tubes are used in some low current circuits to provide a simple form of automatic voltage regulation. We saw in Section 2 that while conducting in the glow discharge region of their characteristic, cold cathode diodes maintain almost constant voltage between electrodes over a considerable current range. This property can be used in many ways, the simplest being as shown in Fig. 36.

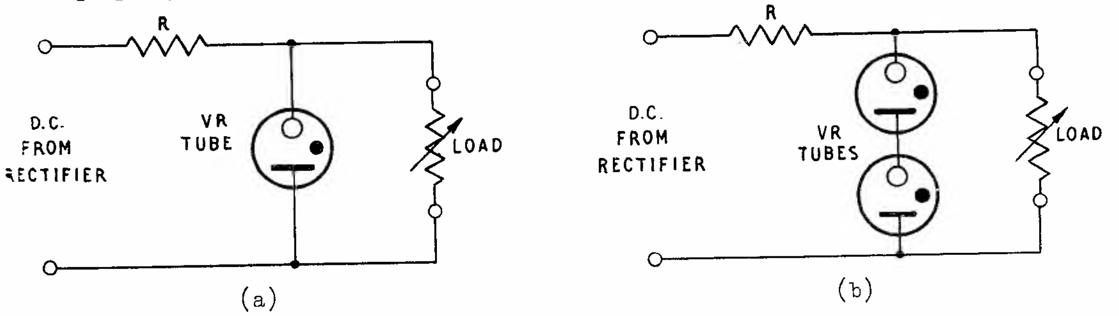


FIG. 36. VOLTAGE REGULATION USING COLD CATHODE DIODES.

The load is connected across a V.R. tube of suitable voltage rating (Fig. 36a) (or tubes in series for voltages above about 150V as shown in Fig. 36b) and the D.C. supply is connected via a resistance R. In maintaining a constant terminal voltage across itself the V.R. tube draws less current when the load draws more, and more current when the load takes less.

For example, if the V.R. tube has a range of from 10 to 50mA, R is adjusted so that the tube draws about 30mA when the load current is midway between maximum and minimum (say 70mA). When the load current rises to 80mA the V.R. current drops to about 20mA and at 60mA load current the V.R. current rises to about 40mA.

This arrangement is suitable for light loads only. V.R. tubes vary a few volts over their full range but are excellent for variations of less than 10mA.

V.R. tubes are used more often as a source of "reference voltage" for more elaborate types of voltage regulation. The constant voltage across a V.R. tube carrying nearly constant current is compared to another voltage which is affected by load variation, and an accurate signal is derived from the two to operate the control device. This is usually a variable impedance or resistance in series with the supply.

For example, in one type of electronic regulator the control signal derived using a V.R. tube as voltage reference is amplified and fed to a triode as shown basically in Fig. 37. The controlling signal varies the grid to cathode voltage which varies the anode to cathode resistance and the varying load is supplied with only very slight variation in load voltage.

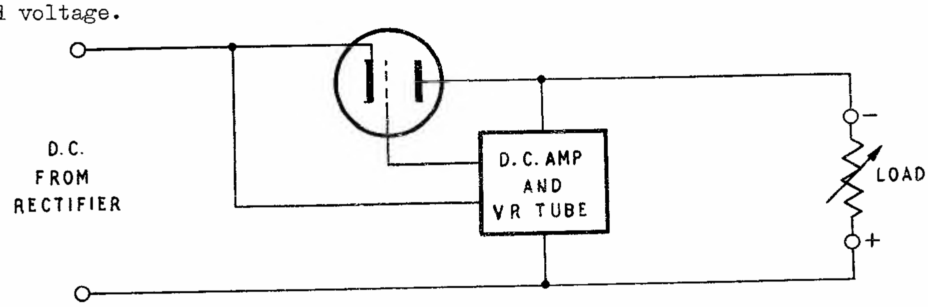


FIG. 37. ELECTRONIC REGULATOR.

Any form of control which uses variable resistance elements in series with the load is only practicable with small output powers because the control resistance wastes a considerable proportion of the total power.

Fig. 36 and 37 show elementary principles of auto control but as such they find little application in modern telecom circuits.

6.4 The Saturable Reactor or Transductor. To control large powers with minimum energy waste sensitive electromagnetic or electromechanical devices are used to vary the A.C. input to the rectifier elements. The transductor is a static, (no moving parts) electromagnetic device which provides a means of controlling large amounts of A.C. with a comparatively small D.C. signal. We have seen that an inductance or choke with low resistance can introduce a large voltage drop in an A.C. circuit and yet waste very little energy. Fig. 38 gives the basic principle of a transductor or saturable reactor. Coil A is a choke of very low resistance and coil B is another winding on the same core. Coil A is connected in series with an A.C. load which receives an input voltage reduced by the voltage drop in A.

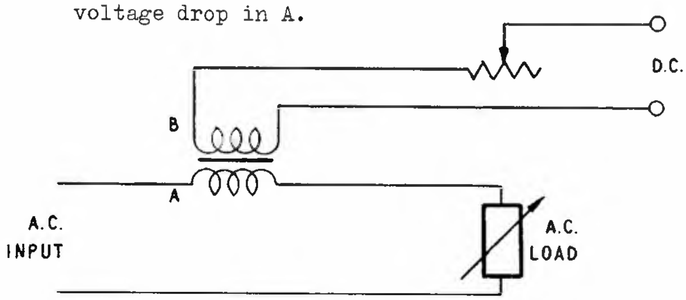


FIG. 38. PRINCIPLE OF TRANSDUCTOR.

When D.C. is connected to coil B, the unidirectional magnetization of the core reduces the flux variation due to the A.C. The inductance of A is thus lowered, its reactance ($X_L = 2\pi fL$) is reduced, and the voltage to the load is increased. The greater the degree of D.C. magnetization of the core, the lower the inductance and reactance of A and the greater the A.C. input to the load. When the core is sufficiently saturated, inductance and reactance of A is zero and the load receives the full applied voltage.

6.5 B/H curves can be used to explain the action of transductors. Fig. 39a shows a typical curve relating variation of core flux density B with the magnetising force H to cover a full cycle of A.C. excitation. For simplicity we will consider that hysteresis is negligible (as is nearly so with some high quality core steels). (See the paper "Magnetism and Electromagnetism" in Applied Electricity 1.)

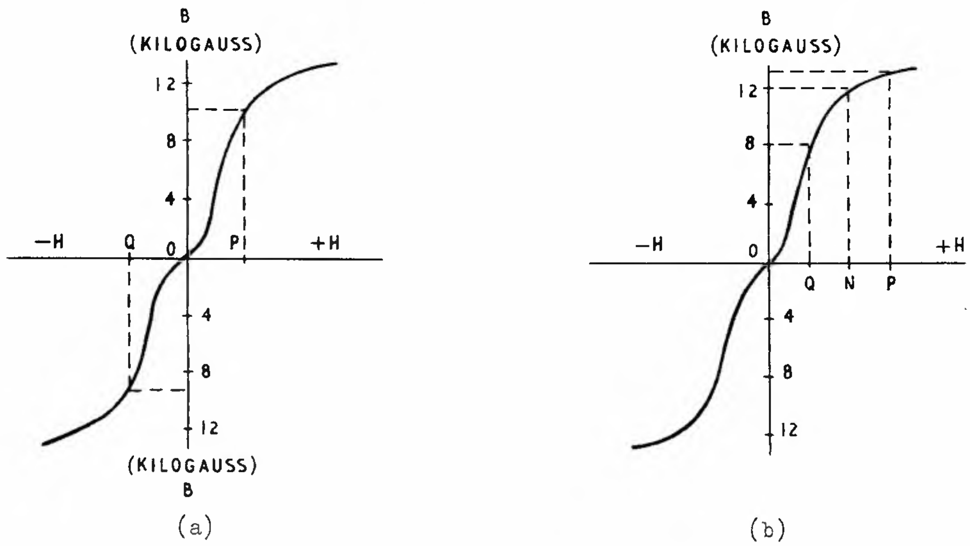


FIG. 39. FLUX DENSITY VARIATION.

Suppose an A.C. swings the magnetising force from P in the positive direction to Q in the negative direction, the resulting variation in flux density is a total of about 20 kilogauss. This corresponds with the region of maximum inductance for the A.C. coil.

Suppose now, the unidirectional magnetising force of a D.C. signal in another coil shifts the mean operating H to point N as shown in Fig. 39b. An A.C. of the same magnitude will now swing the magnetising force over the region PNQ but because of the shape of the curve in this region the corresponding variation in B is only about 6 kilogauss. The inductance of the A.C. winding is therefore greatly reduced.

Shifting point N to the left (less D.C. signal) will result in a greater inductance and shifting it to the right (more D.C.) will reduce the inductance.

Modern transductors use special core materials and winding techniques which permit sensitive control over a wide range for a small energy loss in the D.C. or signal coils.

It is necessary to prevent A.C. being induced into the D.C. circuit and one method of doing this is shown in Fig. 40a. Two identical chokes are used and connected in series so that theoretically the A.C. induced into B1 is 180° out of phase with the A.C. induced into B; the resultant is zero A.C. in the D.C. circuit.

One method of schematically showing this type of transformer connection and operation is shown in Fig. 40b. These coils however may be shown without the details of the connections as shown in Fig. 40c.

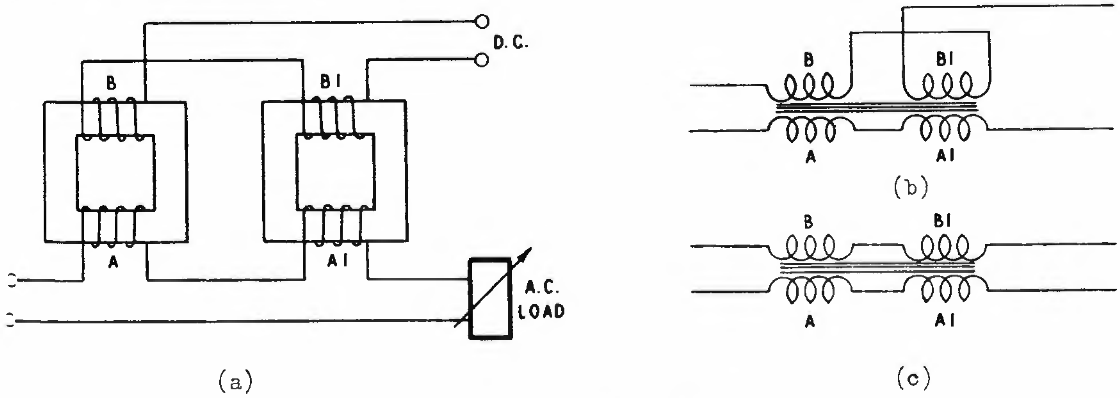


FIG. 40. CONNECTION OF TRANSDUCTOR COILS.

In practice the non-linear magnetization throughout the cycle results in the production of harmonics of the fundamental A.C. supply frequency not all of which are 180° out of phase in B and B1. Having low power they can generally be disregarded although in certain applications of magnetic amplifiers (a refinement of transductors) additional measures are taken to remove them.

Transductor Control of Rectifier Sets. Fig. 41 shows the principle of a controlled rectifier having a simple type of direct control. The signal windings of the transductor have low resistance and are in series with the output.

A decrease in load resistance causes an increase of load current. The extra current in the signal windings of the transductor raises the degree of core magnetization which lowers the reactance of, and the voltage drop, across the A.C. windings and results in an increased A.C. voltage to the rectifier. The increased A.C. voltage to transformer and rectifier elements compensate for the additional voltage drop across them and enables the greater D.C. load demand to be met with very little drop in D.C. terminal voltage. This is the principle of the "Transrector" further details of which are given in the paper "Power Plant Components" in Telephony 5.

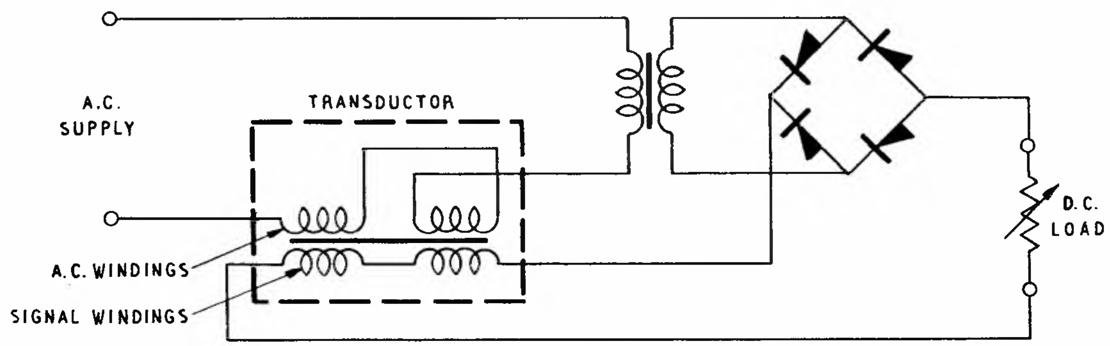


FIG. 41. DIRECT CONTROLLED RECTIFIER.

6.8 Auto Control Using an Amplifier. The direct control cannot compensate for variation of mains voltage and frequency. The sensitive control mentioned in para. 6.1 is only obtained using rather elaborate voltage reference and D.C. amplifier circuits to excite the transductor (or transductors). Three-phase rectifiers have a transductor in each of the three A.C. input leads.

The basic principle of auto control rectifier sets using amplifiers in the control is as shown in Fig. 42.

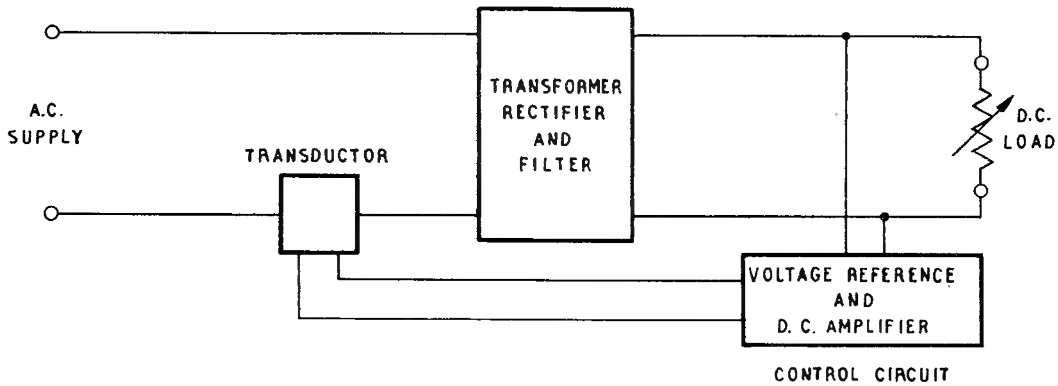


FIG. 42. PRINCIPLE OF AUTO CONTROL RECTIFIER.

An accurate signal is derived by comparing a constant reference voltage to the output voltage. This signal is the input to an amplifier, the output current of which flows through the control windings of a transductor (or transductors).

When the load current increases and the output voltage decreases slightly, the increase in amplifier output current decreases the reactance of the transductor A.C. winding. This allows a compensating increase in A.C. input to supply the increased demand with minimum voltage drop.

Since the output voltage must decrease (or increase) slightly to provide the control, absolutely constant voltages cannot be obtained. However the voltage variation in this system is a fraction of a volt in comparison to a range of several volts obtained when using similar components without automatic control.

By designing the voltage reference circuit to be entirely independent of mains voltage or frequency, the control compensates for variations in these, as well as in the output load.

Further information on transductors and magnetic amplifiers is contained in the paper "Power Plant Components" of Telephony 5.

6.9 Overload protection is provided in all auto control rectifier sets. Should the load current exceed the maximum safe output of the set an additional feature of the control circuit prevents it from forcing the output current to continue rising in an attempt to "follow the load". A voltage proportional to the output current is also applied to the control circuit and at maximum safe output this additional signal acts to prevent further output from the D.C. amplifier to the transductor (or transductors).

For simplicity this additional signal load to the control circuit is not shown in Fig. 42 but it is usually derived from the voltage drop across one of the series filter chokes.

Auto-mechanical regulation of rectifier sets has been used overseas for some time but is now beginning to be used in Australia for large output units of about two hundred amperes and over.

The principle is relatively simple and a simplified circuit of the control is shown in Fig. 42. The three phase input to the main transformer is fed in series with the secondary windings of three small transformers called the "buck boost" transformers. The primary winding of each buck boost transformer is fed from an auto transformer supplied by single phase input between the corresponding line and neutral (N).

Each auto-transformer regulator has two sliding contacts linked mechanically to a small reversable A.C. motor. A contact voltmeter across the D.C. output has high and low voltage contacts which control the motor and its direction of rotation via two relays RR and LR (raise regulator and lower regulator).

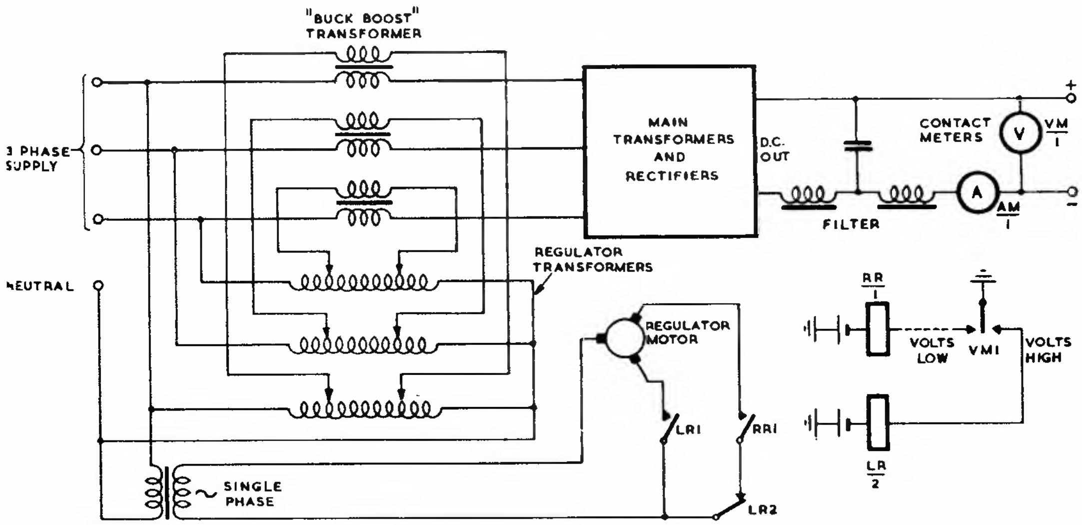


FIG. 42. AUTO-MECHANICAL REGULATION OF RECTIFIER.

In operation the buck boost transformers can either increase or reduce the input voltage to the main transformer depending on the phase relationship of the buck boost inputs to the main line current inputs; this in turn depends on the position of the sliding contacts on the regulator auto transformers. With this arrangement the control transformers handle little power compared to the main transformer and are therefore small in size and have low I^2R losses.

When a change in load or mains voltage alters the output voltage the contact voltmeter operates either relay RR (low output voltage) or LR (high output voltage) which closes the motor circuit to affect the necessary adjustment on the regulator transformers. The contacts of the contact ammeter operate on overload or fault currents and initiate a lowering of output (circuit not shown).

The buck boost type of control allows an additional useful feature to be included with large rectifiers. The input transformers are duplicated and the primary windings operated in parallel. The secondary windings are interconnected with each other, the rectifiers, and an "interphase" reactor in such a way as to produce a D.C. output having a ripple frequency of 600c/s, which can be filtered out more readily using smaller filter chokes than are needed for ordinary single or three-phase rectifiers. (There are many different transformer connections which produce multiphase output but their study is beyond the scope of this paper.)

Auto-mechanical control of this type gives higher efficiency for large outputs than other forms of auto control.

7. TEST QUESTIONS.

1. With the aid of a curve describe what occurs when anode current in a diode is (i) space charge limited,
   (ii) saturation limited.

2. What is the difference between "hard" and "soft" electron tubes?

3. Describe the operating differences of high-vacuum and gas diodes (hot cathode).

4. What is "glow discharge"?

5. List and describe briefly the three main types of photo diodes.

6. Describe the basic principle used in electron multipliers.

7. (i) Using a curve describe the significance of the forward and reverse characteristics of semiconductor or "metal" :
   (ii) How is their behaviour affected by a rise in temperature.

8. How are semiconductor diode elements assembled to increase - (i) the overall voltage rating, and (ii) the overall current rating of a rectifier.

   (i) .... (ii) ....

9. Using the standard semiconductor diode symbol, show by means of sketches a diode's relation to -

   (i) output polarity when used as a half-wave rectifier;
   (ii) the applied D.C. polarity when used to block the current in a resistance.

10. What do you understand by the codes - 1/12A, 2P/6A, 2/1A.

11. What type of mains supply is used for a rectifier set delivering say 200A at 50V? Give a reason for your answer.

12. In what way has the introduction of silicon power diodes affected the design of rectifier sets?

13. Explain with the aid of sketches, the operation of push-pull single-phase rectifiers using electron tube and semiconductor diodes.

14. (i) Explain with the aid of a sketch the operation of a single-phase bridge rectifier.
    (ii) Why is the bridge circuit preferred to the push-pull circuit for selenium rectifiers.

15. Describe the operation of a full-wave voltage doubler.

16. Draw the circuits for three-phase bridge rectifiers using - (i) semiconductor diodes, (ii) gas diodes.

17. What precautions are necessary in the operation of mercury vapour gas diodes?

18. When the terminal voltage of a power supply varies considerably with load changes, it is said to have poor ....

19. (i) Using simple sketches show what determines ripple frequency in single-phase and three-phase full-wave rectifi...
    (ii) What are the ripple frequencies when the supply frequency is 50c/s?

20. (i) Describe the action of two types of L/C ripple filters.
    (ii) One of these cannot be used for all types of circuits. Explain its limitations.

21. How can the output of a rectifier set be manually controlled?

22. Show by means of a sketch how a V.R. tube can be used to stabilise the voltage of a low current circuit.

23. (i) What is a transductor?
    (ii) Describe the principle on which transductors operate.

24. Draw a block diagram showing the principle of automatic voltage regulation used for large rectifier sets and brie... describe its operation.

END OF PAPER.

ELECTRON TUBES

Page

..RODUCTION.

.' Electron tubes, vacuum tubes, thermionic tubes or valves, are the names used to describe the range of devices developed from the early diode and triode valves. This paper describes the general construction and operation of the basic types of electron tubes used in telecom and extends the information given in the papers "Basic Electronics" in Applied Electricity 1 and "Diodes and Rectifiers".

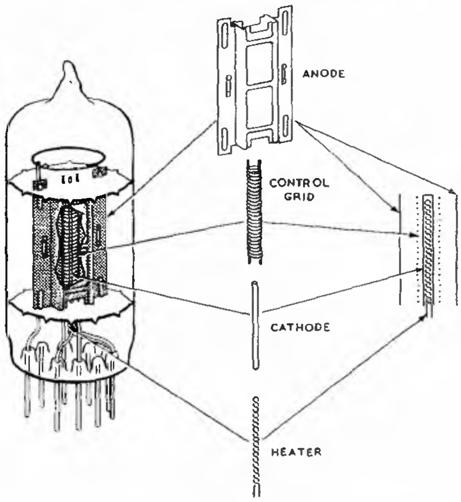
..BE CLASSIFICATION.

..' Because of widely varying requirements of electronic circuits, many tubes are designed for special applications. Although the large number of different types and their associated technical data is often bewildering, it should be remembered that most of these represent adaptions of the basic types - diode, triode, tetrode, pentode, and cathode ray tubes.

..2 The significance of the figures and letter combinations used in tube classifications (6B8-GT, 12BY7A, KT61, etc.) varies somewhat between manufacturers, but as a general rule the prefix figure (6, 12, 25, 50) refers to the heater or filament voltage - 6 for 6.3V heaters, 25 for 25V heaters, etc.

3. TRIODES.

3.1 The basic construction and operation of the three element electron tube (known as a triode) are explained in the "Basic Electronics" paper of Applied Electricity 1. The construction of a typical low power triode is shown in Fig. 1. The control grid is commonly known as the "grid" and in some tubes, connection to the grid is by means of a metal cap on top of the glass envelope. Many high power tubes have the anode plate connected to the top cap. In very high power tubes it is common for the outer surface of the anode to be exposed for air or water cooling.



The dimensions and shape of the electrodes and the physical spacing between them, differ in accordance with the intended applications. Tubes which are designed to handle considerable power have larger and more robust electrodes.

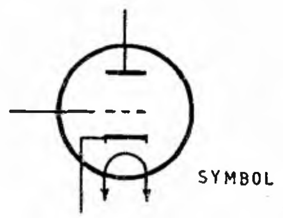
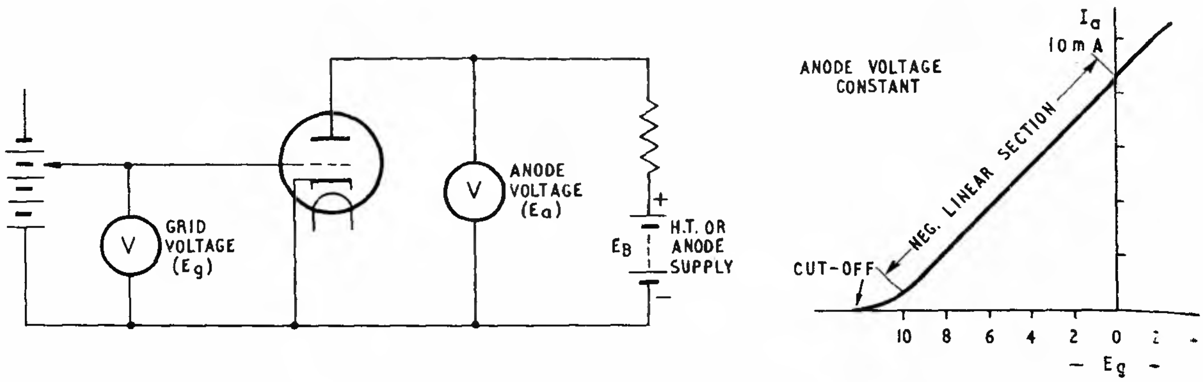


FIG. 1. CONSTRUCTION OF TYPICAL TRIODE.

3.2 We saw in the paper "Diodes and Rectifiers" (para. 2.2) that electron movement within a vacuum tube is controlled by electrostatic forces resulting from the applied electrode voltages and the space charge. The addition of the control grid permits the anode current to be varied by varying the potential between the control grid and cathode.

As the control grid is physically closer to the cathode than the anode, the grid-cathode voltage (known as Grid voltage) exerts a far greater degree of control over the anode current than the anode-cathode voltage (Anode voltage).



(a) (b)

FIG. 2. TRIODE CONNECTIONS AND CURVE.

3.3 When the anode voltage is fixed and the grid voltage is negative and gradually increased the anode current decreases until a point is reached where the combined effect of the negative field of the grid and the space charge cause the anode current to cease. This is called "cut-off" point. The grid potential needed for "cut-off" varies with the design of the tube and the anode voltage. When the anode voltage is increased, a greater negative grid voltage is necessary to cut-off the anode current.

When the grid potential is positive and gradually increased, the anode current increases and the positive grid attracts some electrons to cause grid current. As the grid is driven more positive, the grid current amplitude increases. The curve of a typical triode valve is shown in Fig. 2b.

Necessity for Bias. In an amplifier, when an A.C. signal voltage is applied directly between grid and cathode, anode current varies around the zero grid voltage position of the curve (Fig. 3b). On the positive half cycle of input voltage, the grid attracts electrons and grid current flows. When the grid circuit contains impedance (as is the case in most practical circuits), the grid current causes a voltage drop in opposition to the applied signal which reduces the voltage applied to the grid of the tube (E_g) and the anode current variation is not a true replica of the input voltage waveform as shown in Fig. 3b. This distortion also occurs when the grid voltage extends into the lower bend of the curve.

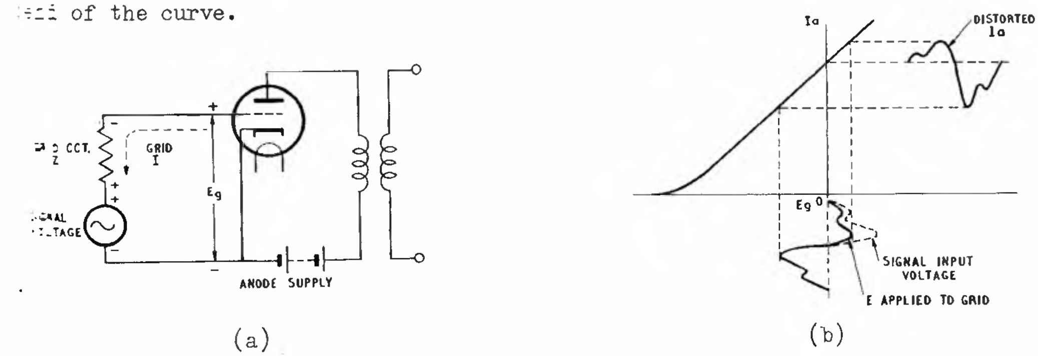
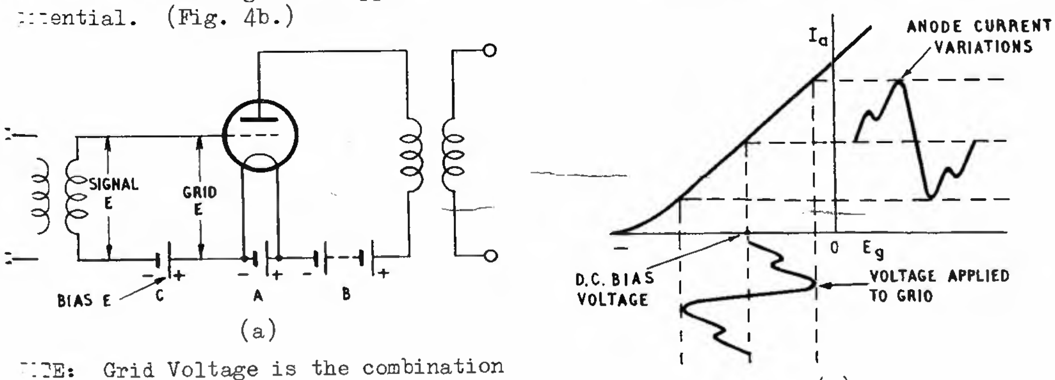


FIG. 3. DISTORTION DUE TO GRID CURRENT.

Grid Bias. Distortion is avoided by preventing the grid becoming positive and operating the tube only on the negative linear section of its I_a/E_g characteristic. To achieve this, the A.C. input signal to the grid is superimposed on a steady negative D.C. voltage which is called the "Grid Bias". Fig. 4a shows the battery method of providing this bias. When the signal is applied it varies the grid voltage above and below the bias potential. (Fig. 4b.)



NOTE: Grid Voltage is the combination of signal and bias voltages.

FIG. 4. BASIC TRIODE AMPLIFIER.

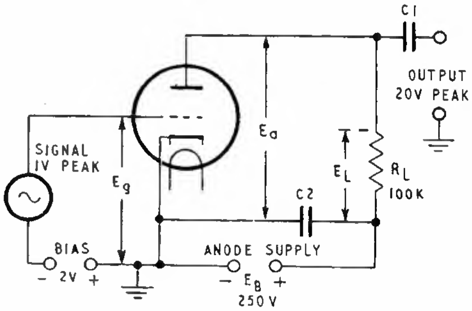
Grid bias, therefore, establishes the "working point" about which the signal voltage varies the grid potential through a range within the straight (or linear) section of the curve. The resulting variations in anode current correspond to those of the input signal voltage. When variations of grid voltage extend beyond the linear section, the anode current waveform is distorted. This arises from bias voltages that shift the working point close to either end of the linear section, or too large a signal input, or both.

Before directly heated tubes and mains operated power supplies were introduced, all tubes were battery operated. Three batteries, designated A, B and C were used for the filament, anode and bias supplies respectively as in Fig. 4a. Although the use of batteries is now mostly confined to portable equipment, the term B+ is still frequently used to designate points connected to a common anode supply.

3.6 Amplification. The grid, biassed to a negative D.C. potential with respect to cathode, controls anode current without any current in the grid-cathode circuit. The anode current which is controlled, may dissipate a considerable power as typical anode supply voltages range from 45V to 300V and typical anode currents range from less than 1mA to above 100mA. This ability of the triode to control power from the anode supply with negligible power input shows that amplification is basically a raising of power level. Since there is no grid current the triode is a voltage operated device having a very high input impedance. Actually no input current implies infinitely high impedance. ($Z = \frac{E}{I} = \frac{E}{0} = \infty$.) This is not quite the case as at this stage we have ignored a number of properties of tubes which in most cases limit the input impedance to a few megohms or less. This is still very high however and the source of signal does not need to be capable of producing current or power.

3.7 Voltage and Power Amplifiers. The small signal voltages from receiving aerials, microphones, pickups, etc. range from a few microvolts to a few hundred millivolts and are unable to "drive" or "swing" the grid of an amplifier, as in Fig. 4a, to produce any useful output power for operating devices such as loudspeakers or recording heads. One or more voltage amplifying stages are used to produce the necessary grid swing for a power output stage.

3.8 Voltage amplifiers produce a large voltage amplification or "gain" between the input circuit and the output circuit. A high impedance in the output circuit achieves this as small anode current variations produce large voltage variations across the high impedance anode "load". Fig. 5 and Table 1 show how a 100,000 ohm anode load R_L enables 1V changes between grid and cathode to cause 20V changes between anode and cathode. An A.C. input therefore of 1V peak value will be reproduced in the output having a 20V peak value. C1 prevents D.C. of the anode supply appearing in the output.



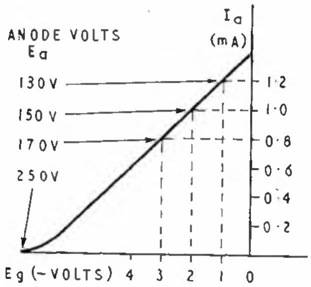


FIG. 5. BASIC TRIODE VOLTAGE AMPLIFIER.

E_g		I_a	E_L	$E_a = E_B - E_L$
D.C. bias and No signal	= 2V	1mA	100V	150V
Bias minus signal +ve peak	= 1V	1.2mA	120V	130V
Bias plus signal -ve peak	= 3V	0.8mA	80V	170V

TABLE 1.

As explained above, input impedance is not infinitely high and all amplification is a raising of power level. For all ordinary purposes, however, a "voltage amplifier" is one in which the voltage output component is required. Voltage amplifiers generally work into high load impedances of up to a megohm but a wide range of impedances is used in practice and there is no sharp line of demarcation between power and voltage amplifiers. The anode load of voltage amplifiers may be resistive as in Fig. 5 or contain inductive components also as in Fig. 4.

3.9 Power amplifiers required to operate power consuming devices such as loudspeakers, recording heads and transmitting antennae use power output tubes. As power is dependent on E x 1, these tubes handle larger anode currents and have lower load impedances than those of voltage amplifiers.

-- TUBE CHARACTERISTICS.

.1 As most tubes can be used in a variety of circuit conditions, manufacturers publish data which is independent of variable values, such as anode load impedance (R_L in Fig. 5) but gives information about performance in the permissible range of electrode voltages and currents. Data is given in two forms -

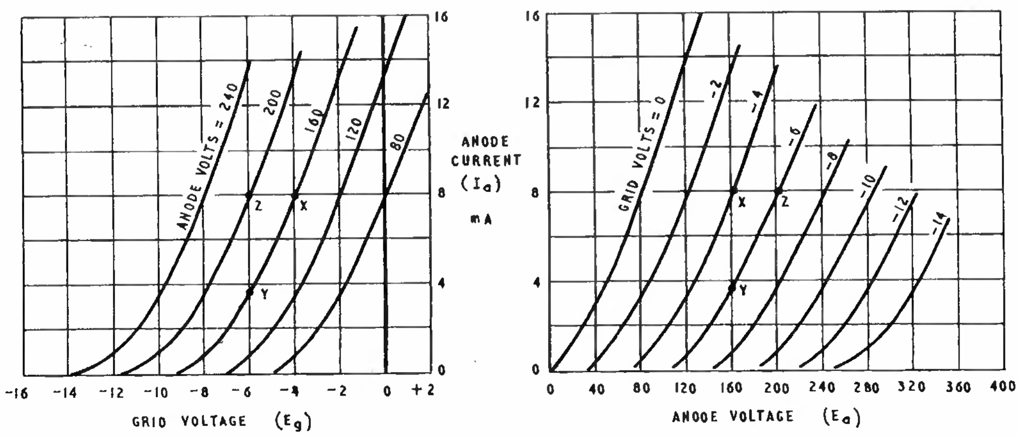
(i) Characteristic curves.
(ii) Tube constants or co-efficients.

Apart from their value to circuit designers, the curves and constants permit us to explain quite simply a great many concepts which would be difficult using only words, and they are therefore used frequently in this and following papers. They are not difficult concepts but to prevent electronics becoming a hard subject it is vital that you understand the significance of curves and constants. Merely memorising definitions etc. is not enough.

.2 Characteristic Curves express the relationships between grid voltage, anode voltage and anode current. Two sets of curves may be plotted which give the same information in a different form -

(i) Mutual characteristic curves (Eg/Ia) which show the variation of anode current with changes in grid voltage, the anode voltage being kept constant during the plotting of each curve. A curve is plotted for each of several values of anode voltage resulting in a "family" of curves on the one graph (Fig. 6a). (Fig. 3 showed a single mutual characteristic curve.) The term mutual signifies that two separate electrodes are being considered.

(ii) Anode characteristic curves (Ea/Ia) which show the variation of anode current with changing anode voltage, the grid voltage being kept constant during the plotting of each curve. A family of curves is plotted for different values of grid voltage. (Fig. 6b.)



(a) Mutual Characteristics. (b) Anode Characteristics.

FIG. 6. FAMILIES OF CHARACTERISTIC CURVES.

Note that the curves are nearly parallel and that the higher the value of anode voltage, the higher the value of negative grid voltage needed to cut-off anode current.

Either family of curves relates the three variables Ea, Ia, Eg on the one graph and shows that anode current can be controlled more effectively by grid voltage changes than by anode voltage changes. For example, on the E_a = 160V curve in Fig. 6a, a change in grid voltage of 2 volts, from -4V to -6V (points X & Y), results in a change of anode current of approximately 4mA. (8mA to approximately 4mA.) To give an equal change in anode current with a fixed bias of -6V, the anode voltage has to be raised approximately 40V, from 160V to 200V (points Y & Z).

The anode characteristics (Fig. 6b) show the same relationship in another way, and with the same example the corresponding changes of X to Y and Y to Z show the 2V grid and 40V anode changes, respectively.

As the same information is contained in either family of curves, data books genera... provide only the anode characteristic family.

Fig. 7 shows the type of circuit used for plotting characteristic curves. These cu... are called "static" characteristics to distinguish them from "dynamic" characteris... which are sometimes prepared to show the voltage and current relationships when the tube has a particular output load (such as R_L in Fig. 5). Dynamic characteristics ... fully explained in the paper "Amplifiers".

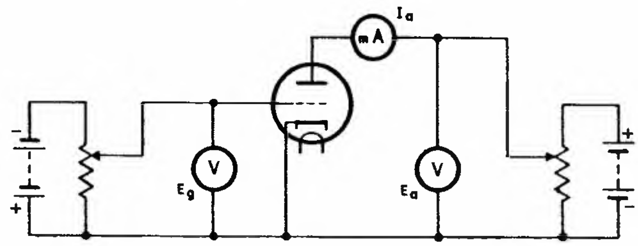


FIG. 7. CIRCUIT FOR PLOTTING CHARACTERISTIC CURVES.

4.3 Tube Constants. Some of the information contained in characteristic curves is als... expressed mathematically in terms of three "constants" or co-efficients which are -

(i) Mutual Conductance (symbol g_m);

(ii) A.C. Anode (or Plate) Resistance (symbol r_a);

(iii) Amplification Factor (symbol μ).

4.4 Mutual Conductance. In varying the anode current independently of anode voltage, ... grid is actually varying the resistance (or conductance) of the anode to cathode path. Using a test circuit such as Fig. 7, the amount by which the grid of a tu... will control the anode current may also be written as a fraction -

$$\frac{\text{Small change in } I_a}{\text{Small change in } E_g \text{ causing it}} \qquad (E_a \text{ is kept constant.})$$

For example, a typical tube may give 2mA change in anode current, I_a, for a 1V c... in grid voltage, E_g. The relationship $\frac{2\text{mA}}{1\text{V}}$ derives the Mutual Conductance in mil... per volt - mutual because it relates two separate electrodes, and conductance be... it is found by $\frac{I}{E}$ (the reciprocal of resistance $\frac{E}{I}$).

Mutual Conductance is defined as the ratio of a small change in anode current to ... small change in grid voltage producing it, anode voltage being constant. That is -

$$\text{Mutual Conductance } g_m = \frac{\Delta I_a}{\Delta E_g} \quad (E_a \text{ constant.})$$

where I_a is anode current.
E_g is grid voltage.
The Greek letter Δ ... "a small change in".

$$\text{or} \quad \frac{\Delta I_a \text{ (in mA)}}{\Delta E_g \text{ (in V)}} \qquad g_m \text{ in mA per V (mA/V).}$$

Mutual Conductance therefore, is a measure of the control E_g has over I_a. A fig... 1.5mA/V immediately tells us that under test conditions with E_a maintained const... a 1V change in grid voltage within the normal working range will result in anode current changing about 1.5mA. A g_m of 4.3mA/V indicates that I_a changes about ... for 1V change in E_g. Some text books use the micromho as the unit for g_m values. As a micromho is 1µA per volt the figure is just 1,000 times that when listed as ... This is, 4.3mA/V is 4,300 micromhos. (1mA = 1,000µA.)

Typical values of g_m for different tubes range from about 1mA/V up to about 10mA/V (1,000 - 10,000μmhos), although some modern special purpose tubes have g_m as high as 15mA/V. Mutual conductance is also known as control grid transconductance or simply transconductance.

In determining g_m a "small change" is specified because as we saw in Fig. 6a the mutual characteristics are not perfectly linear and a small change avoids the inaccuracy that this non-linearity would introduce. However, the non-linearity indicates that the relationship between E_g and I_a are not constant over their full range.

.5 A.C. Anode Resistance is a measure of the control the anode voltage E_a has on the anode current I_a. It is generally defined as the ratio of a small change in anode voltage to the small change in anode current it produces, grid voltage being constant. Or, as a fraction -

$$\text{A.C. Anode resistance} = \frac{\text{Small Change in } E_a}{\text{Small Change in } I_a} \quad (\text{with } E_g \text{ constant})$$

$$r_a = \frac{\Delta E_a}{\Delta I_a} \quad (E_g \text{ constant})$$

where
E_a is anode voltage.
I_a is anode current.
Δ means "a small change in"

$$\frac{\Delta E_a \text{ (in V)} \times 1000}{\Delta I_a \text{ (in mA)}} = r_a \text{ in ohms}$$

For example, suppose a 20V increase in E_a, increases I_a by 2mA, then

$$r_a = \frac{\Delta E_a}{\Delta I_a} = \frac{20 \times 1000}{2} = 10{,}000 \text{ ohms.}$$

It must be remembered that r_a is a dynamic measure relating changes of voltage and current and is not the internal D.C. resistance from cathode to anode. Because it relates changing values it is a measure of a tube's internal impedance to A.C. A.C. anode resistance is also called A.C. plate resistance, or simply anode (or plate) resistance. The term anode impedance is sometimes used but strictly speaking this is not quite correct as r_a is not concerned with anode to cathode capacitance which is part of the impedance at high frequencies.

Triodes have A.C. anode resistances ranging from less than 1,000 ohms up to about 80,000 ohms.

(It is important to note that the D.C. resistance of the tube is not a constant value but depends on the grid voltage. It is not listed by manufacturers but when required, its value can be easily calculated for a particular bias by referring to the characteristic curves.)

.6 Amplification Factor is a ratio expressing the relative effectiveness of the grid voltage to that of the anode voltage in controlling the anode current. It is generally defined as the ratio of a small change in anode voltage to the small change in grid voltage required to cause an equal change in anode current.

$$\text{Amplification factor} \quad \frac{\text{Small Change in } E_a}{\text{Small Change in } E_g}$$

(required to cause the same change in I_a or to maintain I_a constant).

$$\mu = \frac{\Delta E_a}{\Delta E_g} \quad (I_a \text{ constant})$$

where
E_a is anode voltage.
E_g is grid voltage.
Δ means "a small change in".

Considering the examples given in paras. 4.4 and 4.5 for g_m and r_a, a 1V change in E_g changed I_a by 2mA and a 20V change in E_a changed I_a by the same amount. If these figures were obtained with the one tube, then -

$$\mu = \frac{\Delta E_a}{\Delta E_g} = \frac{20V}{1V} = 20$$

There is no unit for μ as it is a ratio of two voltages.

It is important not to confuse the terms amplification factor and gain. Amplification factor is the maximum voltage amplification a tube is capable of under ideal (test) conditions. Gain is the voltage gain or power gain of one or more complete stages of an amplifier and therefore takes into account the performance of the circuit as a whole and not only that of the tube under test conditions. With any one stage, voltage gain is always less than the amplification factor given for the tube, although for triodes it may approach it in value when circuit design so intends. This is dealt with in the paper "Amplifiers".

Different triodes have values of μ ranging from less than 10 up to about 100.

4.7 Relationship between r_a, g_m, and μ. Amplification factor μ actually takes into consideration the values of both anode resistance r_a and the mutual conductance g_m.

r_a relates ΔE_a to ΔI_a

g_m relates ΔE_g to ΔI_a

and μ is $\frac{\Delta E_a}{\Delta E_g}$ for the same ΔI_a.

Therefore μ combines the information of both r_a and g_m. When r_a in ohms is multiplied by g_m in mhos the product is μ for the particular tube. This may be proved by a simple algebra sum -

$$r_a \times g_m = \frac{\Delta E_a}{\Delta I_a} \times \frac{\Delta I_a}{\Delta E_g} \text{ (previously defined)}$$

Cancelling I_a.... $r_a\, g_m = \frac{\Delta E_a}{\Delta E_g}$

Since $\mu = \frac{\Delta E_a}{\Delta E_g}$ (previously defined) $\quad \mu = r_a\, g_m$

where
μ is Amplification factor.
r_a is A.C. anode resistance.
g_m is mutual conductance.

The three forms of this equation are -

$$\mu = r_a\, g_m \qquad r_a = \frac{\mu}{g_m} \qquad g_m = \frac{\mu}{r_a}$$

Combining the figures of the previous examples -

With a g_m of 2mA/V and r_a of 10,000 ohms a tube has an amplification factor of -

$$\mu = r_a\, g_m$$

$$= \frac{2}{1000} \times 10{,}000 = 20$$

When g_m is expressed in micromhos (2000 micromhos for this example)

$$\text{Then} - \mu = \frac{2000}{10^6} \times 10{,}000 = 20.$$

Since μ is the product of r_a and g_m, high values of either or both contribute towards high values of μ.

..8 Variation of r_a, g_m and μ. Individually, the values of the constants are not truly constant but vary with the applied voltages. If the relationships between E_a, I_a and E_g were constant over the whole range, the characteristic curves would be linear, parallel and equally spaced. As we have seen from Fig. 6, this is not so and the figures given in tube manuals for the constants refer to their value at typical anode and grid voltages which are also listed. Referring again to Fig. 6, the figures for triodes generally apply to the region near points X and Z.

Values for r_a, g_m and μ can be calculated by selecting points anywhere on the curves. Note that the ratio of voltage and current changes will have altered for parts of the curves which have a different slope. A fairly uniform slope of the mutual characteristics indicates that the g_m is fairly constant within that region. Uniform slope of the anode family indicates that r_a is fairly constant within that region. (The term "slope" is sometimes loosely applied to g_m such as a "slope of 4mA/V" or a "steep slope" to indicate high value of g_m.) The equal spacing between curves indicates that μ has a fairly constant value.

The variation of the constants is the reason for calculating their value using "small changes".

..9 Significance of Tube Constants. The true significance of r_a, g_m and μ lies in the ways they may be related to actual circuits and the suitability of particular tubes for various applications.

Even when the foregoing derivation of $\mu = r_a g_m$ is quite well understood it is not always easy to appreciate at first why r_a is just as important as g_m in determining gain when the tube is used as a voltage amplifier. It is fairly easy to see that grid control of anode current of say 6mA/V suggests more gain than 1.5mA/V. It may not be so apparent why an r_a of 40,000 ohms compared to one of 10,000 ohms should suggest an equal improvement.

The constants enable us to express in symbols the fact stated in para. 4.2 - a tube is capable of amplification because E_g can control I_a much more effectively than can E_a. It is not the actual values but their relation to each other as expressed in the formula -

$$\mu = \frac{\Delta E_a}{\Delta E_g} \quad (I_a \text{ constant})$$

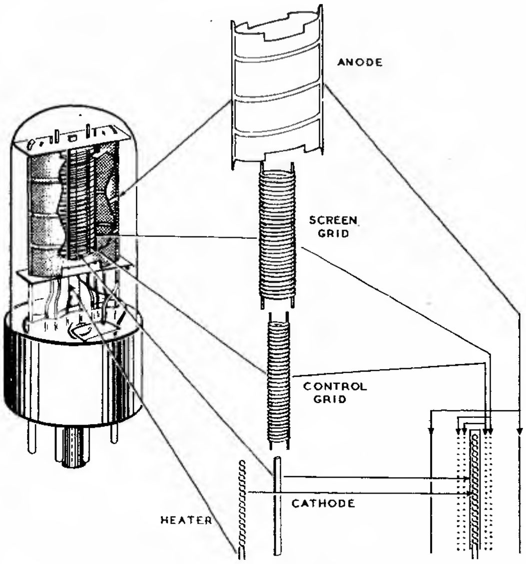
μ will be increased if either ΔE_a is made larger or ΔE_g made smaller in relation to the other (for a given ΔI_a). But making ΔE_a larger for a given ΔI_a is the same as increasing the anode resistance r_a since this is $\frac{\Delta E_a}{\Delta I_a}$ (E_g constant). The larger r_a then, the less effect E_a changes have on I_a, thereby increasing the relative effectiveness of E_g changes.

Once grasped, the relationships between the constant and the changes they represent become simple and significant, but being a threefold relationship they cannot be simply summed up in a few words. Their application will be made more apparent when amplification is examined further in the paper "Amplifiers".

Remember, however, that voltage gain is always less than μ which is only a theoretical maximum.

5. TETRODES AND PENTODES.

5.1 The ability of a triode to amplify depends on the effectiveness of the control grid voltage as compared to that of the anode voltage in controlling anode current. The effectiveness of the control grid in this respect may be increased by placing it closer to the cathode in relation to the anode to cathode distance and by forming the grid wires into a finer mesh. These factors set physical limitations on the ability of a triode to amplify. Another factor limiting conventional triodes under certain conditions is the unavoidable capacitance between the electrodes (inter-electrode capacitance), especially that between grid and anode which at high frequencies results in undesirable feedback from output to input. For example a typical triode grid-to-anode capacitance of 2.5μμF has a reactance of about 64,000 ohms at 1Mc/s but only about 640 ohms at 100Mc/s. (Some modern communications equipment operates at frequencies ranging into thousands of Mc/s.)



5.2 The tetrode was introduced in 1926 and has four electrodes - the three of the triode plus another grid between the control grid and anode which is known as the screen grid or simply "screen". The screen grid is similar in construction to the control grid. Fig. 8 shows the basic arrangement of electrodes and the schematic symbol.

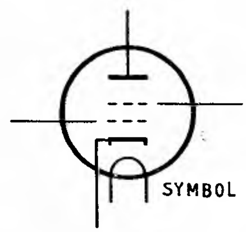
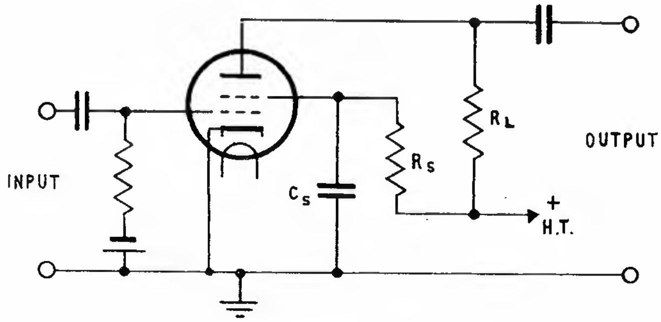
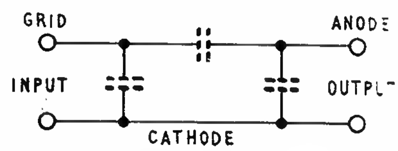


FIG. 8. TETRODE - ELECTRODE ARRANGEMENT AND SYMBOL.

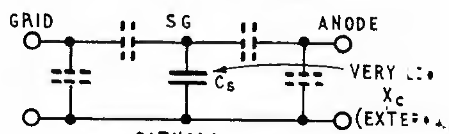
Fig. 9a shows how the screen is connected in a basic tetrode amplifier circuit. The screen is at a positive potential with respect to cathode, usually somewhat less than anode potential but not always. The screen is supplied by a series dropping resistor or a voltage divider, but for A.C. signals it is effectively at cathode potential because of the bypass capacitor C_S which has low reactance at the lowest frequency being amplified.



(a) Basic Tetrode Amplifier.



(b) Triode Inter-electrode Capacitances.



(c) Tetrode Inter-electrode Capacitances.

FIG. 9.

The grid to anode capacitance is therefore divided into two - the grid to screen and screen to anode capacitances. As the screen is effectively earthed to signal voltages, undesirable electrostatic (capacitive) coupling between anode and grid (output to input) is reduced 100 times or more. The respective conditions for triodes and tetrodes are compared in Figs. 9b and c.

The screen has a second important effect on the tube characteristics. Being at a positive potential and closer to the cathode than is the anode, the screen accelerates the electrons through the space between cathode and anode and makes the anode current less dependent on anode voltage. That is, changes of anode voltage do not change the anode current as much as in a triode because the steady positive voltage on the screen masks the effect of anode voltage changes. This has a marked effect on the anode resistance r_a of tubes with a screen grid.

$$\text{Since} \quad r_a = \frac{\Delta E_a}{\Delta I_a} \quad (E_g \text{ constant}) \quad -$$

the constant screen potential causes large changes in E_a to have only a small effect on I_a. When compared to triodes, the value of r_a is increased by about 10 to 100 times or more.

5.3 Secondary Emission. Some of the electrons striking the anode have sufficient energy to knock other electrons from its surface. These secondary electrons constitute what is known as secondary emission. In tetrodes, at certain values of anode and screen voltage secondary emission results in reduced anode current and increased screen current. This is because the positive screen is close to the anode and may collect more of the secondary electrons than the anode. Fig. 10 shows how the anode characteristic curve of tetrodes is affected by secondary emission.

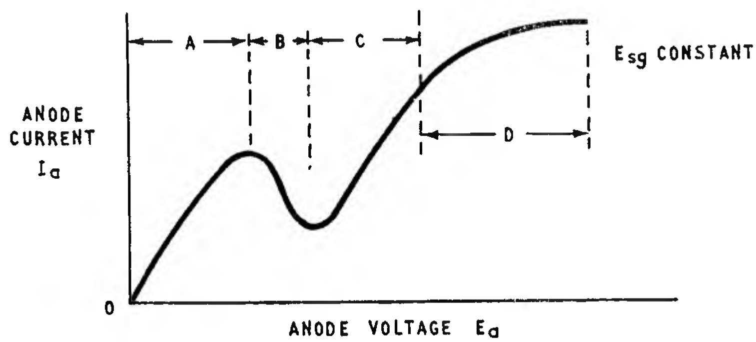


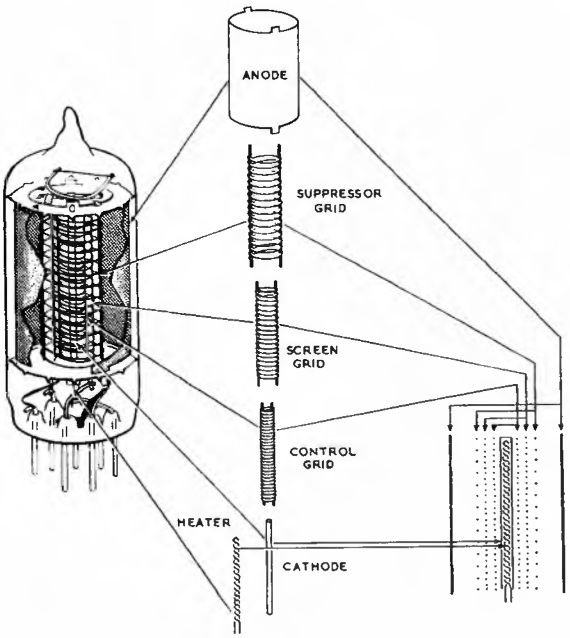
FIG. 10. ANODE CHARACTERISTIC OF A TETRODE.

In the "A" region of the curve the anode voltage is low and electrons do not have sufficient energy to cause secondary emission. In the region "B", secondary emission starts and here the screen voltage is at least as high as the anode voltage so the screen collects all the secondary electrons and the anode current decreases with an increase in anode voltage and vice versa. Because of this, the region is called the "negative resistance" or "dynatron" region of the tetrode. In the region C, the anode voltage is higher than the screen voltage and most secondary electrons return to the anode.

It is only in region "D" that the tetrode exhibits a reasonably constant value of r_a and for effective use as a voltage amplifier must be operated in this region.

5.4 Use of Tetrodes. Tetrodes are seldom used in low power circuits because pentodes will do the same job for most applications. In maintaining a suitable working point pentode voltage requirements are much less critical. One type of oscillator called a dynatron oscillator makes use of the negative resistance portion of the tetrode characteristic. Tetrodes are common in high power amplifiers of broadcast transmitters.

5.5 Pentodes. Excessive screen grid current of the tetrode at lower anode voltages is avoided in the pentode - a five element tube - by the use of a third grid called the suppressor grid placed between screen grid and anode. Fig. 11 shows the basic electrode arrangement for pentodes and the schematic symbol.



The suppressor is generally connected to the cathode which makes it negative with respect to the anode to repel secondary electrons back to the anode. Some tubes have the suppressor connected internally to cathode. The screen grid operates as for the tetrode and the basic connection remains as in Fig. 9a.

The suppressor grid (or "suppressor") helps to further reduce the grid-to-anode capacitance when compared with triodes and tetrodes by acting as an additional electrostatic shield.

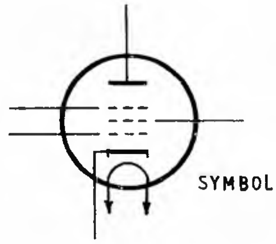


FIG. 11. PENTODE - ELECTRODE ARRANGEMENT AND SYMBOL.

The high value of r_a for tetrodes applies also to pentodes but is usable at lower anode voltages. Fig. 12 shows an anode characteristic family of curves for a typical pentode. Notice the pronounced knee which occurs at a fairly low anode voltage and above which anode voltage increases have a very much smaller effect on the anode current - that is, A.C. anode resistance r_a is very high. Values for r_a of up to [illegible] are very common and some pentodes have values as high as 2.5MΩ.

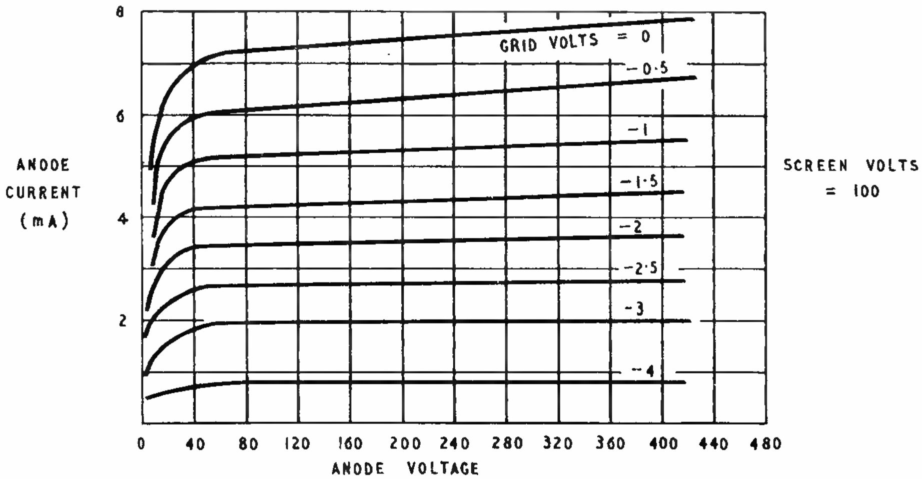


FIG. 12. ANODE CHARACTERISTIC FAMILY OF TYPICAL PENTODE.

5.6 High Gain from Pentodes. The range of mutual conductance values for different pentodes is of the same order as that for triodes - that is from about 1mA/V to about 10mA/V (1,000 - 10,000 micromhos). Now, as amplification factor $\mu = r_a g_m$ the very high values of r_a for pentodes denote very high values of μ which, at first glance, seems to suggest extremely high voltage gains. For example, the pentode 6BH6 has an anode resistance r_a of 1.4MΩ and a mutual conductance g_m of 4.6mA/V.

$$\text{Therefore } \mu = r_a g_m$$
$$= 1.4 \times 10^6 \times \frac{4.6}{1000}$$
$$= 6{,}440.$$

In practice, other factors limit greatly the actual voltage gain obtainable with pentodes. However, in practical resistance loaded audio frequency amplifiers voltage gains of from 100 to 300 are obtainable with pentodes while that for triodes seldom exceeds 70. Even higher gains are realised in narrow band high frequency amplifiers where anode loads are parallel resonant circuits.

All these considerations are examined in the paper "Amplifiers". The theoretical values of μ are not listed for pentodes in tube manuals because r_a and g_m give sufficient information and the virtually unattainable amplification factor is of no practical significance.

5.7 Classification of Tubes. The majority of tubes are classified as "receiving tubes" or low power tubes which because of their size and design are used for such applications as radio and television receivers, public address amplifiers etc. The tubes used in carrier telephone systems, long line V.F. signalling, and miscellaneous amplifiers in telephone and trunk exchanges all come within this category. Receiving tubes may be considered as covering the range up to about 20 or 30 watts; the majority handle much less power. The wattage rating of tubes refers to the anode dissipation only, that is E_a max. X I_a max.

The term "transmitting tubes" is generally reserved for tubes of much larger power handling capacity (and usually large in size) such as those used in the final stages of radio broadcast transmitters and which range from less than 100W rating up to several kilowatts. The dividing line is fairly indefinite however because some tubes suitable for small transmitters are used also to obtain large audio frequency outputs. Also the low power stages of radio telephone and broadcast transmitters are catered for using receiving tubes.

5.8 Comparison of Triodes and Pentodes. The following table compares the essential features of triodes and pentodes within the receiving tube category. The figures give the general range, not the exact upper and lower limits.

	Triodes	Pentodes	Remarks
g_m	1 - 10mA/V	1 - 10mA/V	Majority 2 - 6mA/V. A few less than 1
r_a	1,000Ω - 80kΩ	300kΩ - 2.5MΩ	
μ	2 - 100	Not generally listed (little practical significance)	r_a X g_m about 1,000 to 7,000
Grid-Anode Capacitance	1.4 - 6μμF	.001 - 0.1μμF	
Heater or Filament Current	0.05A - 2.5A	As for triodes	Few exceed 0.6A Most generally 0.3A
Voltage Gain	Up to 80 times	Up to 300 times	As practical resistance loaded A.F. amplifiers

6. BIASSING METHODS.

6.1 The D.C. voltage required to bias the grid negative with respect to cathode is obtained in several different ways. We saw in Section 13 that it is not usually desirable or necessary for the grid to become positive to cathode at any stage of its operation. This condition is met in what is known as Class A amplification and this applies to the majority of amplifiers especially those operating at audio frequencies. Other classes of amplifiers are dealt with in the paper "Amplifiers".

Value of Bias Needed. When the grid is not to be driven positive, D.C. bias must be at least as high as the peak voltage of the A.C. signal to be applied to the grid. For example, if the maximum peak amplitude of the input is 12V, then bias must be at least 12V D.C. If the signal is only a few millivolts, bias may be 1V or less. A tube is chosen which will handle the maximum grid swing (twice the peak amplitude). An ideal Class A amplifier with correct bias allows equal anode current changes for equal positive and negative swings of the signal input. The actual bias voltage is mainly determined, therefore, by the characteristics of the tube and sets the working or operating point at about the centre of that part of the mutual (E_g/I_a) characteristic which is most linear (E_g negative).

6.2 Battery Bias is not greatly used in modern tube circuits except for some battery operated portable equipment. Battery bias is shown in Figs. 4a and 9. As no appreciable current drain is required, bias batteries are small and give reasonably long service between replacements.

6.3 Cathode Bias or Self Bias is the most common method of obtaining bias. Figs. 13a and b show typical cathode bias circuits with two types of input coupling.

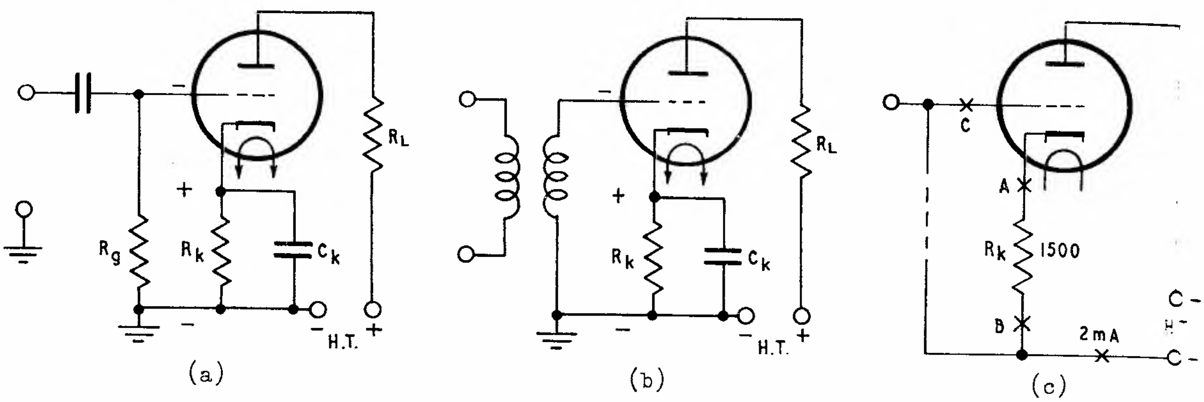


FIG. 13. ELEMENTS OF CATHODE BIAS.

The cathode current flowing in the bias resistor R_k makes the cathode positive with respect to earth by the voltage drop across R_k. Fig. 13c shows this in simplified form. Suppose, for example anode current in the tube is 2mA and R_k is 1500Ω. Using Ohm's Law, the cathode end of R_k (point A) is positive with respect to point B by 3V ($E = IR = 0.002 \times 1500$). Points B and C are at the same potential as there is no direct current through the resistance between them (the grid always has a D.C. path back to —H.T. or earth). Therefore C is negative with respect to A by the voltage drop across R_k. Similarly, the value of R_k can be calculated from the required bias voltage and the cathode current.

With tetrodes and pentodes the cathode current is the sum of anode and screen current. Apart from its simplicity, cathode bias has some important advantages. It stabilises the operation to a useful degree against fluctuations of high tension voltage (H.T.) and changes of tube characteristics with age. It also automatically compensates for slight differences in characteristics between tubes of the same type. Any one of these factors which tends to make the tube draw a larger anode current is counteracted to some extent by the increase in bias resulting from the increased voltage drop across R_k. A fall in anode current has the opposite effect of lowering bias. This keeps the anode current within narrower limits.

Bypassing. Because variations of anode current with signal would be affected in a similar way, R_k is bypassed for the A.C. signal component by a capacitor C_k as it has a very low reactance compared to R_k.

The value of C_k depends mainly on the lowest frequency to be amplified at which frequency it must be a high enough value to have low reactance compared with R_k. This will ensure that negligible A.C. voltage at the lowest signal frequency appears across R_k to be fed back as input to the grid along with the D.C. bias. At audio frequencies, 25μF is a common value for C_k; at radio and carrier frequencies smaller values are adequate. Any signal voltages produced across R_k are superimposed on the bias in the opposite direction to the original signal and this reduces the gain of the amplifier stage at the particular frequency.

Cathode bias has one minor disadvantage in that the anode-cathode voltage is reduced by the drop across R_k. Compared to the drop in R_L, this is negligible in most cases but becomes important where low anode supply voltages such as 50V are used.

Note that a tube cannot be biassed to cut-off with cathode bias no matter how large R_k is made. Bias is developed only while the tube conducts.

.4 Back Bias is obtained from a dropping resistor at the "back" of the high tension power supply. Fig. 14 shows the elements of back bias.

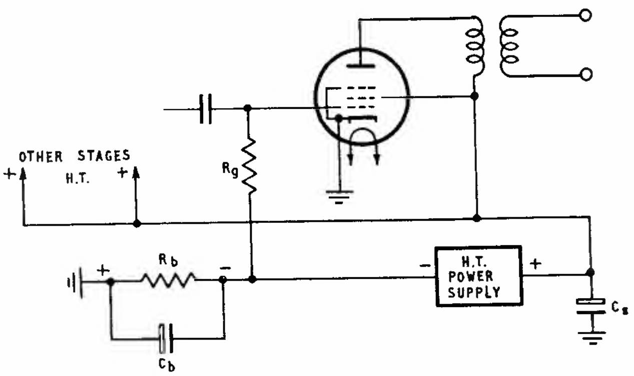


FIG. 14. ELEMENTS OF BACK BIAS.

The negative pole of the high tension supply is usually connected to the earth common, or framework on which components are mounted (which may or may not be actually earthed). When back bias is used, the supply —ve is connected to the common via the bias resistor, R_b. The voltage across R_b is applied between grid and cathode of the tube via the normal grid resistor R_g and the earth common. In principle, it is very similar to cathode bias except that the value of R_b is determined by the required bias and the total current being drawn from the supply. This generally includes the H.T. supply to other stages of the amplifier or associated circuits.

Sometimes back bias is derived for several stages required different bias values, by making R_b a voltage divider tapped at suitable points.

Bypassing for Signal and "Hum". R_b is bypassed by capacitor C_b to prevent unwanted signal feed-back as explained for cathode bias. Whether back bias is used or not, the whole supply is always bypassed by a capacitor C_s to prevent varying voltages being developed across the internal impedance of the supply, especially when it is a mains rectifier or dry cells, both of which have appreciable internal impedance.

Bias resistor bypass capacitors C_k in Fig. 13 and C_b in Fig. 14 have another useful function. Suitably large values of these components help to reduce "hum" in A.C. operated amplifiers. The bypass capacitors filter the 100c/s hum voltage from across the bias resistor which would otherwise be applied between grid and cathode, and amplified.

The small hum voltages arise from two sources - the small ripple from the power supply which may be left after the filtering, and induction and leakage between the A.C. operated heaters and the cathodes of amplifier tubes. For this reason C_k and C_b are frequently made larger than is necessary for good response at the lowest desired frequency. For example, 10µF would bypass an R_k of 1,000 ohms quite well for frequencies as low as about 100c/s but 25µF is often used because of the lower impedance offered to hum.

6.5 Grid Leak Bias. The components necessary for grid leak bias are connected in either one of two ways as shown in Figs. 15a and b. Bias is produced by the action of the input signal and adjusts itself to a value determined by the values of C_g and R_g and the signal amplitude and frequency.

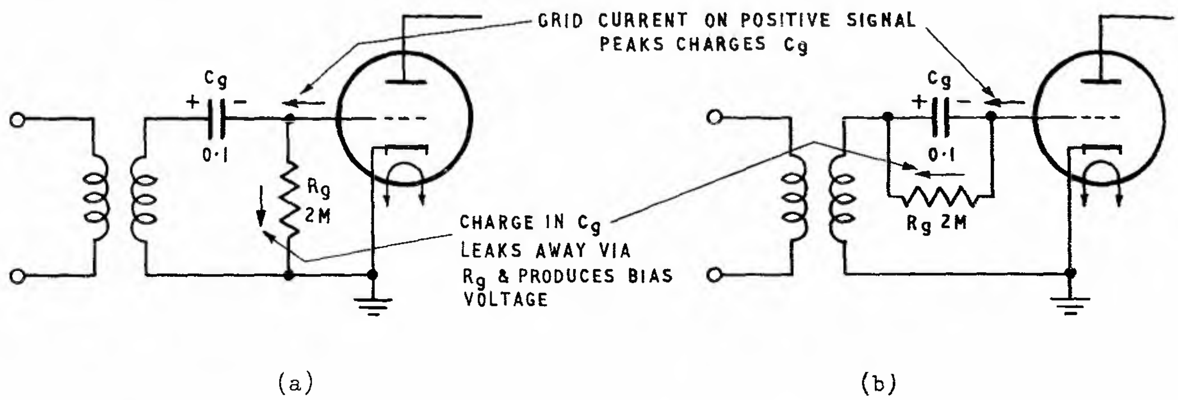


FIG. 15. GRID LEAK BIAS.

The action is similar for either case. When first connected to signal, grid current flows on positive half cycles but not on the negative half cycles. That is, the signal is rectified by the grid and cathode acting as a diode. The unidirectional pulses soon charge C_g to the polarity indicated, but the charge leaks through resistor R_g which has a high enough value to allow C_g to remain charged between signal positive pulses. The combination of C_g and R_g therefore establishes a voltage making the grid negative to cathode. Once the steady value is reached, the grid need only become positive to cathode for a brief part of the cycle on positive signal peaks. When desired, suitable values of C_g and R_g can produce a bias voltage nearly equal to the peak amplitude of the signal voltage.

The two requirements for bias with this method are -

(i) Signal must be present (no signal, no bias).

(ii) Grid current must flow some of the time to maintain C_g charged to maintain bias.

Therefore grid leak bias does not meet the requirements for Class A amplifiers as outlined in para. 6.1. Grid leak bias is used for some oscillators and high power R.F. amplifiers. It is not used for audio frequency amplifiers because signal is absent in silent periods and because distortion would be too great. At low frequencies, the bias would vary because C_g would discharge between charging pulses; very high values of C_g and R_g are not practicable.

Fig. 16 represents how grid leak bias is developed for an R.F. oscillator from the moment of switching on. Once operating, such circuits generally develop a large grid voltage swing with the aid of a tuned circuit which drives the anode current from maximum to zero. Operating bias voltage may be well beyond cut-off and nearly equal to the peak signal voltage, but zero bias is necessary to allow such circuits to be self-starting.

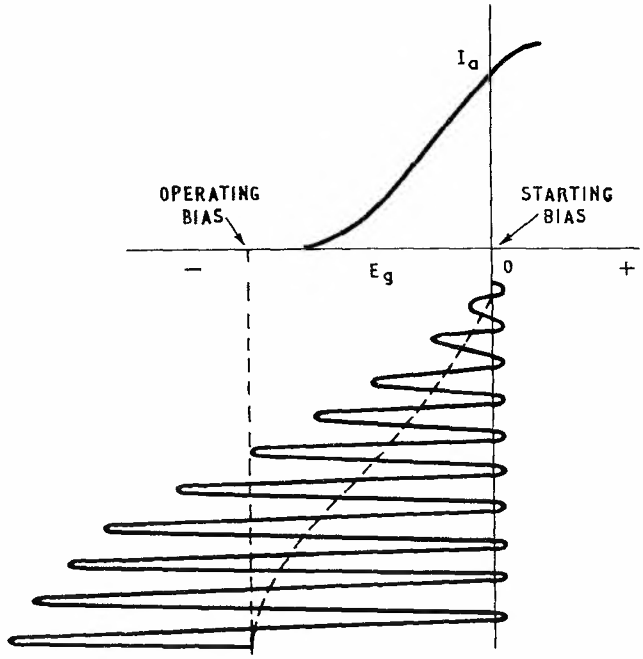


FIG. 16. DEVELOPING GRID LEAK BIAS - R.F. OSCILLATOR.

Since bias is absent when there is no signal, certain circuits such as R.F. power amplifiers may use a combination of grid leak and some other form of bias such as cathode bias. The latter protects the tube against excessive and continuous anode current should the signal input, and thus grid leak bias, fail for any reason.

5.6 Contact Potential Bias is sometimes used with triode tubes used as small-signal A.F. amplifiers. (Fig. 17.)

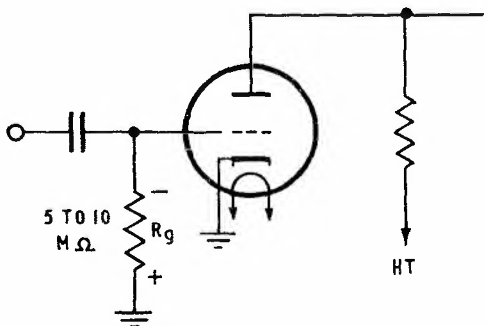


FIG. 17. CONTACT POTENTIAL BIAS.

Because of the different metals used for the various electrodes, electro-chemical activity produces potentials between electrodes without external voltages applied. The grids may be regarded as immersed in the electron stream like the electrodes of a voltaic cell in a liquid. In indirectly heated tubes, the control grid assumes a potential varying from about -0.1V to -1.1V with respect to cathode. With certain tubes only, this is enough for bias, providing the grid to cathode resistor R_g is made high enough not to shunt the weak potential away.

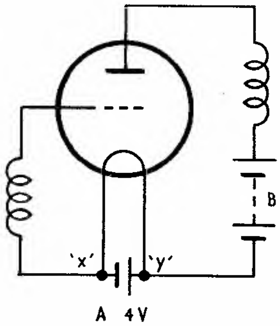
Some explanations hold that a few electrons strike the grid and leak away through Rg to produce the bias. One tenth of a microamp in 10MΩ is sufficient to produce a bias of 1V.

Some textbooks use the term grid leak bias when referring to this type of bias. Irrespective of the names, however, the two types of bias should not be confused. What we have termed contact potential bias reaches only about 1V but is maintained whether signal is present or not, whereas the grid leak bias described in para. 6.[illegible] can be arranged to give quite high values of bias but only when signal is applied.

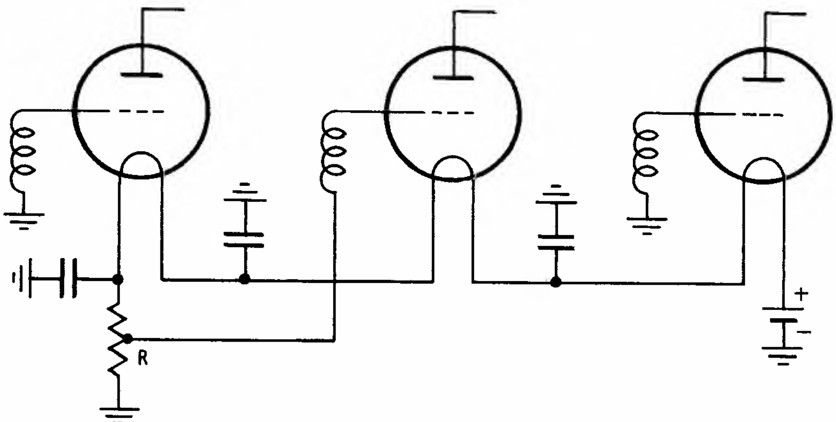
6.7 Filament Bias. This term has been applied to two methods of biassing, which do not have much application in modern equipment, being used mainly with directly heated tubes. Figs. 18a and b represent the elements of each type.

Type (a) is used only with directly heated tubes, and it results in an average bias of half the filament voltage. The grid has no bias in relation to the end of the cathode marked "X", and a bias equal to the filament voltage with respect to the end marked "Y". Average bias is therefore half the filament voltage.

In the type shown in Fig. 18b, the filaments (or heaters if the tubes are indirectly heated) are connected in series and used as a voltage divider to obtain the required bias for the respective grids.



(a)



(b)

FIG. 18. ELEMENTS OF FILAMENT BIAS.

6.8 Fixed and Self Bias. Some text books divide all biassing methods into two categories - fixed bias and self bias. Self bias usually refers to cathode bias, but grid leak and contact potential bias are also forms of self bias. Battery bias and filament bias are fixed bias. Back bias is intermediate in character between fixed and self bias. When the tube concerned draws a large percentage of the total current from the power supply it approaches cathode bias; when it draws only a small percentage back bias is nearly fixed bias.

Other methods of biassing may be encountered, though only rarely. Fixed bias for [illegible] amplifiers is sometimes provided by bias rectifiers entirely separate from the H.T. anode supply rectifier. Because of its simplicity and important advantages, cathode bias now caters for probably 95% or more of all bias requirements.

7. SPECIAL TUBES.

7.1 To suit particular purposes, a number of special tube types are made which are generally adaptions of ordinary triodes, tetrodes or pentodes.

7.2 Beam Power output tetrodes are tetrodes having additional beam forming plates which confine the electron stream into two fairly narrow beams. The plates also induce an electric field between screen and anode which functions somewhat like the suppressor grid of pentodes in limiting the adverse effects of secondary emission. Fig. 19 shows how beam tetrode tubes are constructed to achieve these effects.

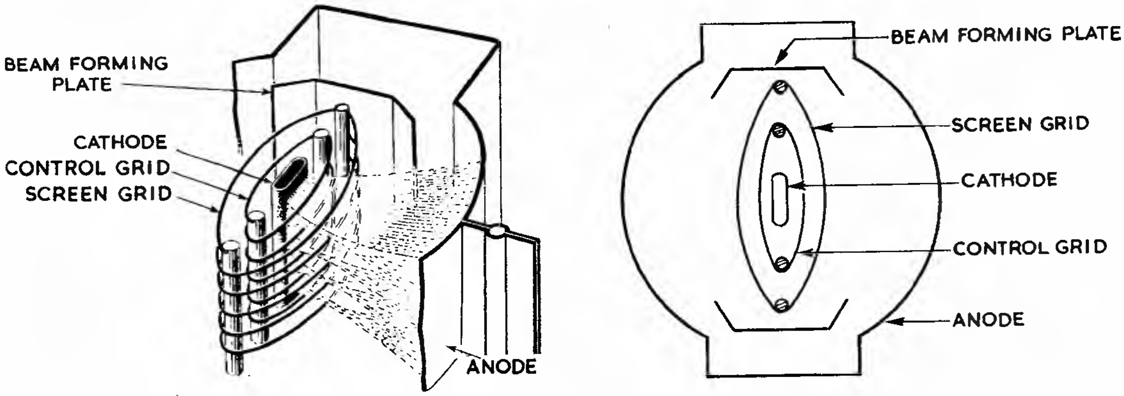
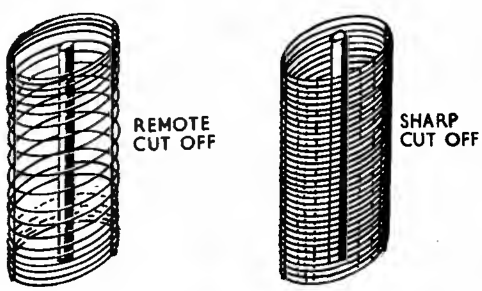


FIG. 19. STRUCTURE OF BEAM POWER TUBE.

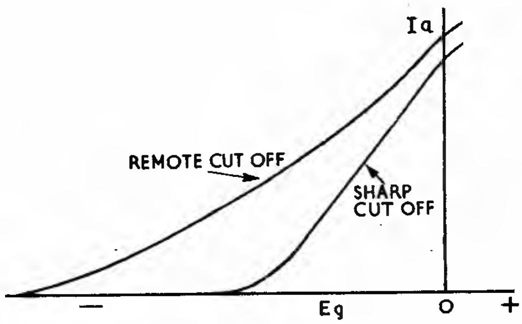
A feature of beam power tubes is the comparatively low screen current drain. The screen grid is wound with its turns in line with the control grid turns. The effect of the beam forming plates and the 'shading' of the screen by the grid is that the electrons travel in 'sheets' between the grid and anode with comparatively few flowing to the screen. Ordinary pentodes generally have screen currents of from about one-third to one-sixth of anode currents, whereas beam power tetrodes generally have a much lower proportion of screen current. In some cases it is as low as one-fifteenth of anode current.

In other respects, beam tubes are equivalent to pentodes and families of characteristic curves have similar shapes to those of pentodes.

7.3 Variable Mu Pentodes, known also as "remote cut-off" and "super control" pentodes are similar to ordinary pentodes in every respect, except that the grid turns are not evenly spaced. Fig. 20 shows the difference in control grid construction and the comparative effect this has on the shape of the mutual characteristics. Ordinary or "sharp cut-off" pentodes have a fairly constant slope until near cut-off while the variable mu. tube has a gradually decreasing slope down to cut-off at a much higher negative bias. The slope indicates that mutual conductance (g_m) varies from maximum to minimum over a wide range of bias values.



(a) Grid Construction.



(b) Mutual Curves.

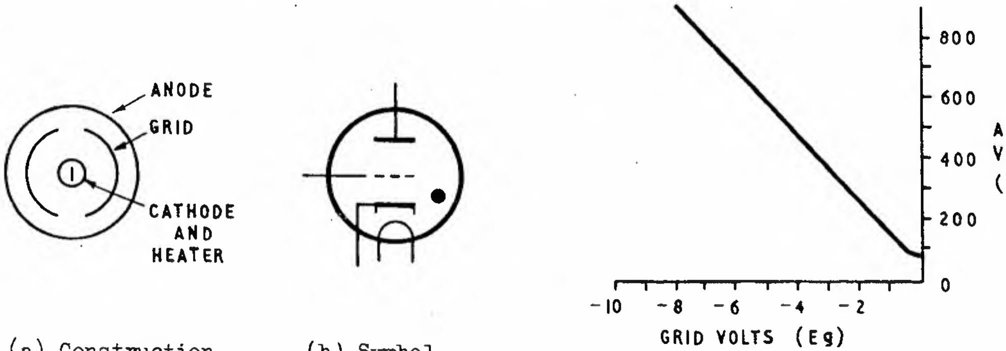
FIG. 20. COMPARISON OF VARIABLE MU AND SHARP CUT-OFF PENTODES.

The feature is used mainly for automatic gain control (AGC) or auto volume or sensitivity control, (AVC), of radio and television receivers, where a large bias is applied for strong signals and a small bias for weak signals. As r_a remains more or less constant, variable mutual conductance also results in variable μ and is often written as such.

Variable mu tubes will amplify either small or large signals without undue distortion.

7.4 Gas Triodes or Thyratrons are triodes having an inert gas at low pressure, and also a special type of grid. Fig. 21a shows the usual construction and Fig. 21b the symbol incorporating the dot to distinguish it as a gas tube. The grid is not of conventional grid construction but a cylinder around the cathode with long slits through which the tube conducts. A relatively small grid voltage is able to prevent conduction almost completely until the anode voltage reaches a critical value in relation to grid voltage. At this point the gas ionizes, the tube conducts heavily (up to several amps in some cases) and anode to cathode potential drops. This is the "striking potential" or "firing point" of the tube. The grid voltage is no longer able to exert any degree of control over anode current and to stop the current anode voltage must be reduced below another critical value or "extinction potential".

The graph of Fig. 21c shows how the grid voltage alters the firing point. The extinction potential is considerably lower than the firing point.



(a) Construction. (b) Symbol. (c) Effect of Grid Voltage on Firing Point.

FIG. 21. GAS TRIODE.

The ionized gas provides the additional free electrons for the heavy current in the same manner as described for gas diodes in the paper "Diodes and Rectifiers". The grid loses control after firing occurs, because many positive ions are attracted to it and form a charge around it which neutralizes its effect.

The Gas triode is widely used in industry as an electronic switch in counting and control circuits. It is also used in one type of oscillator to produce a saw tooth output wave form.

7.5 Cold Cathode Triodes are gas tubes and have much in common with the cold cathode diodes or voltage regulator tubes described in the paper "Diodes and Rectifiers". One type of cold cathode triode is commonly used as a electronic relay or "trigger" tube where a very small current in the gap between two of the electrodes initiates a much larger current in the main gap to a third electrode usually the anode. Fig. 22 shows the elements of such a circuit.

The voltage applied across the main gap is called the maintaining voltage and is not high enough to cause conduction. A lower voltage signal applied across the control gap ionizes the gas in the tube and the main gap conducts to supply a heavier output current which is used to operate a relay or some other control device. Like the hot cathode gas triodes, conduction continues until the anode voltage is reduced below the minimum maintaining voltage. The use of an A.C. anode supply is a simple method of de-ionizing when it is desired that output cease as soon as signal is removed; conduction then occurs only on positive peaks of the anode A.C. supply, and then only while signal is applied to the auxiliary electrode.

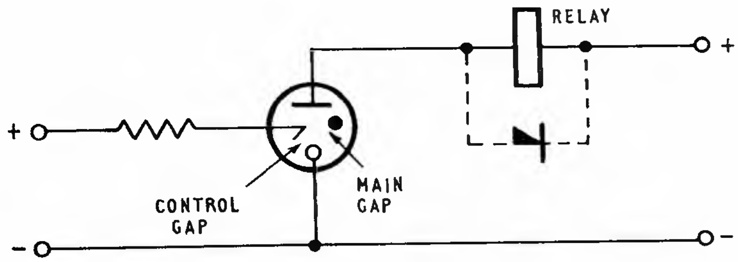


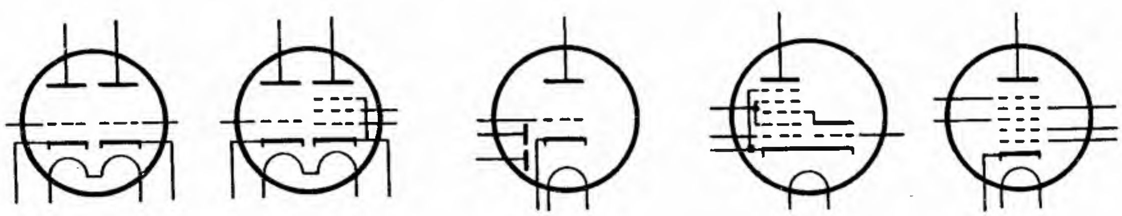
FIG. 22. COLD CATHODE TRIODE AS ELECTRONIC SWITCH.

This auxiliary electrode has various names, depending on its application; a common one is "striker anode". Some gas filled cold cathode tubes have two identical cathodes with the control gap between them in which case either one may be used as striker with the other as cathode.

These tubes do not rely on cathode emission but only on the gas discharge after ionization. For rapid firing after the signal is applied, cold cathode tubes are operated in the presence of some continual (ambient) lighting. In total darkness firing may not be immediate. Another method of ensuring immediate firing is to include with the gas in the tube a minute trace of radio active gas. Triodes having this feature are used in Crossbar exchanges where the radio active trace also ensures random selection of outlets.

Fig. 22 shows only one application. The large variety of tubes and applications are beyond the scope of this paper.

7.6 Multi-Unit Tubes have more than one complete unit within the one envelope and as such are not special tubes in the same sense as those above. Examples are twin triodes, triode pentodes and duo-diode-triodes. The units may have separate cathodes as in Figs. 23a and b, or share a common cathode as in Figs. 23c and d.



(a) Twin Triode
(b) Triode-Pentode
(c) Duo-diode-triode
(d) Triode-Heptode (Converter)
(e) Pentagrid (Converter)

FIG. 23. MULTI-UNIT TUBE SYMBOLS.

Some multi-unit tubes are designed for particular applications and have internal connections and/or additional grids. Triode heptode and pentagrid converters couple the functions of R.F. amplifier and oscillator to produce an intermediate frequency (I.F.) in radio receivers. With the pentagrid tube, the cathode and grids 1 and 2 are used as a triode oscillator while grids 3, 4 and 5 are used with cathode and anode as a normal pentode. The two inputs are "mixed" by internal connection, or by sharing the common electron stream, so that such tubes are often called "mixers".

7.7 Frame-grid tubes are those constructed using a modern technique which permits extremely fine control grid wires to be spaced only a hairs-breadth from the cathode surface. The wires are too fine to be self supporting as in conventional tubes and are stretched between a special frame type of support. High values of g_m and other advantages are obtained.

8. CATHODE RAY TUBES.

8.1 The cathode ray tube (C.R.T.) is a vacuum tube especially designed to display electrical signals so that they may be observed or measured. The size of the dis... screen determines not only the size of the tube envelope but also some of the electrode voltages. Most cathode ray tubes consist of -

(i) An electron "gun" which -

(a) projects a ray or beam of electrons along the tube axis;

(b) provides a means of converging the beam on a small spot at the distant end of the tube (focusing).

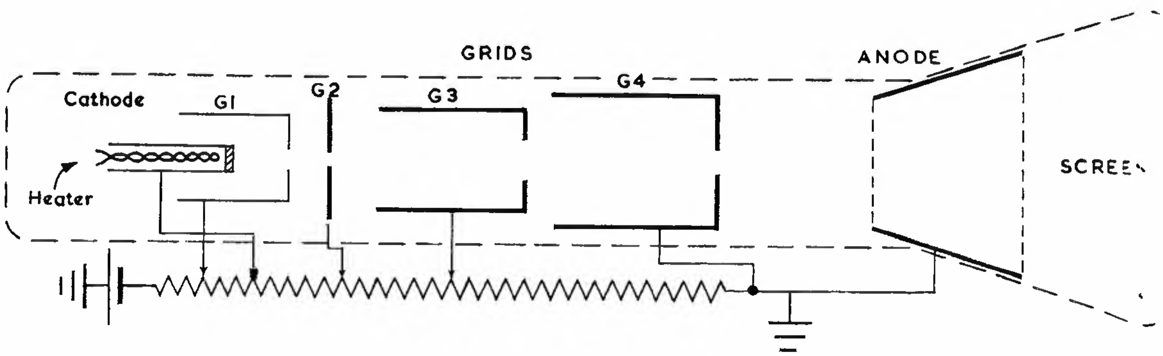
(ii) A means of deflecting the beam horizontally and vertically.

(iii) A fluorescent screen which converts the energy of the beam into light.

The beam of electrons is focused and deflected by electric fields or magnetic fie... An electrostatic C.R.T. uses electric fields and an electromagnetic C.R.T. uses magnetic fields. Some C.R. tubes have electric focusing and magnetic deflection (a very common arrangement for television "picture" tubes). Cathode ray oscillo... (C.R.Os.) generally use electrostatic C.R.Ts. There is a considerable variety of electrode arrangements used in C.R.Ts. Many of these are refinements for televis... use and need not concern us here. The arrangements described in this paper are typical of oscilloscope C.R.Ts.

8.2 The Electron Gun includes the cathode to emit electrons, the control grid to cont... the intensity of the beam, and a number of additional electrodes at a positive potential with respect to cathode which accelerate the electrons away from the cathode at a high velocity. The actual number of accelerating electrodes varies ... different types of tubes and there may be any number from two to five. Fig. 24 represents an electron gun with four accelerating electrodes - G2, G3, G4 and the anode. (The screen is shown but deflection arrangements are omitted.)

Sometimes all the accelerating electrodes are called anodes - A_1, A_2, etc. However the standard term of the Institute of Radio Engineers is "grid" for an electrode ... one or more openings to permit the passage of electrons or ions, while an "anode" collects electrons. In the case of the C.R.T., the electrons pass through the f... accelerating grid to strike the screen and then return to the anode. In some cases the screen itself includes a "metallised" backing which is connected to, and forms part of the final anode.



TYPICAL ELECTRON GUN - BASIC ARRANGEMENT AND CONNECTION.

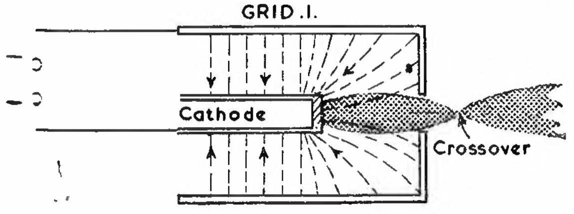
FIG. 24.

The cathode is usually indirectly heated and the emitting surface is confined to the disc shaped end adjacent to grid 1.

The grids take the form of discs with holes, or cylinders of various diameters and very often are a combination of both cylinders and discs.

Grid 1 is the control grid, intensity grid or modulator grid and is generally negative with respect to cathode. In oscilloscopes the potential of G1 is adjusted to give a pattern on the screen of the desired brightness or intensity. A varying signal is applied to this grid only when the beam is required to be interrupted or the brightness varied such as in producing the spot wheel pattern described in the paper "A.C. Measurements" (page 30) or for the black, grey and white elements of a television picture. The remaining grids are all positive with respect to the cathode and the final anode is most positive of all. C.R.Ts. with large screens require very high values of voltage on the final anode. Values up to 15kV and higher are quite common although most oscilloscopes are catered for with an E.H.T. (extra high tension) of under 10kV. As the current drain on the E.H.T. is in the microamp range the problem of the energy supply is not as great as the problems of insulation. The final anode is generally a conductive coating inside the flared portion of the envelope.

:.3 Focusing. When this is achieved electrostatically, it is the second function of the electron gun. The shape of the grids and their position and potential in relation to each other are arranged to form an electron lens system which focuses the electron beam in a manner analagous to that of optical lenses focusing a beam of light. In fact, the phenomena has long been investigated under the name of "Electron Optics".



FIRST ELECTRON LENS.
FIG. 25.

The electrons emitted tend to form a diverging beam as their like charge causes them to repel each other. C.R.Ts. have two electron lenses; the first is formed by the cathode and grid 1. The electric field between them causes the beam to converge and cross over at a point somewhere between grids 1 and 2, as represented in Fig. 25. The path of the electrons which start to diverge is bent by the electrostatic forces indicated by the dotted lines.

The first electron lens thus provides a point source at the crossover point which the second electron lens can focus on the screen.

The second electron lens is generally formed by the last two grids. The shape, spacing and potential between these provides an electric field after the manner represented in Fig. 26. On leaving the crossover point the diverging electron paths are again bent and converge gradually on the distant screen as a small spot. The 'sharpness' of the spot (or trace when deflected) is adjusted by adjusting the potential on the focusing grid (usually the second last grid) which is G3 for the type of gun represented in Fig. 26.

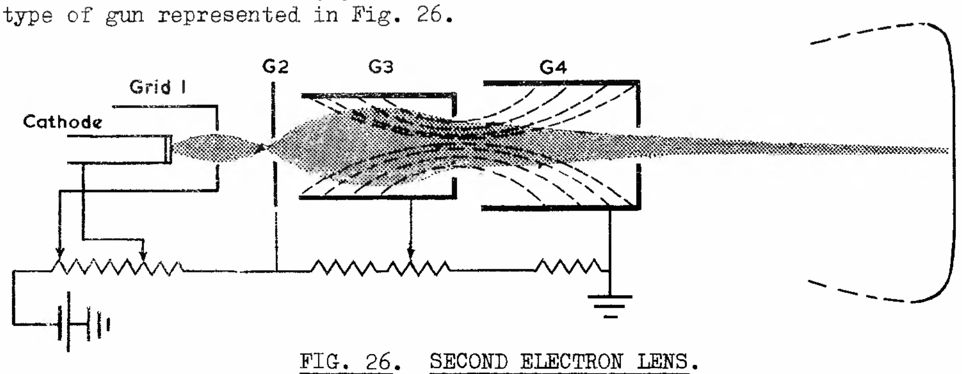


FIG. 26. SECOND ELECTRON LENS.

It should be appreciated that this description is only a broad outline as the theory of focusing is rather complex and of importance to designers of C.R.Ts. rather than users.

Magnetic Focusing. Coils or permanent magnets mounted outside the tube can also be used to focus the beam. Fig. 27 represents the focusing of a beam by the magnetic field through a coil. Correct focus is obtained by adjusting the coil current and thus the field strength.

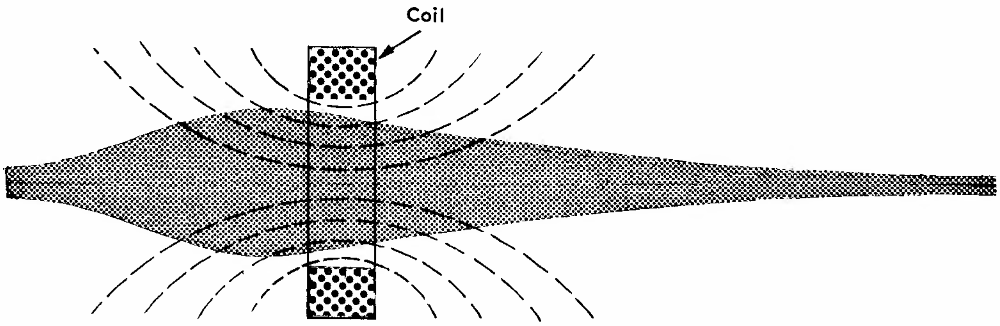


FIG. 27. MAGNETIC FOCUSING.

The magnetic focusing field causes the electrons to take a spiral path to the screen except those travelling straight through the axis of the coil which are unaffected by the equal and opposite magnetic forces.

Permanent magnet focusing generally utilises two magnets, one of which may be moved along the tube to adjust the focus.

Gas Focusing is a form of focusing not often used today. The tube contains a small quantity of inert gas (argon). Some of this is ionised and the heavier ions tend to form a thin positively charged core in the centre which attracts the electrons into a narrow beam. The method is quite effective but ion bombardment of the cathode gives these tubes a shorter life than hard (high vacuum) tubes.

8.4 Electric Deflection of the beam is accomplished by passing the beam through two sets of deflecting plates to which the deflecting voltages are applied (Fig. 28). Deflection may take place after the final anode, or between the last grid and the final anode. In the latter case the C.R.T. is said to utilise "post deflection acceleration" (P.D.A.).

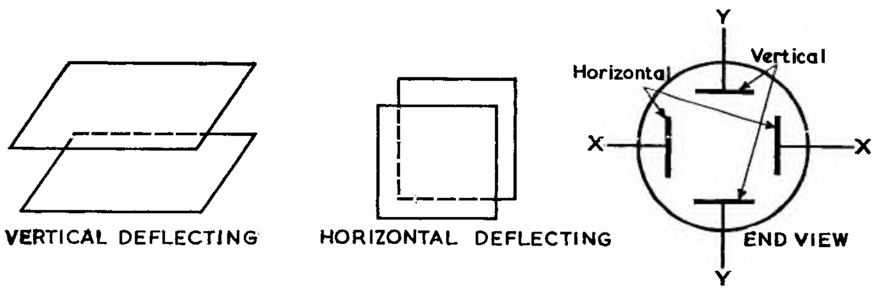
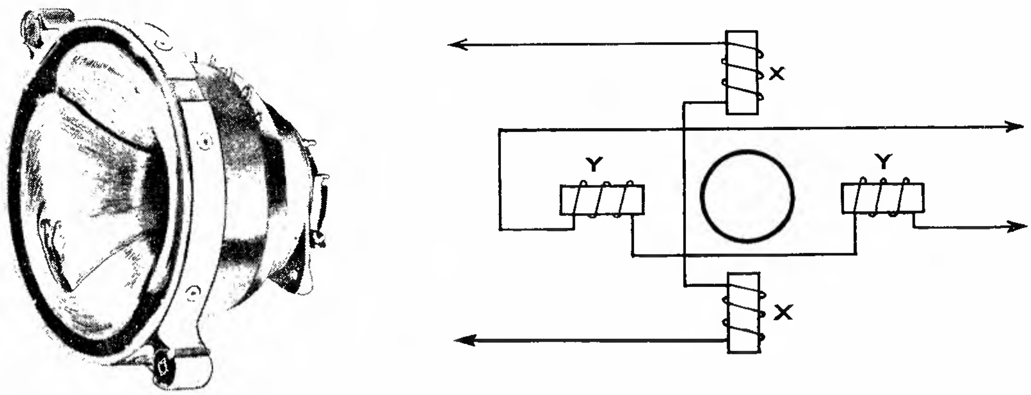


FIG. 28. DEFLECTING PLATES.

Voltages applied between the sets of plates deflect the beam away from the negative plate toward the positive plate, thus moving the spot on the screen. When signals are applied to both vertical and horizontal plates simultaneously the direction the spot moves is a resultant of the two deflecting forces. Because no current is required, (except at high frequencies where the capacitance between plates has to be considered), very little energy and power are taken from the deflecting circuits. The horizontal deflecting plates are called the X plates and the vertical deflecting plates are called the Y plates.

The larger the screen, however, the higher the voltages needed for full deflection so that large diameter tubes generally have magnetic deflection.

:.5 Magnetic Deflection. With this method a yoke consisting of four shaped coils is slipped over the neck of the tube and fits snugly against the flared or conical part of the tube. Fig. 29a shows a typical deflection yoke and 29b shows the principle and manner of connection. An electron beam is deflected at right angles to the deflecting magnetic field.



(a) (b)

FIG. 29. MAGNETIC DEFLECTING COILS.

:.6 The Screen. The end of the tube remote from the gun is coated internally with a compound termed a phosphor which emits light under the impact of the electron beam. Some phosphors continue to emit after the beam is removed and this radiation is termed phosphorescence or afterglow to distinguish it from fluorescence produced only while the beam is acting on the spot. The combination of fluorescence and phosphorescence is called luminescence.

Many different compounds or mixtures of compounds are used for C.R.Ts. providing a variety of colour and persistence which is the time the phosphorescence maintains a visible trace. Some applications require short persistence screens and others medium, long and very long. Where the repetition rate of the sweep is slow (as in radar), long persistence screens of up to a second or more are often used.

Most general purpose tubes have a medium persistence phosphor which gives a green trace. Where the pattern is to be photographed, a phosphor giving blue light is most suitable. White light, medium persistence phosphors are generally used for television tubes.

:.7 The applications of Cathode Ray Oscilloscopes are now so numerous that even a list is beyond the scope of this paper. The principles of measurement and observation with linear and circular sweeps were introduced in the paper "A.C. Measurements". Signals of all types can be applied to the electrodes in all sorts of ways to provide information in a very convenient form. With appropriate auxiliary circuits the C.R.T. becomes the most versatile of all instruments and because of this, new uses for it are continually being found; any physical quantity which can be converted into an electric signal can be observed and measured on the face of a C.R.T.

In addition to the more familiar uses in electronics and air and sea navigation (Radar, etc.) oscilloscopes are being used extensively for research and everyday measurement in Mechanical Engineering, Photography, Medicine and Nuclear Physics. Energy of almost any kind is converted to electrical signals by "transducers" designed for the particular application. (Microphones and pickups are familiar transducers.)

9. TUBE TESTING.

9.1 Maximum Ratings. Absolute maximum voltage, current and power ratings are specified for the respective tube elements in makers published data. Circuits are designed to keep tubes operating well within these limits.

9.2 Tube Faults. A tube may reach the end of its useful life abruptly or gradually as a result of one or more of the following typical faults developing.

(i) Low emission, or low cathode activity owing to deterioration of the emissive coating of the cathode.

(ii) Filament or heater open circuit.

(iii) Poor vacuum - generally caused by faulty sealing or stresses in the envelope and sometimes brought on by rough handling. Tubes with this fault are called "gassy" or "soft". (Tubes with high vacuum are "hard".) Soft tubes may sometimes be detected by the presence of a blue glow.

(iv) Internal short circuits may develop between adjacent elements.

(v) Low insulation between electrodes.

(vi) Microphonic - slight movements of electrodes may generate signals which in severe cases can cause a singing or howl when the tube is subjected to any mechanical vibration, caused, for example, by a loudspeaker.

9.3 Testing. As the condition of tubes determines the performance of equipment, routine tests are necessary where abrupt failure is to be avoided. There are two main types of tube tester. The simpler type are called emission testers as they check a tube's cathode emission. Mutual conductance testers provide a more thorough indication of performance. As a rule, all types of testers have provision for detecting short circuits or low insulation between electrodes and this test is generally done first.

An important feature of testers is a means of ensuring that the testing voltages are correct. This applies particularly to heater or filament voltages as a low heater voltage may cause a good tube to have low emission and a high heater voltage could temporarily restore the emission of a worn out cathode. As most tube testers are mains operated, a separate meter and an adjustment are provided to compensate for mains fluctuations and ensure correct input voltage to the testing circuits.

9.4 Short Circuit Test. In this test the various pairs of electrodes are switched in turn across a source of A.C. in series with a neon lamp or glow tube and capacitor. Fig. 30 shows the elements of a typical shorts test. When performing the test the tube should be at working temperature and gently tapped with the finger to check for loose connections.

The capacitor prevents the lamp glowing due to the rectifying action of the tube under test when the cathode is checked with other electrodes. The capacitor charges on the first cycle and prevents further current through the lamp unless a connection between the elements in the tube allows the capacitor to discharge. The tube glows with small values of current and indicates a low or high resistance connection.

The leads to the electrodes are tested by placing a short circuit across the capacitor and checking that the lamp glows.

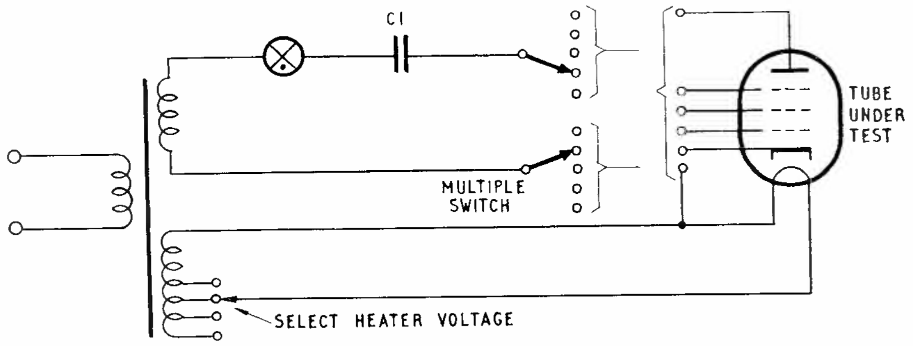
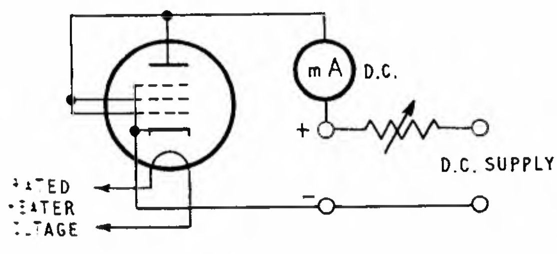


FIG. 30. ELEMENTS OF SHORT CIRCUIT TEST.

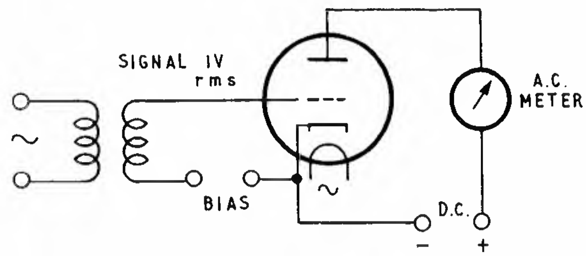
.5 Emission Test. Fig. 31 shows the circuit elements of a typical emission test. All the electrodes except the cathode are connected to the anode. When working temperature is reached, a small D.C. voltage is connected between cathode and the other electrodes, in series with a D.C. milliammeter switched to a range suited to the particular tube. The makers of the tester supply figures for good tubes for comparison, or alternatively the scale is divided into three regions - Good, Doubtful (?) and Bad. Low readings indicate that cathode activity may be below that required for good service.

The emission test has limitations as operating connections and conditions are not simulated. For example, coated cathodes may develop active spots from which emission is too great for control by the small area of grid in that region. Under these conditions the total emission may indicate the tube to be normal although it could well be unsatisfactory over most of the cathode surface. Alternatively, some coated cathodes are capable of such large emission that in many non-critical circuits the tube may perform satisfactorily long after the emission has dropped well below its initial value.



ELEMENTS OF EMISSION TEST.

FIG. 31.



ELEMENTS OF MUTUAL CONDUCTANCE TEST.

FIG. 32.

.6 A Mutual Conductance Test takes into account the basic operating principle of the tube. When properly conducted it therefore gives a better indication of performance than an emission test.

One type of mutual conductance test applies typical anode and grid voltages, and any change in anode current is noted for a specified alteration of grid voltage. This is the static or grid-shift test for g_m.

The dynamic mutual conductance test uses an A.C. input signal and therefore approximates more closely to operating conditions. The resulting A.C. component of the anode current is read by an A.C. milliammeter. Fig. 32 shows the elements of a dynamic mutual conductance tester.

When a 1V signal (R.M.S.) is applied to the grid, the A.C. component of anode current in mA is the value of g_m in mA/V. The meter scale may be calibrated in mA/V or µmhos. Electrode voltages are preselected to suit the tube by means of range switches.

Some testers provide a power output test with circuit elements similar to that of Fig. 32. A load impedance is inserted in the anode circuit and the A.C. voltage across this is proportional to power output.

.7 Tube Tester Limitations. It is impossible for a tube tester to evaluate tubes for performance in all applications and it cannot always be the final authority on whether or not a tube is satisfactory. Where possible, an actual operating test in the equipment where the tube is used will give the best indication of its worth.

10. TEST QUESTIONS.

1. Explain why a triode valve enables signals to be amplified.
2. State what is meant by the expressions:

   (i) anode voltage + 200V; (ii) screen voltage 100V; (iii) grid voltage — 5V.
3. Why are the input signals to electron tube amplifiers generally superimposed on a steady D.C. voltage?
4. With the aid of two simple diagrams, each including a mutual characteristic curve, show the effect of applying a signal to a tube:-

   (i) with bias; (ii) without bias.
5. Draw the basic circuit of a voltage amplifier and state the function of each component other than the electron tube.
6. (a) The three main variable quantities whose relationship to each other governs the performance of a tube as an amplifier are

   (i) .... (ii) .... (iii) ....

   (b) With the aid of a simple diagram, describe how a family of characteristic curves shows the relationship between these variables.
7. (a) Explain the term "mutual conductance" and how it is derived.

   (b) If the g_m of a tube is listed as 3400 micromhos, calculate the approximate change in anode current in mA when grid voltage was increased by 0.5V within its normal operating range (anode voltage maintained constant).
8. (a) Explain the term "A.C. anode resistance" and how it is derived.

   (b) If the r_a of a tube is listed as 50,000 ohms, by what value approximately would the anode voltage need to rise to increase anode current 1mA within its normal operating range (grid voltage maintained constant).
9. (a) Explain the term "amplification factor", how it may be derived, and how it is related to the mutual conductance and A.C. anode resistance.

   (b) If the μ of a triode is listed as 20 and the r_a as 10,000 ohms, state the effect on the anode current when grid voltage is made 0.5V more negative within its normal operating range (anode voltage maintained constant).
10. (a) The two principal effects of a screen grid in a vacuum tube are

    (i) .... (ii) ....

    (b) What is the principal disadvantage of the tetrode.
11. What is the function of the suppressor grid.
12. Draw the circuit of a basic pentode amplifier and explain the function of the screen bypass capacitor, including factors which determine its value.
13. Explain why pentodes allow higher gain than that of triodes.
14. (i) With the aid of a circuit, explain how cathode bias is derived, including the reason for bypassing.

    (ii) Explain the principles of one other method of obtaining grid bias.
15. Explain the differences in construction and characteristics between sharp cut-off and remote cut-off pentodes.
16. Explain briefly, the principle of a gas triode.
17. With the aid of diagrams, describe the principle of a typical C.R.T. electron gun.
18. With the aid of simple diagrams, explain briefly the basic principles of;

    (i) electric focusing and (ii) magnetic focusing of a C.R.T.
19. Describe briefly the principles of:

    (i) electric deflection and (ii) magnetic deflection of a C.R.T.
20. List three typical electron tube faults and describe briefly how a tube tester enables these to be detected.

END OF PAPER.

AMPLIFIERS.

INTRODUCTION.

1.1 An amplifier is a device which reproduces an electric signal at a higher power level. In most amplifiers the small input signal controls a large amount of energy from a separate source. Although there are many components which permit amplification of the signal level, the most widely used are electron tubes, transistors and magnetic amplifiers.

1.2 An electron tube amplifier may contain one tube with its associated circuit or may consist of several similar stages having the output of the first stage connected to the input of the second stage and so on. Single stage amplifiers capable of giving moderate output power from a fairly strong input signal are often used for V.F. trunk line repeaters. Several stages of amplification however may be required to raise the weak signals (ranging from a few microvolts to a few hundred millivolts) from radio aerials, microphones and gramophone pick-ups to a usable power level.

1.3 This paper describes the principles and application of electron tubes in amplifiers. The paper "Transistors and other Semiconductor Devices" describes the application of transistors in amplifier circuits, and magnetic amplifiers are described in the paper "Power Plant Components" in Telephony 5.

2. TYPES OF AMPLIFIERS.

2.1 General. Amplifiers are generally classified with reference to one or more of their notable features of design. Different categories of amplifiers are defined in the following paragraphs but as there are no set rules to be observed they are generally referred to by the features of immediate interest. For example, one amplifier may be described in terms of "a Class A, resistance coupled, audio frequency amplifier with a Class B push-pull output stage" and another as "a Class C, R.F. power amplifier".

2.2 Voltage and Power Amplifiers.

Voltage amplifiers give a voltage gain from input to output. Voltage amplification is always accompanied by an increase in power level at the output of a stage even though only the voltage component may be needed to drive the grid of the following stage.

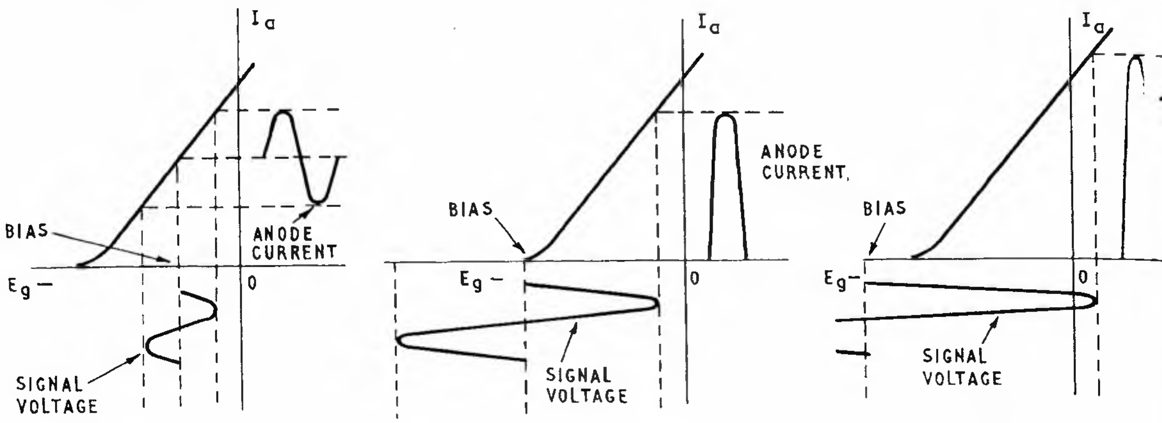
Power amplifiers generally require little or no input power but provide appreciable power to an energy converting device such as a transmitting antenna, loudspeaker or trunk line. Power amplifiers handle relatively large currents by comparison with voltage amplifiers and may give voltage gain also but this is of secondary importance.

A complete amplifier usually consists of one or more voltage amplifier stages and a power amplifying "output" stage.

2.3 Classes of Operation. Each amplifier stage is classified according to its operating conditions referred to the biassing and signal voltages applied. It is convenient to refer these conditions to a particular operating or "dynamic" mutual characteristic curve of the tube working as an amplifier.

The three main classes are Class A, Class B and Class C.

In a Class A operation the bias and signal input voltages are arranged in the design so that anode current flows throughout the whole of the cycle of input signal. Fig. 1a shows this with reference to an E_g/I_a characteristic. Practically all voltage amplifiers operate Class A and the bias voltage fixes the working point near the centre of the linear portion of the characteristic. Signal voltage superimposed on the bias will then result in equal anode current swings for equal grid voltage swings and the output waveform is a true replica of the input waveform. Operation remains Class A as long as bias and the negative signal half cycle are together less than the cut-off voltage. Class A power amplifiers often have signal input voltages large enough to include non-linear parts of the characteristic, which causes some distortion of the output signal.



(a) Class A (or A1). (b) Class B (or B1). (c) Class C.

FIG. 1.

In Class B operation grid bias is approximately equal to cut-off voltage and anode current flows for about half of each input cycle - that is, on the positive input swings. (Fig. 1b.)

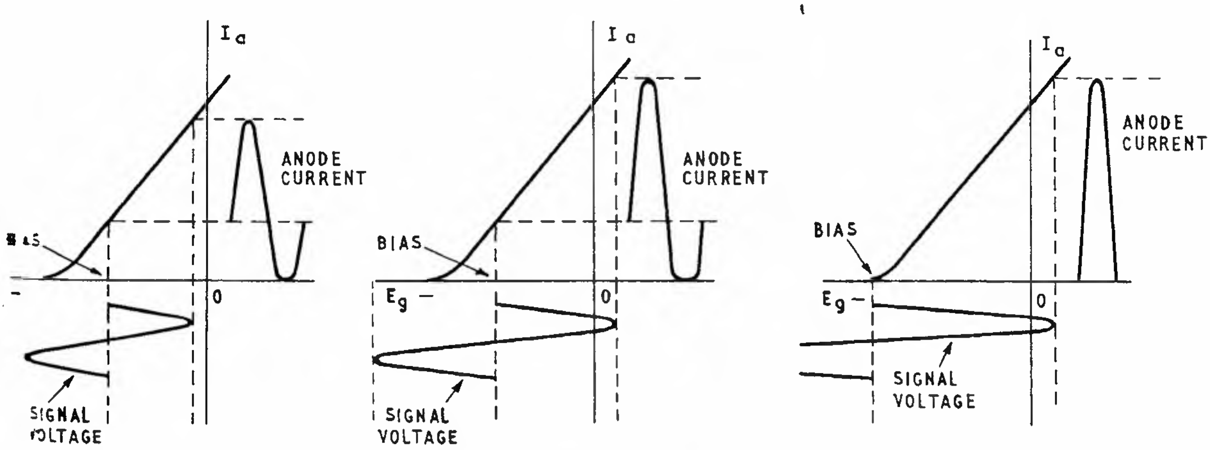
In Class C operation the grid is biassed well beyond cut-off and anode current flows for appreciably less than half of each input cycle. In most cases, bias voltage is at least twice the cut-off voltage. (Fig. 1c.)

Classes A and B are further subdivided in certain instances -

In Class AB operation grid bias and input signal voltages are such that anode current flows for appreciably more than half but less than the entire part of each input cycle; that is, in between Class A and Class B operation (Fig. 2a).

The suffix 1 may be added to the letter or letters of classification to denote that grid current does not flow during any part of the input cycle. For example - A1 as in Fig. 1a, B1 in Fig. 1b and AB1 in Fig. 2a.

The suffix 2 denotes that grid current does flow during some part of the input cycle - that is, the peak signal voltage exceeds the bias voltage. For example - AB2 and B2 (Figs. 2b and 2c).



(a) Class AB1. (b) Class AB2. (c) Class B2.

FIG. 2.

Class AB, Class B and Class C operation are used for power amplifiers. If excessive input signal voltage is applied to Class A1, AB1 or B1 stages the grids will draw grid current on positive signal peaks. The preceding voltage amplifying stage cannot generally provide much power and the input signal voltage is distorted to a reduced positive peak value and this results in distorted output waveform. (Fig. 3.) This is not regarded as changing the Class of operation from say A1 to A2 or AB1 to AB2 but is called "overloading" or overdriving the stage. At the same time excessive signal with Class A operation also causes distortion on negative signal peaks, as operation is extended into the non-linear section of the characteristic and even beyond cut-off if the stage is severely overloaded.

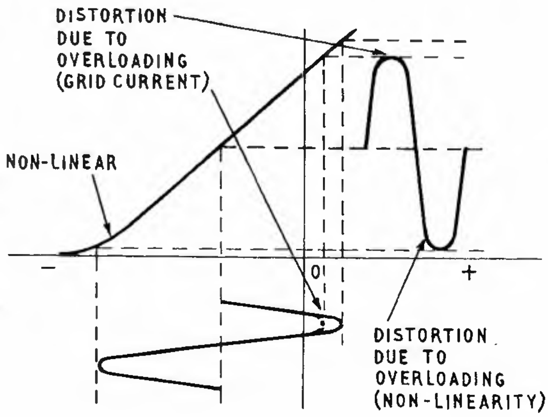


FIG. 3.

When stages are designed to operate Class AB2, B2 and C2 the preceding stage is able to supply the power necessary for grid current without excessive drop in signal peak voltage. Also tubes are used having a linear characteristic which extends well into the positive grid voltage region so that linear amplification of at least one half cycle is obtained, and, as explained in the following paragraphs this is all we need for Class AB and Class B operation.

Single tubes are often operated Class B or Class C for radio frequency (R.F.) power amplifiers of transmitters, and some oscillators are operated Class C. In these cases that part of the input cycle not amplified is regenerated by a tuned or "tank" circuit which generally constitutes the anode load. (Fig. 4.) As long as the tank circuit is tuned to the frequency of the input, a higher amplitude sine wave output will be produced.

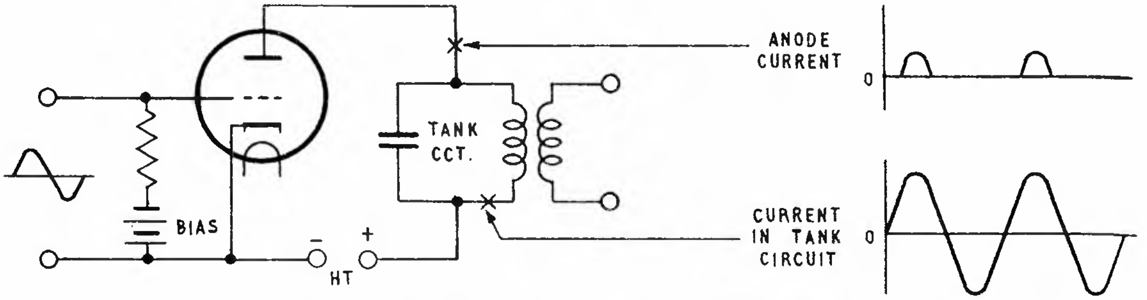
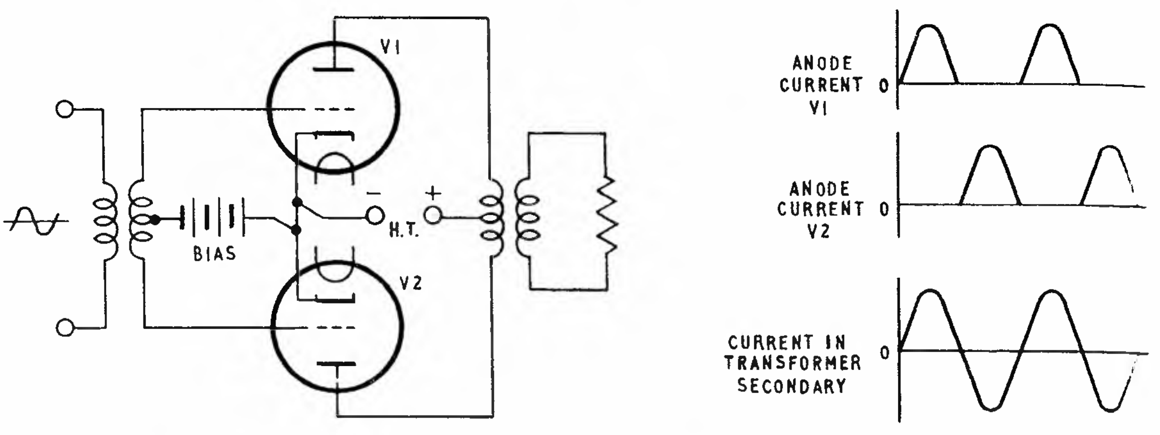


FIG. 4. ELEMENTS OF R.F. POWER AMPLIFIER.

Audio Frequency Power Output - Classes B or AB. We have seen in Figs. 1 and 2 that in all classes of operation except Class A, the anode current waveform is only a part of the signal input cycle. In audio frequency (A.F.) amplifiers, Classes B and AB operation can only be used with a second tube to reproduce the missing part of the cycle. The two tubes are connected in "push-pull" which means that while one grid is on the negative swing the other is on the positive swing; anode current flows in one tube while it is driven beyond cut-off point in the other.

Fig. 5a shows the elements of a push-pull output stage. For audio frequencies, bias and signal voltages are arranged for either Class A, Class AB or Class B operation. Fig. 5b shows how the complete output cycle is reconstructed in the secondary of the output transformer when Class B bias is used. Detailed operation of push-pull circuits is described under the heading of Power Amplifiers in Section 9.



(a) (b)

FIG. 5. PUSH-PULL OUTPUT.

2.4 Classification by Frequency Range. Amplifiers can also be classified according to the frequency range over which they operate.

D.C. amplifiers amplify slow or irregular changes in direct current.

Audio frequency (A.F.) amplifiers cover the whole or a part of the audible range from about 15c/s up to about 15kc/s. Only very high quality (or high fidelity) reproduction of instrumental music extends over or beyond this range. In telecom, speech frequencies are catered for by a much smaller bandwidth of from 200c/s up to about 3kc/s.

Radio-frequency (R.F.) amplifiers operate at frequencies above the audio range. They generally cover a relatively small bandwidth, although some used in television and long line carrier telephony operate over bands several megacycles in width.

The terms narrow and wide (or broad) applied to a frequency band do not denote specific ranges of so many cycles, but are relative to the part of the frequency spectrum occupied. For example, a band ranging from say 50c/s to 10kc/s is a wide band whereas a similar bandwidth from say 1600kc/s to 1610kc/s is a narrow band and from 12.7Mc/s to 12.701Mc/s narrower still.

Narrow bands can be "tuned" using resonant L/C anode loads but wideband amplifiers are not tuned. The further classifications "Tuned" and "Untuned" are also used at times in describing amplifiers.

.5 Classes of Coupling. Amplifiers are sometimes referred to with reference to the type of coupling between stages. For example, an amplifier may be referred to as transformer coupled or R/C coupled or direct coupled. Coupling methods are described in Section 3.

.6 Configuration of Input and Output Circuits. There are three methods of circuit arrangement in the connection of input and output circuits of an amplifier stage -

(i) Common Cathode or Grounded Cathode.

(ii) Grounded Anode or Cathode Follower.

(iii) Common Grid or Grounded Grid.

Common or Grounded Cathode is the conventional arrangement of connecting the input and output of tubes. The input is connected between grid and cathode, and the output between anode and cathode (Fig. 6a). The cathode is therefore common to both input and output circuits, and is usually but not necessarily grounded.

Grounded Anode or Cathode Follower amplifier stages have the load inserted in the cathode circuit (Fig. 6b). As there is no impedance in series with the anode it is at earth potential for the A.C. component of anode current. Input signal is applied between grid and anode and output voltage is produced between cathode and anode (earth).

Cathode follower stages give useful power amplification but no voltage gain. The output impedance is much lower than that of common cathode stages and applications make use of this feature.

Grounded Grid or Common Grid amplifier stages have the input signal voltage applied between cathode and grid with the output being produced between grid and anode. (Fig. 6c.) As the grid is earthed it provides its own shield between input and output, and the grid to anode capacitance does not then affect the high frequency performance as it does in the conventional arrangement.

Grounded grid amplifiers give a voltage gain comparable with that of a conventional stage using a similar triode but the input impedance is lower. They are sometimes used for low noise R.F. amplifiers in preference to a conventional pentode stage, which introduces more noise to be amplified along with the low level signals.

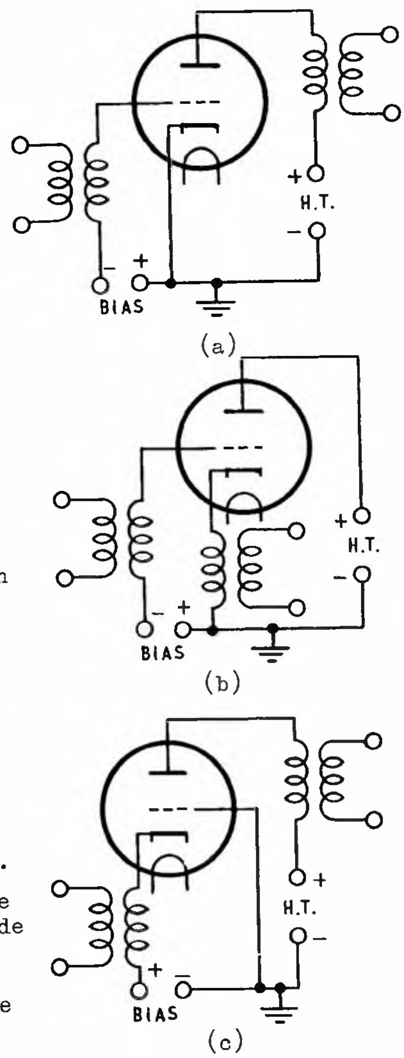


FIG. 6. INPUT AND OUTPUT CONFIGURATIONS.

3. INTERSTAGE COUPLING.

3.1 General. To obtain greater amplification than can be obtained from a single stage, the output signal of one stage is applied to the input of a following stage. Stages are sometimes referred to as being coupled in tandem or "cascade".

An interstage coupling circuit provides a low loss path for the A.C. signal without affecting the D.C. anode and grid bias voltages. The requirements are met by a number of coupling methods each having advantages and disadvantages for particular applications.

3.2 Resistance-Capacity Coupling (Fig. 7) is the most widely used form of coupling in A.F. and wide band amplifiers. The anode load R_L causes variations of anode voltage when signal input varies the anode current. The A.C. component of the anode voltage is applied via the coupling capacitor C to the next stage where it appears across R_g between grid and cathode, in series with the bias voltage (usually obtained by a cathode resistor). The values shown in Fig. 7 are typical for A.F. amplifiers.

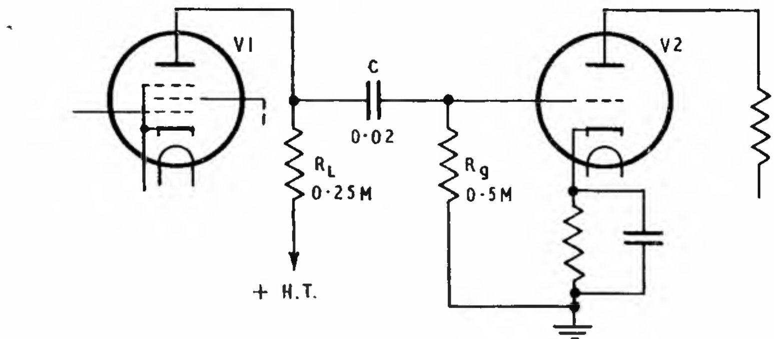


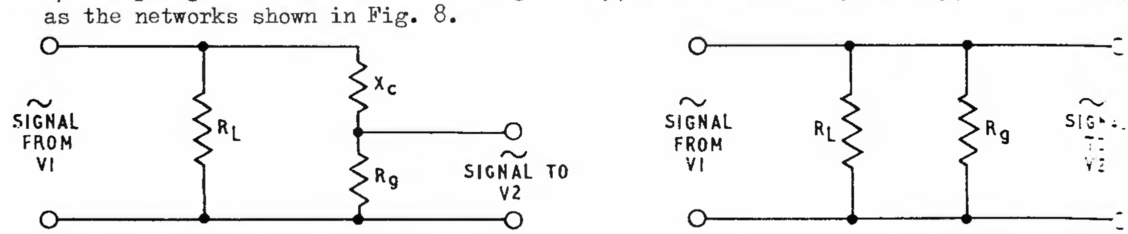
FIG. 7. RESISTANCE-CAPACITY COUPLING.

The choice of values for R_L, C and R_g is determined by many factors and the values of R_L and C vary between wide limits. R_L is determined mainly by the stage gain required, the characteristics of V1 and the H.T. voltage available. Typical values for A.F. amplifiers range from about 50kΩ to about 1MΩ. Wide band amplifiers require much lower values of R_L. (See para. 6.2.)

As C and R_g are in series, and only the voltage across R_g is applied to the input of the reactance of C must be low compared with R_g at the lowest frequency required. Signal voltage dropped across C is wasted. R_g therefore, must have a high value compared to the X_c of C at the low frequency end of the band. R_g is also an unavoidable part of the A.C. load of V1 since it is in parallel with R_L.

When it is desired that the A.C. load of V1 be as high as possible (for maximum gain) R_g must be as high as practicable so that its shunting effect on R_L is a minimum. Typical maximum values for R_g range from about 0.5MΩ to 2MΩ.

Equivalent Networks. Where a combination of impedances are in series and parallel in coupling and bypass circuits, it is very convenient to visualise these as a D.C. resistive voltage divider network. When considering where the maximum voltage is required, it is easy to see which components must have high impedance and which ones low impedance at the particular frequency or range of frequencies. For example, the R/C coupling between V1 and V2 in Fig. 7 may, for the A.C. signal only, be visualised as the networks shown in Fig. 8.



(a) At low frequencies when X_c is appreciable. (b) At frequencies when X_c is negligible.

FIG. 8. EQUIVALENT NETWORKS.

It should be appreciated that the problems of coupling and amplifier performance over the required frequency range often impose conflicting requirements so that the values are a compromise. The effect of the various components on amplifier performance is examined in Section 7.

Upper limits of C and Rg. We have seen that moderately high values for C and Rg are necessary when low coupling losses are desired. However, an undesirable effect known as "grid blocking" can occur when the time constant C X Rg is too great. On a positive signal peak having an amplitude exceeding the bias of V2, the grid draws current and C becomes charged to a higher than normal value (Fig. 9a). When the peak has passed, C can only discharge slowly through Rg (Fig. 9b). If both C and Rg are too high in value (e.g., up to 0.5μF and 5MΩ) a large negative grid voltage is produced. This could cut off V2 for several seconds.

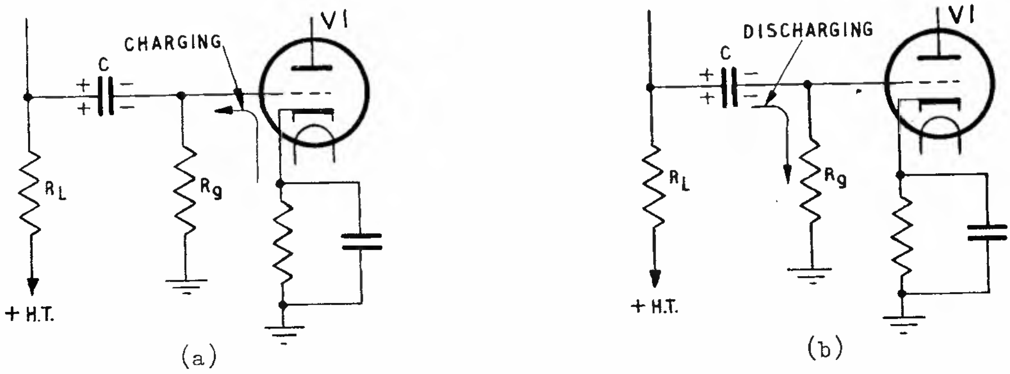


FIG. 9. GRID BLOCKING.

Gas Current and Grid Emission. Another undesirable effect could occur if Rg were made too large as all tubes contain some gas, and positive ions liberated may flow to earth via Rg and tend to reduce the bias. This is called gas current. Also the grid emits a few electrons (grid emission) and these also cause a voltage drop in Rg which opposes the bias. Normally these two effects are very minute but even one tenth of a microamp will produce 1V drop across 10 megohms. Rg therefore rarely exceeds 2MΩ.

3.3 Transformer coupling (interstage) uses the transformer primary as the anode load and the secondary is connected to the input circuit of the following stage (Fig. 10). The transformer provides the necessary D.C. paths for anode and grid while isolating the high positive D.C. anode voltage from the grid. It is also used to match the output impedance of the first tube to the impedance of the following grid input circuit. With the conventional common cathode connection, this requires a step-up turns ratio, primary to secondary, and thus the transformer can also increase the voltage gain of the stage.

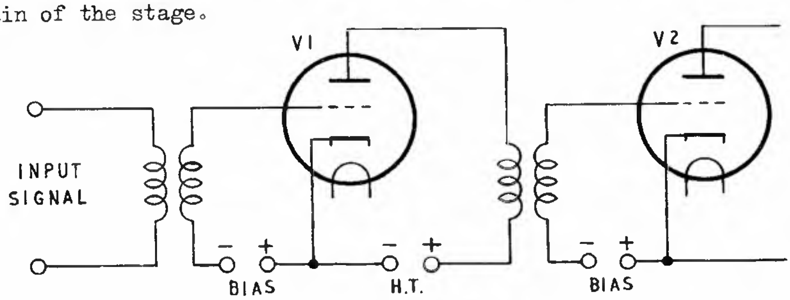


FIG. 10. TRANSFORMER COUPLING.

When used in R.F. amplifiers, coupling transformers are generally tuned by capacitors across primary, or both primary and secondary to increase load impedance at one operating frequency or to tune several stages to cover a particular band of frequencies. The principles of tuned and untuned amplifiers are covered in Sections 7 and 8.

Transformers are generally used to couple power output stages to their load. As most loads have lower impedance than the output circuit of the tube, a step-down turns ratio is then used.

3.4 Impedance Coupling is similar to R/C coupling except that R_L is replaced by either an inductor or an L/C tuned circuit. (Fig. 11.) Like transformer coupling it has the advantage that A.C. load impedance is high while D.C. resistance in the anode circuit is low and this contributes to high stage gain (examined in Section 8). For a narrow band of R.F. a tuned circuit is generally used as the very high impedance at reasonable permits very high gains.

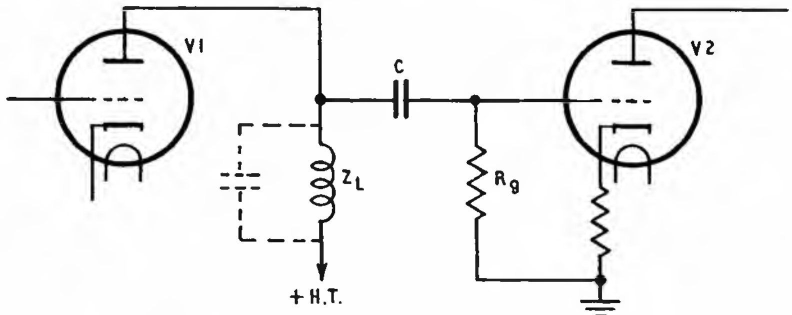


FIG. 11. IMPEDANCE COUPLING.

In some applications Z_L and C are followed by an output transformer and this type of impedance and transformer coupling is useful where it is desired to keep the D.C. component out of the transformer.

3.5 Direct Coupling means that the output circuit of one stage is connected to the input of the next for both A.C. and D.C. - that is, without isolating capacitors or transformers.

Fig. 12 shows the principles of direct coupling. Suppose for example that the no-signal (quiescent) anode voltage of V1 is 100V with respect to its cathode (reference point 'r') then the grid of V2 is also at this potential being coupled directly to the V1 anode. To maintain a suitable bias on V2 its cathode must be positive with respect to the grid, making V2 cathode more positive than V1 anode. V2 anode to cathode voltage is provided by a supply having a still higher positive potential than that of

When more than two stages are direct coupled, the third stage has electrode potentials which are at still higher positive voltages than those of V2.

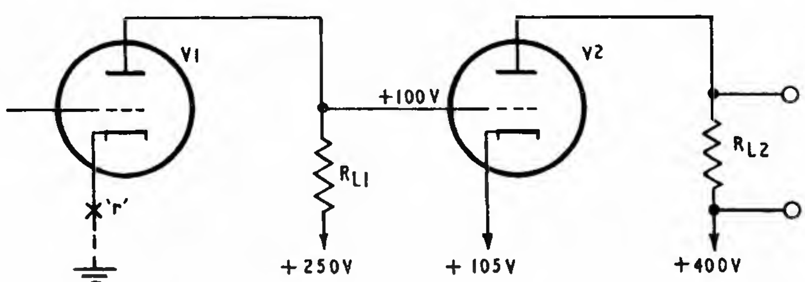


FIG. 12. PRINCIPLES OF DIRECT COUPLING.

The required potentials are obtained in several different ways, generally by the use of one or two voltage dividers. Fig. 12 gives only the basic principle and cannot be regarded as typical because of the variety of direct coupling methods used in practice. Fig. 56 in Section 14 shows an example of direct coupling. Point "r", to which the other voltages refer can also be several volts positive to earth (or the HT negative pole).

Direct coupling is necessary for D.C. amplifiers where slow changes of D.C. are to be amplified. It is also used for some wide band A.F. and video amplifiers where response down to zero frequency or a few c/s is desired. Some direct coupled amplifiers combine all three of the circuit configurations described in Section 2 - common cathode, common grid and cathode follower.

VOLTAGE AMPLIFIER PRINCIPLES.

4.1 Amplification. The principles of amplification cannot be totally divorced from the description and characteristics of triodes, tetrodes and pentodes. Most of the essential principles have been mentioned and some described in the paper "Electron Tubes" and before proceeding further these should be revised. The following sections revise and expand these principles.

Amplification is possible because of the relatively greater control of the grid voltage (E_g) than the anode voltage (E_a) over the anode current (I_a). This relationship is expressed as a factor μ called amplification factor.

$$\mu = \frac{\Delta E_a}{\Delta E_g}$$

Therefore, one tube has a higher value of μ than another when, to give a certain change in I_a -

(i) The change necessary in E_a is larger, and/or

(ii) The change necessary in E_g is smaller.

This is respectively the same as -

(i) A.C. anode resistance (r_a) is higher .... $\left(r_a = \frac{\Delta E_a}{\Delta I_a}\right)$

and/or

(ii) Mutual conductance (g_m) is higher .... $\left(g_m = \frac{\Delta I_a}{\Delta E_g}\right)$

The value of μ is therefore dependent on the value of both r_a and g_m. That is -

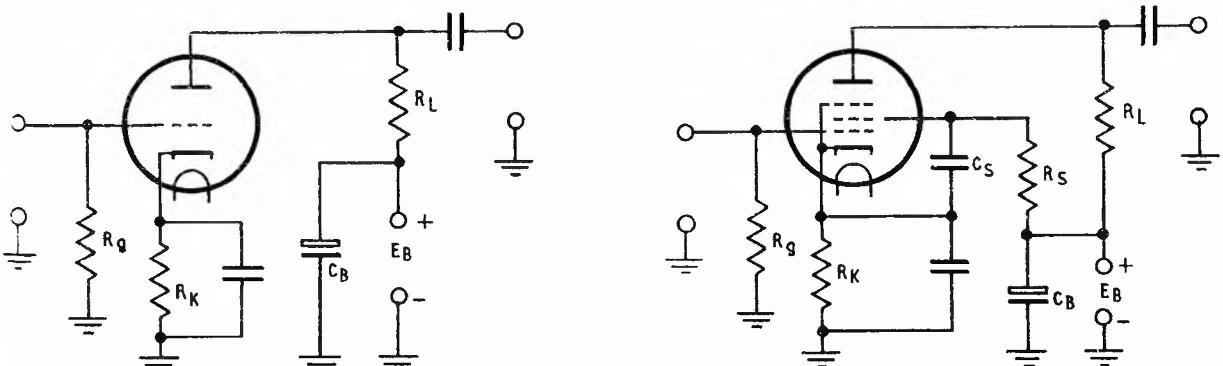
$$\mu = r_a g_m$$

4.2 Anode Load. To use a tube as an amplifier the anode current (varied by the changing signal voltage on the grid) must flow in a load in series with the anode. Tubes may be loaded differently as either -

(i) Voltage amplifiers, where the object is large voltage gain from input to output, or

(ii) Power amplifiers, where the object is power delivered to the load.

Voltage Amplifiers. The anode load of voltage amplifiers is very often a resistance as shown in the two typical voltage amplifier circuits of Fig. 13.



(a) Triode Voltage Amplifier. (b) Pentode Voltage Amplifier.

FIG. 13.

4.3 Triode with Resistive Anode Load (R_L). We have seen from the study of static curves in the paper "Electron Tubes" that the anode current I_a of triodes is affected by change of either anode voltage E_a or grid voltage E_g. With a resistive anode load R_L, the actual change in I_a with a signal voltage applied to the grid, must therefore be a resultant of the changes in both E_g and E_a. Suppose our triode in Fig. 13 (or Fig. 15) has a static g_m of 3mA/V (remember that this is found with E kept constant). With R_L in circuit, the change in I_a per 1V change in E_g will be less than 3mA because the changes of E_g and E_a are such as to exert opposing influences on I_a. (The grid changes of course have the major effect.) Analysing the conditions during one half cycle input we find that -

(i) When E_g becomes less negative I_a increases, but because this also increases the voltage drop in R_L, E_a becomes less positive and thus opposes to some extent the effect on I_a of the change in E_g.

(ii) On the negative swing of the signal, E_g becoming more negative reduces I_a and this increases E_a owing to less voltage drop across R_L. Again E_a is affecting I_a in the opposite direction to E_g.

4.4 Dynamic Characteristics of Triodes. This effect which minimises the amount of change in I_a with signal input may be shown graphically if a mutual curve is plotted with R_L in circuit. Fig. 14 shows this for a typical triode (6J5) with three different values for R_L. The supply voltage E_B is 250V and the static curve (where R_L = 0Ω) is shown also for comparison. These curves showing the E_g/I_a relationship, with E_a varying due to R_L are known as dynamic characteristics. The static g_m is about 1.6mA/V. The three dynamic g_m values in mA/V are about 0.6 (R = 25k), 0.3 (R_L = 50k) and 0.2 (R_L = 100k).

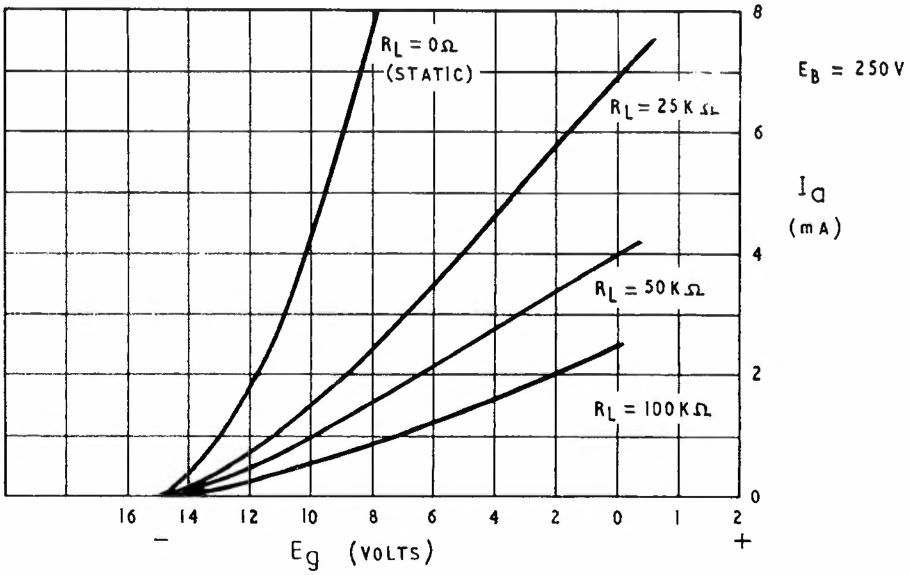


FIG. 14. DYNAMIC CHARACTERISTICS OF TYPICAL TRIODE.

With these curves, the change in E_a with a given change in I_a can be calculated for each value of R_L. For any value of anode current -

$$E_a = E_B - E_{RL} \text{ (where } E_{RL} \text{ is the voltage drop across } R_L).$$
$$= E_B - (I_a \times R_L).$$

Note however, that as the value of I_a rises or falls with signal input the change in E_a is numerically equal to the change in E_{RL}.

Example: Suppose in Fig. 15, R_k is selected to give a bias of -4V and the input signal has a peak value of 2V the grid swing is from -2V to -6V, a peak-to-peak value of 4V.

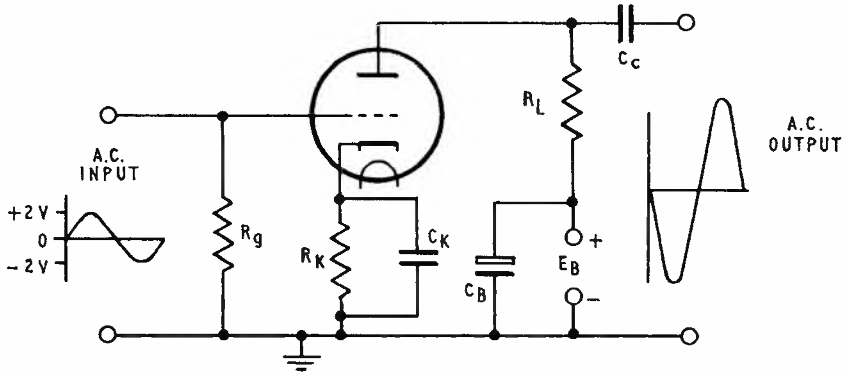


FIG. 15.

The following table compares output peak-to-peak voltage using three values of R_L. The capacitor C_c which isolates the D.C. component has negligible reactance at the signal frequency. The values of I_a are approximations from the curves in Fig. 14.

R_L	Signal (E_S)	E_g	I_a (Approx.)	$E_{RL} = I_L \times R_L$ $E_B - E_{RL} = E_a$	Peak-to-Peak A.C. Output (E_{SO})	Voltage Gain $\frac{E_{SO}}{E_S}$ (Approx.)	Peak Power Output
25kΩ	+2 -2	-2V -6V	5.8mA 3.5mA	250 - 145 = 105V 250 - 88 = 162V	57V Approx.	$\frac{57}{4}$ = 14	33 mW
50kΩ	+2 -2	-2V -6V	3.4mA 2.2mA	250 - 170 = 80V 250 - 110 = 140V	60V Approx.	$\frac{60}{4}$ = 15	12.25 mW.
100kΩ	+2 -2 (4V peak-to-peak)	-2V -6V	2 mA 1.3mA	250 - 200 = 50V 250 - 130 = 120V	70V Approx.	$\frac{70}{4}$ = 17	

..5 Calculation of Stage Gain. The stage voltage gain, or simply stage gain, can be calculated from the above figures by dividing the peak-to-peak A.C. output voltage (E_{SO}) by the peak-to-peak signal input voltage (E_S). That is -

$$\text{Voltage or Stage Gain} = \frac{E_{SO}}{E_S} \qquad \text{where} \quad E_{SO} = \text{output signal voltage.} \quad E_S = \text{input signal voltage.}$$

The figures in the above table show that the higher values of R_L give higher voltage gain, even though Fig. 14 shows that the dynamic characteristic has less slope as R_L is increased. There is a limit to how high a value of R_L can be used, as above a certain value there is insufficient anode current for the tube to work normally and gain is reduced.

Maximum possible voltage gain is not always required and values of R_L for triodes vary from 2 to about 20 times the r_a of the tubes, with a maximum of about 200kΩ for normal supplies of up to 300V. The tube in Fig. 15 has an r_a of about 7,000 ohms and an amplification factor μ of 20. The gain of about 14 - 17 in the above example shows how a triode may give voltage gain approaching μ.

In the above examples peak-to-peak voltages have been used for convenience in calculation from the curves. The use of peak values or peak-to-peak values is common practice in referring to A.C. signals in electronic circuits.

..6 Phase Shift in Amplifiers. When an input signal, applied to an amplifier with a resistive load, is on the positive half cycle the anode current increases, and the voltage across R_L increases making E_a less positive, that is the A.C. output signal is on the negative going half cycle. Similarly when the input signal is on the negative half cycle, anode current decreases and the voltage across R_L decreases making E_a more positive. This represents a phase change from input to output of 180°. The input and output curves in Fig. 15 represent this displacement which is further examined in para. 5.6.

4.7 Pentode with Resistive Load (Fig. 16). When a signal is applied to the grid, variations in anode current produce variations in anode voltage because of the changing voltage drop across R_L. In the same way as explained for triodes (para. 4.4), changes in anode voltage tend to offset the effect of the grid voltage changes on anode current. But, because anode current of pentodes is effected much less by anode voltage changes than that of triodes (higher values of r_a and nearly horizontal E_a/I_a curves of pentodes indicate that changes in anode current of pentodes for given grid voltage swing are nearly as great with a load (R_L) as without it. Therefore the slope of dynamic mutual curves is nearly as steep as that of the static mutual curve.

4.8 Dynamic Characteristics of Pentodes. Fig. 17a compares dynamic curves for two values of R_L with a part of the static curve of the same pentode (6AU6).

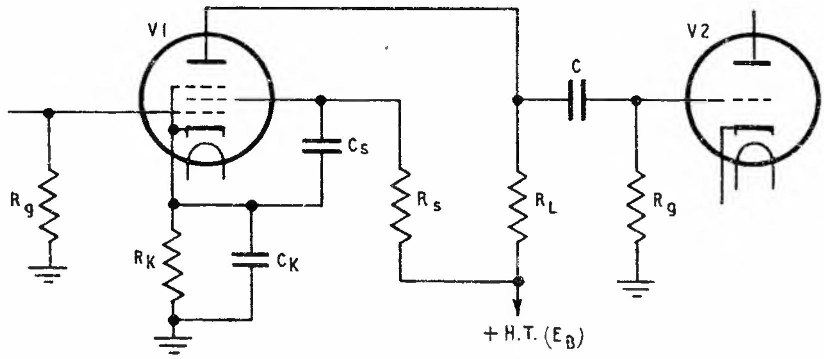


FIG. 16. PENTODE WITH RESISTIVE LOAD.

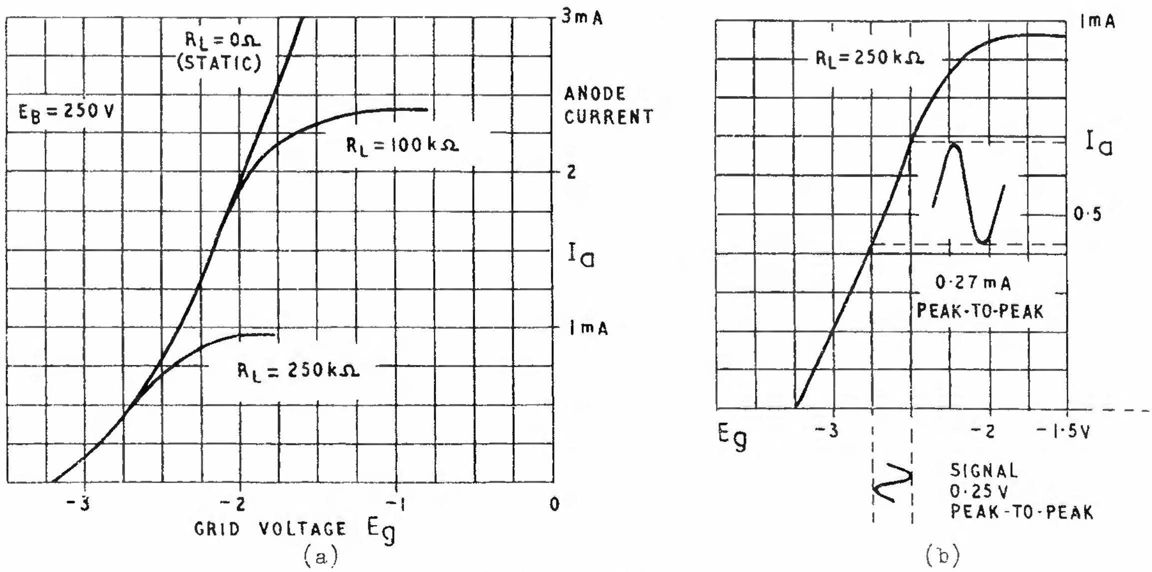


FIG. 17. DYNAMIC CURVES OF TYPICAL PENTODE.

Note that the linear portions of the dynamic curves indicate a dynamic value of g_m practically equal to the static value. Note also that the dynamic curves bend sharply before the maximum current is reached. Compare these dynamic curves with those of a triode in Fig. 14. With high values of R_L the sharp bend confines operation within narrower limits of grid swing than is the case with triodes. The bend occurs when the anode current reaches a point where the anode voltage drops below the screen voltage.

It might appear from Fig. 17a that the R_L = 250KΩ dynamic curve has a linear section short to be of practical use. This is not the case however, as small input signals are readily handled and even higher values of R_L are sometimes used. To show such application more clearly the R_L = 250kΩ curve of Fig. 17a is redrawn in Fig. 17b to an enlarged current scale.

Example: An applied signal of 0.25V (250mV) peak-to-peak (E_g 2.5V to 2.75V) gives a change in anode current of 0.27mA. However, across the 250kΩ load this results in a voltage change of 67.5V peak-to-peak (change in $I_a \times R_L$ = 0.27mA x 250kΩ).

$$\text{Therefore voltage or Stage Gain} = \frac{E_{SO}}{E_S}$$

$$= \frac{67.5}{0.25} \text{ or 270 approx.}$$

For small-signal amplifiers therefore, one pentode stage can give a very high voltage gain. (Signals from receiving aerials, microphones etc. may be only a few millivolts or less.)

As with triodes the higher values of R_L give higher voltage gains than the lower values but the permissible peak input signal voltage is lower with pentodes because of the sharp bend at the upper end of the dynamic characteristics.

. ANODE LOADS AND LOADLINES.

5.1 Use of Loadlines. We have seen how dynamic mutual curves can be useful in determining a tube's performance and optimum operating conditions in an amplifier stage. However, dynamic curves are rarely supplied by tube makers; the possible combinations of E_B and R_L for any tube are numerous and each would require a dynamic curve to represent it. The same information can be obtained from a family of static anode characteristics (supplied by makers) on which a loadline may be plotted to suit any desired combination of E_B and R_L. Loadlines are straight lines for resistive loads and the two points necessary for plotting a resistive loadline may be calculated from the values of E_B and R_L. This is explained in para. 5.2.

Fig. 18 shows the family of anode characteristics for a typical triode on which has been plotted a loadline to suit a load R_L of 50kΩ and anode supply E_B of 250V. The loadline intersects the various E_g curves at points corresponding to the instantaneous I_a for the particular E_g, of a tube operating under the given conditions. This E_a/I_a dynamic relationship is the same information as we obtained from a dynamic mutual characteristic (Fig. 14). In addition, the corresponding anode voltage E_a can be read off directly instead of being calculated.

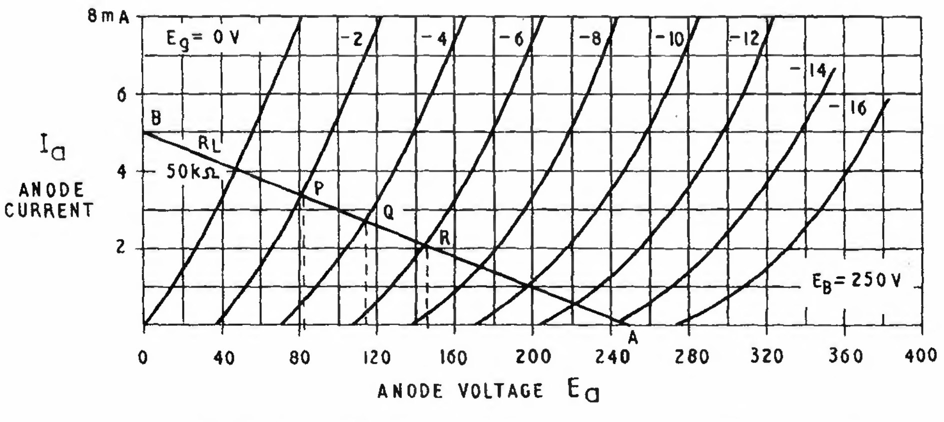


FIG. 18. ANODE CHARACTERISTICS OF TYPICAL TRIODE WITH LOADLINE.

Suppose a bias of -4 volts is chosen. This sets the operating point at Q which is generally called the "quiescent" point of operation and gives the values of E_a and I_a when no signal is applied (114V and 2.7mA approx.). When a 2V peak signal is applied the grid swings from -2V to -6V which on the graph corresponds with the intersection of these two grid voltage curves with the loadline - that is P and R respectively. These points correspond with anode voltages of approx. 81V and 145V - a total change of 64V for a total grid voltage change of 4V (peak-to-peak). This indicates a theoretical voltage gain of $\frac{64V}{4V}$ or 16 times.

5.2 Plotting Anode Loadlines. The method generally used for voltage amplifiers is to choose values for E_B and R_L and from them determine two points as follows :-

Assuming E_B = 250V and R_L = 50kΩ

(i) Use the value of anode voltage E_a when I_a is zero (cut-off) as the first point. This is the supply voltage E_B which in the example is 250V and mark as point A (Figs. 18 and 19).

(ii) Calculate anode current I_a when all the supply voltage is dropped in R_L; that is when E_a is zero

$$I_a = \frac{E_B}{R_L}$$

which in the example $= \frac{250}{50} = 5\text{mA}.$

Mark this as point B (Figs. 18 and 19).

I_a could only be raised to this value by a deliberate anode to cathode short circuit. However, it gives us the direction in which I_a increases with decreasing E_a.

Using the same set of anode characteristics and loadline as in Fig. 18, Fig. 19 shows how the corresponding dynamic mutual curve may be plotted if required, using the co-ordinates where the loadline intersects the anode curves. The dynamic curves in Figs. 14 and 15 were plotted by this method.

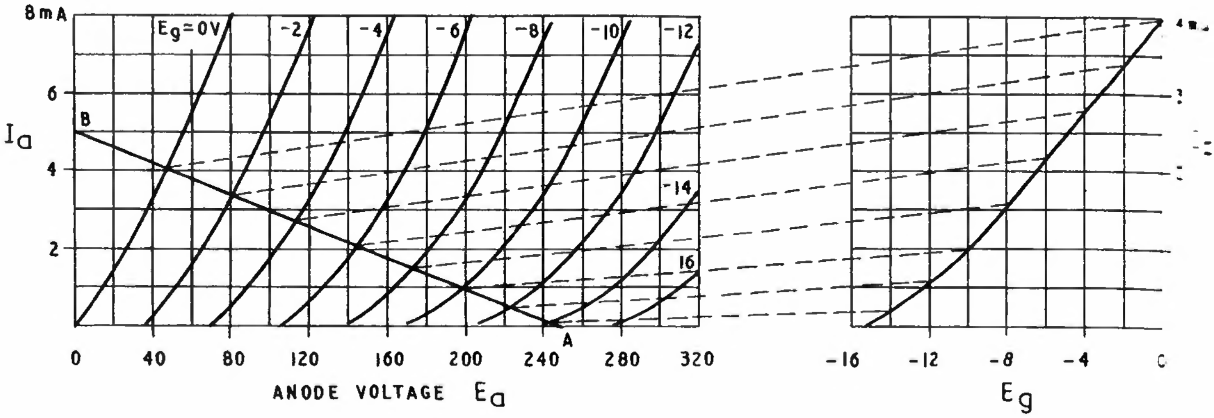


FIG. 19. PLOTTING DYNAMIC CURVE USING LOADLINE.

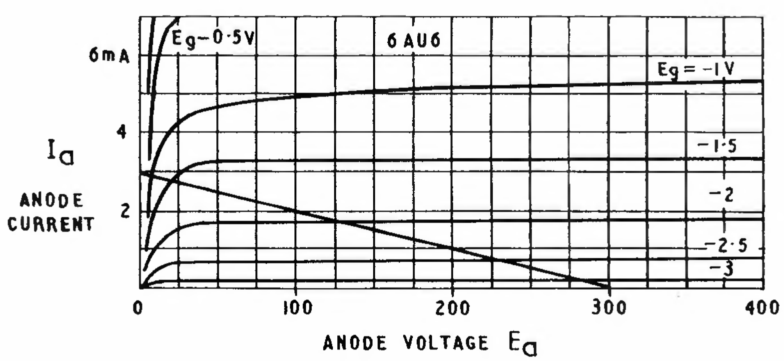


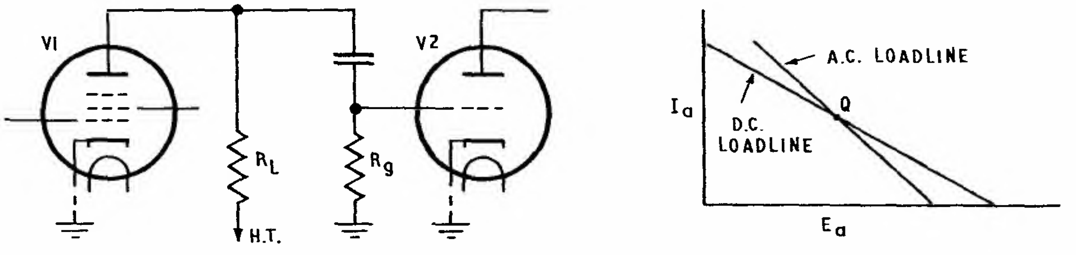
FIG. 20. PENTODE CHARACTERISTICS WITH LOADLINE.

Fig. 20 shows a family of pentode characteristics with a loadline for E_B = 300V and R_L = 100kΩ. When compared to Fig. 18 note how the shape of the pentode characteristics allows a smaller grid voltage swing to result in greater changes in E_a. For example, a change in E_g from -2V to -2.5V results in a change in E_a from about 125V to about 225V.

D.C. and A.C. Loadlines. To introduce loadlines in a simple manner we have, in paras. 5.1 and 5.2, neglected certain factors which sometimes make the loadline, as plotted, a little inaccurate for practical use. The loadlines in Figs. 18, 19 and 20 are called D.C. loadlines because they represent the anode load to D.C. An amplified A.C. signal may meet a somewhat different value in the output circuit.

Anode load for A.C. Up to this stage we have considered the anode load as being the resistance R_L. Referring to Fig. 21a, and assuming that coupling capacitor C has negligible reactance at the signal frequency, the A.C. anode load of V1 is actually R_L in parallel with both R_g and the input impedance of V2. Therefore, the resultant of these impedances is the actual load across which the output voltage of V1 is developed. The input impedance of V2 is generally several megohms and very often the value of R_g is many times that of R_L. In such cases the A.C. and D.C. loads are approximately the same and equal to R_L (which is low compared to the parallel A.C. impedance of R_g and V2 input). The D.C. loadline is then sufficiently accurate and we have assumed these conditions apply in the examples of Figs. 14-20.

A.C. Loadlines. In many cases however, R_g may not be much more than twice R_L and the A.C. anode load is approximately equal to their equivalent parallel resistance. The D.C. loadline will not then show the correct dynamic relationship between I_a and E_a during operation, and it becomes necessary to add an A.C. loadline. Ideally the quiescent point Q remains on the D.C. loadline at the selected bias voltage and the A.C. loadline passes through Q at a slope determined by the A.C. load of R_L and R_g in parallel. A typical result is represented in Fig. 21b.



(a) (b)

FIG. 21. D.C. AND A.C. ANODE LOADS.

There are other methods of constructing anode loadlines besides the method described. It is possible to draw the loadline to cross the curves at suitable points and then to calculate from this the optimum load impedance. This is often done for power pentodes.

D.C. and A.C. loadlines can be plotted for all types of anode load, but the A.C. loadline is straight only when the load is resistive. When reactive components are present, current and voltage are out of phase, and theoretically the A.C. loadline becomes an ellipse.

The same effect can be shown on a C.R.O. when an ellipse is produced by out of phase voltages applied to the X and Y plates. (Refer to para. 10.6 of "A.C. Measurements".) The X and Y axes of the graph on the C.R.T. correspond to the E_a and I_a axes of the graph in Fig. 21b.

There are other factors which may affect the position and shape of both D.C. and A.C. loadlines. Also, loadlines are sometimes used for calculating screen grid and control grid requirements. As these considerations are rather theoretical and concerned with design, they are beyond the scope of this course. However, a basic knowledge of loadlines assists greatly in the understanding of amplifier principles.

5.6 A.C. Load and Phase Shift. Fig. 22 shows the phase relationship between input voltage anode current and output voltage in a single stage resistance loaded amplifier. Because of the drop across R_L, anode voltage E_a decreases as I_a increases and vice versa, making the A.C. component of E_a 180° out of phase with the A.C. input signal.

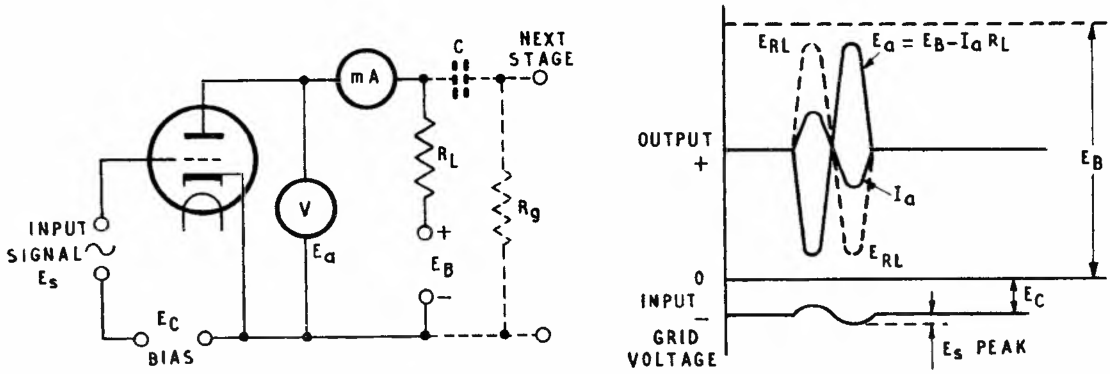


FIG. 22. 180° PHASE CHANGE IN RESISTANCE LOADED STAGE.

When reactive components constitute a significant proportion of the A.C. load there will be a phase difference between the signal component of I_a and the A.C. drop across the load. Consequently phase displacement between the input and output voltages will be either less or more than 180° depending on whether the load is capacitive or inductive in character. In multistage amplifiers the phase change per stage will depend also on whether reactive components are in series or in parallel with R_g. For details of phase relationships in reactive A.C. circuits refer to the A.C. papers at the beginning of this book.

5.7 A.C. Load Varies with Frequency. We have seen that high values of R_L for a given tube give more stage gain than low values of R_L. Similarly, any factor which lowers the value of A.C. load must reduce the gain. A load which is resistive only would present a constant impedance at any frequency and if this could be achieved stage gain would be independent of frequency. All tubes however have some capacitance shunted across the input and output as well as some stray capacitance in the circuit wiring. This can be kept to a small value and may total from about 6 to 60µµF but, as we saw in studying capacitive reactance, even very small capacitors become quite good conductors of high frequency A.C. (20µµF offers about 800kΩ reactance at 10kc/s but only 80kΩ at 100kc/s and 8kΩ at 1Mc/s.)

The frequency bandwidth over which an ordinary R/C coupled amplifier can give uniform gain is therefore limited mainly by the unavoidable shunt capacitance which reduces the value of A.C. load impedance with an increase in frequency.

Series capacitance in the coupling capacitor also affects bandwidth as its reactance increases at low frequency, as we have noted with coupling methods in Section 3, Fig. 8.

6. FREQUENCY RESPONSE AND BANDWIDTH.

6.1 Main Requirements of Amplifiers. As a general rule amplifiers are designed so that the fewest number of stages will provide the necessary gain over the desired frequency band. Each stage therefore provides the maximum gain which is consistent with a uniform "response" to all frequencies in the band. The two demands are to a large extent conflicting, so that, to obtain wide uniform response, gain is sacrificed; conversely the highest stage gain is obtainable only over narrow frequency bandwidth.

Fig. 23 compares typical gain versus frequency response curves for three different types of amplifier stage. Curve A is that for an R/C coupled audio amplifier. Curve B is that of a narrow band radio frequency (R.F.) amplifier using a "tuned" LC or parallel resonant circuit which gives high load impedance at resonance and thereby high gain.

Curve C is the response of a wide band video amplifier (for television picture signals). A similar very wide bandwidth is required in many long line and radio "bearer" circuits carrying many hundreds of telephone channels. (In this field the accepted term is broad band bearer to distinguish from the earlier use of wide and narrow in referring to different classes of speech channel.) To obtain such wide uniform or "flat" response, a great deal of stage gain is sacrificed and in addition, "compensation" of the A.C. load is necessary.

The foregoing is a broad outline. In order to explain the relationship between gain and bandwidth we must examine the effect of A.C. load and gain still more closely.

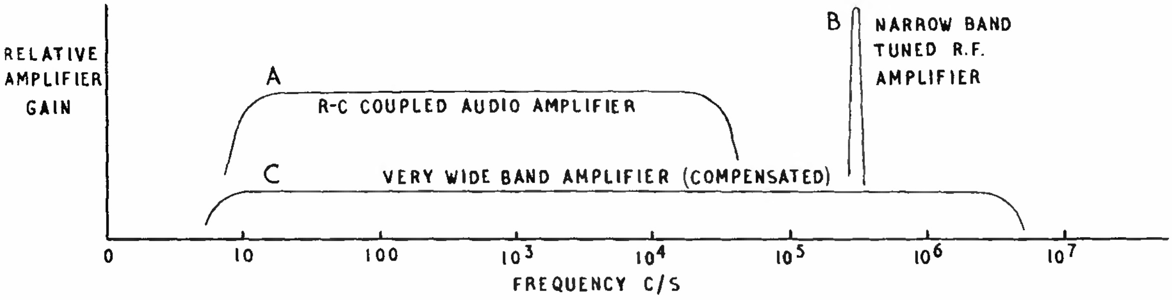


FIG. 23. TYPICAL AMPLIFIER RESPONSE CHARACTERISTICS.

.2 Equivalent Amplifier Circuits and Stage Gain. The factors which determine stage gain and overall frequency response are more readily understood by replacing the complete tube circuit with an equivalent circuit which neglects all D.C. potentials and presents the tube and coupling circuit as they affect the A.C. signal only.

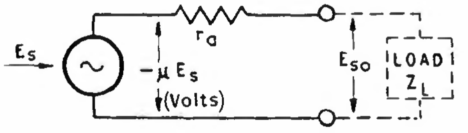


FIG. 24. EQUIVALENT CIRCUIT.
Constant Voltage Generator.

FIg. 24 shows the basic equivalent in which the tube is regarded as a constant voltage A.C. generator with a series impedance equal to the A.C. anode impedance r_a.

The generator terminal voltage is equal to the A.C. signal input voltage E_s, multipled by the amplification factor μ of the tube, that is $-\mu E_s$, the minus sign being used to indicate the normal 180° phase change from input to output. This voltage is applied to the load in series with r_a. The output signal E_{so} across the load Z_L is therefore that proportion of μE_s dropped across Z_L. Since the whole of μE_s is dropped across the total circuit impedance $(r_a + Z_L)$, then -

Output voltage = total amplified signal voltage X proportion of Z_L to total Z.

$$\therefore \quad E_{so} = \mu E_s \times \frac{Z_L}{r_a + Z_L}$$

$$\therefore \quad \frac{E_{so}}{E_s} = \mu \frac{Z_L}{r_a + Z_L}$$

$$\text{But} \quad \frac{E_{so}}{E_s} = \frac{\text{Output voltage}}{\text{Input voltage}} = \text{Voltage gain of stage (A)}$$

$$\therefore \quad A = \frac{\mu Z_L}{r_a + Z_L} \qquad \text{——————— (1)}$$

where
E_{so} = Output signal voltage
E_s = Input signal voltage
μ = Amplification factor *
r_a = A.C. anode resistance *
Z_L = A.C. load impedance.

* at working point.

Formula (1) and Fig. 24 are useful for triodes which have μ and r_a listed in maker's data for typical working points. We can see from the formula that when Z_L is much greater than r_a in value, stage gain will approach μ in value, which we saw also from calculations based on triode dynamic curves (Fig. 14).

However, the μ value of a pentode is not generally listed, nor is it readily determined from the anode family of static characteristics.

From formula (1) we can readily derive another formula and equivalent circuit using g_m instead of μ.

$$\text{Stage gain } (A) = \frac{\mu Z_L}{r_a + Z_L} \quad \text{.......... (1)}$$

Where r_a = A.C. anode resistance, g_m = Mutual conductance, Z_L = A.C. load impedance } at working point

$$\text{But} \quad \mu = r_a g_m$$

$$\therefore \quad A = g_m \frac{r_a Z_L}{r_a + Z_L}$$

Formula (2) can be used for triodes or pentodes. Note, however, that high values of Z_L (and R_L) generally restrict operation to that part of the characteristics where g_m is lower than the static value given in the tube manuals. This should be allowed for and a more appropriate value determined from the curves or other published data. The loadline on Fig. 20 shows this restriction of working point. (μ of triodes is affected less, but for greater accuracy when using formula (1) its variation with load should be allowed for.)

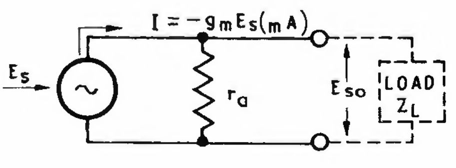
Formula (2) suggests a more suitable equivalent circuit for pentode amplifiers.

$$\text{Stage gain } A = g_m \frac{r_a Z_L}{r_a + Z_L} \quad \text{........... (2)}$$

$$\therefore \quad \frac{E_{so}}{E_s} = g_m \frac{r_a Z_L}{r_a + Z_L}$$

$$\therefore \quad E_{so} = g_m E_s \frac{r_a Z_L}{r_a + Z_L}$$

Note that $\frac{r_a Z_L}{r_a + Z_L}$ is equivalent to the formula for finding the joint R of R1 and R2 in parallel, and therefore represents the joint opposition in ohms of r_a and Z_L in parallel. Also, as g_m expressed in mA/V is a measure of the anode signal current milliamps per grid signal volt, then $g_m E_s$ will give the A.C. signal component of anode current resulting from a grid signal E_s.



The last formula then indicates that a tube may be also regarded as an A.C. generator producing a constant current output equal to g_m E_s and having an internal shunting impedance equal to r_a, across which the load Z_L is connected in parallel. This is represented in Fig. 25.

FIG. 25. EQUIVALENT CIRCUIT.

Constant Current Generator.

Just as stage gain A can be found with either formula (1) or (2) making them equal expressions, Fig. 24 and Fig. 25 represent the same thing in two ways; either may be used for any type of tube even though at first they may look very different. Whichever circuit is used is a matter of convenience. Fig. 25 is more often used, as most voltage amplifiers use pentodes which because of their high r_a are nearly "constant current" sources. The r_a of triodes is low by comparison and they approach the characteristics of "constant voltage" sources.

"Constant Voltage" and "Constant Current" Sources. The idea of a "constant current" source is often hard to grasp at first, as we have become accustomed to thinking in terms of sources which supply appreciable power (alternators and batteries) the low internal impedance of which gives them constant terminal voltage over wide variations in load impedance. Sources in which the internal impedance is much lower than any load are therefore constant voltage sources.

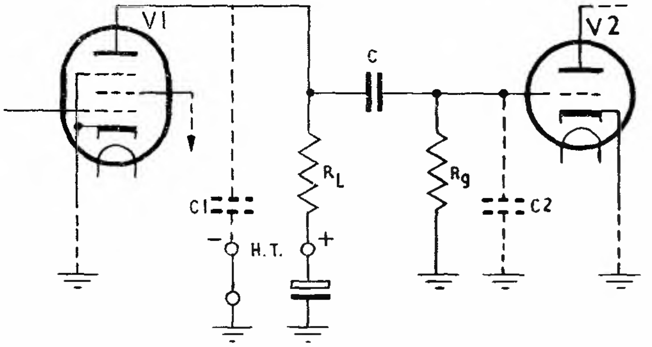
In electronics, however, we can often use voltage without any appreciable power so that devices having high internal impedance are commonly sources of signal. When a source has internal impedance much higher than that of any likely load, it does not make much difference to the output current whether the load is a high resistance, low resistance or even a short circuit.

For example - if a generator has an impedance of 1.5MΩ and 10V e.m.f., output current into 100kΩ load is 6.25μA, and into a short circuit is 6.6μA (by Ohm's Law). Output current therefore is nearly constant over a wide range of loads and the source may be thought of as having constant current characteristics. Examples of high impedance or "constant current" sources are voltage amplifier pentodes, receiving aerials and certain types of microphones.

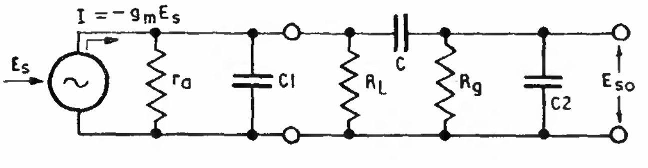
No sources have either zero impedance or infinite impedance and the terms are therefore purely relative to the loading and are really convenient approximations to aid in explanation.

7. R/C COUPLING FREQUENCY RESPONSE.

7.1 Equivalent Circuits. Fig. 26a shows a pentode amplifier stage including all the factors which determine the value of the A.C. load Z_L and Fig. 26b shows the full equivalent circuit with the tube represented as a constant current generator.



(a)



(b)

FIG. 26.

The A.C. load consists of four shunt components, -

(i) C1, the output capacitance of V1 (anode-to-cathode), including stray wiring capacitances,

(ii) R_L, the D.C. anode load resistance of V1,

(iii) R_g, the grid load of V2,

(iv) C2, the equivalent input capacitance of V2, including stray wiring capacitances,

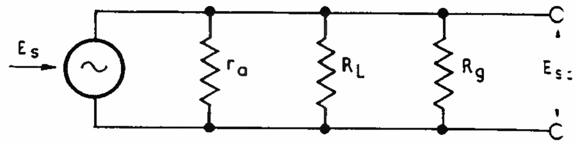
and one series component -

(i) C, the coupling capacitor.

We have already seen in Section 3 that C is chosen to have negligible reactance compared to R_g. This applies over the mid-frequency and high-frequency (h-f) sections of the band but as any capacitor (no matter how large) is open circuit to zero c/s or D.C. the reactance of C must rise at the low-frequency (l-f) end of the band. The shunt components C1 and C2 have a low value and their reactance is so high at the l-f and mid-f sections of the band that their shunting effect on R_L and R_g may be neglected. (The value of C2 can be much greater than grid-to-cathode capacitance especially with triodes. Para. 7.6 explains how C2 is derived.)

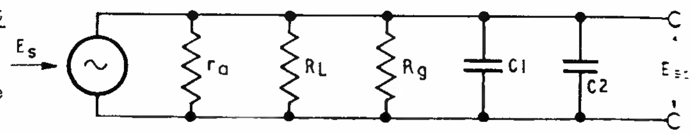
It is possible therefore, and convenient, to simplify the full equivalent circuit of Fig. 27 to -

(i) The mid-frequency equivalent where C is regarded as a short circuit compared to R_g, and C1 and C2 as open circuit compared to R_L (Fig. 27a).



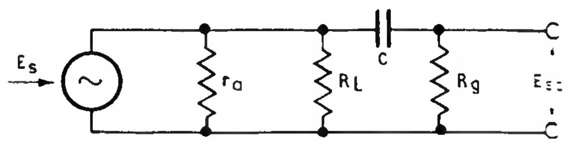
(a) Mid-frequency.

(ii) The high-frequency equivalent where C is a short circuit, but the reactance of C1 and C2 become low enough to have appreciable shunting effect on R_L (Fig. 27b).



(b) High-frequency.

(iii) The low-frequency equivalent where C1 and C2 are virtually an open circuit but the reactance of C is no longer negligible compared to R_g (Fig. 27c).



(c) Low-frequency.

FIG. 27. EQUIVALENT CIRCUITS.
(Constant Current Source.)

7.2 Factors affecting Response. R/C coupling is used in all types of wide band amplifiers - audio, video and broad band bearer. For easy reference the audio and video amplifier response curves (Fig. 22) are shown again in Fig. 28.

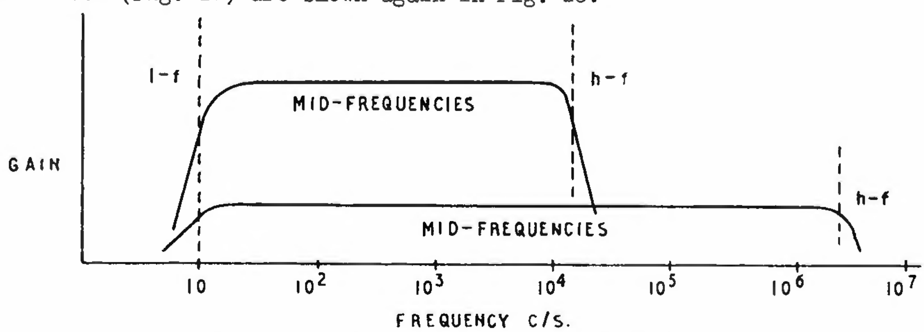


FIG. 28. RESPONSE OF WIDE BAND STAGES.

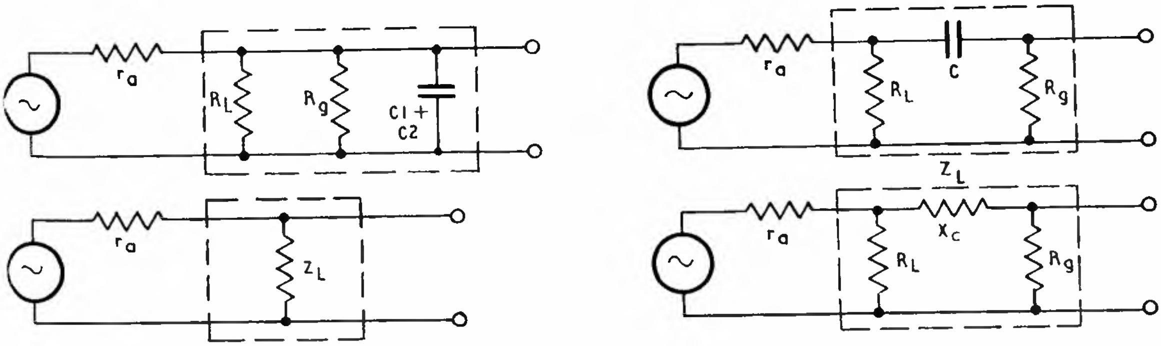
The shape of the curves is now explained in terms of the equivalent circuits :-

(i) Gain is constant over the flat section or mid-frequencies (Fig. 27a) because the A.C. load is predominantly resistive and the voltage drop across its practically constant value is the output signal.

(ii) Gain at the h-f end of the band (Fig. 27b) commences to fall off when the reactance of C1 and C2 become low enough compared to the parallel equivalent of resistive components R_L and R_g to appreciably reduce the A.C. load impedance. The constant current generator produces a lower voltage drop across the lower value A.C. load comprising R_L, R_g, C1 and C2 all in parallel with r_a. Response continues to fall with further frequency rise as reactance of C1 and C2 become progressively lower.

(iii) Gain at the l-f end of the band (Fig. 27c) commences to fall off when the reactance of coupling capacitor C becomes appreciable compared to the resistance of R_g. As the frequency is lowered the voltage drop across C is increased giving a progressive decrease in the voltage drop across R_g - the input to the next stage.

Fig. 27 uses the constant current generator analogy. If you find it easier to think in terms of the equivalent constant voltage source with series r_a this is shown in Fig. 29 which also further simplifies the h-f and l-f equivalent circuits to look like resistive voltage dividers as we did for R/C coupling in Fig. 8, page 6.



h-f Response. The load impedance Z_L is lowered by the shunt reactance of C1 and C2, resulting in more voltage drop across r_a and less across Z_L.

(b) l-f Response. The voltage drop across Z_L is divided between X_c and R_g and only that across R_g is available at the output. The more voltage drop across X_c the less across R_g.

FIG. 29. EQUIVALENT CIRCUITS.
(Constant Voltage Source.)

Bandwidth and Gain. Response is uniform or flat as long as the load is predominantly resistive. Since we cannot get rid of all shunt capacitance we can only keep its shunting effect on R_L negligible over wider bandwidths, by using a lower value of R_L with a consequent reduction in gain. That is, wider bandwidth is obtained at the expense of gain.

In amplifiers having a bandwidth of several megacycles, R_L is only a few thousand ohms compared with a few hundred thousand ohms in a 5kc/s band audio amplifier. To give useful gain in spite of very low load resistances, tubes having very high values of g_m are used (10-15mA/V). These tubes draw larger anode currents than tubes used in other resistance loaded amplifiers but, because of the low values of R_L, excessively high supply voltages are not necessary. However, power requirements are considerably greater than for audio amplifiers.

Low-frequency Response. From Figs. 27c and 29b, it would seem that low-frequency response may be extended (to still lower frequencies) by increasing the value of the coupling capacitor C and/or the value of R_g. This is done, but the possibility of grid blocking, and gas current and grid emission of the following tube, sets practical limits on the value of C and R_g as explained in para. 3.2. For response down to a few c/s, direct coupling becomes necessary.

Up to this stage, we have neglected the effect of frequency change on the reactance of the capacitors used to bypass cathode bias and screen dropping resistors. (Ck + Cs in Fig. 13.) If these are not adequate, the low-frequency response will be affected - bias and screen voltages will alter with signal and act on anode current to reduce gain.

Usable Bandwidth. In practice, some drop in gain is tolerated at the upper and lower frequency limits. The bandwidth includes the flat mid-frequency section plus the lowered l-f and h-f sections down to points where only half the mid-frequency power is dissipated in R_g and they are sometimes termed the half power points.

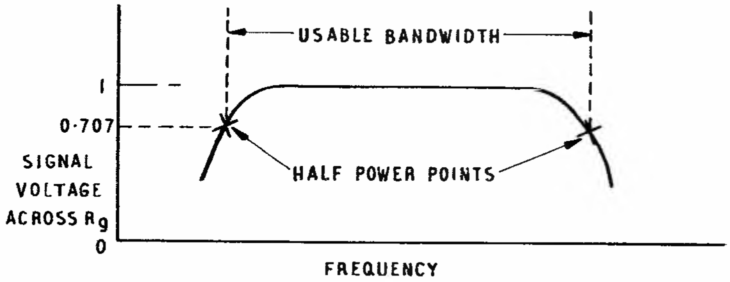


FIG. 30. HALF POWER POINTS.

As power in resistance = I^2R or $\frac{E^2}{R}$, then the voltage squared across the grid resistor (R_g) at half power points equals half the voltage squared across R_g at mid-frequencies.

$$\text{Since } E_2^2 = \frac{E_1^2}{2}$$

$$\text{and } E_2 = \sqrt{\frac{E_1^2}{2}} = \frac{E_1}{\sqrt{2}} = \frac{E_1}{1.414} = 0.707\,E_1$$

or 70.7% of E_1

where E_1 = Voltage across R_g at mid-frequency.
E_2 = Voltage across R_g at half power points.

The half power points therefore occur when the voltage across R_g is 0.707 of that at the mid-frequencies.

At the h-f end of the band the half power point occurs when the reactance of shunt capacitance falls to the value of mid-f Z_L thus reducing it by one half. At the l-f end the half power point occurs when the reactance of coupling capacitor C rises to equal R_g.

Mid-frequency Gain of wideband amplifiers can be determined using a much simplified form of formula (2) which we derived for pentode amplifiers from equivalent circuit (Fig. 25).

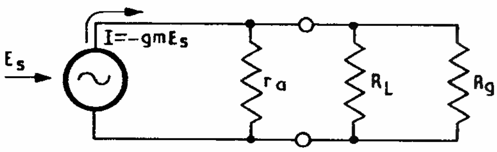


FIG. 31.

$$A = g_m \frac{r_a Z_L}{r_a + Z_L} \qquad \text{............. (2)}$$

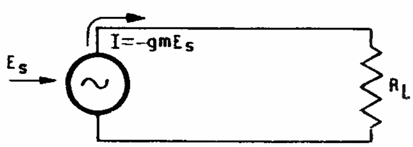
From Fig. 27a, we saw that Z_L over mid-frequencies consisted substantially of R_L and R_g in parallel. This is shown again for easy reference in Fig. 31.

Except in amplifiers having very high gain and limited bandwidth (R_L 250kΩ or more) R_g is generally many times R_L in value and has therefore only a small effect on Z_L. That is, Z_L is practically equal to R_L and the following formula suffices -

$$A = g_m \frac{r_a R_L}{r_a + R_L} \qquad \text{............. (3)}$$

(For narrower bands where triodes may be used, formula (1), page 17, can be similarly simplified by regarding $Z_L = R_L$.)

When R_L is only a few thousand ohms (say 2000Ω to 10,000Ω) it is so much lower than r_a as well as R_g that they may both be neglected and a further simplification of the formula and equivalent circuit (Fig. 32) are sufficiently accurate.



$$A \text{ (very wide bands)} = g_m R_L \qquad \text{............. (4)}$$

FIG. 32.

-.4 Phase Shift. While the load is predominantly resistive, phase change per stage is 180° or nearly so, but shunt capacity which reduces gain at the h-f end of the response curve also causes the output signal voltage to lag behind the output current of the tube, and phase change is less than 180°. At the low frequency end series capacitance C causes the current and voltage in R_g to lead the signal current in R_L and phase change is more than 180°.

This results in phase shift between the harmonics and fundamental frequency of a complex wave and is not serious in sound reproduction but it can be a serious form of distortion with video and other very wide bands. This is known as "phase distortion".

-.5 "Compensation" is a means of extending either or both l-f and h-f response and reducing the phase shift in wide band amplifiers. It is accomplished by including additional components in the coupling circuit which to some extent compensate for the effect of shunt capacitance at high frequencies and series capacitance at low frequencies. There are several circuits used, some being rather complex.

For h-f compensation the simplest and most widely used arrangement is shown in Fig. 33, together with the equivalent circuit. It is assumed R_L is low in value making r_a and R_g a negligible shunt load by comparison. This is called "shunt peaking".

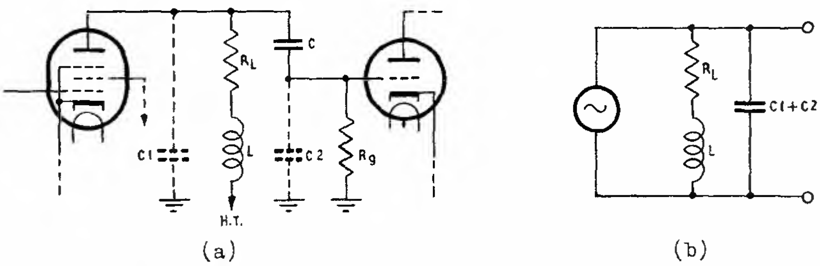


FIG. 33. h-f COMPENSATION BY "SHUNT PEAKING".

A small inductance in series with R_L has negligible reactance at low and mid-frequencies. Its reactance rises at high frequencies as that of C1 and C2 commences to fall and the combination maintains Z_L and gain constant to a higher frequency than would be possible without it. The phase shift due to C1 and C2 is counteracted by that due to L although correction is not perfect when L is proportioned to extend the flat response to as high a frequency as possible. (Half power point may be extended to about $1\frac{1}{2}$ times the frequency attained in uncompensated stages.)

Low frequency compensation is achieved fairly simply as shown in Fig. 34. A high value resistor R3 in series with R_L is shunted by a capacitor of large value C3.

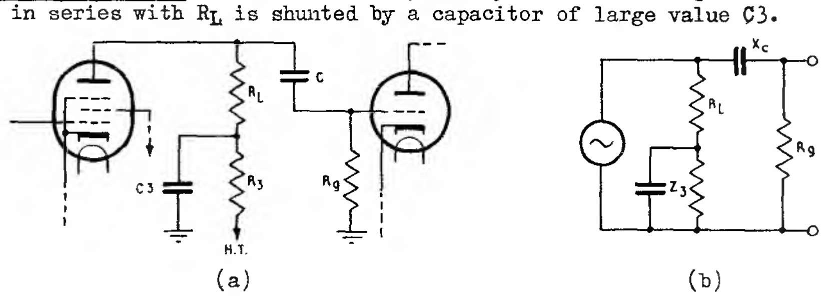


FIG. 34. TYPICAL l-f COMPENSATION.

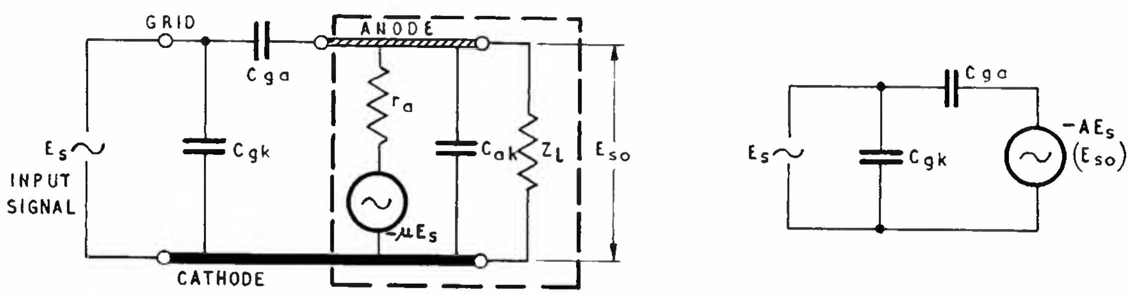
At the mid and high frequencies there is no effect on the A.C. load because of the reactance of C3. At low frequencies the reactance of C3 rises and the combined impedance of R3 and C3 (shown as Z3 in the equivalent circuit, Fig. 34b) increases the value of A.C. load and gain to compensate for the increasing voltage drop across coupling capacitor C. A more constant output voltage across R_g is maintained as frequency is lowered.

As frequency is lowered X_c causes the voltage across R_g to start leading the anode signal voltage. At the same time however Z3 becoming capacitive in character causes the anode signal voltage to lag the anode signal current and thus compensate to some extent for the phase shift caused by X_c. The values can be proportioned to permit only a small resultant phase shift down to quite low frequencies. Section 14 shows typical circuits incorporating all these principles.

Another way of improving response characteristics of amplifiers is the use of negative feedback the details of which are examined in Section 11.

7.6 Input Capacitance and "Miller Effect". We have represented input capacitance in the equivalent circuits of Figs. 26 and 27 by the capacitor C2 in parallel with R_g. The effective input capacitance of a tube is greater than the simple grid to cathode inter-electrode capacitance because of a property of amplifiers known as "Miller effect". Stated simply, this means that input capacitance is increased by an amount which depends on both grid-to-anode capacitance and voltage gain of the stage. An equivalent circuit can help explain this phenomena, which if fully analysed involves complex calculations beyond the scope of this course. A simplified explanation suffices to show that the Miller effect cannot be neglected, because in some tubes it accounts for the greater part of the unwanted shunt capacitance (which limits high frequency response).

Fig. 35a shows a complete A.C. equivalent circuit for a triode amplifier including the three inter-electrode capacities, grid-to-cathode C_{gk}, grid-to-anode C_{ga} and anode-to-cathode C_{ak}. The output circuit consists of the equivalent A.C. source producing $-\mu E_s$ volts in series with r_a and the load Z_L. We have already seen in para. 6.2 that the A.C. output voltage E_{so} is greater than the input voltage E_s by the voltage gain (A). We can further simplify the equivalent circuit by replacing the entire section of Fig. 35a within dotted lines by an imaginary A.C. generator producing $-AE_s$ volts as represented by Fig. 35b. (The minus sign denotes the 180° phase change when Z_L is resistive.) The effect of C_{ak} is small enough to be neglected.



(a) (b)

FIG. 35. INPUT CAPACITANCE.

We see from this that grid-to-anode capacitance C_{ga} becomes an additional shunt capacity in series with the output voltage, which being A times input voltage causes C_{ga} to accept from the input signal a charge A times as great.

For example, a typical triode has $C_{gk} = 4\mu\mu F$, $C_{ga} = 3\mu\mu F$ and is connected with resistive load to give a gain of 16. Then -

$$\text{Equivalent Input Capacitance} = C_{gk} + C_{ga} + AC_{ga}$$
$$= 4 + 3 + 3 \times 16 = 55\mu\mu F.$$

For multi-element tubes such as pentodes the formula is modified slightly to include the capacitance from the grid to the other electrodes. The total capacitance from grid to the other electrodes including anode and cathode all tied together is called C_{in}.

For example, a typical pentode has $C_{in} = 6\mu\mu F$, $C_{ga} = 0.005$ and typical gain of ~~150~~, 160.

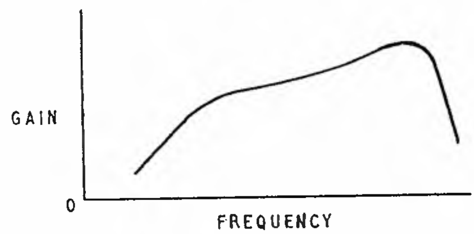
$$\text{Equivalent Input Capacitance} = C_{in} + AC_{ga}$$
$$= 6 + 160 \times 0.005\mu\mu F = 6.8\mu\mu F.$$

Note that because the screen and suppressor grids make C_{ga} so low in value, the additional input capacitance due to Miller effect is quite a small proportion, even though voltage gains of pentodes may be 10 to 20 times that of triodes. Comparing the results of the two typical examples it is easy to see why triodes are not used in wideband voltage amplifiers. At 100kc/s, $55\mu\mu F$ has a reactance of about 30kΩ whereas $6.8\mu\mu F$ has a reactance of about 234kΩ at the same frequency. Stray wiring capacities add a few $\mu\mu F$ to input C in both cases and careful attention is paid to component layout to keep stray capacitance in wideband amplifiers to a minimum.

8. FREQUENCY RESPONSE WITH REACTIVE LOADS.

8.1 Transformer and Impedance Coupling. Transformer and impedance coupling do not permit the very wide band flat response obtainable with R/C coupled amplifiers. Their use is therefore restricted to narrower bands of frequencies.

Fig. 36 shows a typical response characteristic for a transformer coupled stage. Gain is less at the l-f end of the band than at the h-f end because the inductive reactance at low frequencies is too low to provide an adequate A.C. load for the tube. Response falls off at high frequencies where shunt inter-turn capacitance and transformer losses appreciably lower the load impedance. By special transformer design however, fairly flat mid-frequency response can be obtained, and a bandwidth up to 10kc/s is not uncommon for voltage amplifiers.



TYPICAL RESPONSE CHARACTERISTIC WITH TRANSFORMER COUPLING.

FIG. 36.

An important advantage of transformer coupling is the low D.C. primary resistance in series with the anode which permits high gains with fairly low supply voltages; also, the step-up turns ratio increases the voltage gain by that factor. Except for very narrow bands, however, high turns ratios are not desirable as too many secondary turns increase shunt capacitance, and too few primary turns reduce primary impedance which reduce h-f and l-f response respectively. Where appreciable bandwidth is desired the transformation ratio is generally no higher than 2 to 4 times. For speech band amplifiers in telecom (about 100 to 3,000c/s) transformer coupling is very suitable and fairly widely used.

8.2 Tuned voltage amplifiers have one or more tuned circuits in the A.C. anode load of each stage as shown for one stage in Fig. 37a. Basically, such circuits would provide maximum gain at one frequency only; when required, ganged variable capacitors permit "tuning" of the amplifier over a range of frequencies. When only a small range of

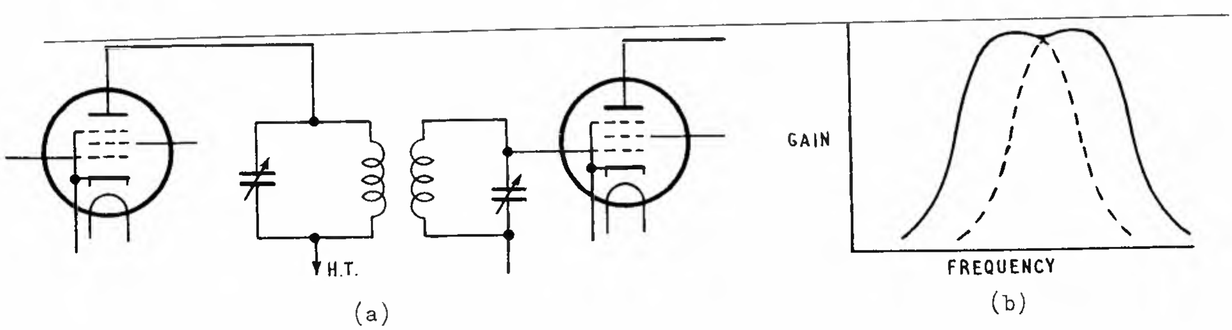


FIG. 37. TUNED VOLTAGE AMPLIFIER.

9. POWER AMPLIFIERS.

9.1 Main Features. We saw in Section 2 that practically every tube produces a greater output power than the power delivered to its grid and is therefore an amplifier of power. In contrast however, with circuits designed to produce high voltage gain and/or high output voltage, the term "power amplifier" is reserved for circuits which have their output connected to an energy consuming device such as a trunk line, a radio transmitting antenna or a loudspeaker. Most of the principles of voltage amplifiers still apply, but with power amplifiers, additional factors need to be considered. The more important of these are -

(i) The device forming the load generally has an impedance unsuited to the load requirements of the output stage. An output transformer is used having a turns ratio that presents the optimum A.C. load to the output stage. Most loads range from only a few ohms to a few hundred ohms and step down transformers are required. The transformer also isolates the load from the HT supply.

(ii) To produce appreciable A.C. power, large anode current swings are necessary. This requires large "exciting" voltage input to the grid (the function of the voltage amplifying stages).

(iii) Operating efficiency has to be considered especially where large outputs are required. That is, the ratio of useful A.C. output power to D.C. input power is generally as high as practicable to avoid wasteful energy loss and unwanted heating.

(iv) To meet requirements (ii) and (iii) the tube or tubes must be operated over the greater part of the dynamic characteristics including part of the curved regions. The non-linear current and voltage relationships met with, introduce distortion of the signal. (In voltage amplifiers, the comparatively small input signal swings can be confined to the linear region of the characteristics.) As a rule, the output stage introduces more distortion than all the other stages combined.

(v) The values of load impedance and bias are therefore critical. For any given tube and supply voltage, maximum possible power output is not consistent with low distortion and the choice of bias and load impedance is therefore a compromise between adequate power output and acceptable distortion.

9.2 Single tube output stages operating Class A1 are widely used for audio and video frequency amplifiers giving moderate outputs of up to about 5 watts ("single ended" amplifier). Output tubes are sometimes operated in parallel to obtain higher output power. Fig. 38 shows a single ended Class A output circuit with typical operating figures listed. These values vary considerably with different tubes and with different loads for the same tube, and are given as a matter of interest only.

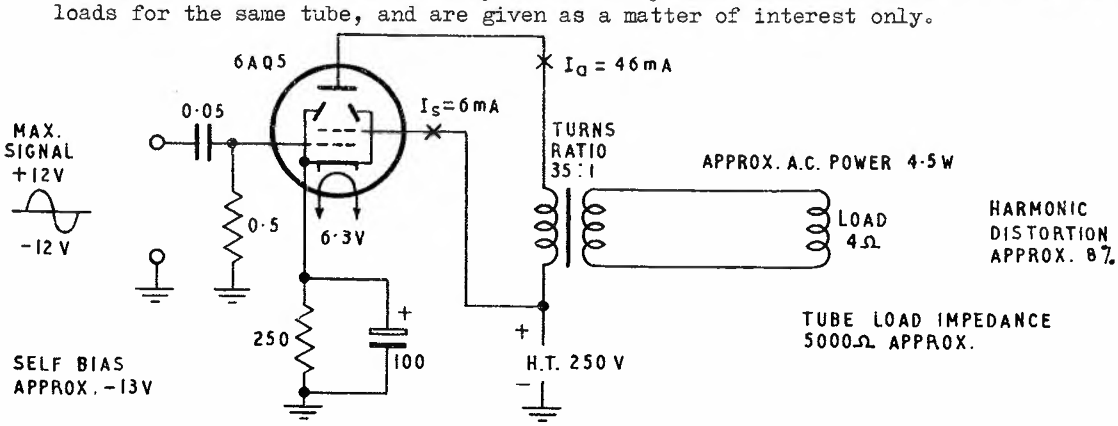


FIG. 38. TYPICAL CLASS A1 POWER AMPLIFIER (SINGLE ENDED).

9.3 Push-pull output stages are used in many audio frequency amplifiers. Fig. 39 shows a typical arrangement. The interstage transformer T1 has a secondary centre-tap connected to both cathodes for the signal frequency and its ends connect to the output tube grids. The H.T. D.C. is applied to the centre-tapping of the output transformer primary and with matched tubes the equal and opposite D.C. components in the output produce no magnetization of the core.

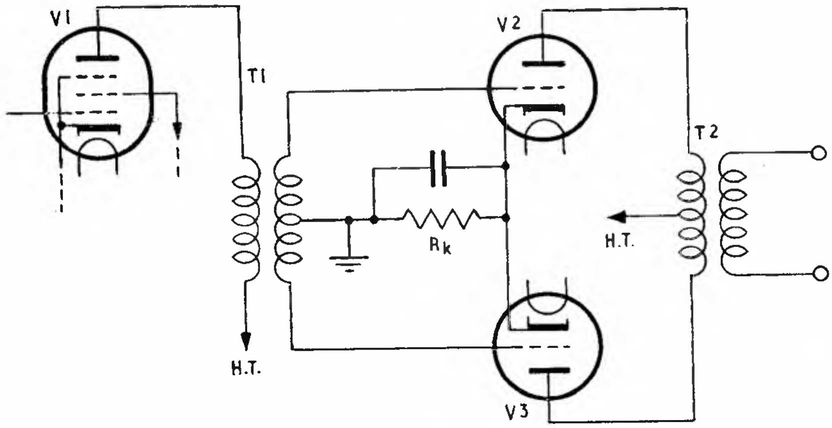


FIG. 39. PUSH-PULL A.F. OUTPUT.

When input signal is applied, the grid of V2 is on the positive swing while the grid of V3 is on the negative swing and vice versa. With Class A bias (from R_k in Fig. 39). The current in one half of T2 primary increases as the current in the other half decreases and as these currents are in opposite directions their magnetic effects are additive. The signal is thus amplified and the signal power output induced into T2 secondary is a little more than twice that of similar tubes in single ended output.

Push-pull audio output stages can also be operated Class AB or Class B. With Class B operation one tube remains cut off while the other amplifies the positive grid swing and a more appropriate expression for this would be "push-push" output. The full cycle of input is reproduced in the secondary of the output transformer as described in Sect. 2 (Fig. 5). With Class AB operation more than half the input cycle is handled by each tube.

As a means of handling large powers, push-pull operation has the advantage that the two D.C. anode currents do not reduce the transformer inductance - their magnetising effects are equal and opposite. Many of the effects of non-linearity in the tube's characteristics are also largely cancelled out and distortion introduced can be quite low when tubes are well matched.

9.4 Anode Efficiency of output stages is a measure of the useful output (A.C.) with respect to the total D.C. power fed to the anode. In Class A operation this is only about 20-40% because an "unproductive" D.C. component flows at all times whether there is signal input or not. Overall efficiency is a little less than anode efficiency and takes into account the additional D.C. power wastage of the screen grid.

Higher efficiency is obtained with Class B and Class C operation because there is no anode current until signal is applied. Where large power outputs are required this is an important consideration and the wastefulness of Class A operation cannot be tolerated. Radio transmitter Class C single ended final stages are the best example of this. As we saw in Section 2, Fig. 4, anode current is in the form of short pulses lasting only a fraction of a cycle and which utilise the full range of the tube's control from cut-off to grid current. The anode load tank circuit reproduces the full cycle.

Another example is the Class B or AB push pull output stages often used to obtain the considerable audio output power needed for such applications as large public address systems.

9.5 Output Tubes. Triodes, pentodes and beam tetrodes are all used in power amplifiers but each has advantages and disadvantages:-

- Triodes require large input signal voltage to produce adequate power output, however, distortion is lower than that of pentodes and beam tubes.
- Pentodes and beam tubes are more sensitive than triodes in that lower exciting voltages on the grid produce adequate anode current swings. Ordinarily distortion produced is greater than that of triodes, although this is generally corrected by the use of negative feedback. (See para. 11.3.)

Output tubes handle far heavier currents than most voltage amplifying tubes. Cathode emission is greater and the electrodes are constructed to cope with the greater heat dissipation, particularly the anode. These factors result in power tubes having lower values of r_a than other tubes - generally about one tenth of corresponding types of voltage amplifiers.

9.6 Output Transformers. Modern high quality A.F. output transformers are made using special core materials and winding techniques and are capable of flat response characteristics over a range of at least 10c/s to 100kc/s. This is much greater than can be achieved with interstage transformers (para. 8.1) because with low impedance step-down transformers, shunt capacitance is much less and its relative effect on the A.C. load is also less.

9.7 Phase Inversion. The grids of push-pull stages require signals 180° out of phase and the simplest way to obtain this is by using a transformer as shown in Fig. 39. Very often however, the transformer is replaced by a phase inverter or phase splitting circuit to avoid the bulk of a transformer or to avoid the non-uniform frequency response it would introduce.

There are several different phase splitting circuits each having its advantages and disadvantages. All make use of R/C networks for the coupling and use a tube or tubes to provide the out of phase signals. Typical phase inverters are shown in Fig. 40.

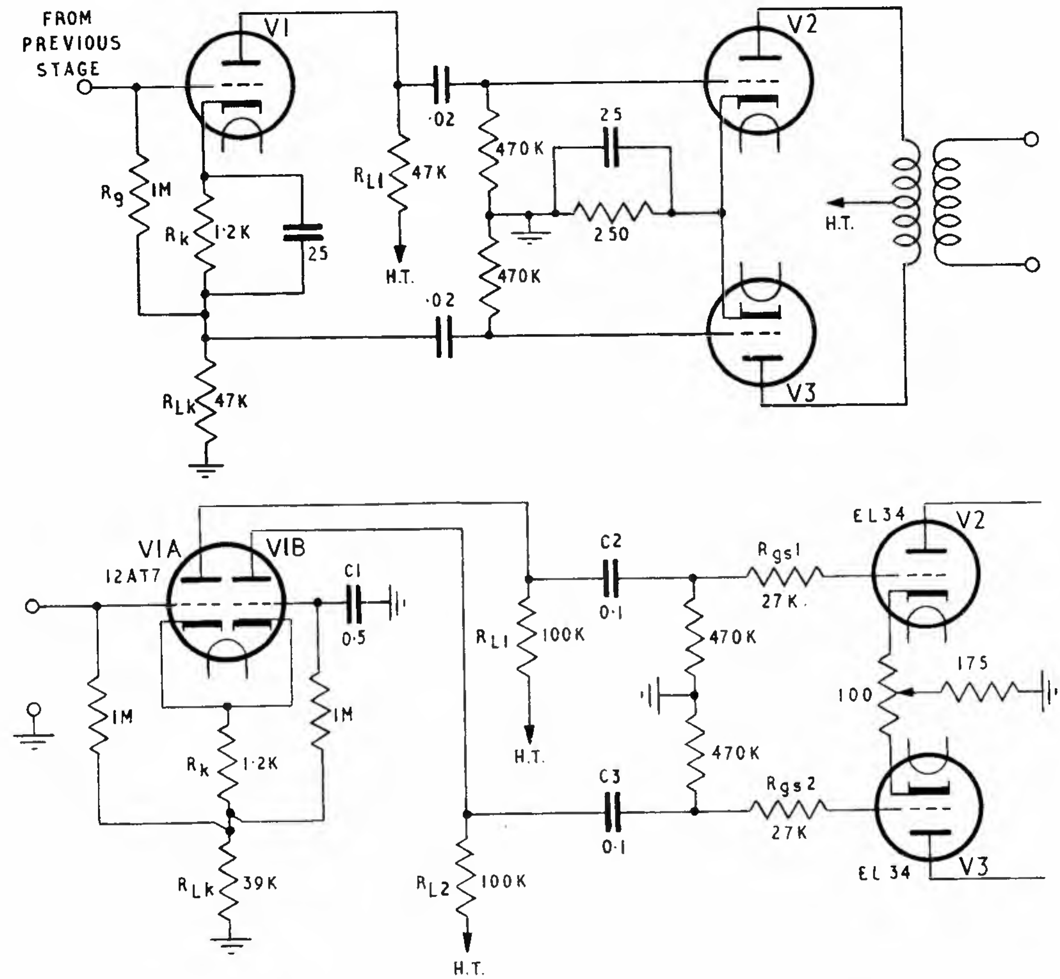
In Fig. 40a the load of V1 is divided in two, with half in the anode circuit (~~R_{La}~~ R_{L1}) and half in the cathode circuit (R_{Lk}). With respect to A.C. ground (earth and H.T.) the cathode goes negative as the anode goes positive and vice versa giving the required signal to V2 and V3 grids via C2 and C3.

Although the D.C. bias of V1 is fixed by the bypassed resistor R_k, the signal voltage across the cathode follower part of the load (R_{Lk}) is in series with the grid input voltage and in opposition to it. This is negative feedback and is an important subject in itself which we will examine fully in Section 11. In the circuit of Fig. 40a it results in the stage gain of V1 being less than 1; that is, a voltage loss. Therefore the signal input to V1 must be slightly higher in voltage than that required between the grids of V2 and V3.

Fig. 40b is another type which uses a twin triode as the phase inverter. V1A has most of its load in the anode circuit (R_{L1}), and its anode signal excites the grid of V2 via C2. V1A also has a cathode load (R_{Lk} + R_k) across which a smaller signal is developed. R_k gives self bias.

The grid of V1B is earthed for A.C. via C1 and its input signal is cathode coupled from V1A as the signal voltage across the common cathode load. As this signal is 180° out of phase with V1A grid, the effective signal voltage between V1B grid and cathode is out of phase with that between V1A grid and cathode. Therefore, the signal at V1B anode which excites V3 grid via C3, has a 180° phase difference from that at V1A anode which excites V2 grid.

The unbypassed $R_k + R_{Lk}$ give negative feedback which prevents the stage having much voltage gain. In this respect Figs. 40a and 40b are similar; feedback is examined in Section 11. Practically all phase inverting arrangements have an additional tube which contributes no appreciable stage gain. This is their main disadvantage and where space is not critical and wide flat response is not needed the interstage transformer is still widely used.



(b)

FIG. 40. TYPICAL PUSH-PULL OUTPUTS WITH PHASE INVERTERS.

The two 27kΩ series grid resistors in Fig. 40b ($R_{gs1} + R_{gs2}$) are called "grid stoppers". In some amplifiers undesirable oscillations (known as parasitic oscillations) often occur due to long leads (which act as inductance), interelectrode capacities etc. behaving as a resonant circuit. These oscillations are generally high in frequency and occur through the valves introducing spurious frequencies and distortion. Oscillations of this type are more prevalent when valves are operated in parallel and it is generally essential to provide non inductive resistors in each grid lead to eliminate this effect.

9.8 Cathode Follower Power Amplifiers. Although cathode loading gives no voltage gain the arrangement makes a very good power amplifier for certain applications. Low output impedance and low distortion are its principal features. A knowledge of negative feedback is necessary to understand its operation and the description appears in para. 11.5.

10. DISTORTION.

10.1 Definition and types. Fidelity is perfect reproduction of the original signal. Distortion is lack of fidelity and, in practice, is always present in some degree. In sound reproduction the actual effect of distortion (that is, whether perceptible, tolerable or objectionable) depends on many factors. The listener may or may not have a critical "ear" and this is one important factor which cannot be expressed as a quantity. Distortion itself may be divided into several types the most important of which are -

(i) Non-linear distortion (also known as amplitude distortion) and resulting in -

(a) Harmonic Distortion.

(b) Intermodulation distortion.

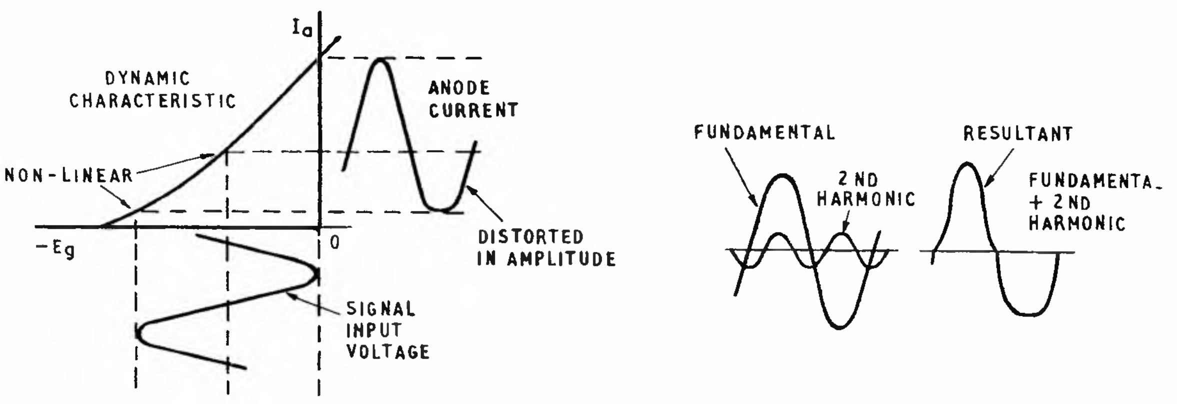
(ii) Frequency distortion.

(iii) Phase distortion.

(iv) Transient distortion.

10.2 Harmonic Distortion. Speech and music have very complex waveforms which are the combination of one or more fundamental frequencies and the associated harmonics which give the sound its characteristic quality. Any non-linearity in an amplifier will produce additional harmonics, not present in the original signal. The 2nd harmonic predominates with single ended output and 3rd harmonic with push-pull output. Higher order harmonics up to the 25th may be produced in certain cases but their level becomes less as the order of harmonic increases.

Using a sine wave input, Figs. 41a and b represent how an output distorted in amplitude on one half cycle is approximately equivalent to an undistorted wave plus a smaller wave at twice the frequency (second harmonic). By combining various higher order harmonics of smaller amplitude an exact equivalent of the distorted waveform can be plotted. This indicates that the non-linear characteristic of an amplifier produces new harmonics not present in the original signal.



(a) (b)

FIG. 41. NON-LINEAR DISTORTION.

The proportion of harmonic voltage to sine wave fundamental is expressed as a percentage. As a general rule the wider the frequency band the less tolerable a given amount of harmonic distortion and more precautions are taken in the wider band audio amplifiers to keep it to a low percentage. For example, with a 5kc/s bandwidth 6% of harmonic distortion may be tolerable whereas with an amplifier response covering a 15kc/s band, 1 to 2% may be less tolerable.

Non-linear distortion is reduced when output stages are operated at a much lower maximum output power than they are capable of handling by limiting signal input voltage to a low value. Very low non-linear distortion is obtained at the cost of lower efficiency. On the other hand, severe non-linear distortion results from excessive signal or incorrect bias giving rise to overloading which we have seen graphically represented in Section 2, Fig. 3.

10.3 Intermodulation Distortion. The non-linear amplifier allows different frequency components of the output to modulate each other and produce spurious sum and difference frequencies. The products of harmonic distortion are also affected in this way and the tones produced from them are actually more objectionable than the harmonics themselves. One reason for this is than higher order odd harmonics such as the 7th, 9th, 11th, etc. are discordant with respect to the fundamental and lower music (where the amplifier response includes the frequency of these harmonics).

10.4 Frequency Distortion is the variation of amplification with the frequency of the input signal. This type of distortion has been dealt with in para. 7.2 under the heading of frequency response. Frequency distortion is present therefore when the response of the amplifier is not uniform or flat over the full range of the signal. In sound reproduction, however, a wide flat response and low frequency distortion are only acceptable to the listener when other forms of distortion are imperceptible.

10.5 Phase Distortion is the alteration of the phase angle between any two component frequencies of a complex wave, including phase shift between a fundamental and its harmonics. We have seen in para. 7.4 that the effect of capacitive reactance and resistance in amplifiers is to produce phase shift at the upper and lower frequency limits. Phase distortion is sometimes called time-delay distortion as a difference in phase represents a displacement in time.

10.6 Transient Distortion. In sound reproduction, transients are the short sharp sounds produced mainly by percussion instruments (cymbals, triangles, drums, etc.) or plucked strings. Such sounds are characterised by steep rise and decay of the waveform. Some amplifiers with quite good response to tones do not reproduce transients realistically and the result is called transient distortion. For good transient response an amplifier needs a wide frequency response (beyond the limits of audibility), no phase distortion and no tendency to prolong the pulses.

11. FEEDBACK IN AMPLIFIERS.

11.1 Principle of Feedback. When part of the output signal is combined with the input signal, feedback is said to exist. If the net effect of the feedback is to increase the effective input signal the feedback is positive, direct or regenerative. If the resultant input signal is reduced by feedback it is said to be negative, inverse or degenerative. Feedback is most positive when it is in phase with the input signal and most negative when it is 180° out of phase with the input signal.

Fig. 42 represents the basic principles of applying feedback, positive or negative. The feedback network or feedback "loop" includes the components used to select the required fraction of the output (voltage divider, transformer, etc.) and may also include frequency discriminating circuits when it is desired to have more feedback at certain frequencies than others.

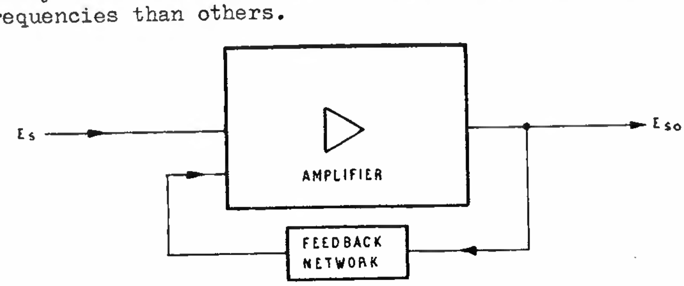


FIG. 42. PRINCIPLE OF FEEDBACK.

The feedback loop may enclose one or more stages and may also include the output transformer.

11.2 Positive Feedback is used intentionally to produce self oscillation and this aspect is examined in the paper "Oscillators". If it occurs in amplifiers where it is not usually intended the result is a tendency to oscillate on signal peaks and such a condition is called instability. Positive feedback is sometimes used in amplifiers in conjunction with larger amounts of negative feedback but this is not common.

11.3 Negative Feedback reduces amplifier gain but confers many important advantages -

(i) Non-linear, frequency and phase distortion are reduced.

(ii) Gain is stabilised against changes in components (e.g. tubes) and changes in supply voltages.

(iii) Noise and hum originating within the amplifier are reduced.

(iv) Output impedance can be lowered to permit more effective matching with the load or to obtain other advantages.

Distortion and noise are only reduced for those parts of the amplifier enclosed by the feedback loop. The greater the feedback voltage the greater the reduction of gain as well as distortion. Negative feedback is further subdivided into -

(i) Negative voltage feedback where the feedback voltage is a definite proportion of the output voltage (Fig. 43).

(ii) Negative current feedback where the feedback voltage is proportional to the output current (Fig. 44).

(It will be apparent, however, that with purely resistive loads, the two are equivalent. Final loads are rarely resistive.)

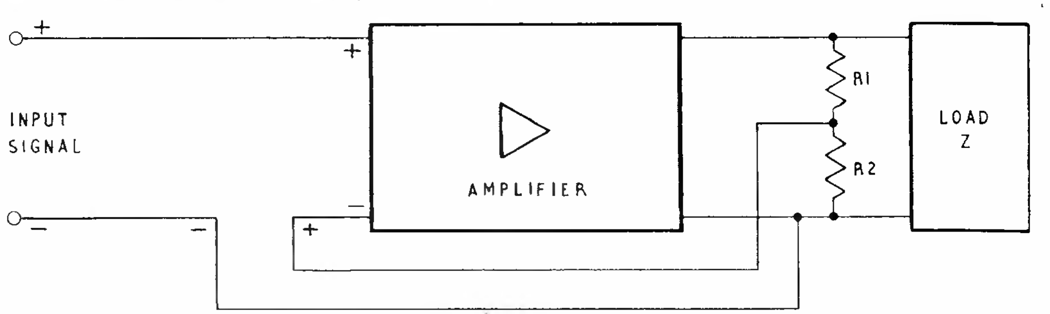


FIG. 43. PRINCIPLE OF VOLTAGE FEEDBACK.

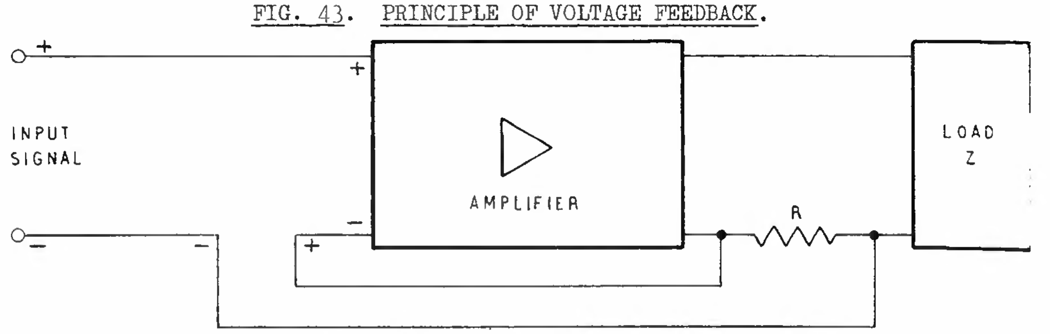
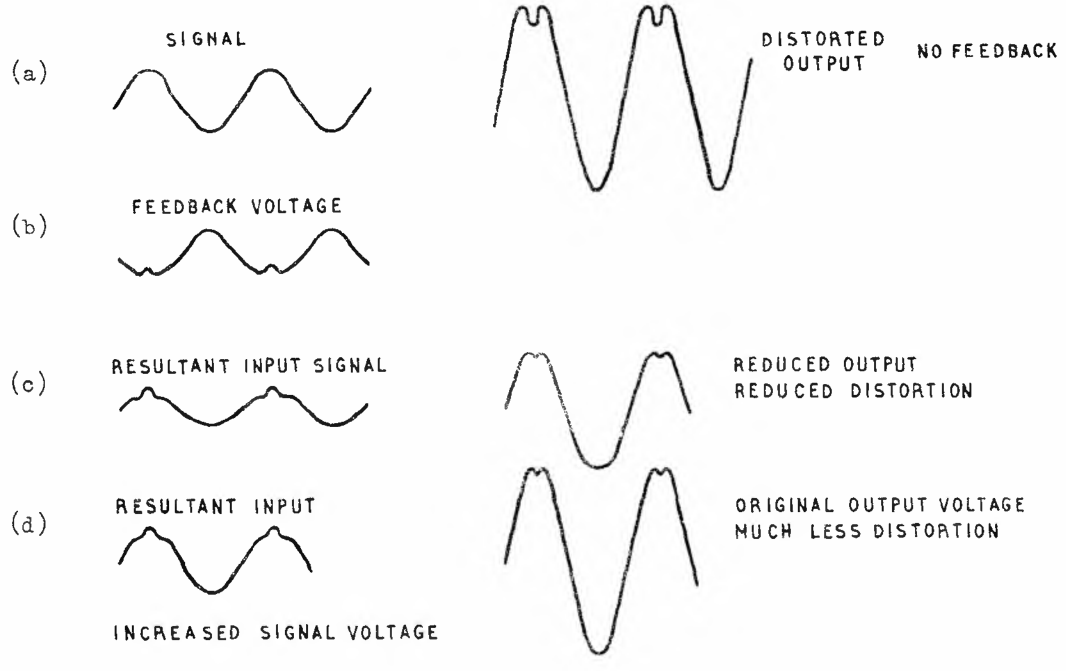


FIG. 44. PRINCIPLE OF CURRENT FEEDBACK.

The amount of feedback is best described by the amount it reduces gain. With a feedback factor of 10, gain is one tenth of that produced by the same amplifier without feedback; distortion is reduced to one tenth and 10 times the input signal voltage is required to produce the same output. The gain reduction factor can also be expressed in decibels or db which is logarithmic scale for expressing power or voltage ratios and is fully explained in Section 12. (A power ratio of 100 to 1 can also be expressed as 20db.)

Reduction of distortion. The manner in which negative feedback reduces distortion is shown in Fig. 45. An improbable type of distortion is assumed to make the process clearer. The feedback voltage (Fig. 45b) is 180° out of phase with the signal but of somewhat lower peak voltage. The resultant input signal (c) is a combination of (a) and (b) but has a waveform which can partly compensate for the distortion produced in the amplifier. Distortion and output voltage are reduced. By applying a larger signal the original output voltage (a) can be achieved with much less distortion (d).



FEEDBACK REDUCES DISTORTION.

FIG. 45.

Output Impedance. Voltage and current feedback have similar effects in reduction of distortion, gain stabilisation and noise reduction, but have an opposite effect on the operating impedance of the output stage. Voltage feedback reduces the amount of change in output voltage with change in output impedance, but as a constant voltage/low impedance source is indicated when the output voltage remains constant with a change in load, any tendency to stabilise output voltage is equivalent to a lowering of output impedance. That is, the output tube behaves as though its r_a were lowered and this is generally desirable with inductive loads.

Current feedback, on the other hand tends to stabilise output current with load impedance changes and this is equivalent to raising output impedance or r_a. (We saw in para. 6.1 that no appreciable current change with load change indicated a constant current, high impedance source.)

Negative feedback in amplifiers is sometimes a combination of voltage and current feedback. A multistage amplifier may have more than one feedback loop. Care is taken in design to ensure that feedback which is negative at mid-frequencies cannot become positive at high or low frequencies owing to additional phase change occurring in both amplifier and feedback network at the ends of the frequency band.

11.4 Typical applications of Negative Feedback. Feedback circuits are so numerous that examples of only the more basic schemes will be given here. The feedback network however can be made frequency selective to provide a form of frequency compensation with either fixed or variable components. In audio amplifiers this is called bass or treble "boosting".

(i) Current Feedback. The simplest feedback circuit utilises a cathode bias resistor which is unbypassed for signal or only partly bypassed. (Fig. 46.) We saw in "Electron Tubes" how a cathode resistor is bypassed to prevent signal voltage being superimposed on the D.C. bias in such a direction as to oppose the input signal. Without a bypass, a positive grid swing increases cathode current and the voltage drop in the cathode resistor R_k, this opposes (by 180°) the input signal as it tends to make the cathode more positive with respect to grid while the grid is driving less negative with respect to cathode. Negative grid swings are similarly opposed by the reduced voltage drop in R_k.

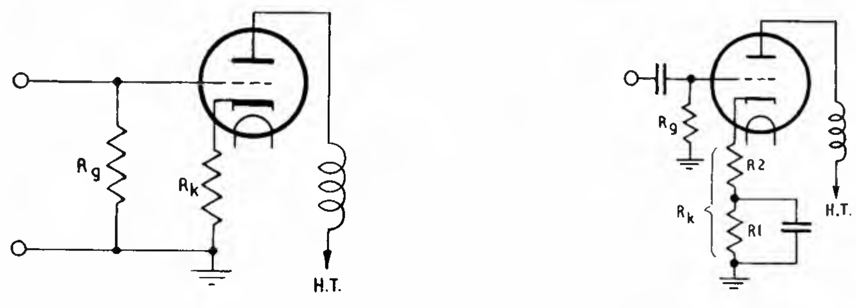


FIG. 46.

Since R_k is in series with the anode load, negative current feedback is obtained by unbypassed cathode resistors. When the full value of R_k would introduce more feedback than desired it is divided into two resistors, one of which is bypassed as in Fig. 46b. The value of both resistors determine the bias voltage but only the signal voltage across R2 constitutes the feedback voltage.

(ii) Voltage Feedback. Fig. 47a shows a typical method of applying voltage feedback over one stage. Since there is 180° phase change between grid and anode signal voltages an A.C. connection from anode to grid will normally introduce negative feedback. The anode signal voltage is applied to voltage divider R1, R2, via blocking capacitor C. The proportion across R2 is applied to the grid in series with the input signal.

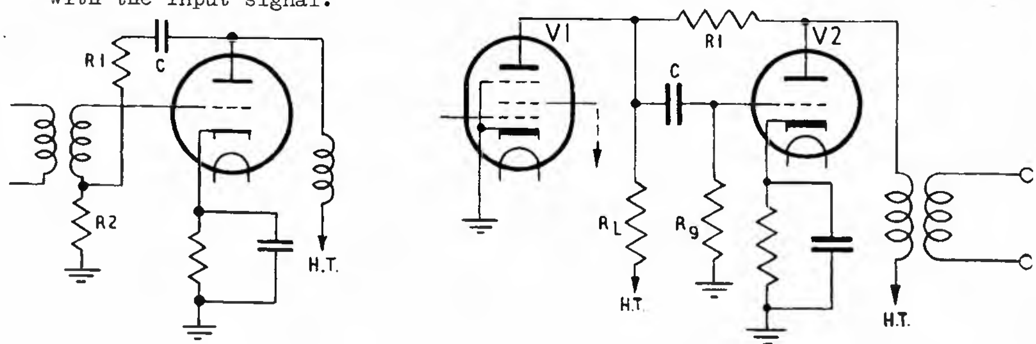
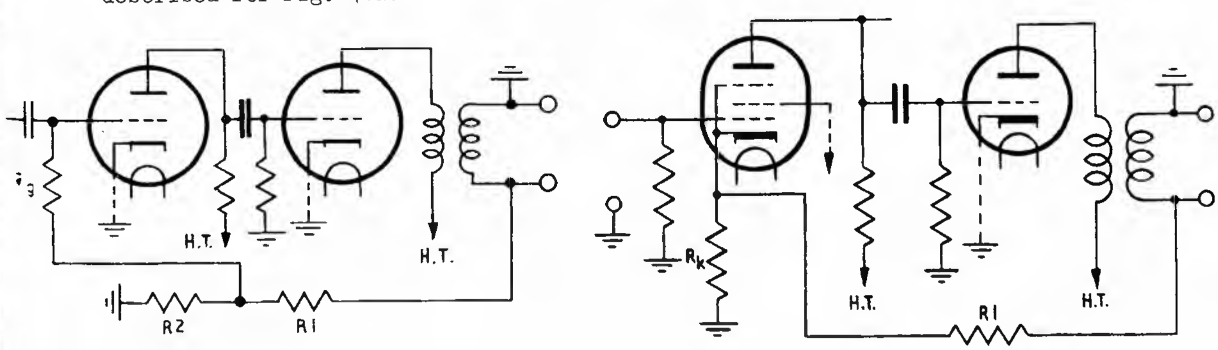


FIG. 47.

Fig. 47b shows a similar arrangement with R/C coupling. The feedback voltage from the anode of V1 is fed via R1 to the impedance of V1, R_L and R_g in parallel which together take the place of R2 in Fig. 47a to form the voltage divider with R1. The feedback voltage from V2 is applied in parallel with the output signal of V1 and in this respect it differs from Fig. 47a which has the feedback voltage in series with the signal. The normal coupling capacitor C provides the D.C. blocking in the V2 anode to grid feedback path.

Fig. 48 shows the elements of typical arrangements where the feedback loop encloses two stages and the output transformer. In Fig. 48a, R1 and R2 divide the voltage and that across R2 is fed to V1 grid via R_g; this is voltage feedback. In Fig. 48b the feedback voltage is fed to V1 via R_k which takes the place of R2 in the voltage divider; this is also voltage feedback. In addition however, R_k is (necessarily) left unbypassed and therefore applies some negative current feedback to V1 alone, as described for Fig. 46a.



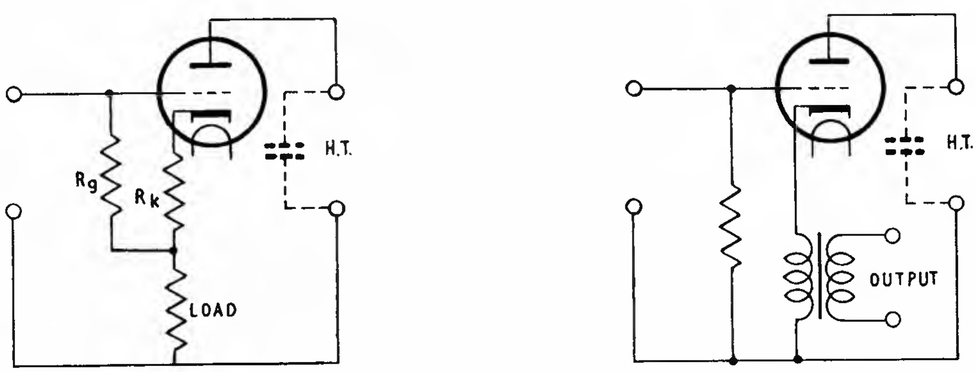
(a) (b)

FIG. 48.

The output transformer introduces approximately 180° phase change as well as the 180° each of V1 and V2. The manner of connection to the output transformer will therefore decide whether feedback is in phase or 180° out of phase with the signal input of V1. A wrong connection is easily rectified by reversing the transformer connection as positive feedback causes A.F. amplifiers to "howl" (break into oscillation).

1.5 The Cathode Follower amplifier is one having the whole of the load in the cathode circuit making the anode common to input and output as far as the signal is concerned (Fig. 49). Since R_L is common to both input and output the total output voltage constitutes a negative feedback voltage superimposed on the input signal. As a result voltage gain is less than 1; that is, output voltage is lower than the input voltage (usually only slightly lower). However, the arrangement results in input impedance being very high and output impedance being quite low; the cathode follower therefore makes a very good power amplifier where these conditions are desirable, such as in wide band amplifiers for cathode ray oscilloscopes and television service where, in certain cases, the load may be supplied direct without an output transformer.

The large amount of negative feedback inherent in cathode follower output stages makes distortion practically negligible.



(a) (b)

FIG. 49. CATHODE FOLLOWER OUTPUT STAGES.

11.6 Decoupling. Amplifier stages normally share a common power supply and this has an internal impedance which is in series with all the anode loads as shown in Fig. 50a. This results in a small amount of feedback between stages, even though the supply includes filter and bypass capacitors.

In a high gain three stage amplifier the anode current variations of V3 develop a signal voltage across the supply impedance which finds its way to the grid of V2 via the anode load of V1 and this is in phase with the signal. This unwanted positive feedback or regeneration would cause instability.

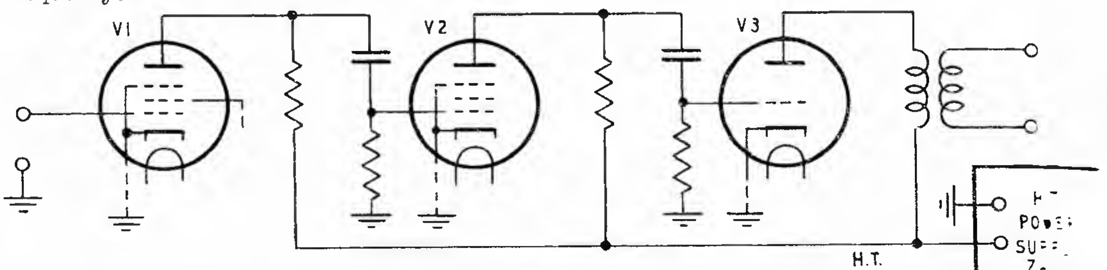
For example, the power supply may have an impedance of only 1Ω but if V3 has an an... current swing of 50mA a signal voltage of $\frac{1}{20}$V peak-to-peak is produced across the supply (I x R). If V2 has a gain of say 200, its input signal voltage will be ab... the same order. The in-phase feedback will result in considerably increased input ... V3. This will in turn increase the feedback voltage, and on signal peaks the ampl... may tend to howl or oscillate and may even continue to oscillate in the absence of applied signal.

The possibility of this is avoided by the use of R/C decoupling filters in series ... the anode loads of V1 and V3 (Fig. 50b). Unwanted signal voltage is developed acr... R1 and R3 and bypassed to earth via C1 and C3.

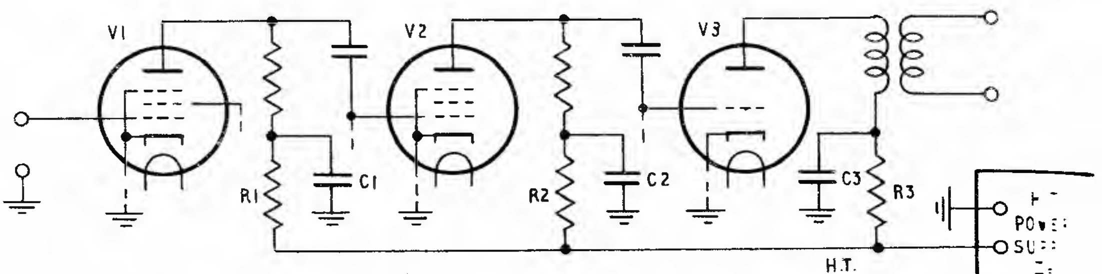
It may appear that the additional bypassing effect of C1 and C3 in parallel would suffice. It must be remembered however that the H.T. supply itself contains some very large filter capacitors and C1 and C3 would also have to be very large (and inconvenient) to appreciably lower shunt reactance. Even then, the three anode ... supply leads are at the same potential for D.C. and A.C.

If we think in terms of a resistive voltage divider as we did for R/C coupling (Fig. 8) we can see that when the signal current in V3 is made to pass in series ... R3 and impedance Z_s of the supply, a negligible voltage appears across Z_s in compar... to that across R3. This voltage is readily bypassed to earth by a small capacitor which need have negligible reactance compared to R3 but not to Z_s. Any slight sig... voltage appearing across Z_s is similarly isolated from V2 grid by the comparatively high resistance of R1 and low reactance of C1. R2 and C2 may also be included to prevent degenerative signals between V3 output and input or V2 output and input.

A typical value for decoupling resistors is about one-fifth of the anode load (R... The decoupling capacitors are chosen to have negligible reactance at the signal frequency.



(a) Without Decoupling.



(b) With Decoupling.

FIG. 50. DECOUPLING OF H.T. SUPPLY.

12. EXPRESSION OF GAIN AND LOSS.

12.1 Power Ratios. As we have seen, voltage gains (or voltage ratios) are conveniently expressed as an ordinary multiplying factor - for example, a voltage gain of 150 times or simply 150. Overall amplification of a multistage amplifier or its output stage alone, is basically a raising of the power level and can likewise be expressed as the ratio $\frac{\text{output power}}{\text{input power}}$.

12.2 Bels and Decibels. Power gains however, may range from several hundred to several million times and such figures can be inconvenient for several reasons. A more convenient expression is based on the logarithm of the power ratio using a unit called the bel. A power ratio of 10 times $(\frac{10^1}{1})$ is 1 bel; 100 times $(\frac{10^2}{1})$ is 2 bels, 1,000 times $(\frac{10^3}{1})$ is 3 bels, 10,000 times $(\frac{10^4}{1})$ is 4 bels and so on. Decibels are smaller practical units and 1 decibel = $\frac{1}{10}$ bel, or 10 decibels = 1 bel.

Decibel is abbreviated to db. Fig. 51a represents a typical amplifier producing 5W output for 0.5mW input and Fig. 51b another producing 1W output for 2mW input.

(a) (b)

FIG. 51.

(a)

Power Amplification $= \frac{\text{Output}}{\text{Input}}$

$= \frac{5 \times 1{,}000}{0.5}$

= 10,000 times

Gain in Bels = log 10,000

= 4

Gain in db = 4 X 10

= 40 db.

(b)

$\frac{\text{Output}}{\text{Input}}$

$= \frac{1 \times 1{,}000}{2}$

= 500 times

Gain in Bels = log 500

= 2.699 (from tables)

Gain in db = 2.699 X 10

= 27 db approx.

To find gain in db therefore we may use the formula indicated by the above examples -

$$\text{Gain db} = 10 \log_{10} \frac{\text{output P}}{\text{input P}}$$

Actually the difference in power level between any two parts of a circuit whether as a result of amplification or attenuation (loss) is generally expressed in db and the more general formula becomes

$$\text{db} = 10 \log \frac{P_2}{P_1} \quad \text{Where} \quad \text{db is gain or loss in decibels and } P_1 \text{ and } P_2 \text{ are two power levels.} \quad \ldots\ldots\ldots\ldots (7)$$

(For ease in calculation always regard P_2 as the larger of the two powers.)

It is important to remember that a figure of so many db does not represent any particular output power. That is, db are not absolute units like volts or watts or inches but are merely a logarithmic way of expressing an arithmetic ratio.

For instance we can get 30db for any loss or gain where $\frac{P_2}{P_1} = \frac{1000}{1}$ such as

$$\frac{1\text{W}}{1\text{mW}} \quad \text{or} \quad \frac{400\text{mW}}{400\mu\text{W}} \quad \text{or} \quad \frac{20\text{W}}{20\text{mW}} \quad \text{etc.}$$

The advantages of using db are -

(i) Although power levels in telecom cover a tremendous range, inconvenient figures are avoided; for example, a power ratio of 2 to 1 is 3db and one of ten million 70db.

(ii) When a circuit consists of amplification and attenuation in tandem (such as a long trunk line with repeater stations) the overall gain or loss is simply the sum and difference of the successive gains and losses (Fig. 52).

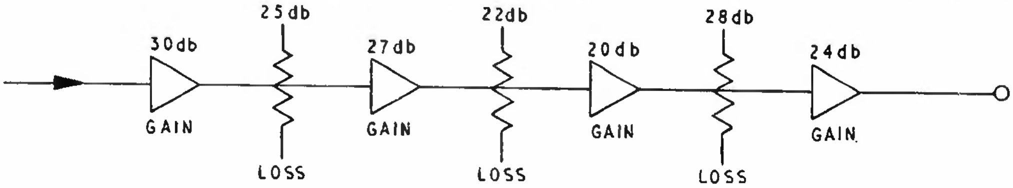


FIG. 52.

$$\text{Overall power gain} = \text{total gain} - \text{total loss}$$
$$= (30 + 27 + 20 + 24) - (25 + 22 + 28)$$
$$= 26 \text{ db.}$$

This is obviously much simpler than the tedious multiplication and divisi... (THAT ARITHMETIC RATIOS WOULD REQUIRE)

(iii) The human ear responds to sound waves of varying acoustic power measured in watts, mW, etc., in accord with a logarithmic scale. Irrespective of the intensity of any sound, when the power is increased 10 times, the loudness at the ear is approximately doubled, a further power increase of 10 times (i.e. 100 times the original) the second change in loudness would appear to the ear the same as the first and the sound about four times as loud. Therefore in sound reproduction, the comparison of output powers in db bears some relation to relative loudness (this is not exact owing to varying efficiencies of reproducing devices).

It is useful to remember that a power ratio of $\frac{2}{1}$ = 0.3 bel or 3db. The ... power points on a frequency response curve therefore represent a gain of ... less than that of the flat response section (Fig. 30).

12.3 Use of Voltage Ratios. Voltage ratios can also be expressed in db.

Since $P = \frac{E^2}{R}$ and $db = 10 \log \frac{P_2}{P_1}$

$$db = 10 \log \frac{(E_2)^2}{R_2} \times \frac{R_1}{(E_1)^2}$$

When input and output resistances are equal.

$$db = 10 \log \frac{(E_2)^2}{(E_1)^2}$$

$$\therefore db = 20 \log \frac{E_2}{E_1} \quad \ldots\ldots\ldots\ldots (8)$$

Where
P = Power in Watts
E_1 = Input Voltage
E_2 = Output Voltage
R_1 = Input Resistance
R_2 = Output Resistance

In general the input and output resistances are not equal. Despite this, formula is sometimes used as a convenient expression for db voltage gain of amplifiers. Strictly speaking db expresses power ratio and where used to indicate a voltage ratio this should be specified, since when input and output resistances differ the actual gain in db (power gain) will be a different value. Formula (8) therefore must be used with caution and only when its possible inaccuracy is clearly under... or stated.

13. NOISE.

13.1 Definition. In the transmission of electric signals noise is any spurious signal arising from points in the circuit other than the source of intelligence.

13.2 Thermal-agitation Noise. All conductors contain electrons that are in continuous random motion. This produces a minute voltage or current which varies in a random manner to constitute a noise signal distributed over a very broad frequency band from the very lowest frequencies to frequencies well above the highest used in telecommunications. The effect is called thermal-agitation noise because the electron movement results from thermal action. It is also called resistance noise or Johnson noise after the man who first showed how it could be evaluated.

The noise voltage produced in this way depends on the resistance, the temperature and the bandwidth of the system. All resistance introduces some noise; higher value resistances or higher temperatures produce more noise than lower resistance values or lower temperatures. For example, a 500kΩ resistor at room temperature produces a noise voltage of about 6 microvolts.

13.3 Tube Noise. Random noise similar to that produced in resistances is produced in tubes as a result of irregularities in electron flow. These irregularities arise from a number of conditions which vary between tubes of different type. The principal one is called "shot effect" and results from the random nature in which cathode emission replenishes the space charge. The presence of grids, gas, secondary emission and division of current between two or more electrodes all produce additional noise which in some text books are included as shot effect and in others are given additional names.

Tube noise is rated by a figure called equivalent noise resistance (in ohms). A figure of 5000Ω equivalent noise resistance for a tube indicates that its noise is equivalent to that produced by thermal-agitation in a 5000Ω resistance. Triodes produce less noise than any of the multi-element tubes. Pentodes produce from 3 to 10 times as much noise as triodes.

13.4 Inductive Interference. When a number of circuits operate with components and lines in close proximity some energy is transferred between them by electrostatic and electromagnetic induction. In telecom this is sometimes lumped under the heading of "crosstalk"; it is not generally intelligible but merely adds to the noise level in the disturbed circuit.

13.5 Signal to Noise Ratio. It is very important when amplifying weak signals that the noise level be kept well below the signal level as subsequent stages will amplify the noise as a part of the signal. The relative level of signal and noise is called the signal-to-noise ratio and in telecommunications every effort is made to keep the noise level at least 45db below the signal level; in practice a much better figure is generally achieved.

The first stage of an amplifier is obviously the most critical because even with very weak input signals the output of the first stage should be far above the noise likely to be introduced by subsequent stages. For this reason many low level amplifiers use low noise triode tubes in the first stage in preference to pentodes which introduce much higher levels of noise. A typical example of this is found in many television receivers where low noise is vital for high quality reception, yet incoming signals may be very weak. The first stage may consist of a twin triode arranged as a "cascode" stage to achieve good gain with low tube noise.

Fig. 53 shows the main elements of a typical cascode stage. The signal input goes to the grid of V1A which is a normal grounded cathode configuration except that the anode load (tuned R.F. choke) is fed via the cathode of V1B making the two anode circuits in series for D.C. The output signal of V1A appears between cathode of V1B and earth and is impressed between grid and cathode of V1B via capacitor C1 which earths V1B grid for the A.C. signal; V1B is therefore a grounded grid configuration. To bias V1B, its grid is maintained at a slightly less positive D.C. potential than its cathode by means of the voltage divider R1, R2. Gain achieved is equivalent to that of a pentode.

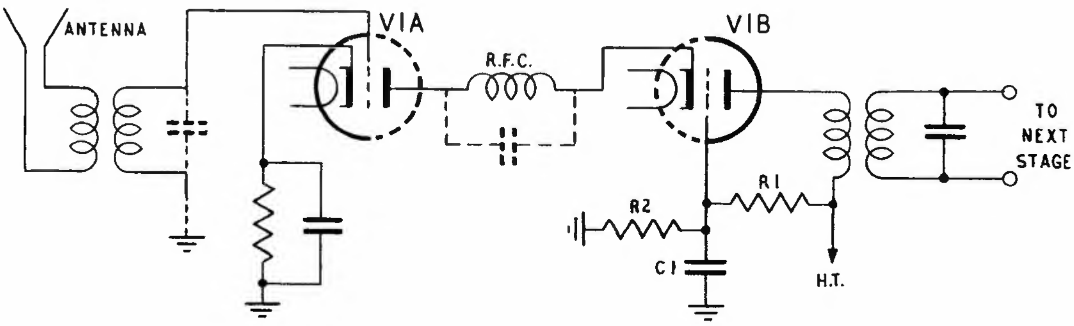


FIG. 53. "CASCODE" LOW NOISE R.F. STAGE.

14. TYPICAL AMPLIFIERS.

14.1 This Section includes three amplifier circuits which together incorporate most of the circuit features described in the preceding sections. The questions listed below each circuit are to test your assimilation of the principles. Should you be unable to answer any question restudy the relevant sections.

14.2 Manual Gain Control is provided with most amplifiers and is usually a simple potentiometer controlling the input voltage to one stage. Where the input level is very low the gain control should not be part of the input circuit to the first (high gain) stage as any noise introduced by the potentiometer is amplified together with the weak signal.

14.3 Fig. 54 shows the circuit of a high quality audio amplifier which is used as a programme monitoring amplifier and for other applications in broadcast studios.

One feature of this circuit not previously described is the manner of connection for the screen and suppressor grids of V1. This is virtually a form of triode operation and is not greatly different from the more conventional method of triode connecting a pentode where both screen and suppressor grids are commoned to the anode.

Another feature of interest is the manner of connection for the screen grids of the two output pentodes V3 and V4. This gives what is known as partial triode or "ultra-linear" operation and to some degree gives to the stage the more important advantages of both triode and pentode operation - the lower distortion of triodes and higher sensitivity of pentodes.

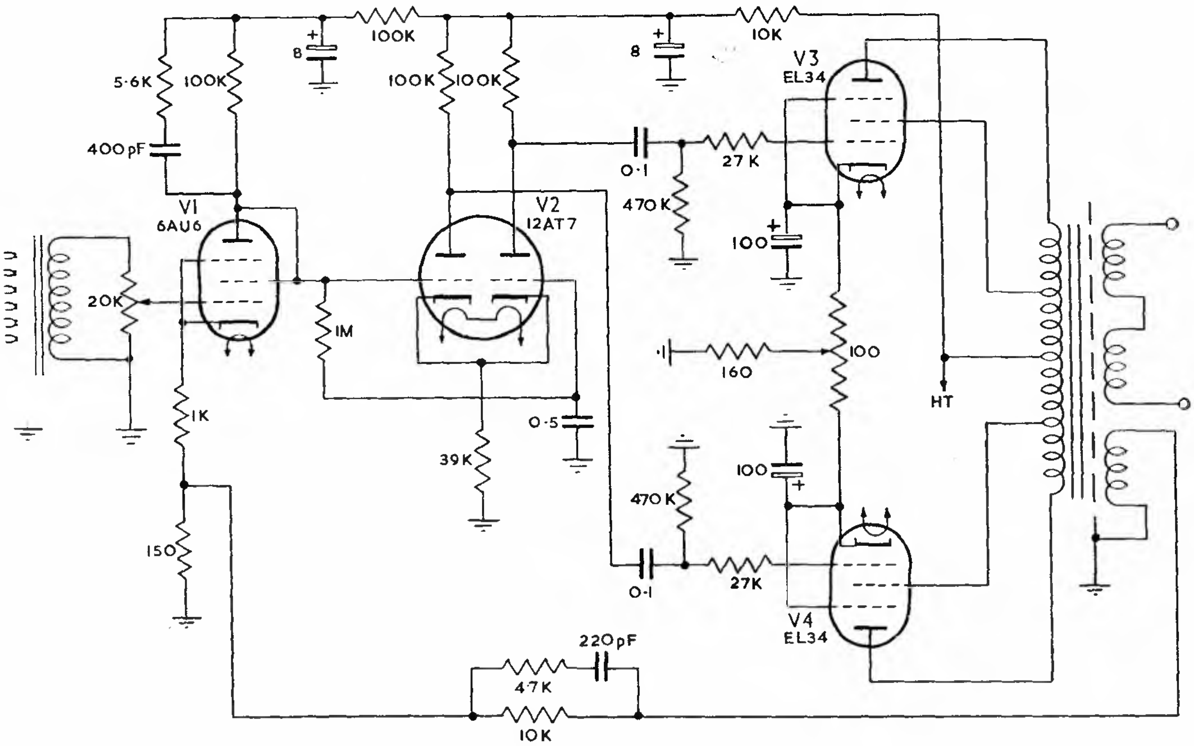


FIG. 54. AUDIO FREQUENCY AMPLIFIER.

QUESTIONS.

(i) List separately the components and circuit currents which determine the value of the bias voltages for V1, V2, V3 and V4.

(ii) Describe the coupling circuit between V1 and V2.

(iii) What functions are served by the 100kΩ resistor and 8μF capacitor in the H.T. lead between V2 and V1?

(iv) Describe the phase inversion process introduced by the circuit of V2.

(v) All grids must have a D.C. path to cathode. How is this met for the grids of V2?

(vi) Why is the 1MΩ grid resistor of V2 returned to earth via a capacitor?

(vii) Which components provide decoupling between stages?

(viii) What is the purpose of the 27kΩ resistors in series with the V3 and V4 grids?

(ix) Sketch out separately the elements of the circuit which provide negative current feedback and those which provide negative voltage feedback.

(x) The circuit includes components to limit the response above 15kc/s; which components do this and how do they operate?

14.4 Fig. 55 shows the circuit of the transmitting amplifier used in some typical modern 4 channel carrier systems. It is designed to operate over a band extending from approximately 3kc/s to 30kc/s.

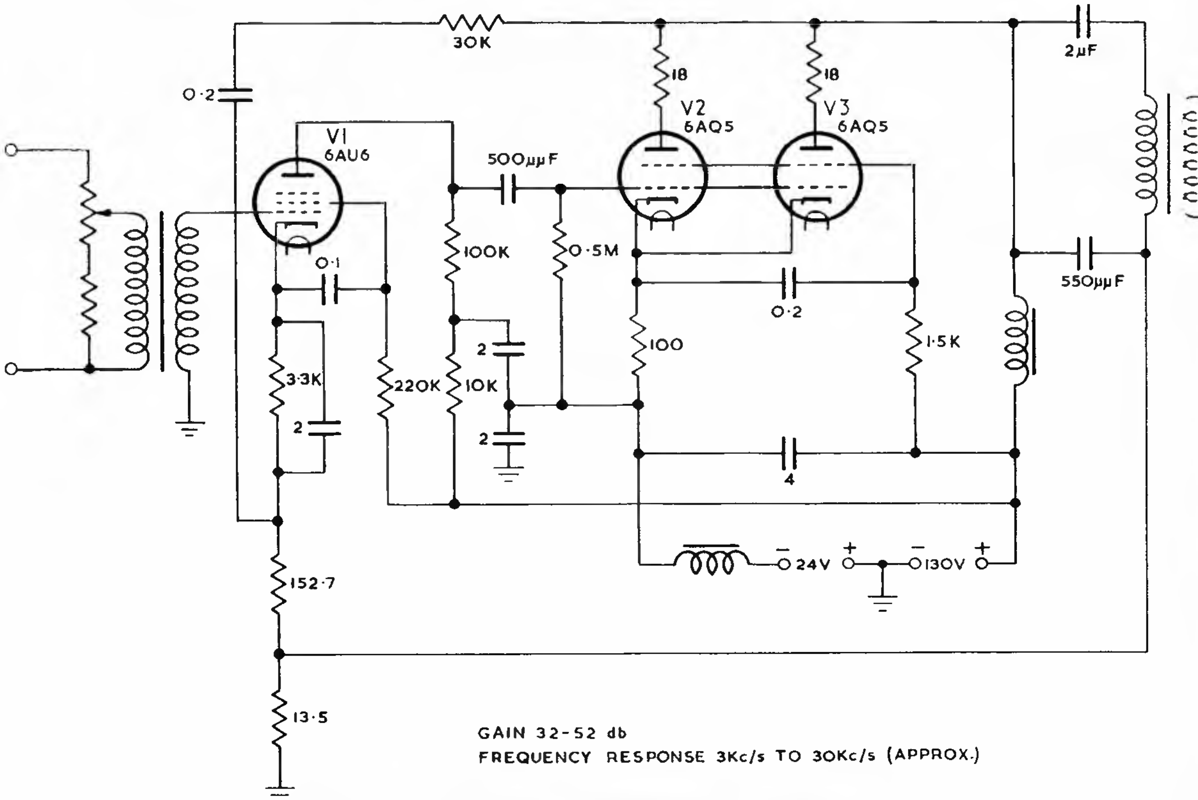


FIG. 55. TYPICAL TRANSMITTING AMPLIFIER.

QUESTIONS.

(i) List separately the components and the circuit currents which determine the value of the bias voltages for V1 and V2 - V3.

(ii) What is the function of the 0.1μF capacitor between V1 screen and cathode?

(iii) Why is only part of V1 cathode resistance bypassed?

(iv) Which components provide decoupling between stages?

(v) Sketch the elements of that part of the circuit which provides negative voltage feedback.

(vi) Sketch the elements of that part of the current which provides negative current feedback.

(vii) What type of coupling is used between the output stage and the load?

(viii) What purpose is served by the choke in series with the D.C. supply?

(ix) Which capacitors bypass the H.T. supply?
Why are two used?

(x) The H.T. supply for the output stage is .... volts.
The H.T. supply for the input stage is .... volts.

.5 Wideband Amplifier. Fig. 56 shows the essentials of a circuit for amplifying the deflecting voltages applied to the vertical plates of a 5" cathode ray oscilloscope and covering a band extending from less than 1c/s to higher than 3.5Mc/s. An output voltage of up to about 400V peak-to-peak can be obtained between the anodes of V4 and V5 which connect direct to the Y plates of the C.R. tube.

The circuit includes typical examples of all the special features discussed in Sections 7 and 8 which are common to most wideband amplifiers with upper and lower frequency response extended. One feature of interest not previously mentioned is the push-pull output stage which includes its own phase splitting drive instead of being preceded by a phase splitting circuit. The signal inputs to V4 and V5 are 180° out of phase but of unequal magnitude. However, in this case the output signal is the relative voltage change between plates Ya and Yb, and a precise balance is not needed.

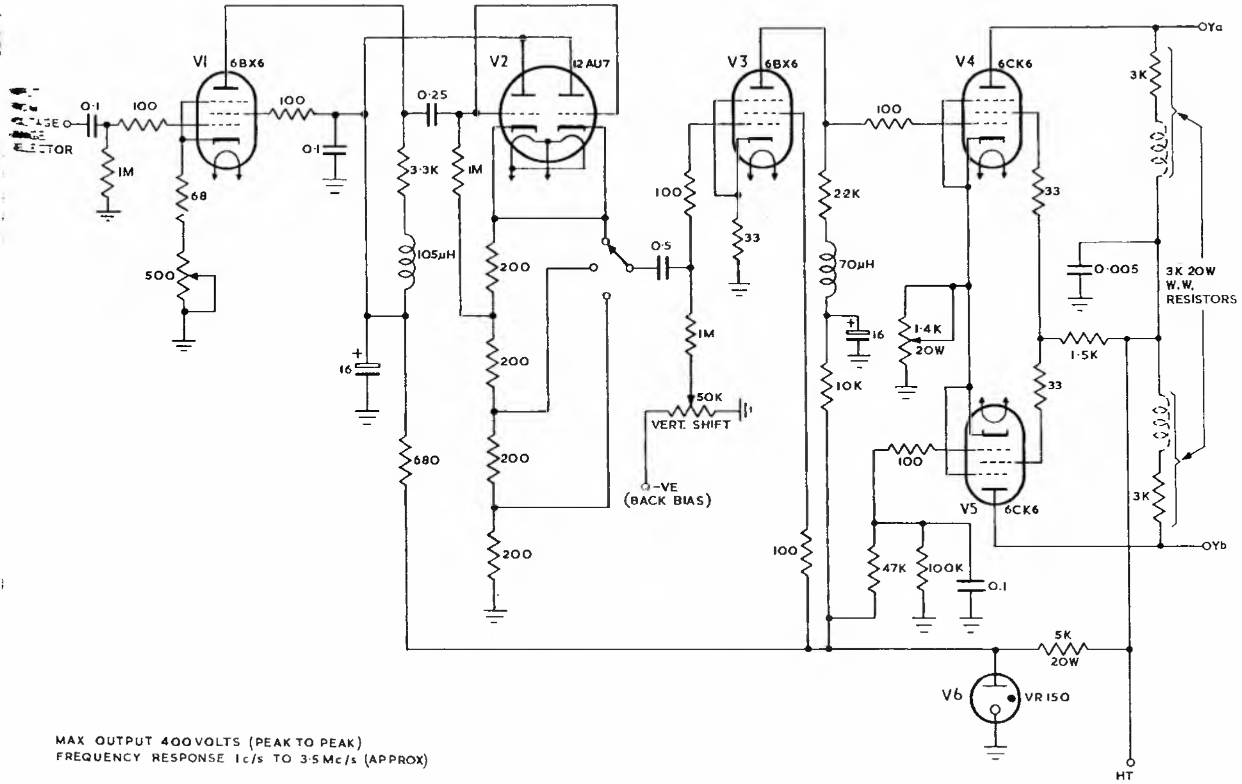


FIG. 56. WIDEBAND AMPLIFIER.

QUESTIONS:

(i) Sketch the circuit elements of the components which contribute to extended high frequency response and briefly explain how they perform their function.

(ii) Sketch the circuit elements of the components and features which contribute to extended low frequency response and briefly explain how they perform their function.

(iii) Explain why the anode load resistances of V1, V3, V4 and V5 are so much lower in value than those in most other amplifiers. What is the effect of this on amplifier performance?

(iv) The anode load resistors of V4 and V5 dissipate considerable power, yet voltage output only drives a C.R. tube with electrostatic deflection. Explain this.

(v) Why are the interstage coupling capacitors many times the value of those used in Figs. 54 and 55?

15. TEST QUESTIONS.

1. Why are voltage amplifiers needed when the final requirement is output power to an energy consuming device?

2. With the aid of simple diagrams explain what is meant by the following classes of operation - A, B, C, AB1, AB2, B1.

3. Sketch and name the basic amplifier circuit configurations which can be used with electron tubes.

4. (i) What do you understand by the terms wide, broad and narrow as applied to amplifier frequency bandwidth?
   (ii) Which type may be used with "tuned" loads and why?

5. Show by means of a circuit how two amplifier stages may be coupled using an R/C network. Describe the function of each component.

6. What are the advantages and disadvantages of transformer and impedance coupling when compared to R/C coupling?

7. A pentode and a triode having equal g_m values are connected with the same value of anode load (the pentode has su... screen voltage applied). Explain why the pentode gives higher voltage gain by comparing the behaviour of the tw... circuits with a similar grid signal voltage applied.

8. Explain why triode dynamic mutual curves have reduced slope as the load resistance is increased.

9. Explain with the aid of a diagram, the phase relationships between grid voltage, anode current and anode voltage ... resistive loaded amplifier stage.

10. What is the effect on the phase angle between input and output voltage, when an appreciable part of the output si... passes through a capacitive path across the D.C. load resistance?

11. Explain the factors which determine the voltage gain of one stage of an R/C coupled amplifier over all parts of ... usable frequency bandwidth.

12. (i) Why is uniform response over wide bands a compromise between gain and bandwidth?
    (ii) How is the uniform response range extended to a higher frequency limit (excluding compensation)?

13. Describe, with the aid of simple circuits, typical methods of achieving h-f and l-f compensation.

14. Why are operating conditions for power output stages generally more critical than those of voltage amplifier sta...

15. (i) Which is the least efficient class of power amplifier and why?
    (ii) What types of output stage circuit can be used for audio amplifiers when a relatively high efficiency is ...

16. (i) List the advantages of incorporating negative feedback in amplifiers.
    (ii) With the aid of simple diagrams describe the difference between negative voltage and negative current ...

17. (i) Why are logarithmic ratios more convenient for comparing power levels than ordinary arithmetic factors?
    (ii) An input signal of 400μW is applied to an amplifier adjusted to give a gain of 40db. What output power is fed to the load? The gain is readjusted and output becomes 2 watts. What is the new gain figure?

18. A typical triode and a typical pentode have similar values of grid to cathode capacitance. Explain why their ... input capacitances differ by a wide margin under operating conditions in typical circuits.

19. Describe the process of decoupling in amplifiers and the reason for its use in some circuits.

20. List four types of distortion which occur in amplifiers and describe what each means in terms of amplifier per...

21. Describe how a loadline can be used to obtain the same information as a dynamic mutual curve.

22. The formula $A = g_m R_L$ is applicable with some R/C coupled amplifier stages and not with others. Why is this so?

END OF PAPER.

OSCILLATORS

---

1. INTRODUCTION.

1.1 We saw in the papers "A.C. Parallel Circuits" and "Waveforms, Timing and Oscillatory Circuits" that L/C parallel circuits are oscillatory in nature. In electronics however, an Oscillator is a device for generating continuous A.C. signals of the desired frequency and waveform, when supplied with energy from a D.C. source.

1.2 Although this paper describes the principles of oscillators which use electron tubes to control the release of energy from the D.C. supply, the principles also apply to oscillators using transistors instead of electron tubes.

1.3 In oscillators, the electron tubes themselves function as amplifiers, the actual oscillation being brought about by additional external circuit arrangements. Therefore, the principles of amplification, biassing, coupling, loading, feedback etc., described in "Electron Tubes" and "Amplifiers" must be understood before the circuits in this paper can be fully comprehended.

2. OSCILLATOR PRINCIPLES.

2.1 General. There are numerous types of electron tube (or transistor) oscillator circuits but common to all types are certain fundamental characteristics which are listed below and represented in the block diagram Fig. 1.

(i) Positive feedback or regeneration of sufficient energy to promote and sustain oscillation.

(ii) Sufficient amplification to meet the energy lost in the circuit and any supplied to a load.

(iii) A suitable arrangement of the circuit constants (L & C, R & C or an electromechanical equivalent such as a tuning fork or crystal) to confine oscillations to the required frequency and to produce the desired waveform.

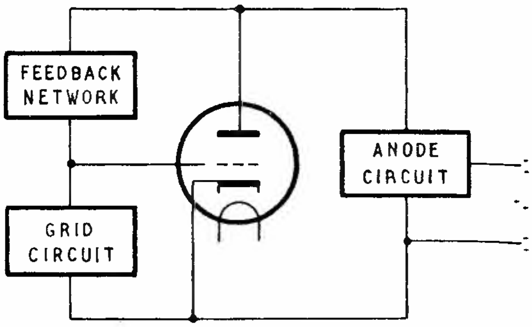


FIG. 1. OSCILLATOR - BASIC PRINCIPLE

2.2 Feedback Networks. The function of the feedback network is to feed back a portion of the output voltage in correct phase to sustain oscillation at the desired frequency. An oscillator therefore can be regarded as a self-excited amplifier; no external input signal is needed.

We have seen in the paper "Amplifiers" that there is a normal 180° phase shift between the grid and anode voltages when the anode load is resistive.

For full regeneration the phase change around the complete loop must be 360°, so the feedback network is used to introduce a further phase shift to provide this. The various devices used for this purpose (separately or in combination) are -

Transformers.

L/C networks.

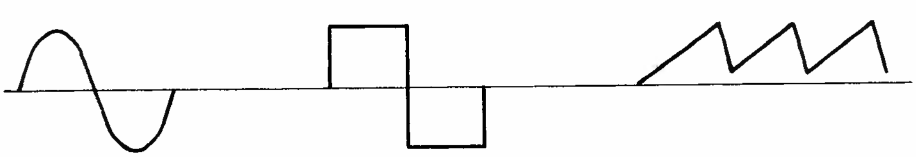
R/C networks.

Interelectrode Capacitances.

Additional electron tubes (or transistors).

2.3 Waveforms. We have seen that the sine wave is a graph representing the simplest kind of cyclic or periodic function, and that non-sinusoidal waveforms can be resolved into sine waves of a fundamental frequency, plus multiples called harmonics. Also, when a circuit is switched on the resulting voltage and current surge (or transient) can be rich in high frequency components.

In oscillators, sine waveform is usually required but many oscillators produce complex forms such as square or sawtooth waves which are extremely rich in harmonics (Fig. 2). The output waveform is largely determined by the design of the feedback network although additional waveshaping circuits often follow the oscillator especially for the more complex waveforms such as "spikes" or square pulses.

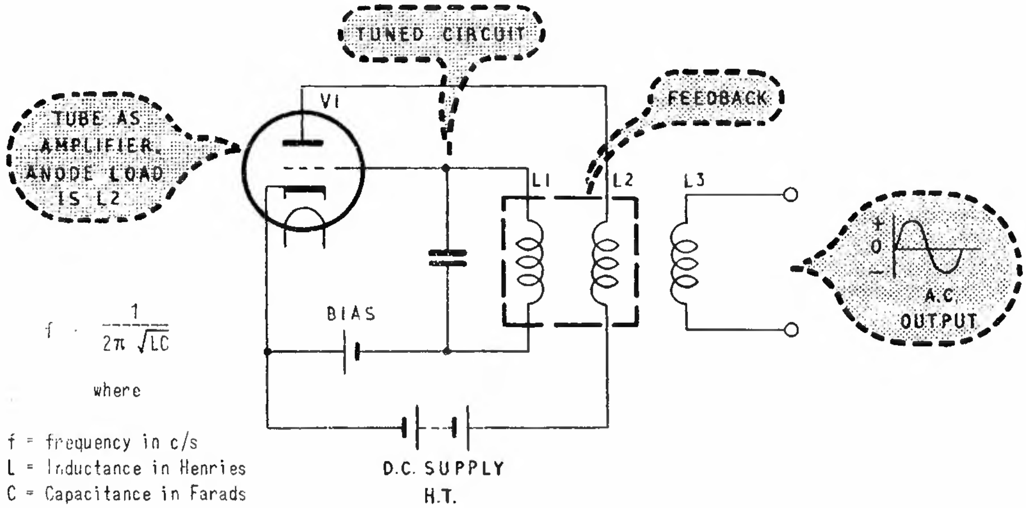


(a) Sine wave. (b) Square wave. (c) Sawtooth wave.

FIG. 2. TYPICAL WAVEFORMS.

..4 Simple Oscillator. Fig. 3 shows the circuit of a simple "Tuned Grid" oscillator. The triode amplifier has the grid circuit coupled to the anode circuit by the induction between L1 and L2. This is the feedback path and the connections are arranged to give a 180° phase change between anode voltage and grid voltage. In addition to the 180° introduced by the tube itself this gives a phase change of 360° in the complete circuit; that is, the feedback is positive. (The angles given assume resistive conditions at resonance which may not apply exactly in practice.)

The effective inductance of L1 is tuned by capacitor C to form a resonant circuit and maximum feedback voltage is fed to the grid circuit at the frequency of resonance. Therefore, by choosing a suitable combination of effective L1 and C the circuit can be made to oscillate at the desired frequency. The effective inductance of L1 is stipulated because its actual value is affected by conditions in the circuits connected to L2 and L3.



$$f = \frac{1}{2\pi\sqrt{LC}}$$

where

f = frequency in c/s
L = Inductance in Henries
C = Capacitance in Farads

FIG. 3. SIMPLE OSCILLATOR (TUNED GRID).

Operation. When the circuit is switched on, the anode current rises in a rapid surge and a voltage is induced across the tuned circuit via the coupling between L2 and L1. This provides the energy for the tuned circuit to shape the grid input signal to the desired frequency by permitting maximum voltage across it at its resonant frequency only (the induced transient will have a component at or near this frequency). The grid input signal is thus rapidly confined to the required frequency.

The signal is amplified and again fed back in phase so that each successive cycle is increased in voltage until a signal of constant amplitude is reached, its final value being determined by the circuit characteristics.

An exact description of what occurs in the first moments after switching on an oscillator would not definitely apply, because of the many possible circuit differences to be found in practice; nor is it necessary to attempt such descriptions. What actually happens before frequency and amplitude become stabilised, depends on variable factors such as the Q of the tuned circuit (if used), the tube characteristics, the circuit gain, biassing arrangements, the amount of feedback, etc. The important thing to understand is how oscillators excite themselves while producing a continuous output. As long as the conditions listed in para. 2.1 are met, any irregularity could begin the excitation, and the switch-on surge is more than enough to provide it.

Although the frequency of L/C oscillators is determined by their resonant circuits many oscillators described in the following Sections do not use L/C circuits. The general rule to be remembered therefore, is that oscillation occurs at the frequency which provides for maximum positive feedback voltage. (There is an important exception to this rule described in Section 4.)

Oscillators using L/C tuned circuits produce an output which is essentially of sine waveform especially when feedback is just sufficient to sustain oscillation. Overdriving an oscillator produces distortion just as it does in amplifiers.

2.5 The output of an oscillator can be picked off the circuit at any convenient points which do not interfere with its operation. One method is shown in Fig. 3 where L3 is a third coil mutually coupled with L1 and L2.

2.6 Frequency Variation. Oscillator frequency is varied by altering any of the circuit constants which decide the frequency of maximum feedback. In L/C oscillators such as Fig. 3, frequency variation (or adjustment) is generally achieved by changing the value of capacitor C. However, any change in effective inductance of L1 will also change the frequency of oscillation.

2.7 Frequency stability is an important requirement of many oscillators. That is, the frequency must remain constant or within very narrow limits, irrespective of temperature, loading, or ageing of components. Temperature changes and ageing alter the values of the circuit constants slightly and this alters the frequency at which maximum feedback occurs. Constant temperature is often achieved by mounting the oscillator or its temperature critical components in a thermostatically controlled oven.

Load variations alter the effective value of tuned circuit constants and thus alter the frequency. Referring to Fig. 3, it will be seen that varying amounts of energy taken from the circuit by the load on L3 must alter the effective inductance of L1 and thus the frequency of oscillation.

Overloading the circuit can reduce the feedback to a point where it is insufficient to sustain oscillation. Where loads are heavy or varying, the oscillator is coupled to a "buffer" or isolating amplifier which supplies the load; its input presents a constant (and negligible) load on the oscillator.

2.8 Class of Operation. Oscillators may be biassed to operate Classes A, B or C. Class A is now general for sine wave oscillators as it produces least distortion of the waveform. Where very pure waveform is required, Class A1 operation is used; cathode bias and minimum feedback voltage are typical features of such circuits. The higher efficiency of Classes B and C is not generally needed as most modern oscillators have fairly low output and can be followed by a buffer amplifier when necessary.

Grid leak bias is convenient for many oscillators as the zero bias existing when switching on assists them to be self starting. However grid leak bias needs the flow of grid current for a small portion of each cycle and some distortion results even with Class A2 operation.

The paper "Electron Tubes" (Fig. 16, page 17) shows how grid leak can be used to obtain any desired bias for an oscillator up to that voltage needed for Class C operation where the tuned circuits sustain oscillation during the long cut-off period of the tube.

3. L/C OSCILLATORS.

3.1 L/C Oscillators are those which use L/C tuned circuits or "tank" circuits to establish the frequency.

The tuned circuit may be in the grid circuit as in Fig. 3, in the anode circuit, or common to both anode and grid; others have both anode and grid circuits separately tuned. Positive feedback may be inductively or capacitively coupled. There are many varieties of L/C oscillators, with some having circuit arrangements more suited for use at high frequencies than others, and some having merits for special applications only.

It is important to remember that stray capacitances in the wiring, interelectrode capacitances and interturn capacitance of coils must all be considered in determining correct operation and frequency. This applies to nearly all oscillators, but especially at the higher frequencies where the comparative effect of these factors is so much greater.

There are two distinct ways of feeding the high tension voltage to the anode circuits of L/C oscillators so that they are further subdivided as "series fed" or "shunt fed" L/C oscillators. The simple tuned grid oscillator in Fig. 3 is series fed which means that the anode circuit inductance and the tube are in series for the anode current D.C. and A.C. components. Fig. 4a is also series fed. In shunt fed L/C oscillators the anode tuning inductance is isolated from the D.C. component of anode current by a form of impedance coupling which uses a high reactance choke in series with the H.T. supply to the anode as shown in Fig. 4b. As far as the A.C. anode signal is concerned the D.C. supply is in parallel with the anode load part of the tuned circuit; it presents a high impedance shunt which has little effect on the signal voltage.

Shunt feed is used where it is desirable to keep high voltage off a tuned circuit which may require adjustment, or where series feed introduces shunting of the tuned circuit via the filament and H.T. power supplies.

.2 The Hartley Oscillator (Fig. 4) uses a tuned circuit common to both the anode and grid circuits.

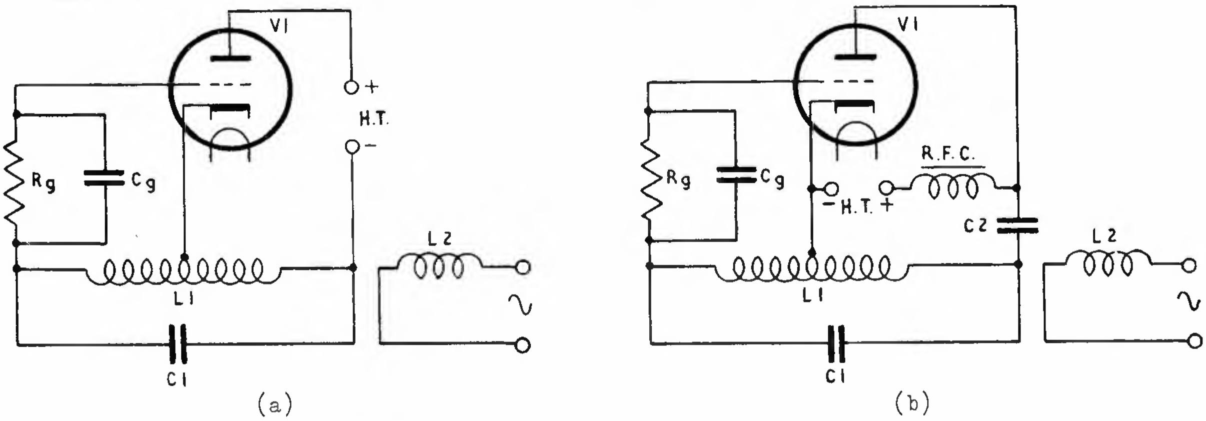


FIG. 4. HARTLEY OSCILLATOR.

Frequency of oscillation is determined by the resonant frequency of L1 and C1. Bias is obtained from the grid leak combination C_gR_g. Feedback is positive because anode and grid are connected to opposite ends of L1 with respect to cathode. Therefore, when the anode is on the positive going half cycle of signal the grid is on the negative going half cycle and vice versa; that is, a phase difference of 180°.

This, plus the 180° introduced by the tube itself gives the right condition for maximum positive feedback at the L1, C1 resonant frequency.

The position of the tapping on L1 is selected to give the correct amount of feedback voltage for the required amplitude of oscillation.

In the shunt fed Hartley circuit (Fig. 4b) capacitor C2 couples the tuned circuit to the anode for A.C. only, the D.C. being confined to the high reactance R.F. choke.

.3 The Colpitts Oscillator (Fig. 5) is similar to the Hartley oscillator and was developed to avoid the necessity of providing a tapped inductance. The capacitive part of the tuned circuit is "tapped" using two series capacitors. The frequency is determined by L1 and the joint capacitance of C1 and C2. The ratio of C1 and C2 determine the proper operating conditions to suit any particular tube and control the amplitude of oscillation.

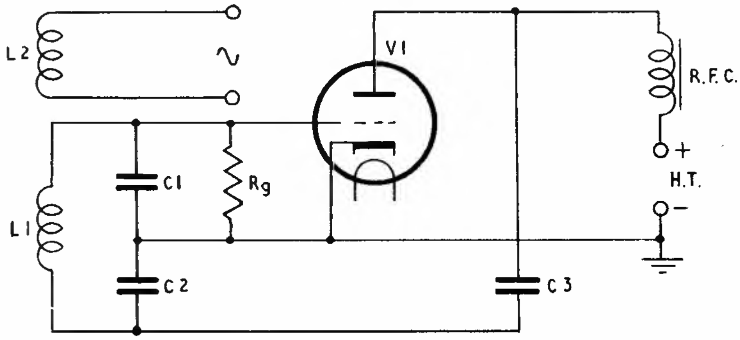


FIG. 5. COLPITTS OSCILLATOR (SHUNT FEED).

3.4 The Tuned-Plate Tuned-Grid Oscillator (Fig. 6) as the name states, has both anode and grid circuits tuned. The arrangement is used mainly at high frequencies where the anode-to-grid interelectrode capacitance C_{ga} has reactance low enough to complete the feedback path. A small external capacitor may augment this where necessary at somewhat lower frequencies.

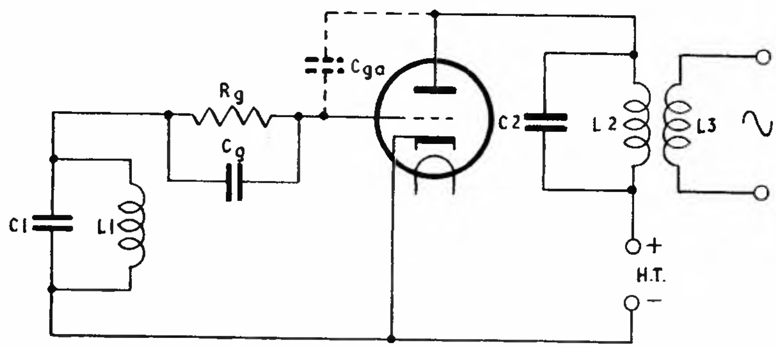


FIG. 6. TUNED-PLATE TUNED-GRID OSCILLATOR.

Conforming to the general rule for oscillators stated in Section 2, this type of circuit automatically oscillates at the frequency which provides maximum positive feedback. At first glance it may appear that interelectrode capacitance C_{ga} would provide a path for negative rather than positive feedback as, in most circuits, the anode and grid are 180° out of phase. We have seen however that this applies only when the load is resistive in character. Also tuned circuits are resistive only at their resonant frequency, but experience rapid change from zero phase angle at frequencies slightly off resonance.

For any suitable combination of L1 C1 and L2 C2 tuned to resonate at frequencies not exactly the same, there is a third frequency somewhat lower than either of these at which the right conditions exist for a total phase shift of 360° around the circuit (including the tube). The oscillator produces a sine wave output at this frequency.

A more explicit description of operation can only be given by mathematical or vector analysis. It can then be shown for specific values of circuit constants, that oscillation occurs at a frequency where both tuned circuits are inductive in character. The output frequency is therefore lower than the natural frequency of both tuned circuits. The tuned circuit whose natural frequency is nearest to the output frequency may be in either the grid or anode circuit. This tuned circuit is the least inductive of the two and has the most affect in determining the frequency of oscillation.

3.5 Electron Coupled Oscillators are those where the actual oscillator is coupled to the output, only by the electron stream of the oscillator tube. The usual method is to use a pentode tube with the screen acting as the oscillator anode of a triode as shown in Fig. 7.

The electron stream is varied at the frequency of oscillation and energy is thus delivered to the load in the anode circuit via the electron stream. The suppressor grid is earthed to serve as an electrostatic shield and the screen may be bypassed also and serve as an additional shield.

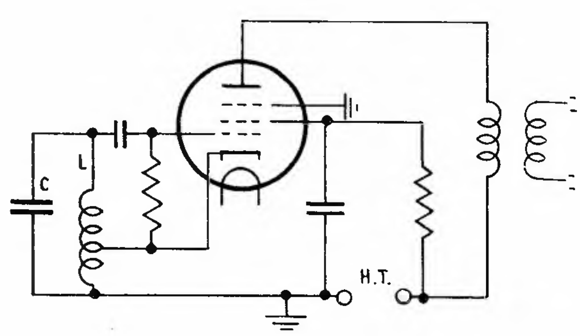


FIG. 7. ELECTRON COUPLED (HARTLEY) OSCILLATOR

This scheme makes the oscillator frequency virtually independent of variations in the load impedance. It can be regarded as oscillator and buffer amplifier incorporated in the one stage.

Fig. 7 shows a Hartley oscillator but the principle of electron coupling is not confined to L/C oscillators. Section 4 includes a circuit of an electron-coupled crystal-controlled oscillator.

3.6 The Beat-frequency Oscillator (B.F.O.). A single oscillator using variable capacitors or inductors cannot be tuned over a wide band without switching in different components to give several consecutive ranges. This can be inconvenient especially for test oscillators. The disadvantage is overcome by the beat-frequency oscillator, the principle of which is shown in Fig. 8.

Two R.F. oscillators are used (usually L/C oscillators) one generating a fixed frequency output, and the other continuously variable over the required range, which at R.F., is a comparatively narrow band and readily covered by one sweep of the tuning capacitor.

For example, a fixed oscillator operating at 650kc/s "beating" its output with that of another oscillator variable from 500kc/s to 650kc/s will produce an output which contains the difference frequencies of 0c/s to 150kc/s.

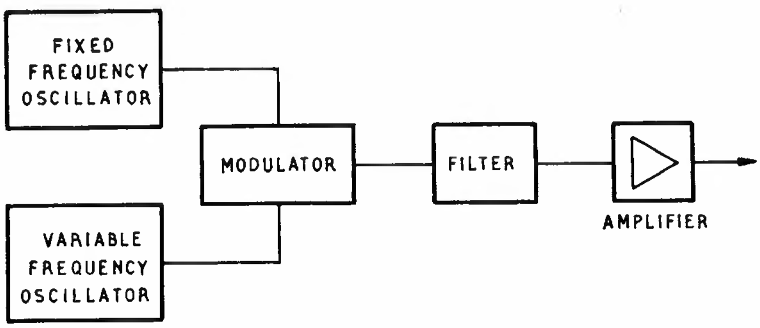


FIG. 8. PRINCIPLE OF B.F.O.

The two outputs are fed into a modulator (or detector). The wanted signal is then amplified and the unwanted R.F. is blocked from the output, either by a low pass filter which precedes the amplifier or an amplifier designed to have no response to frequencies above the desired band.

B.F.Os. are widely used as laboratory or test instruments. Some B.F.Os. operate mainly over the audio frequencies up to about 20 or 25kc/s. Others range up to about 400kc/s in two separate ranges.

A modulator is a circuit with non-linear characteristics allowing two injected voltages to produce new signals at different frequencies. These are predominantly the sum and difference frequencies of the two input signals and are called "products of modulation". Modulation and demodulation are dealt with in "Long Line Equipment 1". The term detector is sometimes loosely applied to modulators or demodulators, although more applicable to the latter.

4. CRYSTAL AND TUNING FORK OSCILLATORS.

4.1 General. In many applications of oscillators in radio and long line telephony a very high degree of frequency stability is required and ordinary L/C oscillators generally are not stable enough. Oscillators are used which incorporate a crystal or tuning fork in the oscillatory circuit. These components vibrate at or near their natural frequency of mechanical resonance and influence the electrical circuit in such a way as to keep the oscillations "in step".

4.2 Peizo-electric Effects are exhibited by certain crystalline materials such as quartz, Rochelle salts and a few other mineral salts. That is, when compressed or otherwise deformed by mechanical stress, electric charges appear on opposite faces of the crystal. This property is used in crystal pick-ups and microphones.

Conversely, when electric charges are applied to opposite faces, mechanical strains are set up which deform the crystal. The voltage produced by mechanical strain varies with different crystals from a fraction of a volt up to more than a hundred volts for Rochelle salts.

Quartz is the most widely used crystal; although its electric response to stress is less than Rochelle salt it is mechanically much more robust. Rochelle salt is also more susceptible to heat and ageing.

"Crystals" for controlling oscillators are not really full crystals but thin wafers or slabs cut from a natural or "mother" crystal. There are various ways of cutting crystals from the mother quartz to suit particular applications and producing crystals is an art in itself, the study of which is beyond the scope of this course.

The crystals are accurately ground to size to have mechanical resonance at the desired frequency and then inserted in a special holder with the electrodes contacting opposite faces but leaving the crystal free to vibrate. Fig. 9 shows an assortment of crystals in holders together with a mother crystal of quartz.

Fig. 10 shows a typical crystal mounting, dismantled.

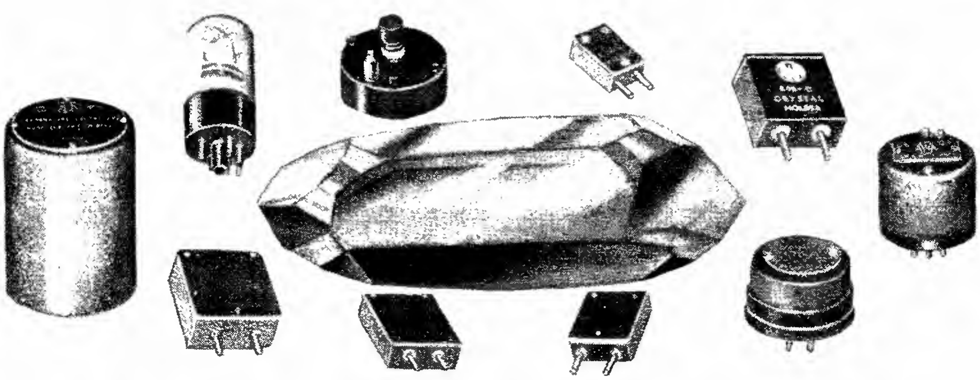


FIG. 9. TYPICAL HOLDERS AND QUARTZ "MOTHER" CRYSTAL.

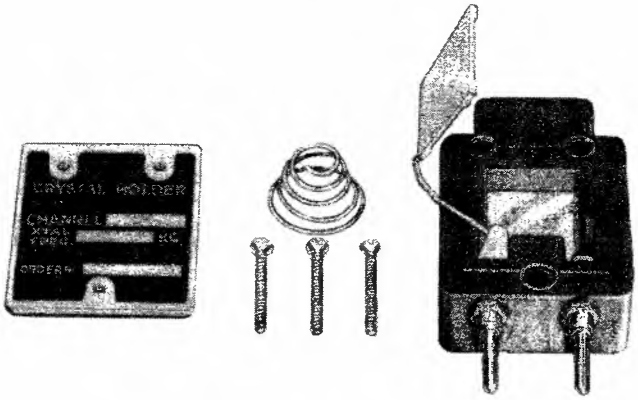
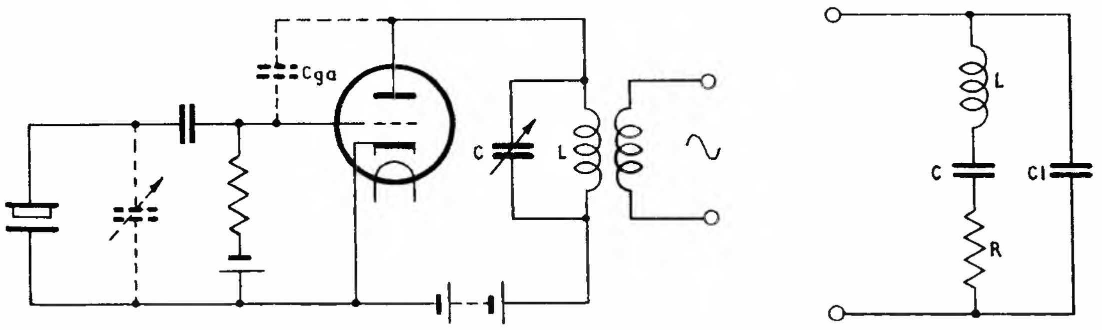


FIG. 10. TYPICAL CRYSTAL MOUNTING.

1.3 Crystal Controlled Oscillators. Fig. 11a is the basic circuit of a typical crystal controlled oscillator used at radio frequencies. Note the similarity to the tuned-plate tuned-grid circuit of Fig. 6 with the crystal taking the place of the grid L/C circuit.

Electrically the crystal performs like an L/C resonant circuit having a very high Q and can in fact be represented by an equivalent L, C and R circuit as shown for typical crystals in Fig. 11b. The crystal voltage is similar to that across a series L, C and R circuit when it is vibrating at its natural frequency. The mass and inertia of the crystal is represented by L, its resilience or ability to flex when a deforming voltage is applied or removed is represented by C, and frictional losses are represented by R.

The shunt capacitance C1 represents the capacitance between the electrodes with the crystal forming the dielectric. When connected in circuit the equivalent input capacitance of the tube, the stray capacitance of the wiring and crystal holder all add to the value of C1.



(a) Basic Crystal Oscillator. (b) Equivalent Circuit of Crystal.

FIG. 11. CRYSTAL CONTROLLED OSCILLATOR.

At a particular frequency slightly higher than its natural frequency, the series L and C of the crystal present a reactance equal and opposite to that of C1 and the combination becomes the equivalent of a parallel resonant circuit.

Quartz crystals are usually calibrated at this frequency where they exhibit the features of parallel resonance. A small "trimming" capacitor in parallel with C1 is often used to adjust the output to the exact frequency required.

Operation. The anode L/C circuit is tuned above the resonant crystal frequency to be inductive enough for positive feedback via the grid to anode capacitance C_{ga}.

The feedback voltage is limited to confine amplitude of crystal vibration so that there is no likelihood of damage. This is generally achieved by adjusting the anode tank C until the crystal oscillates satisfactorily although phase change may be less than 360° and feedback voltage less than the possible maximum. Oscillators controlled by the mechanical resonance of crystals (or tuning forks) are therefore an exception to the general rule stated for other types of oscillators which oscillate at the frequency which produces maximum positive feedback.

Frequency Stability. Crystal oscillators are designed to have "loose" electrical coupling between the crystal and the rest of the circuit, and only sufficient feedback is provided to keep the crystal vibrating. This minimises any tendency for the less stable circuit components to force the crystal to shift its operating frequency and a high degree of stability is ensured.

Some crystals have zero temperature coefficient and others are mounted in temperature controlled ovens to give frequency stabilities ranging from one part in 10^4 up to one part in about 10^8. The precision of the latter figure is needed only for rare applications such as frequency standards.

Above about 10-20Mc/s crystals would generally have to be too thin for practical use. However, using lower frequency crystal oscillators to excite frequency multiplying circuits much higher frequencies are attained. Modern techniques have produced some crystals for operation up to about 40Mc/s.

4.4 Crystal Oscillators in Long Line Telephony. The arrangement shown in Fig. 11 is used at radio frequencies and is not suitable for frequencies below several hundred kc/s. Fig. 12 shows a typical oscillator circuit used in the frequency range from about 5 to 30kc/s which uses a four terminal type of crystal. Many L/C carrier oscillators used in early type long line carrier telephone systems have been replaced with this type of circuit.

The output is electron coupled using a pentode as described for Fig. 7, the screen grid performing the function of oscillator anode.

A typical crystal of this type is shown in Fig. 9 and is suspended within a small vacuum tube. The crystal wafer for these comparatively low frequencies is much larger than those used at radio frequencies and there is ample space for two terminals on each face.

With the crystal vibrating the two electrodes on one side are on the positive going half-cycle while the opposite pair are on the negative going half-cycle, a phase difference of 180°. Positive feedback is therefore a simple matter of connecting oscillator anode and grid to electrodes on opposite sides of the crystal which can be seen more readily in the simplified circuit of Fig. 13.

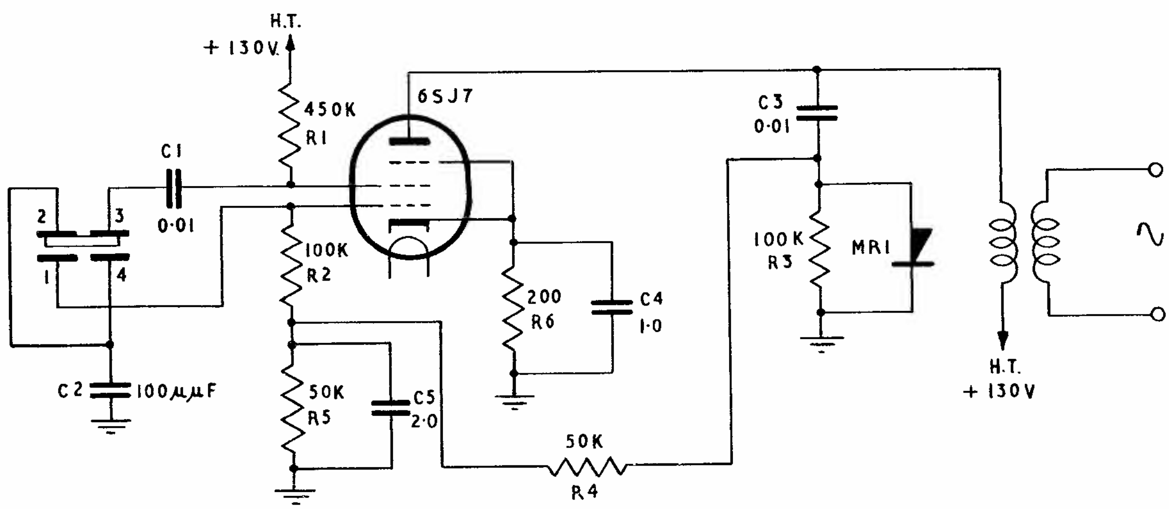


FIG. 12. TYPICAL CRYSTAL OSCILLATOR FOR LOW FREQUENCIES.

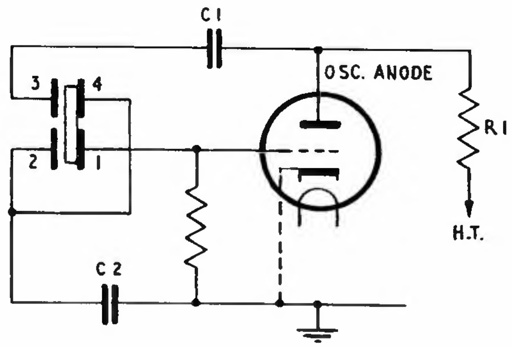


FIG. 13. BASIC OSCILLATOR CIRCUIT FROM FIG. 12.

The grid connects to terminal 1, the oscillator anode (screen of pentode) connects to terminal 3 for the A.C. via C1. Remaining terminals 2 and 4 are commoned and return to cathode potential via C2, the high reactance of which ensures a low crystal voltage and loose coupling between anode and grid circuits. The oscillator anode D.C. supply is shunt fed via R1.

The bias circuit (Fig. 12) is of interest. R6 provides a small cathode bias voltage which is low enough to allow the circuit to be readily self-starting. Once operating, a voltage proportional to the output voltage is fed via C3 and a rectified voltage appears across R3 due to MR1 shunting out positive half-cycles. A negative potential fed via R4 appears at the grid end of R5 as an additional bias voltage. Unwanted A.C. component is filtered out by R4 and C5.

.5 Tuning Fork Oscillators are used in long line carrier telephony to generate highly stable carrier signals of lower frequencies than are practicable for crystals. Fig. 14 shows the basic circuit of a typical tuning fork oscillator.

The steel tuning fork is mounted in the magnetic field of one or more coils from which it absorbs sufficient energy to become magnetised and vibrate at its natural resonant frequency. In turn, a voltage of constant frequency is maintained across the coils as the magnetised fork induces a voltage in the coils at its frequency of vibration.

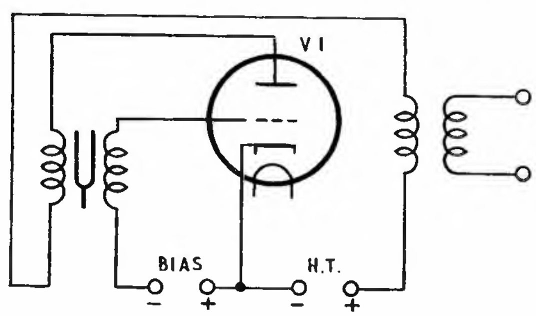


FIG. 14. BASIC TUNING FORK OSCILLATOR.

The tuning fork is made of an alloy having very low coefficient of expansion and is sealed in an evacuated envelope or mounted in a thermostatically controlled oven. Output is stable to within one part in a million. In a typical application the 4kc/s output signal is distorted in a special amplifier called a harmonic generator to produce numerous harmonics several of which are selected and amplified.

5. R/C OSCILLATORS.

5.1 Oscillators which use only resistance and capacitance for regeneration and frequency selection are now widely used for frequencies up to about 200kc/s. Their principal advantage over L/C oscillators is the elimination of inductors which for low frequencies can be both large and costly.

5.2 Two-Stage R/C Oscillator. (Fig. 15.) A loop from output to input of a two-stage R/C coupled amplifier gives positive feedback since each tube provides 180° phase change. An R/C network C1 R1, C2 R2 in the feedback loop ensures that the feedback voltage is in phase at one frequency only, and thus determines the frequency of oscillation.

A large amount of negative feedback in the amplifier provides stability and low distortion. When the negative feedback is nearly as great as the positive feedback the output is remarkably free from harmonics, or practically a pure sine wave.

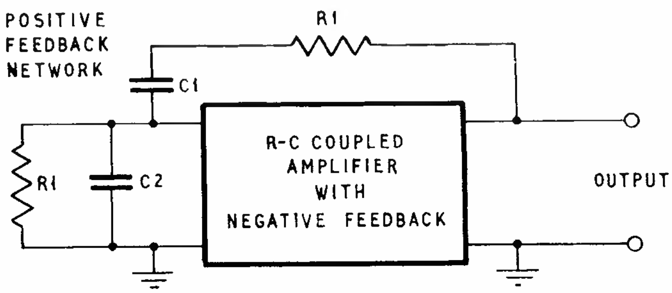


FIG. 15. PRINCIPLE OF TWO STAGE R/C OSCILLATOR.

Wien Bridge Oscillator. In the practical form of the two stage R/C oscillator circuit the positive and negative feedback paths work in conjunction to regulate the input voltage to the first stage. Fig. 16 shows a typical circuit. 5.3

Energy is fed back from the second stage output via the isolating capacitor C3. The frequency selective voltage divider network R1 C1, R2 C2 applies a portion of this signal to V1 grid in the correct phase for positive feedback to promote and sustain oscillation.

In parallel with this is another voltage divider R3 R4 and the voltage across R4 constitutes the negative voltage feedback signal since the anode current is 180° out of phase with the grid voltage.

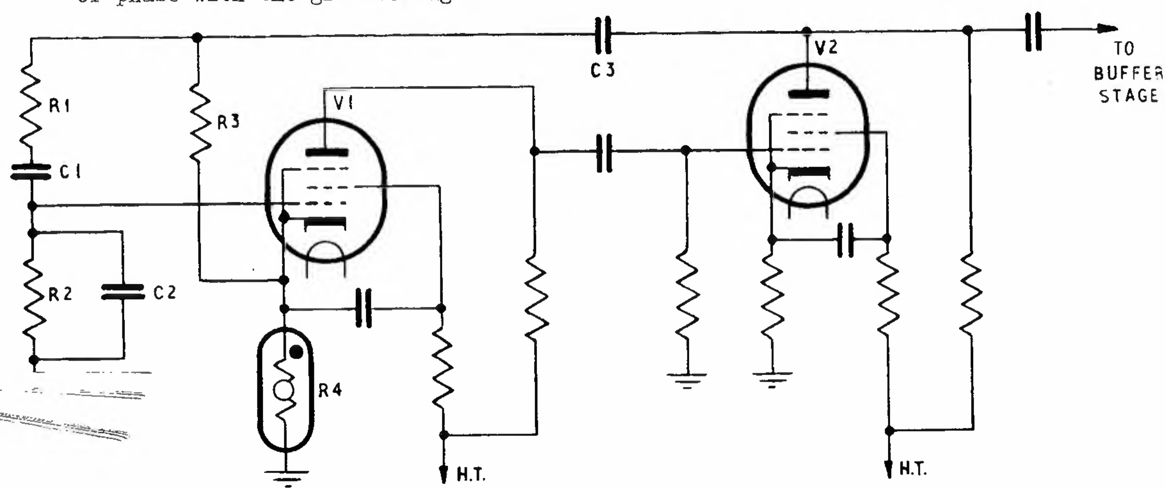


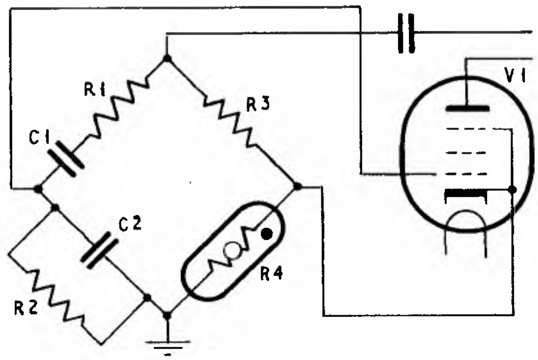
FIG. 16. TWO STAGE R/C OSCILLATOR.

In addition, because R4 is unbypassed the signal voltage across it due to anode current signal constitutes a negative current feedback component superimposed on the D.C. bias voltage across R4. The actual grid input signal is the resultant of the opposing voltages across R2 and R4.

The principles of negative voltage and current feedback are described in the paper "Amplifiers".

A tungsten filament lamp is used for R4. Any tendency for the output to increase due to higher positive feedback at certain frequencies is offset by an increase of current through the lamp which automatically increases its resistance and thus the negative feedback voltage across it.

A buffer amplifier follows the two stage oscillator section and maintains a constant load on the oscillator.



POSITIVE AND NEGATIVE FEEDBACK AS "WIEN BRIDGE".

FIG. 17.

The negative and positive feedback loops can be redrawn in a bridge circuit (Fig. 17). This bridge is similar to that developed by Wien for frequency and capacitance measurements and this type of oscillator is often known therefore as a "Wien Bridge" oscillator.

This type of oscillator is widely used as a test instrument providing variable frequency output, a typical coverage being 20c/s to 200kc/s. Different values of R1 and R2 are switched in for the several ranges and C1 and C2 are a ganged variable capacitor for tuning within each range.

5.3 The phase shift oscillator is a one-stage R/C oscillator. (Fig. 18.) The principle is very simple. An R/C network shifts the phase of the signal 180° at the desired frequency. This displacement gives positive feedback in conjunction with the 180° displacement of the tube. With gain adjusted so that feedback is just sufficient to maintain oscillation, the output has almost pure sine waveform.

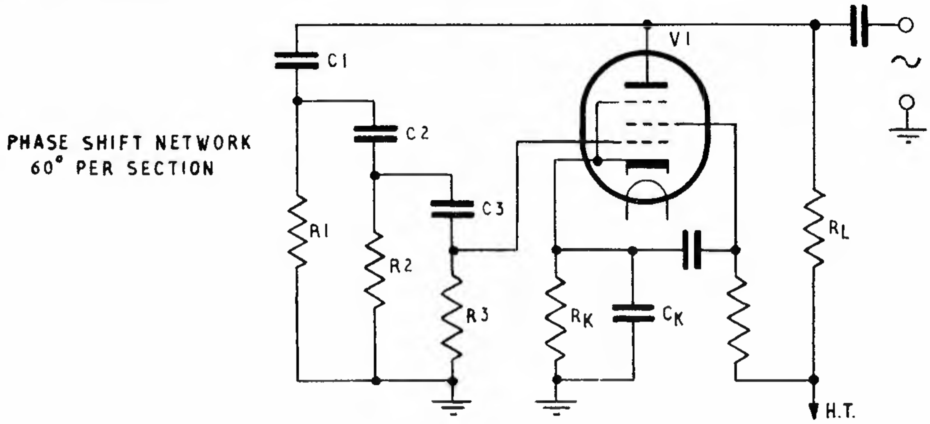


FIG. 18. PHASE SHIFT OSCILLATOR.

With equal values of C1, C2, C3 and R1, R2, R3, there will be a phase shift of 60° per section for the frequency at which current in each series section leads the voltage across it by 60°. The voltage across R1 will be 60° ahead of anode voltage, the voltage across R2 60° ahead of that across R1 and the voltage across R3 60° ahead of that across R2.

Four section networks can be used to give an average phase shift of 45° per section.

6. RELAXATION OSCILLATORS.

6.1 General. Relaxation oscillators have the following characteristics -

(i) They make use of a process involving the building up or breaking down of energy stored in the electric field of a capacitor or the magnetic field of an inductor.

(ii) Their output is non-sinusoidal and extremely rich in harmonics.

(iii) Their frequency is not very definitely fixed by the circuit elements and may be easily synchronised to external signals which can have a high degree of frequency stability.

There are many types of relaxation oscillators but one form or another is generally used when numerous harmonics, square waves, saw-toothed waves or timing pulses are required.

In the application of relaxation oscillators and associated circuits a number of descriptive terms are used, the more common of which we must first define to simplify the circuit descriptions to follow.

6.2 Definitions. Many types of relaxation oscillators do not produce a continuous symmetrical output like all other oscillators. Some are arranged to stay in a quiescent state until excited by a small external signal; this process is called "triggering".

Circuits which respond to trigger pulses to change their state can be used as electronic or static switches and the term switching circuit is often used.

Such circuits can be made to block or pass certain other signals and are also known as "gates". This term is rather loosely applied and "gate" may refer to a circuit used as an electronic switch but it is also used to refer to the signal or pulse which initiates the gating function in the circuit.

There are many types of switching circuits, and relaxation oscillator principles are used in only some of them. Nowadays, the majority of these circuits use cold cathode tubes or solid state devices such as semiconductor diodes and transistors.

The study of static switching using electronic gates is often classified under the heading of "pulse techniques" as pulses are generally the means of initiating the required gating operations. Pulse techniques have become an important branch of electronics owing to their widespread application to electronic data processing and computing "machines" as well as their use in many communication circuits. A detailed study of pulse techniques is beyond the scope of this paper but some information on the production of trigger pulses is given in para. 6.9.

Relaxation oscillators can be divided into three classes -

(i) Astable or "free running" circuits produce a continuous output with or without external synchronising signals.

(ii) Monostable, "one shot" or "start-stop" circuits stay in a quiescent or stable state until an external signal is applied and return to that state in a fixed time interval after the signal is removed.

(iii) Bistable, "flip-flop" or "binary" circuits have two different quiescent states and remain in either one until changed to the other state by an external signal.

Relaxation oscillators which stay in a quiescent state until triggered are not strictly oscillators as defined in Section 1 but are often regarded as such.

Relaxation oscillators were first developed and have found wide use using ordinary triode tubes and are simplest to describe in that form.

6.3 Sawtooth Generators are mainly used to produce the time base or horizontal sweep voltage for cathode ray oscilloscopes. An early method of producing sawtooth waveform voltages was by using the simplest relaxation oscillator - an R/C circuit in conjunction with a gas diode or gas triode (Fig. 19a).

The capacitor C charges from the H.T. supply via R. When the voltage across C reaches the striking voltage of the cold cathode diode it conducts and C discharges rapidly until extinction voltage is reached; C recharges as before. The output voltage waveform is shown in Fig. 19b. The frequency of oscillation depends on the time constant (C X R) and the voltage characteristics of the tube.

A gas triode can be used to obtain readily adjustable frequency as varying the grid voltage alters the striking voltage of the tube (Fig. 19c).

A synchronising pulse of the correct polarity may be used to make the tube strike a little earlier and thus raise the frequency into synchronism with that of the injected signal. Therefore, although a high degree of frequency stability is not a characteristic of relaxation oscillators, they may be rendered as stable as required by a synchronising signal from a more stable source.

We saw in the paper "Waveforms, Timing and Oscillatory Circuits" that the rise in voltage across C confirms to an exponential law so that the long edge of the sawtooth is not perfectly linear. When only a small part of the curve is utilised the non-linearity is scarcely noticeable. Owing to this disadvantage however, high quality C.R.Os. have more elaborate sawtooth generator circuits using "hard" tubes.

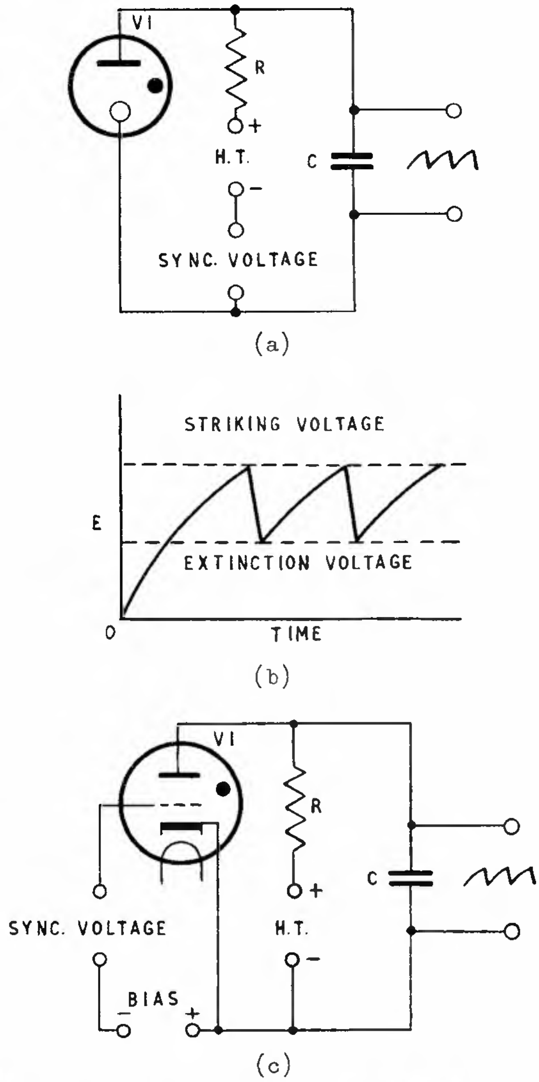


FIG. 19. SAWTOOTH GENERATORS.

6.4 The Blocking Oscillator is a type of relaxation oscillator which is used to produce pulses of relatively large amplitude, short duration and waveform having very steep rise and fall. Fig. 20a shows the basic circuit and Fig. 20b the pulsing nature of the output. The time between pulses depends mainly on the time constant of the C,R combination.

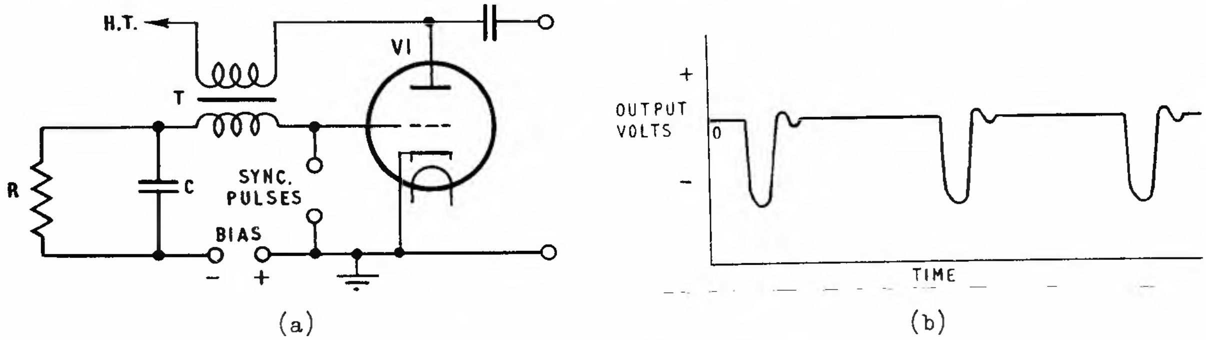


FIG. 20. BASIC BLOCKING OSCILLATOR.

Fig. 21 shows the operation of a typical blocking oscillator in stages.

Transformer T provides a large positive feedback voltage. When anode current increases the regenerative voltage induced into the grid circuit drives the grid abruptly positive making the anode current rise abruptly to maximum at a rate limited only by the L/R ratio of transformer T. The grid current which flows charges capacitor C with the grid end negative with respect to the cathode end (Fig. 21a).

A point is reached where anode current rises less rapidly. This may result from anode current approaching saturation in some circuits and from the comparatively large grid current robbing electrons from the anode current in others. The voltage induced into the grid circuit makes the grid less positive and the anode current increase rate is slowed some more. This cumulative action brings the anode current momentarily to a steady value and there is no feedback voltage. C stops charging and begins to discharge.

Anode current commences to fall and the flux in the transformer starts to collapse inducing into the grid circuit a voltage opposite to that which accompanied the rapid rise in flux. This regenerative negative grid signal drives anode current abruptly to zero and the grid voltage to well beyond cut-off. (Fig. 21b.) Feedback ceases as there is now no current in transformer T.

Capacitor C is now discharging slowly through R and the voltage across C and R is high enough to maintain the grid beyond cut-off for a comparatively long time which will depend on the time constant CR (Fig. 21c).

The grid becomes gradually less negative as C discharges and when the grid voltage is reached which allows anode current to recommence, the rising flux in feedback transformer T drives the grid positive again and the regenerative cycle is repeated.

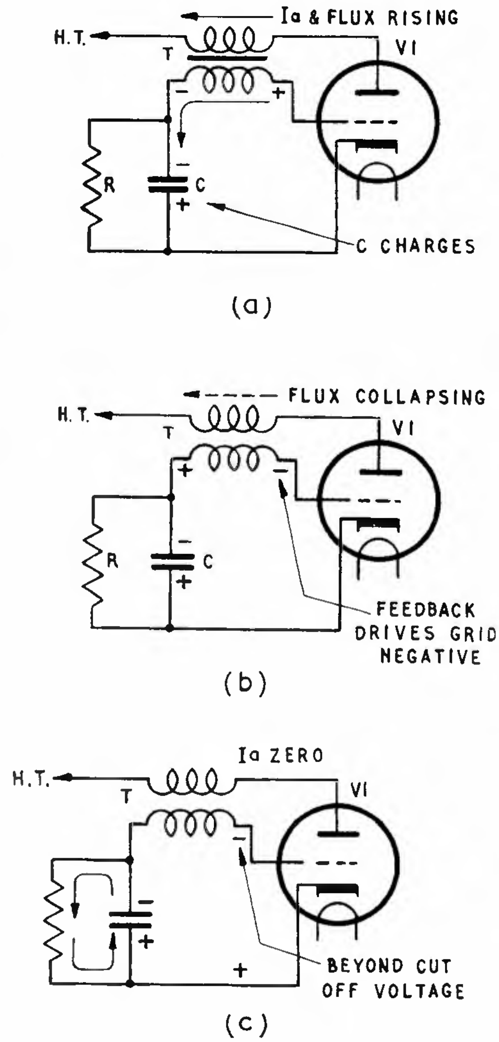


FIG. 21.

With typical blocking oscillators, the rate of rise and fall in anode current depends on the transformer resistance and inductance ratio but can be extremely rapid. The low level oscillations following the main pulse are caused by the energy stored in the winding capacitances of transformer T.

A blocking oscillator is readily synchronised by an external voltage pulse with a frequency slightly above that of the free running frequency and applied to the grid so as to raise it above cut-off voltage a little earlier than the free running discharge of C would allow. The term "forced frequency" is sometimes used to describe the control of a synchronised oscillator.

Alternatively, blocking oscillators can be readily biassed beyond cut-off and become monostable – requiring one input trigger pulse for each output pulse.

The type of blocking oscillator described here is sometimes called the "single swing" type to distinguish it from the "self pulsing" type which oscillates for several cycles in charging C progressively beyond cut-off.

:.5 Multivibrators are relaxation oscillators using two tubes and having the output of each coupled to the input of the other. There are no elements in the circuit to limit the feedback to one frequency so feedback occurs at all frequencies including very high order harmonics. Their main use is for the generation of square waves or pulses. The circuits may be astable (free running) to produce continuous output or triggered and be either monostable (one-shot or start-stop) or bistable (flip-flop).

In astable multivibrators (Fig. 22) extremely rapid changes or transients are separated by relatively long periods of little apparent change or relaxation, the duration of which is determined by circuit constants.

:.6 Fig. 22 shows the circuit of an astable multivibrator. Being a two stage device, feedback is positive without the need of a phase reversing transformer or network. Each tube alternately conducts and is cut-off for a definite interval of time. When V1 is conducting V2 is cut-off and vice versa. The sequence for one full cycle of operation can be summarised as follows -

(i) An extremely rapid change from V1 conducting to V2 conducting.

(ii) A long period during which the circuit is "relaxed" and V2 keeps conducting while V1 remains cut-off.

(iii) A second violent change to V1 conducting and V2 cut-off.

(iv) A second long period during which the circuit is again relaxed with V1 conducting and V2 cut-off.

The cycle is recommenced when condition (i) follows condition (iv).

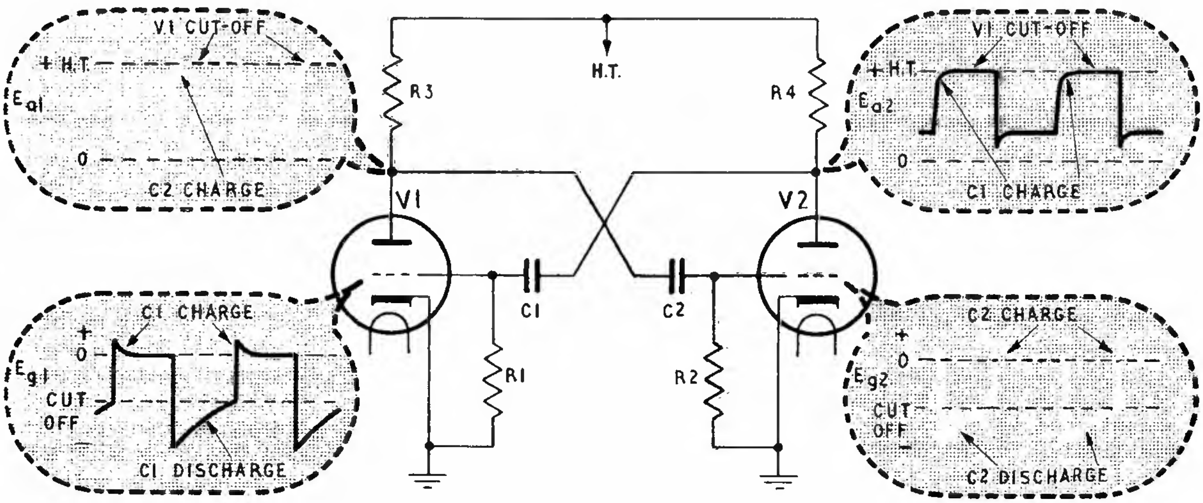


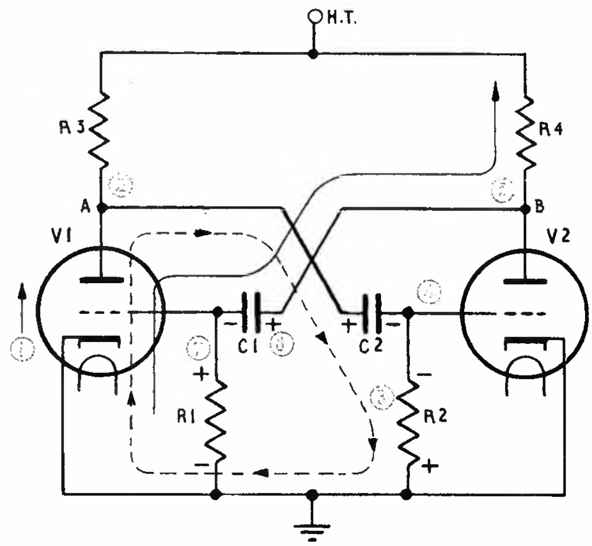
FIG. 22. ASTABLE MULTIVIBRATOR (FREE RUNNING).

When the circuit is switched on anode current rises in both tubes. Circuits which have equal value components in each tube circuit are called symmetrical but perfect balance never exists and any slight irregularity will cause the current in one tube to increase at a greater rate than the other. This is sufficient to start the regenerative multivibrator action. The unbalance is amplified and the cumulative effect drives the tube with the greatest rate of current increase to maximum while the other is simultaneously driven back beyond cut-off.

Supposing the initial anode current in V1 increases at a greater rate than that in V2. Capacitors C1 and C2 take on a certain charge when the circuit is first switched on. The following then occurs in extremely rapid sequence:

- The greater current increase in V1 increases the voltage drop across R3 and the anode voltage of V1 is reduced. (Point A.)
- Capacitor C2 was charged to a higher voltage than this and begins to discharge via R2 and V1 as shown by the dotted arrows in Fig. 23.
- The voltage drop across R2 becomes a negative going transient signal to V2 grid which reduces V2 anode current.
- The reduced voltage drop across R4 increases anode voltage of V2 to become a positive going transient at B (of greater magnitude than the negative going signal from A by the voltage gain factor of V2).
- This positive transient at B is applied to V1 grid via C1 which further increases anode current in V1 to produce an amplified negative going transient at A which is again applied to V2 grid via C2.
- This regenerative process continues until V2 is cut-off and point B is at H.T. voltage. The grid of V1 is therefore driven positive and capacitor C1 charges to this voltage by the passage of grid current in V1 and R4 as shown the full arrows in Fig. 23.
- Thus the initial unbalance has received regeneration from the two stages of amplification and this cumulative positive feedback can only cease when V2 is cut-off and V1 anode current is a maximum.

This action is not gradual; the change is accentuated to an extent that it becomes a practically instantaneous "avalanche", and might occur in less than a microsecond under typical circuit conditions. The signals between stages during the switching action are therefore transients.



(1) Current increases in V1.

(2) Increased drop across R3 reduces anode voltage of V1.

(3) Capacitor C2 discharges via R2 to reduced anode voltage of V1.

(4) Drop across R2 produces negative going signal on V2 grid.

(5) Anode current V2 decreases; less drop in R4 makes V2 anode more positive.

(6) V1 grid driven positive and C1 charges by grid current via R4 and V1.

(7) Amplified positive grid signal on V1 greatly reinforces the initial slight increase in (1) above and so on until V1 draws maximum current and V2 cuts off.

FIG. 23.

The circuit is now in a relaxed state with V1 conducting and V2 cut-off. The only change occurring is the continuing discharge of C2 via R2 and V1 which maintains V2 cut-off for a time. (During operation C2 is charged to H.T. voltage on the previous cycle. As we have considered the circuit starting from zero the initial charge taken on by C2 may be somewhat less than this value.)

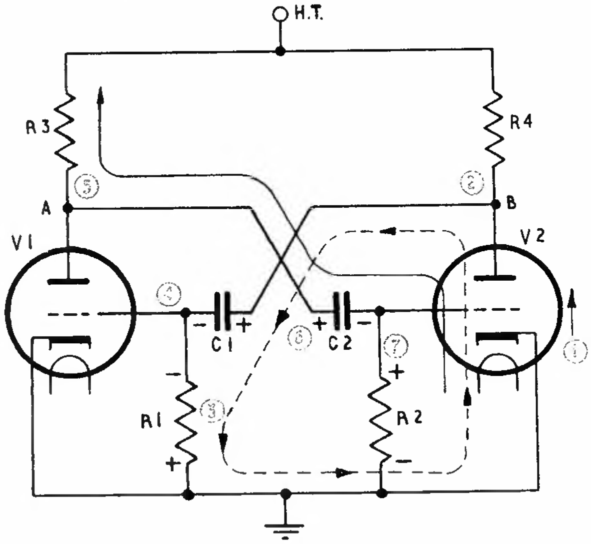
As C2 discharges the voltage drop across R2 is gradually reduced and a point is reached where V2 grid becoming less negative allows V2 anode current to recommence again.

The first slight current in V2 ends the period of relaxation and the regenerative process starts again to switch the circuit in a virtually instantaneous surge to the opposite condition:

- Slight current in V2 and R4 reduces the anode voltage of V2 (point B).
- C1 begins the discharge to this reduced potential via R1 and V2 as shown by the dotted arrows in Fig. 24.
- The reduced V2 anode voltage therefore becomes a negative going transient on V1 grid which reduces the anode current in V1.
- An amplified version of this transient appears on V1 anode (point A) owing to reduced voltage drop in R3 and constitutes a positive going transient applied to V2 grid.
- C2 charges rapidly to the H.T. voltage by the grid current of V2 via R3 as shown by the full arrows in Fig. 24.
- The initial slight current in V2 after the relaxation period is thus greatly accentuated by the positive going signal on its grid. The regenerative process continues driving V2 to maximum anode current and V1 to cut-off.

The circuit is now again in the relaxed state which continues while C1 gradually discharges via R1 and V2 to maintain V1 cut-off by the voltage drop across R1. V1 grid gradually becomes less negative and when anode current recommences the regenerative process is repeated as listed for Fig. 23 and the circuit switches once more to the opposite state.

Fig. 22 also shows the simultaneous anode voltage and grid voltage waveforms of both tubes for two full cycles (not the first after switching on but after uniform oscillation has been established with full charging of C1 and C2 to H.T. voltage each cycle). The output is taken from either anode and as shown has a fairly square waveform which is extremely rich in harmonics.



Following on from step (7), Fig. 23, circuit is relaxed as C2 discharges via R2 and V1 to hold V2 cut-off. Voltage drop across R2 reduces until -

(1) V2 begins to conduct via R4.

(2) Voltage drop in R4 reduces anode voltage of V2.

(3) Capacitor C1 discharges via R1 to reduced anode voltage of V2.

(4) Drop across R1 produces negative going signal on V1 grid.

(5) Anode current V1 decreases; less drop in R3 makes V1 anode more positive.

(6) V2 grid driven positive and C2 charges by grid-current via R3 and V2.

(7) Amplified positive grid signal on V2 greatly reinforces the initial slight current in (1) above and so on until V2 draws maximum current and V2 cuts off.

FIG. 24.

This abundance of multiples of the basic frequency has many practical applications and harmonics up to the 150th have been used. Astable multivibrators can be synchronised to run in step with slightly higher frequency signals injected into the circuit. A crystal oscillator arranged to trigger a multivibrator is often the basis of very stable frequency multipliers.

Pulse width. The time each tube remains in the relaxed state determines the number of pulses or cycles per second; the "pulse width" in milliseconds or microseconds is another measurement often used. This time duration is determined mainly by the time constant C1 R1 and C2 R2 and can be varied to give pulses lasting from microseconds to minutes.

Asymmetrical Output. In a symmetrical circuit, component values for each tube are equal, giving equal switching times. The astable multivibrator can also be made to produce relatively short duration pulses with longer time between them. For example, the time constant of C1 and R1 in Fig. 22 may have a lower value than C2 and R2 and produce an output as represented in Fig. 25 from the anode of V1. The anode of V2 will, of course, furnish the reverse waveform - long pulses at short intervals.

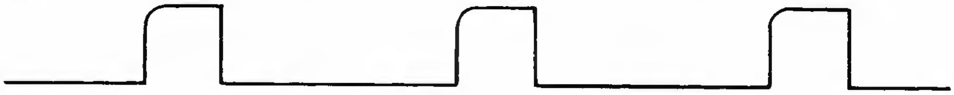


FIG. 25. ASYMMETRICAL OUTPUT.

6.7 Monostable Multivibrators (one-shot or start-stop). The astable multivibrator (Fig. 22) can be readily converted to be monostable by the addition of a biassing voltage to one tube which maintains it cut-off. The circuit stays quiescent until a trigger pulse opposes the cut-off bias and allows the circuit to switch to the opposite condition, stay relaxed as the coupling capacitor discharges and then switch back to the original condition where the cut-off bias maintains the quiescent condition until another trigger pulse is applied.

More generally monostable multivibrators achieve the same result using a modified circuit which provides a form of self-bias. Fig. 26 shows a typical monostable circuit in which a common cathode resistor R_k provides both the necessary bias and part of the regenerative coupling between stages.

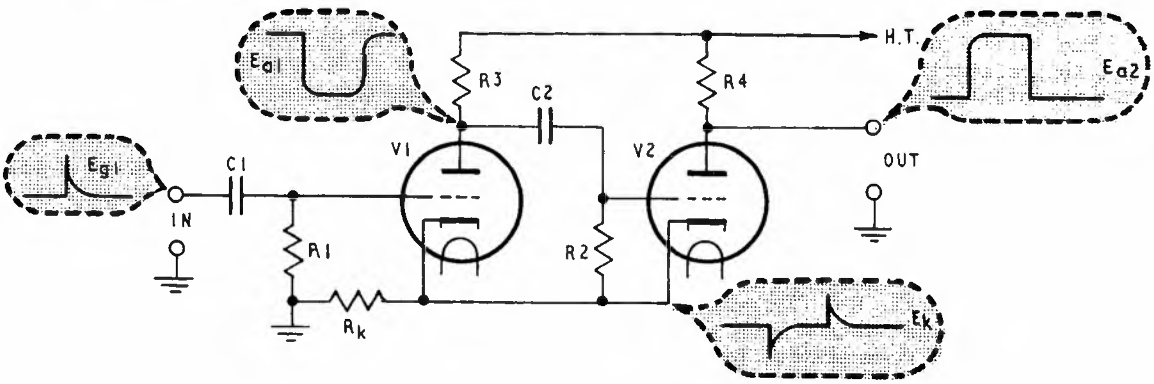


FIG. 26. MONOSTABLE MULTIVIBRATOR (ONE-SHOT).

Operation. In the quiescent state V2 conducts and its anode current produces a voltage drop across R_k sufficient to maintain V1 biassed beyond cut-off. Changes in V2 anode current are coupled back to V1 grid also via the changing voltage drop across R_k. Fig. 26 is therefore known as the one-shot cathode-coupled multivibrator circuit. Cathode coupling is a form of direct coupling for both D.C. and A.C.

A positive going trigger pulse applied to V1 grid via C1 has sufficient amplitude to raise it above cut-off voltage. V1 conducts and the regeneration takes over. The exact process which follows is similar to that described for the astable circuit with Figs. 22, 23 and 24 and can be analysed in a similar way:

- V2 is driven to cut-off as V1 rises to maximum anode current.
- The circuit remains relaxed in this condition while C2 discharges via R2 and V1 to hold V2 cut-off by the drop across R2.
- When V2 grid voltage rises above cut-off, V2 again conducts and the regenerative signal is fed to V1 grid via R_k and R1.
- V1 is driven to cut-off while V2 grid is driven positive as C2 recharges. V2 anode current drops to normal and holds V1 cut-off by the voltage drop across R_k.

The cycle is complete and the circuit remains quiescent until the next trigger pulse. Note one trigger pulse provides one full cycle and one square wave output pulse the width of which depends on the A.C. coupling circuit between V1 and V2; that is the time constant of C2 and R2.

:.8 Bistable Multivibrators have two stable states and two trigger pulses are needed to complete one full cycle of operation. Fig. 27 shows the basic circuit of a bistable multivibrator (binary or flip-flop circuit). It is similar to the astable circuit of Fig. 22 except that:

- bias is provided to maintain either tube cut-off (cathode bias in Fig. 27);
- pulse width depends on the timing of the trigger pulses and not on circuit time constants;
- direct or D.C. coupling between anodes and grids replaces the A.C. coupling used for free running circuits.

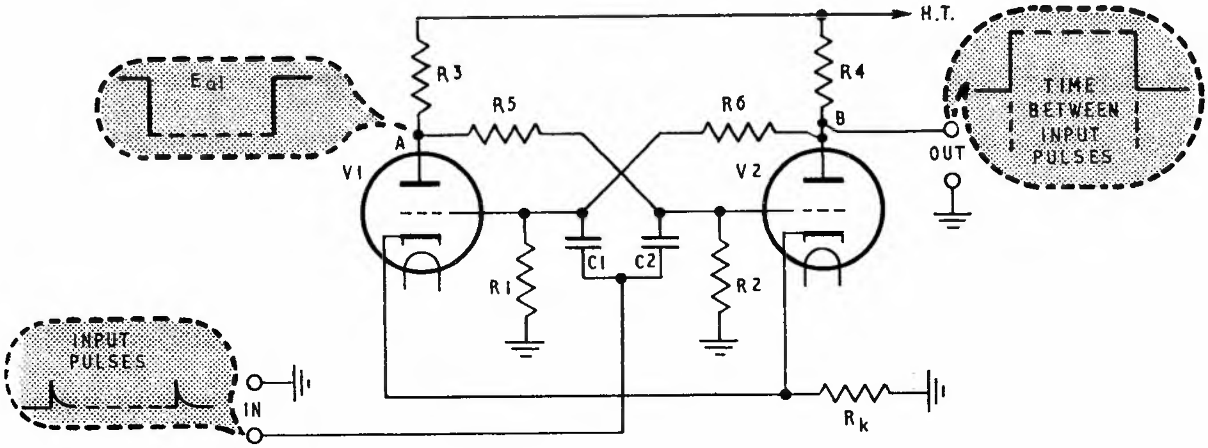


FIG. 27. BISTABLE MULTIVIBRATOR (FLIP-FLOP).

Operation. Suppose V2 is conducting and V1 is cut-off. V2 anode current in R_k keeps both cathodes positive with respect to earth by the voltage drop across R_k. The anode-cathode voltage of V2 (point B) is low because of the voltage dropped across R4 and R_k. R1 is therefore able to keep V1 grid negative to cathode by a voltage sufficient for cut-off. As there is very little current in R3, V1 anode (point A) is at nearly H.T. voltage. The high anode-to-cathode voltage of V1 is applied between V2 grid and cathode via R5 and R2 and these resistors are proportioned to allow sufficient voltage drop across R2 to overcome the opposing bias voltage across R_k. V2 is thus kept conducting fully by a grid-cathode voltage which is about zero or slightly positive.

An input trigger pulse is applied to both grids via C1 and C2. A positive pulse starts conducting in V1 and a negative pulse reduces current in V2; either may be used providing its magnitude is enough to overcome the cut-off bias on V1. Regeneration takes over and switches the circuit to V1 conducting and V2 cut-off in a similar manner to that described for the previous astable and monostable circuits. However, the difference lies in the direct coupling of both stages. The negative going transient at A and the positive going transient at B are applied directly to the V2 and V1 grids respectively without having to charge and discharge coupling capacitors in the process. As a trigger pulse is needed to initiate each switching action there are two quiescent states and no period of relaxation.

When V2 is cut-off the high voltage at B is able to keep V1 biassed to full conduction via the voltage drop across R1 opposing that across R_k. The much lower voltage at A with V1 conducting keeps V2 grid near enough to earth potential for the drop across R_k to bias it beyond cut-off. That is, the initial state described is completely reversed and this opposite quiescent state continues until another trigger pulse starts conduction in V2. The regenerative switching action takes over and restores the original quiescent state - V2 conducting V1 cut-off.

Output signal may be taken from the anode of either tube. Since two pulses are needed to restore the output potential to the original value, bistable circuits are used to provide an on-off switch or electronic gate for any time interval.

Binary Counting. When the output of one bistable circuit is connected as the input of another bistable circuit and so on for several stages, with suitable indicators in each stage, a binary counter is formed. Binary notation is a system of counting in twos and lends itself to electronic computing more readily than decimal notation.

Transistors have proved to be very suitable devices for switching circuits of the multivibrator type and in these applications they have largely succeeded tubes. Multivibrator principles remain the same, whichever amplifying device is used and these are somewhat simpler to explain using tube circuits. (A transistorised binary counter is described in the paper "Transistors and other Semiconductor Devices".)

6.9 Synchronising pulses used for synchronising or triggering of other circuits are usually required to have a special type of waveform to ensure reliable triggering. A sharp rise and fall of voltage occupying a time duration very much less than a half-cycle of the triggered oscillator has a waveform like that shown in Fig. 28 and is called a "spike".

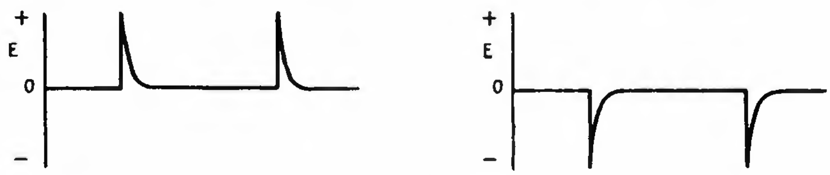


FIG. 28. "SPIKES".

The very short duration is necessary to avoid the possibility of the triggering signal distorting the output waveform or the switching characteristics of the triggered circuit. Where this is not important however, relaxation oscillators can be synchronised by sine wave input signals.

Spikes are produced by a simple process called pulse differentiation. This consists of passing any source of e.m.f. having a sharply rising waveform through an R/C circuit of short time constant. Fig. 29 shows how positive and negative spikes are produced from an input voltage of square waveform and another of trapezoidal waveform.

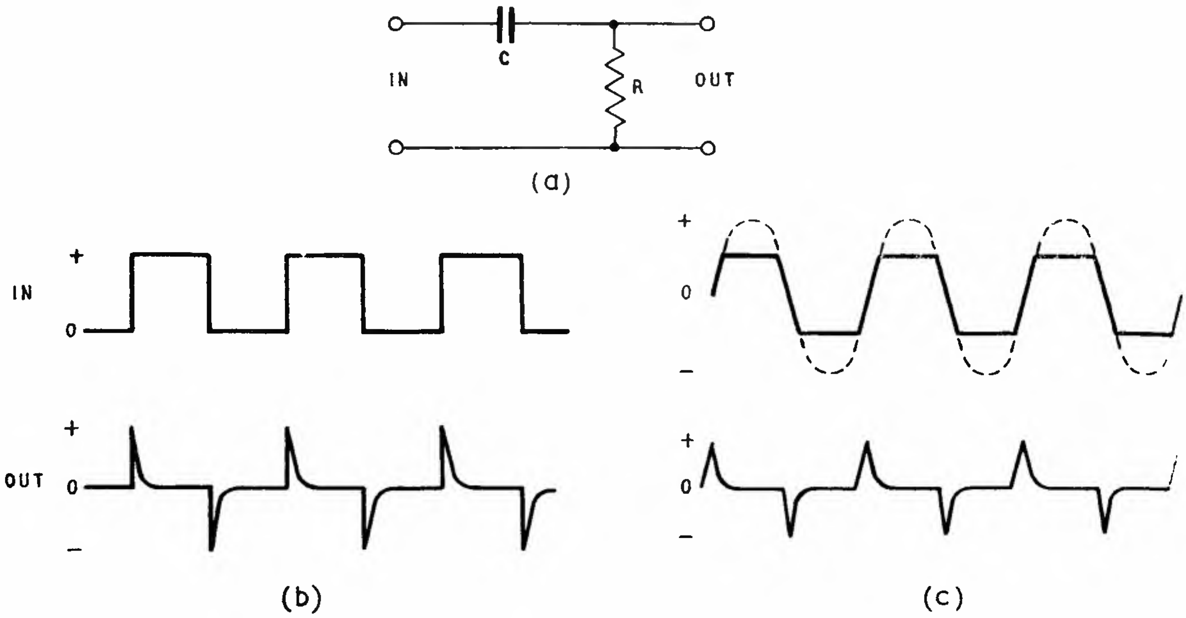


FIG. 29. PULSE DIFFERENTIATION.

When the time constant (CR) of the differentiating circuit (Fig. 29a) is only a fraction of the pulse width of the input, the output pulse becomes a spike whose width is the charging or the discharging time of C. The steep rise of the output in Fig. 29b occurs because the charging current is maximum at the beginning of the pulse, the discharge current maximum at the end of the pulse, and output is the voltage drop across R through which C charges and discharges.

When the input voltage does not reach maximum voltage instantaneously the wavefront of the output spikes is less steep as shown in Fig. 29c.

A sine wave cannot be differentiated to produce spikes directly but other pulse shaping circuits called "limiters" and "clippers" are used to produce from sine waves other wave shapes which can be differentiated to produce spikes. Fig. 29c also indicates that the trapezoidal waveform was produced by limiting the peak amplitude of a sine wave. When only positive or negative spikes are wanted the unwanted one is removed by rectification.

NOTES

7. TEST QUESTIONS.

1. List the circuit requirements which must be present to produce self-oscillation.

2. List the various component arrangements commonly used to keep oscillations to the desired frequency.

3. With the aid of a diagram describe the principle of operation of a basic type of electron tube oscillator.

4. What is frequency stability and what are some of the precautions taken to secure it with different types of oscillators?

5. Compare and contrast the Hartley and Colpitts oscillator circuits.

6. Explain what is meant by "shunt feed" and "series feed" for oscillator circuits.

7. (i) Describe a common method of obtaining grid bias with L/C oscillators.
   (ii) What is the principal advantage of this class of bias?

8. (i) What class of operation is used when a pure waveform is required? (ii) Explain the reason for this.

9. With the aid of a diagram describe the operation of a tuned-plate tuned-grid oscillator.

10. Describe the principles of electron coupling in oscillator circuits.

11. (i) With the aid of a block diagram describe the principle of beat-frequency oscillators. (ii) Why are they widely used?

12. Explain what is meant by the term "peizo electric effect".

13. Why are crystal oscillators so widely used?

14. With the aid of a simple diagram describe the basic principle of a crystal oscillator suitable for generating a carrier signal voltage at 10kc/s.

15. (i) With the aid of a diagram explain how a tuning fork can be used to stabilise an oscillator.
    (ii) Is such a device used at low or high frequencies? Give the reason for your answer.

16. (i) Describe the principle of a two stage R/C oscillator.
    (ii) How is good waveform secured with this type of oscillator?

17. With the aid of a diagram describe how a single stage resistance loaded amplifier can be made to oscillate at a particular frequency.

18. What do you understand by the terms -

    (i) astable (ii) monostable (iii) bistable
    (iv) electronic switch (v) gate (vi) quiescent.

19. Describe a simple oscillator for producing a voltage of sawtooth waveform.

20. With the aid of a diagram explain the operation of a typical blocking oscillator.

21. In synchronising a relaxation oscillator with a more stable oscillator what is the correct frequency relationship before the synchronising signals are injected?

22. With the aid of a simple diagram describe the operation of a free running multivibrator.

23. With the aid of a diagram explain the operation of a "flip-flop" circuit.

24. How are triggering spikes produced?

END OF PAPER.

TRANSISTORS

AND OTHER SEMICONDUCTOR DEVICES.

---

1. INTRODUCTION.

1.1 At present, the most prominent semiconductor device is the transistor which was invented in 1948. However, the use of germanium crystal, from which most transistors are made, is not new. In the early days of radio it was found that certain crystals were capable of rectifying A.C. of a low value when one of the two connections was made to a 'sensitive spot' on a crystal by adjusting a pointed wire known as the "cat's whisker".

1.2 Thermionic valve rectifiers replaced crystal detectors until their re-introduction in wartime Radar circuits where they were sometimes superior to valves at ultra high frequencies. This promoted a great deal of research into the properties and behaviour of substances now classified as "semiconductors" which include copper-oxide, selenium, germanium and silicon. For rectifiers, including power rectifiers, copper-oxide has largely been superseded by selenium, which is in turn being gradually superseded by germanium and silicon.

1.3 The use of semiconductors is now extended beyond the original province of rectification to a wide variety of amplifying and controlling devices. Rapid development of new and improved types of semiconductor devices has taken place, and although a great deal of information has been published, terms and symbols are not yet uniformly standardised. This paper follows the general trend and important alternatives are given.

2. SEMICONDUCTORS FOR TRANSISTORS.

2.1 Semiconductors possess the following characteristics:-

(i) Electrical conductivity (and resistivity) between that of metallic conductors and insulators.

(ii) A rise in temperature decreases the resistivity. (In metals, a rise in temperature increases the resistivity.)

(iii) At very low temperatures (approaching absolute zero, -273° C.) semiconductors become insulators, whilst metals approach zero resistance.

(iv) Impurities in semiconductors decrease the resistivity. (In metals, impurities increase the resistivity.)

Until recent years, these phenomena were little understood, but now mathematical calculations and experiments have produced explanatory theories.

2.2 Atomic Structure. In the paper "Electron Theory" (Applied Electricity I) we saw how matter is composed of atoms, with each atom regarded as having a nucleus of positive electric charges or protons around which revolve an equal number of negative charges or electrons. Substances mainly differ in the number of protons and electrons comprising their atoms. Elements having some electrons only loosely bound to their nucleus conduct electricity when these electrons move readily between atoms. Insulators have tightly bound electrons.

2.3 Crystals. To understand semiconductors we must expand the electron theory to include chemical bonds and crystal structure.

The paths or orbits of electrons revolving around the nucleus are known as "shells" and the number of electrons that any one shell may contain is limited. The number of shells ranges from one for the simplest and lightest atoms to seven for the heaviest and most complex atoms. The innermost shell may contain a maximum of two electrons, the second shell up to eight electrons, and the next four shells more than eight. Fig. 1a represents the structure of the germanium atom, and Fig. 1b shows a further simplification for germanium and silicon which are both semiconductors.

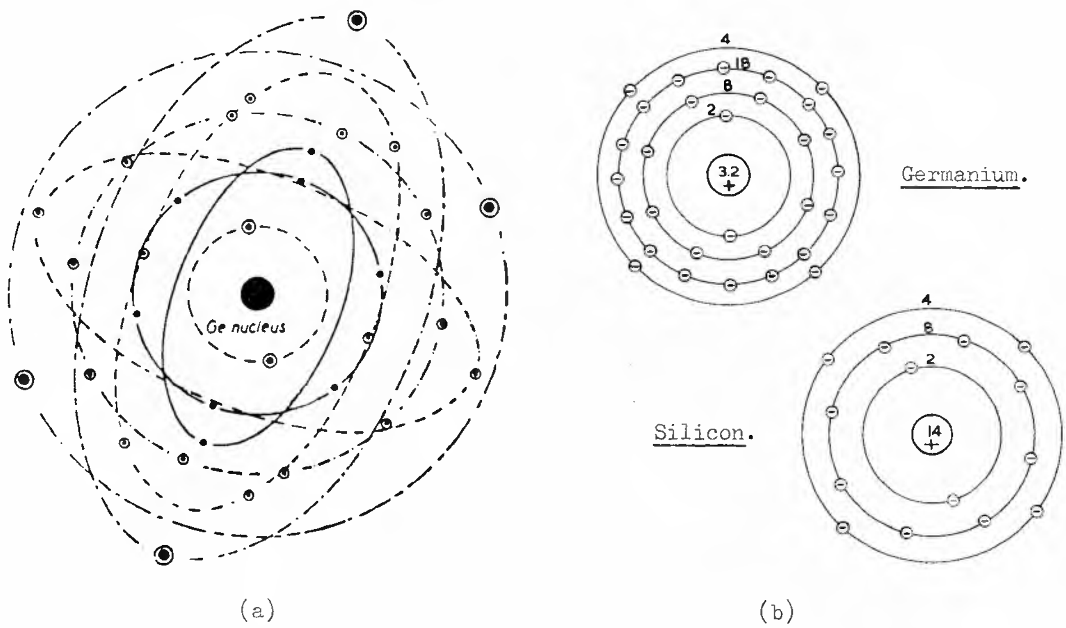


FIG. 1. REPRESENTATION OF ATOMIC STRUCTURE.

The maximum number of electrons which may form the outer shell is eight; an outer shell of eight electrons is a very stable atomic state and substances normally in this state show no inclination to enter into chemical combination or to conduct electricity. A single shell is complete and stable with two electrons.

The atoms of most substances show a marked tendency to reach this stable state, and may do so by sharing electrons in their outer shell with similarly placed electrons of other atoms. Although this sharing of electrons can take place in several ways we are concerned with only one of them, producing what is known as a covalent bond between atoms each of which lacks one or more electrons in its outer shell. Fig. 2 represents an example of such combination, where an atom of carbon combines with four atoms of hydrogen to form one molecule of the gas methane.

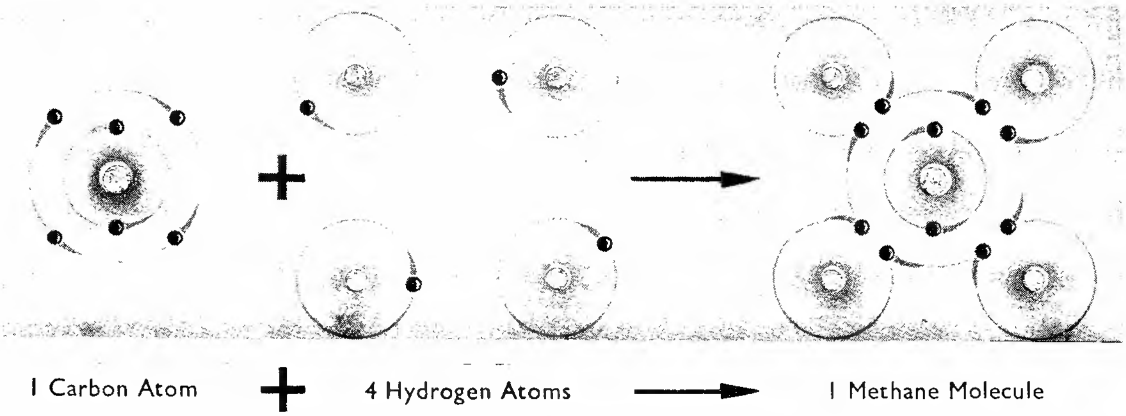


FIG. 2.

The stable state is achieved by the atoms of a single substance when mutual covalent bonds result in a regular pattern of the atomic structure for the whole of a pure piece of the substance. This regular arrangement of atoms or "lattice" structure results in what is termed a crystal. Crystalline carbon or diamond is so stable that it is virtually a perfect insulator and chemically inert.

Pure germanium and silicon become crystalline when each atom forms covalent bonds of its four outer electrons with those of four adjacent atoms. Fig. 3 represents a germanium crystal lattice. Only the four valence electrons are shown, as those in the inner orbits do not concern us at the moment. Notice how by sharing electrons, each atom achieves the effect of an outer shell of eight electrons.

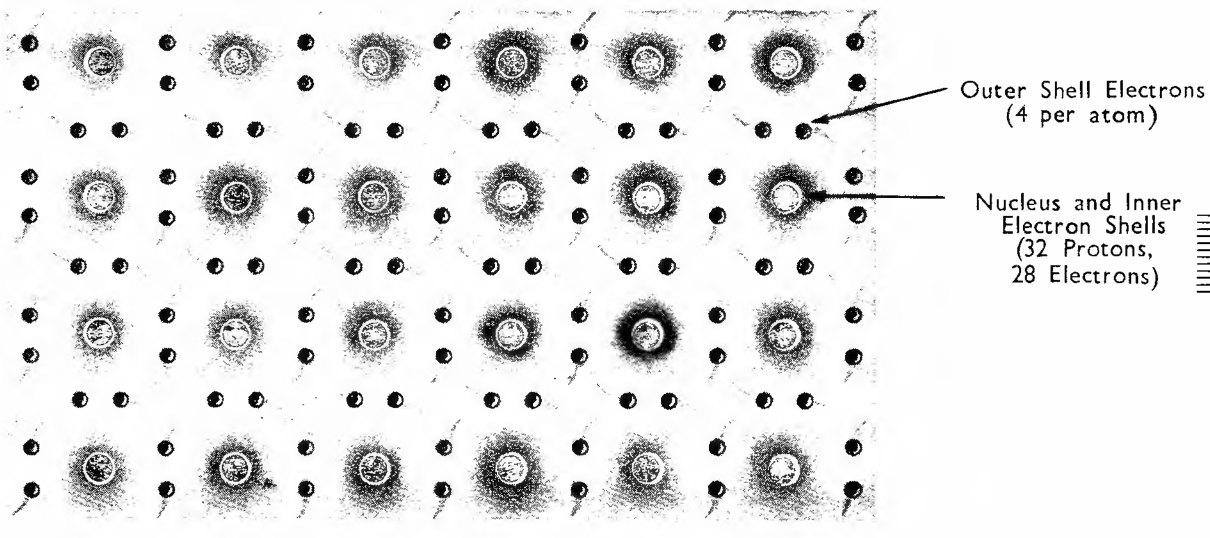
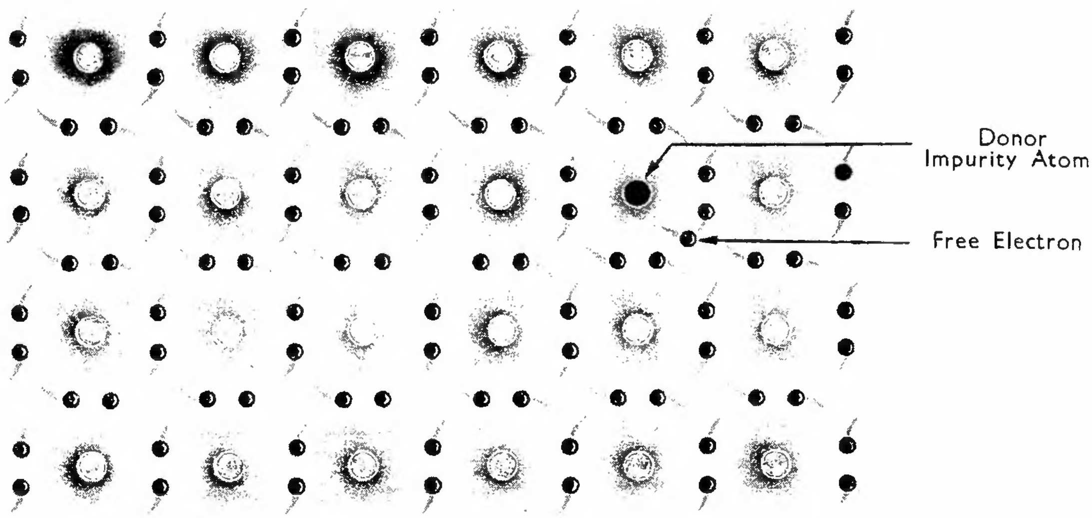


FIG. 3. GERMANIUM CRYSTAL LATTICE.

In this type of pure crystalline germanium, no free electrons are available as carriers of current. (The term "carriers" is used in semiconductor theory, as conduction can take place in two distinct ways and movement of free electrons is only one of these.) The covalent bonds are much weaker than those in a diamond so that pure germanium crystal and similar semiconductors are only insulators when no energy in the form of heat or light can enter to break some of the bonds. At room temperatures, sufficient electrons are freed by thermal agitation to give germanium crystal a resistivity of about 60 ohms per centimetre cube compared with 1.75 microhms/cm^3 for copper and 10^{16} ohms/cm^3 for mica. When the temperature of the crystal is raised, the resistivity falls quite rapidly as the greater thermal vibrations of the atoms free still more electrons as current carriers.

Pure germanium becomes much more conductive when "doped" with minute traces of certain impurities whose atoms become included in the crystal lattice.

2.4 "N"-Type Germanium is formed when pure germanium is doped with an element such as arsenic or antimony. These elements have five electrons in the outer atomic shells. Four of these enter into covalent bonds with adjacent germanium atoms; at normal temperatures the fifth electron is free to wander throughout the crystal. The current carriers are negative electrons, and this material is called "N"-type germanium. Fig. 4 represents the idea. As impurities of this type donate electrons to serve as current carriers they are known as donor impurities.



REPRESENTATION OF "N"-TYPE CRYSTAL STRUCTURE.

FIG. 4.

2.5 "P"-Type Germanium is formed when pure germanium is doped with an element such as indium or aluminium which have only three electrons in the outer shell. These three electrons form covalent bonds with adjacent germanium atoms. The fourth covalent bond cannot be completed except by the impurity atom accepting an electron from elsewhere. Wherever a bond is not complete, the impurity atom can accept an electron from a neighbouring atom. The resulting absence of an electron creates a positively charged "hole" in the lattice. Fig. 5 represents the idea.

This is called "P"-type germanium and the impurities are called acceptor impurities. At normal temperatures holes wander freely in the crystal as an electron released from an adjacent bond occupies a hole, and, in effect, shifts the hole to the vacated position.

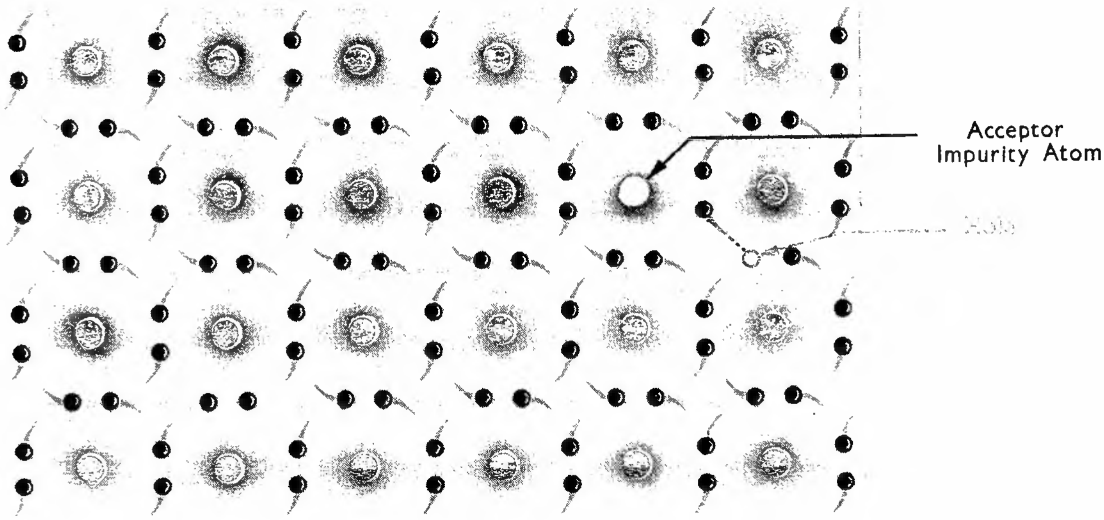


FIG. 5. REPRESENTATION OF "P"-TYPE CRYSTAL STRUCTURE.

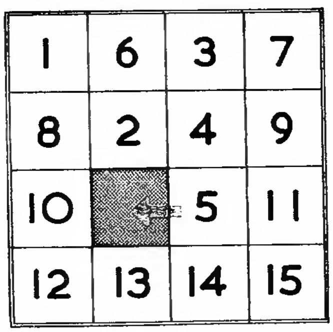


FIG. 6.

Holes therefore move in the opposite direction to electrons in much the same way as with the sliding pieces of the familiar puzzle (Fig. 6). When one of the pieces moves to the left, the hole shifts to the right.

Conduction in P-type crystal is clearly of a different character to that in N-type and is regarded as a movement of positively charged holes; that is, the current carriers are positive holes.

Note that in doped germanium the total number of electrons and protons remains equal so that separate pieces of N or P-type crystal have no charge; this is, they are electrically neutral.

Silicon is doped in a similar way to give N and P-type crystals.

2.6 Majority and Minority Carriers. To give N and P-type materials the desired conductivity, the amount of impurity required is extremely small - of the order of one part in several million. The crystal before doping must therefore be extremely pure and this can only be attained by complex refining processes.

In practice it is very difficult to produce crystal without some impurities of the wrong kind and there are always some holes present in N-type crystal and some free electrons in P-type. Crystal is therefore N-type when the majority of carriers are electrons and P-type when the majority of carriers are holes.

Majority carriers are holes in P-type crystal and electrons in N-type; minority carriers are electrons in P-type and holes in N-type. Generally a minority carrier lasts only until it is absorbed by recombination with one of the much more numerous majority carriers. That is, a particular hole in N-type crystal is soon filled by a free electron, and a free electron in P-type crystal soon occupies a hole.

The entry of heat or light energy creates both majority and minority carriers in any type of semiconductor crystal. Expanding the idea in para. 2.3, the breaking of covalent bonds in this way not only frees electrons, but creates what are called electron-hole pairs; that is, an electron knocked from a bond by thermal energy also leaves a hole.

3. CRYSTAL DIODES.

3.1 The P-N junction is the fundamental building block of most semiconductor devices. When a single crystal is made having a sudden transition from P-type to N-type a crystal diode is formed.

At the instant of formation of the junction, holes near the junction on the P side tend to diffuse into the N region and these combine with some free electrons, while some electrons in the N region tend to diffuse into the P region and these combine with some free holes. We saw that separate pieces of N or P crystal are electrically neutral or uncharged, but a movement of positive and negative charges in this way builds up a charge in the vicinity of the junction. Electrons leaving the N region leave it positively charged and holes leaving the P region leave it negatively charged. A state of equilibrium soon exists because the positive charge on the N region repels further holes from the P, and the negative charge on the P repels further electrons from the N. The junction now takes the form of a narrow layer depleted of current carriers. This is generally called the depletion layer, or potential barrier. Fig. 7 represents the idea.

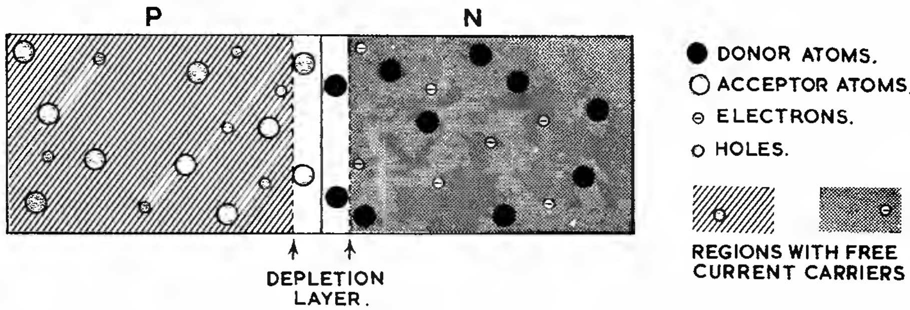


FIG. 7.

3.2 When an external voltage is applied with the — pole to the P region and + to the N, the junction potential is raised further and the barrier is made wider as the majority carriers recede still farther from the junction (Fig. 8). This is the non-conducting or reverse direction.

In practice a very slight leakage current flows and this is accounted for mainly by the presence of thermally released electron-hole pairs close to the junction. A few minority carriers (electrons) released in the P region are swept into the N region by the + potential there and similarly a few holes in the N region are attracted into the P region. Having crossed the junction they are then majority carriers and promote an equivalent current in the external circuit. A junction diode is thus very high resistance in the reverse direction. A small proportion of leakage current is caused by surface leakage across the insulation between the leads.

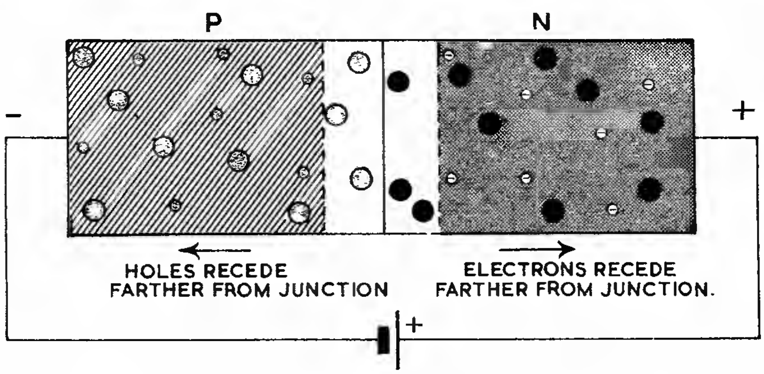


FIG. 8.

When the applied voltage is reversed, the potential barrier is cancelled and a current results; electrons are injected from N to P and holes from P to N; electrons enter the external circuit.from the P region to create more holes, and enter the N region to make up for those lost combining with holes in the P region. (Fig. 9.) This is the low resistance or forward direction.

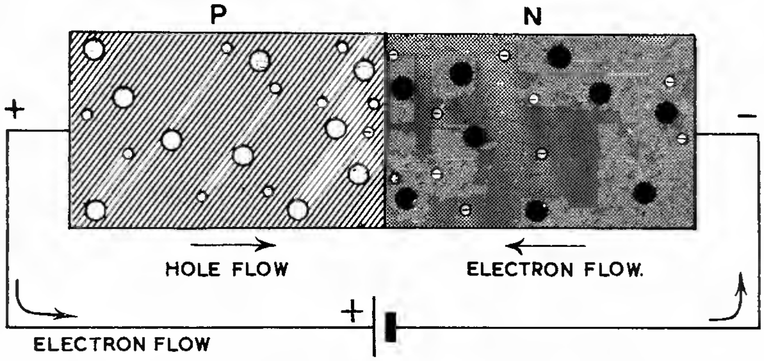
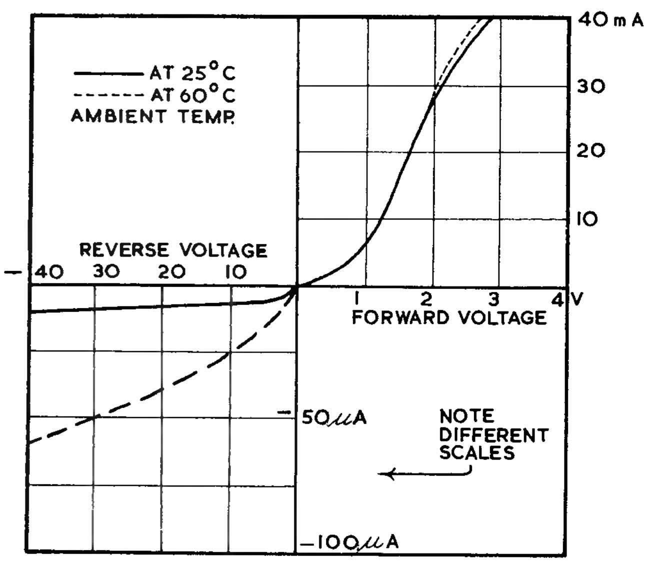


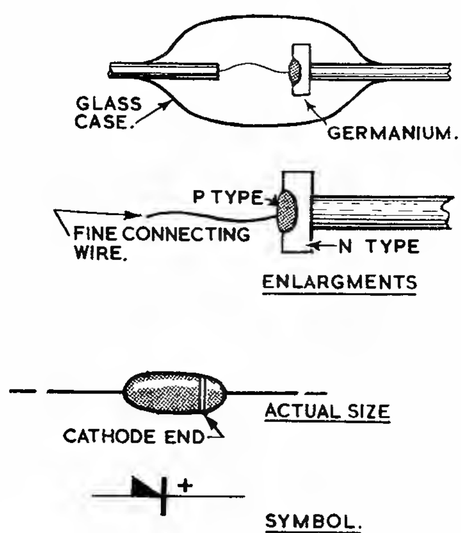
FIG. 9.

3.3 Junction Diode Characteristics. The P-N junction is therefore a diode or rectifier. Germanium diodes have similar characteristics to selenium rectifiers (which are thought to function in a similar way) but, as they have greater reverse resistance and lower forward resistance, crystal diodes are more efficient rectifiers. Fig. 10a is a typical characteristic curve for a germanium diode. Notice the very small leakage current even with high inverse voltages. This leakage current largely consists of the minority carriers and a rise in temperature releases more of these; the dotted line on the graph shows how the leakage current increases with a rise of temperature to 60° C.

P-N junctions are made by a number of different processes - alloying, diffusion or growing, but these need not concern us as the ultimate structure is the same.



(a) Typical Characteristic (OA85).



(b) Construction, etc.

FIG. 10.

In small current circuits, germanium diodes are finding increasing use as their small size is often an advantage. Fig. 10b shows the size and construction of a typical germanium diode.

3.4 Maximum Ratings for crystal diodes are specified by the manufacturers and these must not be exceeded or the diode may be destroyed or its performance permanently impaired. The important ratings and typical figures are listed below for the general purpose germanium diode OA85 -

OA85

ABSOLUTE MAXIMUM RATINGS

At Ambient (Surrounding Air) Temperature Of	Inverse Voltage		Forward Current		
	Average	Peak	Average	Peak	Surge (Max. Duration 1 Second)
25° C.	90 V	115 V	50 mA	150 mA	500 mA
75° C.	75 V	100 V	17 mA	150 mA	500 mA

Note how the values are derated at the higher ambient temperature. This is to prevent the internal power dissipation from raising the junction temperature above the safe maximum when the diode is less able to lose heat to its surroundings; operation above the safe maximum would seriously shorten its life. The maximum allowable junction temperature varies but is in the range 55 - 80°C. for germanium and 130 - 150°C. for silicon.

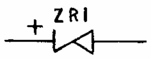
3.5 Silicon Power Diodes are discussed in the paper "Diodes and Rectifiers". A more recent development in the field of power rectification is the "controlled" rectifier which is the semiconductor equivalent of the gas triode or thyratron. Like the latter, the silicon controlled rectifier is a three terminal device with cathode and anode electrodes plus a low power controlling element. It is not a true diode therefore but is sometimes classified as such. The typical controlled rectifier has four regions of conductivity (P-N-P-N) with the control lead connecting to one of the intermediate regions.

A description of operation is beyond the scope of this paper. It is anticipated however rectifier sets with currents up to 100A or more will appear and use the new device in obtaining a sensitive form of automatic output control.

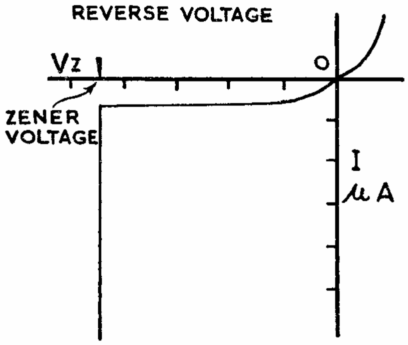
3.6 Zener Diodes. When the maximum inverse voltage is exceeded, a diode may break down in one of two ways -

(i) "punch through" which destroys the diode and leaves it short-circuited; or

(ii) "Zener" breakdown. (The name is derived from the relationship to experiments of C. Zener in 1934.)



(a) Symbol.



(b) Characteristic.

FIG. 11.

At a somewhat lower voltage than "punch through", a voltage may be reached where the carriers collide with other atoms with enough energy to free more carriers. The phenomenon is similar to that of ionization of a gas. This is Zener breakdown and, when it occurs, the voltage drop across the diode remains virtually constant; as long as the dissipation is limited by external resistance, it is not harmful. The feature is used in diodes made especially for use as voltage regulators.

Fig. 11a shows the standard symbol of the Zener Diode and Fig. 11b a typical Zener Diode characteristic; with suitable design the Zener voltage may be quite low, -5V being typical.

4. JUNCTION TRANSISTORS.

4.1 A junction transistor (or crystal triode) has three distinct regions of conductivity arranged in a 'sandwich' to give two P-N junctions or diodes so close to each other that interaction occurs between them. Two arrangements are possible, P-N-P and N-P-N. Operation is similar for both types, the only important difference being that opposite polarities are required for the external circuit connections.

The three connections of a transistor are called the Emitter, Base and Collector. Fig. 12 shows the arrangement of the three elements for P-N-P and N-P-N transistors and the circuit symbols. As the collector and emitter regions appear identical in relation to the base, either can be used as collector or emitter, but generally the area of the collector-base junction is made larger than that of the emitter-base junction as this improves the performance. This can be seen in Fig. 13a which shows a cross section of a typical P-N-P transistor made by fusing indium pellets into opposite sides of an N-type germanium slab.

For satisfactory operation, the thickness of the base region (between the emitter and collector) must be very small, about one thousandth of an inch being typical.

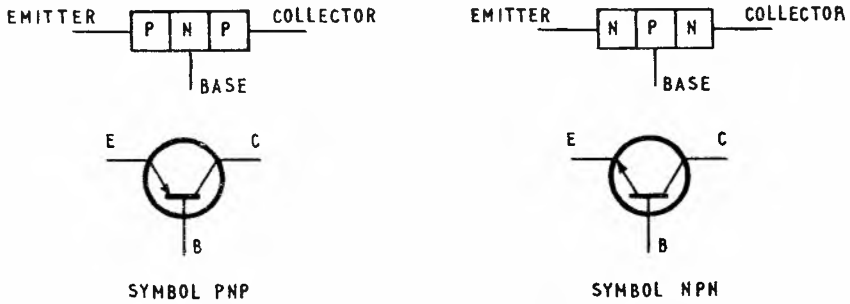
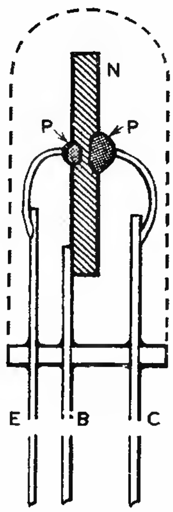
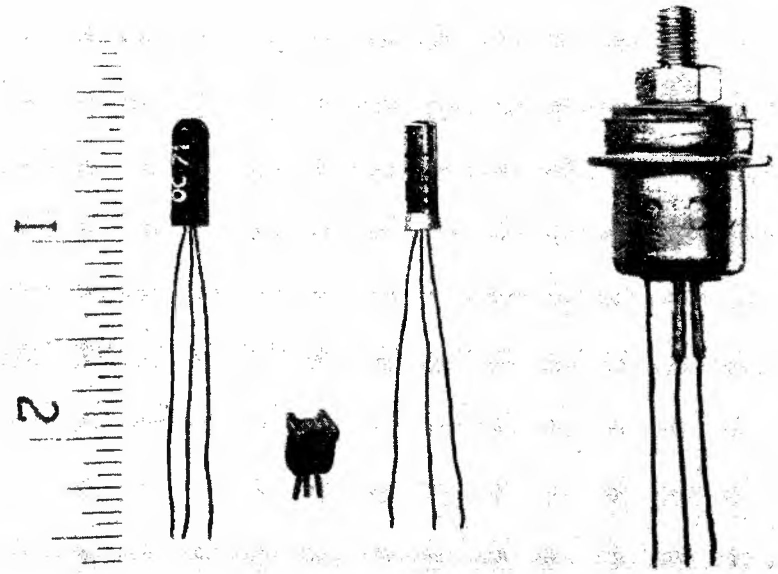


FIG. 12.



(a) Typical Construction.



(b) Typical Transistors and Socket.

FIG. 13.

4.2 Transistors are encased to prevent their characteristics being altered by contamination from the air or water vapour. Hermetical sealing in glass or metal envelopes is generally used; the free space within the envelope is filled with an inert gas, oil or grease. Glass envelopes are painted black to prevent entry of light.

Transistor symbols and the arrangement of terminal leads are not uniformly standardised. Fig. 12 shows the symbols most generally used and which are the A.P.O. standard. For low power and medium power transistors, the three leads are brought out of the envelope in a straight line with the base in the middle position. The collector lead is marked by a white or coloured dot or it may be denoted by larger spacing from the base lead than the emitter. Very often both methods are used. Higher power types in metal cans generally have the collector connected to the can; the base and emitter leads are colour coded and reference should be made to the maker's data. Transistors are generally soldered into the circuit directly but miniature sockets are sometimes used; one of these is shown in Fig. 13b.

4.3 Transistor Action. Before we consider how a pair of P-N junctions are able to amplify, let us see what happens when D.C. voltages are applied to the three terminals of a typical transistor. Fig. 14 shows the circuit for our first "experiment".

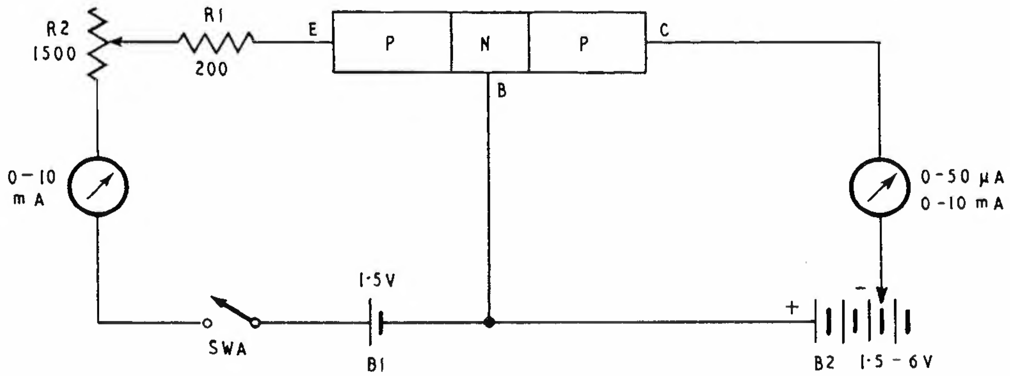


FIG. 14.

The emitter-to-base junction and the collector-to-base junction separately tested, have low forward resistance and very high reverse resistance in the same way as the crystal diode.

When the 1.5V battery is connected between collector and base, with the emitter open-circuit, a small leakage current flows which has a value of about 4μA; the value of B_2 is raised to 6V and the leakage current increases very slightly to 5μA. This current is called I_{co} or the cut-off current, the emitter circuit being cut off or open circuit. As with the reverse current in a crystal diode, I_{co} is highly dependent on temperature and will approximately double itself for every 10°C. rise in temperature. This is easily demonstrated in the above circuit if a finger and thumb are placed lightly on the transistor; the meter needle will rise rapidly to about 8μA in 10 seconds (providing ambient temperature is below body temperature).

Note that the battery in the emitter-base circuit is connected in the forward direction. As a transistor can be destroyed in a matter of moments should excessive forward currents pass in the junctions, a limiting resistor R1 is included as well as a rheostat R2 to vary the emitter current. The meter in the collector circuit is switched to the 0-10mA range and switch SWA then closed. With R2 adjusted to give 1mA in the emitter it will be found that the collector current rises to very nearly 1mA. Using accurate measurements typical figures would show the collector current I_C to be say, 985μA, composed of the 980μA caused by the 1mA of emitter current and "transistor action" plus the original 5μA of leakage current. In other words, nearly all the emitter current is collected by the collector; the remaining 15μA flows in the base circuit.

Leaving the emitter current unchanged (I_E = 1mA) and reducing the collector voltage B2 to 1.5V causes negligible change in I_C showing that the impedance of the collector circuit is very high (at this low rate of change a typical value is in excess of 1 megohm.)

4.4 Current Gain. Increasing I_E (by reducing R2) will result in I_C increasing in proportion - about 980μA increase in I_C for every 1000μA increase in I_E. The ratio of the change in I_C to the change in I_E if $\frac{980}{1000}$ or 0.98 and although a little less than unity it is called the current gain of the transistor and is designated by the Greek letter alpha (α).

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad (E_C \text{ constant})$$

where -
I_C = collector current.
I_E = emitter current
α = current gain (common base).
Δ = small change in

This applies to common base transistor circuits only (base common to input and output as in Fig. 14.) Although the current change in the output is less than that in the input, useful amplification is obtained because the current change in the high impedance collector circuit represents a much higher power level than the similar current change in the low impedance emitter circuit. (Amplification, properly defined, is a raising of power level, even though many types of electron tube and transistor amplifiers have figures given for voltage and current gain when it is convenient to ignore the different input and output impedances.) Note that similarly to tubes, the transistor is a device which allows a low power input signal to control the release of a larger output signal power from a D.C. energy supply.

Now, let us return to the motion of current carriers in the two P-N junctions and see why it is possible for the current in the low impedance emitter circuit to inject itself into the high impedance collector circuit.

4.5 Theory of Operation. Referring to Fig. 15, the emitter-base junction (1) and the collector-base junction (2) will each raise a depletion layer or potential barrier as described for the junction diode (Fig. 7). The P-type collector region becomes negative with respect to the N-type base. Connection of the battery B2 raises this barrier still further so that the strong negative charge on the collector exerts a strong attraction on the base for holes, but which the base cannot supply having only free electrons. (Neglecting for the moment the leakage current I_{CO}.

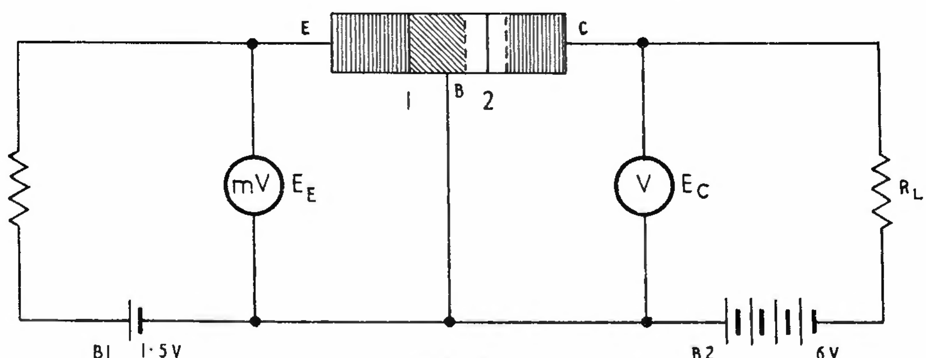


FIG. 15.

When battery B_1 is connected the potential barrier at junction 1 is overcome and holes are injected from the emitter region into the base. Now because the base is very thin, most of the holes soon reach the field of influence of the collector whose negative attraction sweeps them across junction 2 to become the collector current; thus a current of holes is set up between the emitter and collector. The voltage between emitter and base (E_E) governs the size of the hole current and the voltage between collector and base (E_C) absorbs this current as fast as it is supplied by the emitter. A comparatively small number of holes is lost by recombination with electrons in the base region. A flow of electrons in the external circuit from emitter to collector keeps up the supply of holes through the two junctions. A few electrons flow from the base lead to make up for those lost by recombination with holes. As we saw above however, in a typical transistor about 98% of the holes emitted are collected. Individual transistors vary considerably with alphas (α) between 0.95 and 0.99.

4.6 Internal currents. Using the current values of our 'experimental' circuit in Fig. 13, let us examine the various electron and hole currents, including the leakage current I_{co}. Fig. 16 represents this as simply as possible.

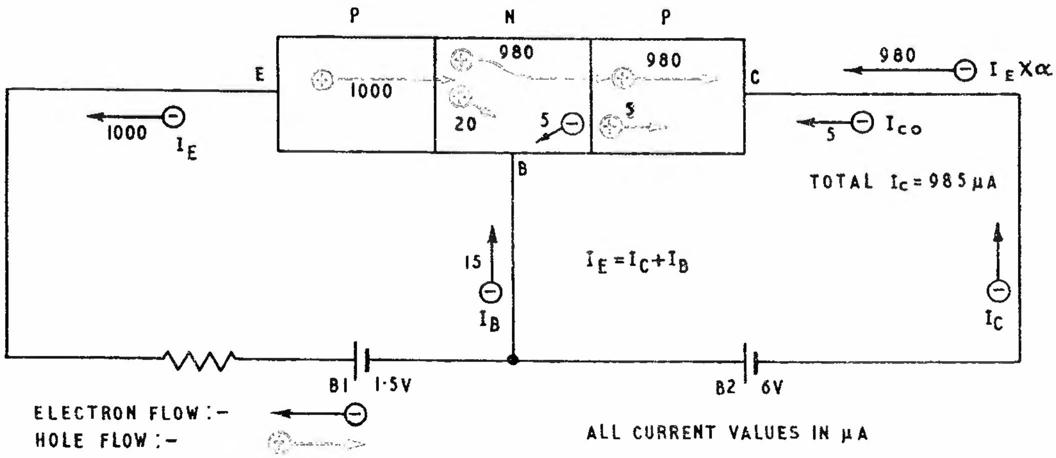


FIG. 16.

The 1000µA hole flow in the emitter region (1000) is maintained by the equal electron flow in the emitter lead (1000).

0.98 or α times this emitter current crosses the base region as holes (980) and passes through the collector region to the collector lead where it is maintained (or neutralised) by an equal electron flow (980).

As explained in paragraph 3.2, the leakage current (I_{co}) consists mainly of thermally released minority carriers, which after crossing the junction become majority carriers moving as holes in the collector (5) and electrons in the base (5). The collector lead supplies a further 5µA of electrons (5), which, added to the 980µA, gives a total collector current I_C of 985µA.

20µA of holes from the emitter combine with electrons in the base (20).

Only 15µA of electrons from the base lead (15) is needed to maintain the electron supply in the base, since as we saw above, 5µA of electrons are released in the base by the leakage current I_{co}.

When I_E is doubled, I_C rises another 980µA and I_B increases by 20µA. I_{co} does not increase owing to transistor action but may increase because the dissipation raises the junction temperature and, as we saw, the leakage current is highly temperature dependent. When the operating temperature has been established, I_{co} remains constant.

The current in an N-P-N transistor may be analysed in a similar way; the essential difference is that the main conduction is by electrons.

As well as keeping the base extremely thin to minimise the number of emitter carriers that combine with the base carriers, it is usual to use a base material of lower conductivity than the emitter and collector material; that is, the amount of impurity is less, thus making the base carriers less numerous.

Note that the main current in a transistor is actually minority carriers while passing through the base. Also note, that under any circuit conditions $I_E = I_C + I_B$.

4.7 Amplification. To enable the maximum number of holes to be collected, the collector voltage need be only in the very low region of 0.3 to 0.5V; beyond this, the collector voltage has little effect on the value of emitter to collector current. It is possible therefore to insert a high resistance load (R_L) in the collector circuit without it affecting I_C as long as the voltage drop across R_L with maximum I_C does not reduce the actual collector (to base) voltage (E_C) to less than the 0.5V or so mentioned above. Owing to the low impedance of junction 1, very small variations of E_E give quite large variations of I_E; corresponding variations of I_C through R_L give large variations of E_C. Thus a considerable voltage gain can be achieved.

4.8 Example. Suppose we connect a transistor as in Fig. 17 and vary the emitter current between the values 0.5mA and 1mA by means of rheostat R2. Assume an approximate emitter-to-base resistance of 100 ohms, which is typical for the chosen values of I_E. In practice there is some variation of input impedance with input voltage or current.

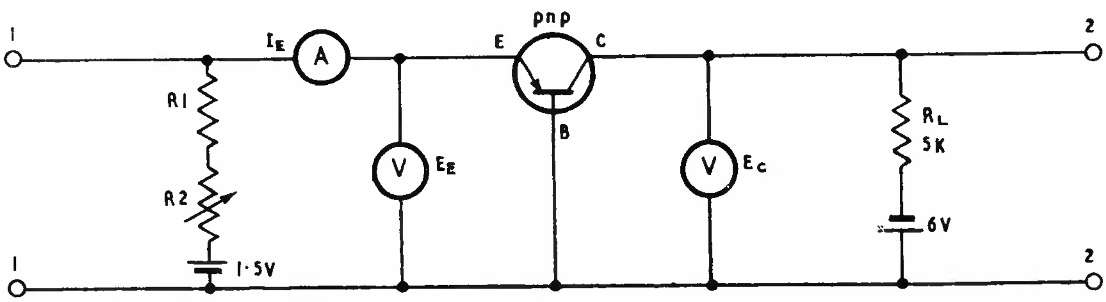


FIG. 17.

$$\text{Change in } E_E = \text{Change in } I \times \text{input R}$$
$$= (1 - 0.5) \times 100 = \underline{50 \text{ mV}}.$$

Neglecting loss in base, $I_C = I_E$ approx.

Collector voltage when I_C is 0.5 mA -

$$E_C = 6\text{ V} - \text{P.D. across } R_L$$
$$= 6\text{ V} - I_C R_L$$
$$= 6 - \frac{0.5 \times 5000}{1000}$$
$$= 6 - 2.5\text{ V} = \underline{3.5\text{ V}}.$$

Collector voltage when I_C is 1 mA -

$$E = 6\text{ V} - I_C R_L$$
$$= 6 - \frac{1 \times 5000}{1000} = \underline{1\text{ V}}.$$

$$\text{Change in } E_C = 3.5 - 1 = \underline{2.5\text{ V}}.$$

$$\text{Voltage gain} = \frac{\text{Change in } E_C}{\text{Change in } E_E}$$
$$= \frac{2.5 \times 1000}{50} = \underline{50}.$$

When the emitter current is varied by an A.C. signal connected to the terminals shown 1, 1, the amplified signal will be available at terminals 2, 2. As any signal input must appear at the base-emitter junction as varying D.C., a standing D.C. bias must still be provided, otherwise the A.C. input would be rectified. (Biassing methods are explained in Section 5.)

4.9 The example (Fig. 17) illustrates in a fairly simple way how a transistor is capable of amplifying, but it is not a practical circuit for several reasons:

- With a resistive load (R_L), the gain of the circuit is greatly limited as the value of R_L cannot be increased without increasing the collector battery voltage. For example, increasing R_L to 10,000 ohms would require a collector supply of more than 10V to preserve a working collector-base potential at 1mA collector current. The voltage gain would have risen to only about 100.

- The very low input resistance would act as a shunt on most sources of A.C. signal unless the source had a similarly low impedance.

Transformer coupling of input and output enables impedances to be matched and much greater voltage and power gains are attainable. Using a circuit similar to that shown in Fig. 18, voltage gains of 1,000 or more and power gains of about 30db may be attained.

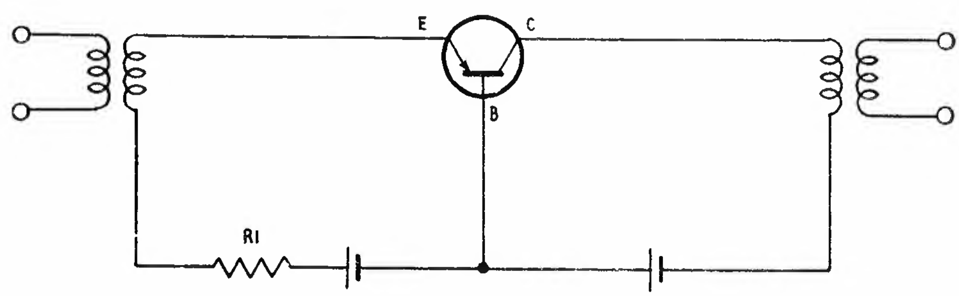


FIG. 18.

4.10 Transistor Amplifiers - Basic Types. Like valve amplifiers, transistors may have the input and output circuits arranged in three different ways. A useful analogy may be drawn between valves and transistors at this stage but like most analogies, the comparison should not be taken too far. Fig. 19 shows the three basic types of transistor amplifier and the valve circuit to which each is analagous.

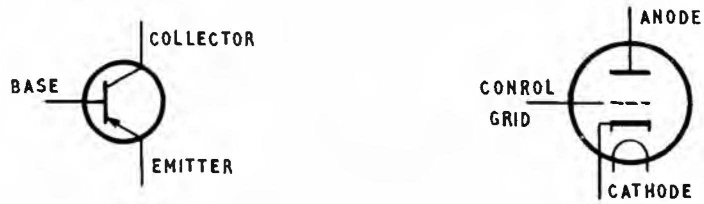
Fig. 19a compares the corresponding electrodes of a transistor and a triode valve.

Fig. 19b compares the common base transistor circuit with common grid valve circuit frequently called 'grounded' base and 'grounded' grid circuits because these electrodes are usually (but not necessarily) connected to the earthed or common pole of the battery.

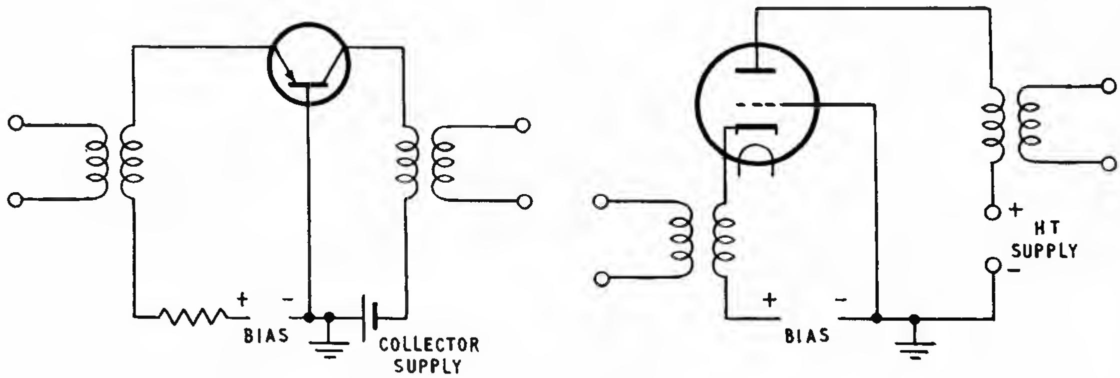
Fig. 19c compares the common emitter circuit with the common cathode circuit. These are both the most widely used configuration; known also as grounded emitter and grounded cathode respectively.

Fig. 19d compares the common collector circuit with the common anode or "cathode follower" circuit.

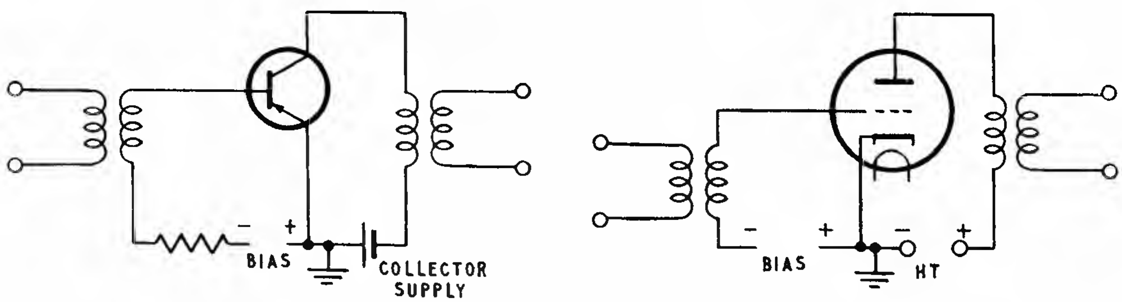
In Fig. 19, the transistors are all P-N-P types but N-P-N transistors are equally applicable with reversed battery potentials.



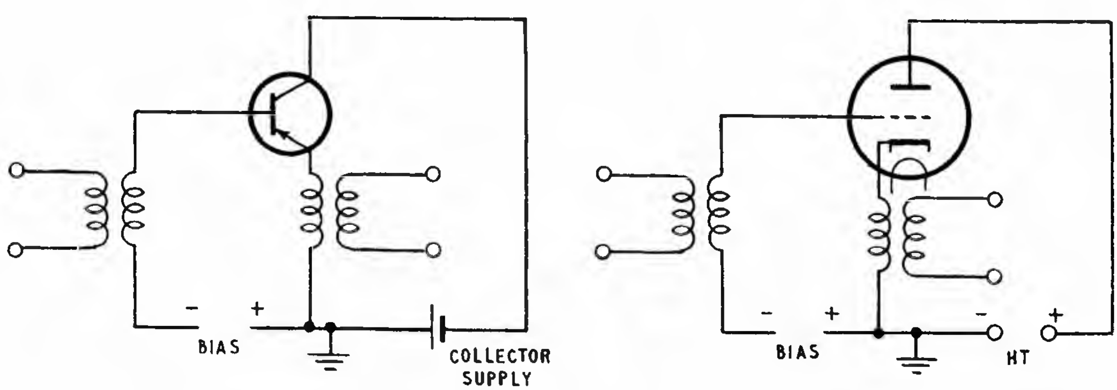
(a)



Common Base. (b) Common Grid.



Common Emitter. (c) Common Cathode.



Common Collector. (d) Common Anode (Cathode follower).

FIG. 19.

4.11 Common Emitter Amplifiers. We saw in para. 4.6 how small variations of base current accompanied larger changes in emitter and collector current. Viewed in another way, the transistor action - (Fig. 16) can be regarded as a flow of electrons from the base lead to the emitter junction which combine there with an equal number of holes and thereby stimulate a far greater hole current from emitter to collector. By completing the collector circuit via the emitter instead of the base (Fig. 20) the same transistor action permits a small input signal current applied to the base to control a much larger output signal current across both emitter and collector junctions. In this way the common emitter amplifier can achieve current gain as well as power and voltage gain, even though the basic current relationship $I_E = I_C + I_B$ still applies. 4.12

When we rearrange the "experimental" hook up of Fig. 14 to that of Fig. 20, typical results are as follows -

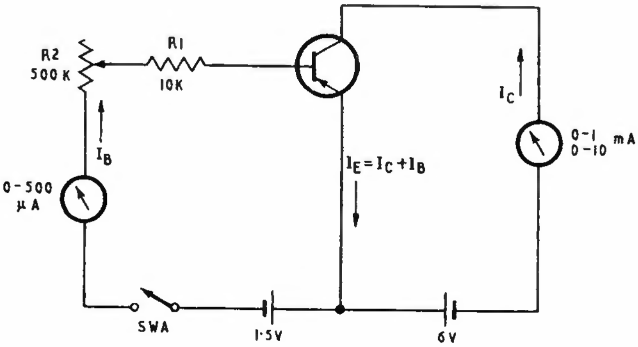


FIG. 20.

Base Current I_B	Collector Current I_C	Emitter Current $I_E = I_C + I_B$
0μA	200μA (leakage I_{co}')	200μA
20μA	1.1mA approx.	1.12mA
40μA	2.1mA "	2.14mA
60μA	3.1mA "	3.16mA
80μA	4.1mA "	4.18mA

From this we can see that a change of 20μA in I_B (40 - 60) gives a change of about 1mA in I_C (3.1 - 2.1). Current gain is therefore approximately

$$\frac{1000}{20} = 50.$$

Current gain for common emitter connection is denoted by various symbols in technical literature - as yet no standard has been set. We will use the Greek letter Beta (β); others frequently used are α' or α_{fe}.

$$\beta = \frac{\Delta I_C}{\Delta I_B} \quad (E_C \text{ constant})$$

where
I_C = collector current.
I_B = base current.
β = current gain (common emitter)
Δ means "a small change in"

In the experimental circuit, Fig. 20 therefore, β = 50.

Leakage. From the table we can also see that the 200μA collector-to-emitter leakage is very much greater than the collector to base leakage in common base circuits (typically 4-5μA). With the base open circuit, the collector to base leakage electrons can only return via the emitter-base junction where they stimulate an emitter-to-collector current approximately β times as great, just as if they had been injected via the base lead. Common emitter leakage is therefore an amplified version of the normal collector-to-base leakage. 4.13

To distinguish the leakage currents of common base and common emitter connection, they are designated I_{co} and I_{co}' respectively.

I_{co}' is a maximum when the base is open circuit and minimum when the emitter-base junction is shorted out externally. When there is an external D.C. resistive path from base to emitter, I_{co}' is intermediate between these values; the portion of leakage current taking the external path is not amplified since it does not cross the emitter junction.

4.12 Interstage Coupling in transistor amplifiers follows similar lines to the methods used in electron tube amplifiers. Transistors, however, are essentially current operated devices and input impedances are low compared to tubes which in Class A operation are purely voltage operated.

The basic connections of transformer coupling for the three types of amplifier are shown in Fig. 19 where the similarity to valve amplifiers is apparent. The main differences are in the turns ratios which are calculated to give suitable impedance matching, that is, a turns step-down from output to input giving a current step-up.

Resistance - capacity coupling was noted in paragraph 4.9 as being generally unsuitable for common base stages. The common emitter circuit presents higher input and lower output impedances than the common base circuit. (About 1000Ω input and 60kΩ output are typical values.) With R/C coupling as in Fig. 21, impedance mismatch is therefore still considerable; transformer coupled common emitter stages give highest gain, over 30db being readily attainable. For low level audio frequency stages R/C coupling is preferred, however, because it is less susceptible to hum pick up than transformers and parts are smaller and cheaper.

The coupling capacitor C has a much higher capacitance than in tube circuits to ensure that its reactance at the lowest frequency is small compared to the input impedance. Values from 10 to 100µF are usual; electrolytic capacitors are therefore used and must be connected in the correct polarity. The A.C. collector load of VT1 is R1, R2, and the base-emitter input impedance of VT2 all in parallel. (R2 is generally the equivalent resistance of the biassing circuit of VT2 and this is dealt with in Section 5.)

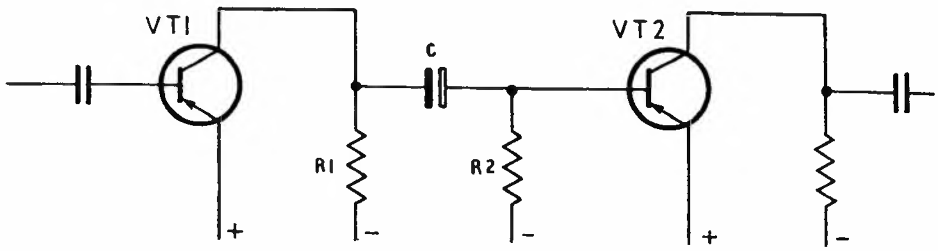


FIG. 21.

With impedance coupling, R1 in Fig. 21 is replaced by a choke of suitable impedance; the arrangement is rarely used.

Direct coupling allows the output electrode of the first stage to be directly connected to input electrode of the next (collector to base in common emitter stages). The collector and biassing voltages are maintained at the correct relative values using voltage dividers, dropping resistors or a tapped battery. Direct coupling is simpler than in valve circuits because of the low voltages involved.

4.13 Common base and common collector amplifiers will not be examined in detail as they are not often used in Departmental equipment.

Common collector amplifiers have high input impedance and low output impedance and are sometimes used as an impedance matching stage between two common emitter stages.

Common emitter amplifiers introduce a 180° phase change of signal between input and output. Common base and common collector stages do not cause any appreciable phase shift.

4.14 Characteristic Curves. Performance and operating data supplied by makers include sets of characteristic curves. Transistor constants are more complex than those of valves because even at audio frequencies they have some internal feedback which causes the input impedance to vary with load and the output impedance to vary with source impedance. The curves and working constants (or parameters derived from them) have to cover a more comprehensive field than do tube curves and constants (r_a, g_m and μ). (Parameters are constants derived to express the performance of a device but the value may vary with operating conditions and differ from that of other similar devices. Examples of parameters are β and α of transistors, r_a, g_m and μ of valves, resistivity ρ and coefficients of expansion, which are all constants in particular circumstances for any one device or material; the variable factor is disregarded or understood for calculations.)

Fig. 22 shows a typical set of curves for a popular type of audio frequency transistor in common emitter connection.

These are static curves and for convenience are arranged in four adjacent segments. For N-P-N transistors the same arrangement may be used though polarity signs are reversed. The four segments, A, B, C and D, relate the following variables -

A - Collector current to base current at a typical collector voltage. The slope of this graph therefore indicates the current gain.

B - Collector current to collector voltage. A family of curves for different base bias currents. The slope of these curves indicates the collector impedance.

C - Base voltage to base current with collector open and with a typical collector voltage. The slope of these curves indicates the input impedance and shows also how the collector voltage affects it.

D - Collector voltage to base voltage. A family of curves for different base bias currents. The effect of collector voltage changes on the base voltage indicates the internal feedback ratio. Note that for all except the lowest values of bias the effect is too slight to be noticeable on the graph at the scales used. Ratios of the order of $\frac{1}{10^3}$ or less are typical.

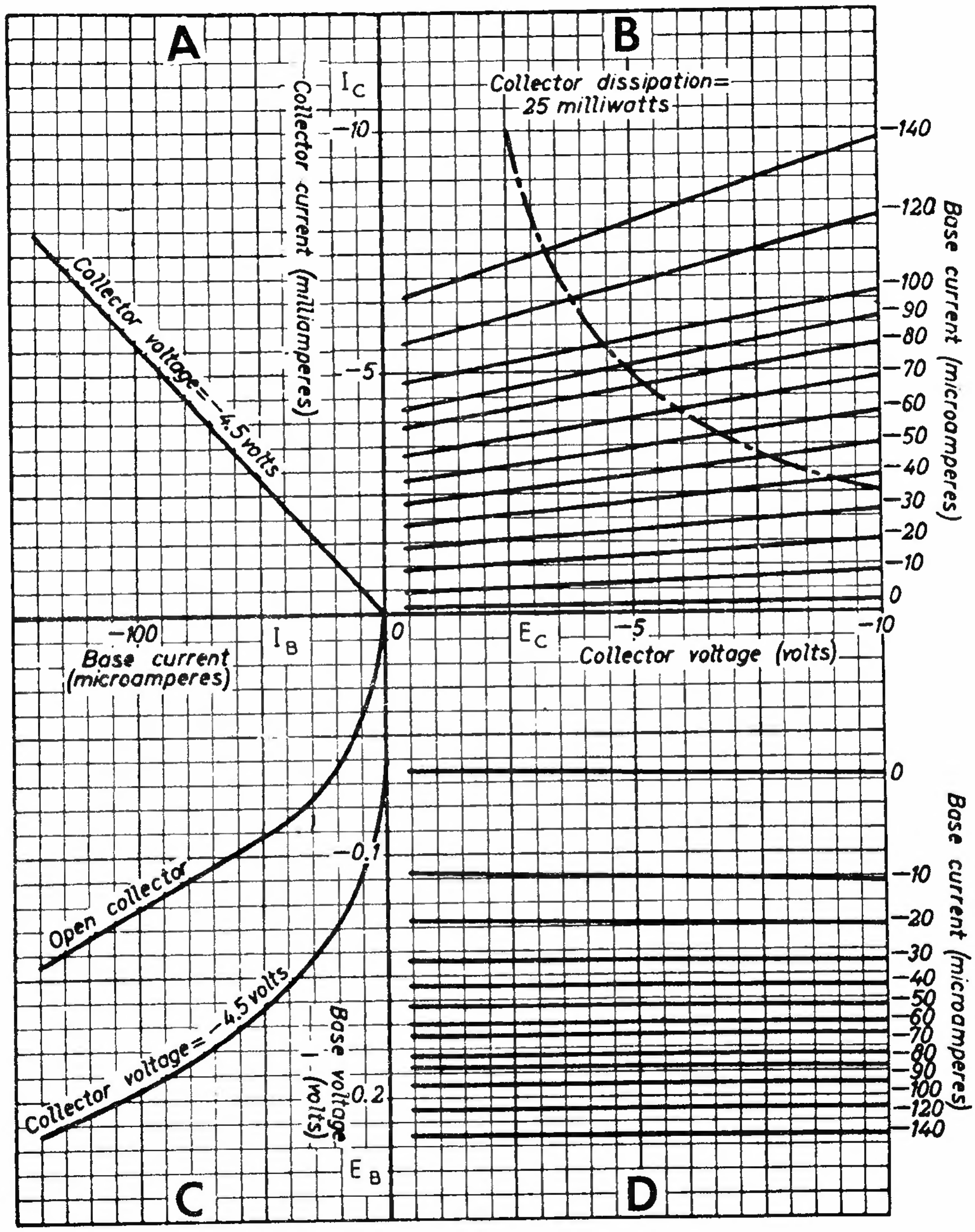
The most useful curves are those in Graph B relating collector voltage and current. By the use of load lines as is done for valve E_a/I_a curves suitable operating conditions and circuit values can be calculated.

All these E_C/I_C curves start from zero but become linear as shown at about 0.2V. For amplification with minimum distortion, circuits are designed to maintain the transistor working on the linear portion of the curves. The point on the curves at which collector dissipation reaches 25mW is shown by the dotted line. This serves as a guide in design; whether this figure may be safely exceeded depends on ambient temperature and arrangements made for the transistor to dissipate heat to its surroundings.

4.15 Point Contact Transistors were invented before junction transistors. They have a base of either P or N type material with emitter and collector leads of pointed wire embedded in it very close together. The development of the junction transistor followed not long after the original discovery and, being a superior device in many respects, has replaced the point contact type for most applications.

Point contact transistors had better performance at high frequencies than any early junction transistors; special junction transistors are now made to handle very high frequencies. Point contact types are little used in Australia.

The theory of operation differs from that of junction transistors; further information is given in Section 7.



TYPICAL CHARACTERISTICS FOR COMMON EMITTER CONNECTION.

FIG. 22.

5. PRACTICAL TRANSISTOR CIRCUITS.

5.1 Biassing. We have seen how an input signal must be superimposed on a D.C. bias in order that both half cycles of the signal will be effective. In a similar way to tube voltage bias the actual bias current for transistors must be set at a value which allows equal changes in input current for equal positive and negative swings of the signal - that is, for Class A amplification and minimum distortion. The actual bias current will depend largely on whether small or large signals are to be amplified.

Transistor bias circuits, however, are generally more complicated than valve bias circuits for two main reasons:

(i) Transistors have a leakage current component which is highly temperature sensitive and changes in ambient and operating temperature will seriously alter the operating point unless the bias circuit is designed to counteract this. Temperature rise also affects other characteristics but to a lesser extent.

(ii) In producing transistors at reasonable cost, present production techniques allow considerable variation in characteristics between transistors of the same nominal classification. The published data is therefore an average rating; actual samples may have characteristics which are better or inferior than average by a specified amount. Tubes vary in this way also but to a much smaller extent. The difference between maximum and minimum characteristics is called the production "spread".

Practical transistor circuits therefore are generally stabilised to maintain the working point near the desired value in spite of reasonable temperature changes and possible changes of transistor. It is important for circuits which may use transistors with either maximum or minimum characteristics, to operate without any instability (commercially mass produced equipment for example).

Fortunately, stabilised bias circuits generally deal with both problems together. Because of higher leakage current values and high gain, common emitter circuits are most in need of stabilisation.

5.2 Series Bias. Fig. 20 showed also that in common emitter circuits, both collector and base are of the same polarity. This suggests the use of one battery instead of two and the basic circuit (unstabilised) becomes as shown in Fig. 23; base bias is current supplied from the collector battery by a series resistor R_b, the value of which is chosen to give the desired bias current.

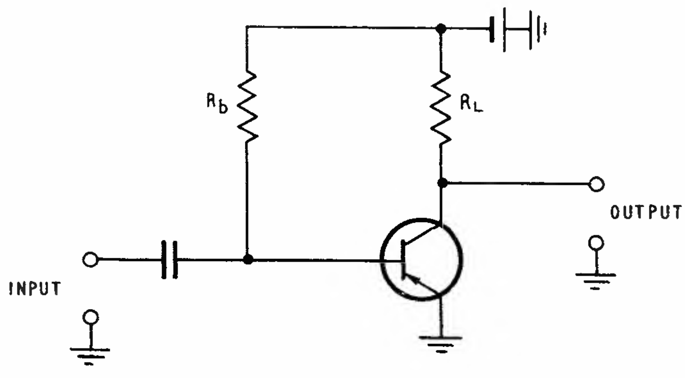


FIG. 23. SERIES BIAS.

The circuit as in Fig. 23 is inherently unstable. As well as a shift of operating point with temperature changes, a condition known as "thermal runaway" can occur especially if the D.C. collector voltage is fairly high. Any increase in junction temperature increases the leakage current I_{co}'. When this causes sufficient increase in collector power dissipation to further increase junction temperature and I_{co}', the cummulative effect can overheat and destroy the transistor in a short time.

For these reasons series bias is not often used.

5.3 Collector bias. Some stabilisation is provided when the series resistor R_b is taken from the collector instead of the battery as in Fig. 24a. The bias current is determined by the average collector voltage and the value of R_b, The collector voltage is the battery voltage minus the drop in R_L. The tendency for I_{co}' to increase is partly offset, as any slight increase raises the voltage drop across R_L; the slightly lowered collector voltage applied to R_b reduces the bias current which in turn reduces collector current, thus tending to stabilise I_C against changes in its component I_{co}'. Collector bias would give no stabilisation if the output were transformer coupled because of the low D.C. resistance of the primary winding.

The effectiveness of collector bias in stabilising the circuit depends on how high an ambient temperature is to be allowed for and the relative values of battery voltage, collector voltage, R_L and β. If sufficient supply voltage is available to allow half of it to be dropped across R_L with no signal, then any change in operating temperature can only decrease the heat dissipated by I_C in the junction since this is at maximum only when the collector impedance equals the load impedance. This application of collector bias effectively stabilises the circuit and is sometimes called the 'half supply voltage principle'.

A disadvantage of collector bias is the reduction of gain because the negative feedback via R_b applies to the A.C. signal as well as the average collector D.C. voltage. This can be overcome by dividing R_b into two equal resistors, and using a bypass capacitor as in Fig. 24b.

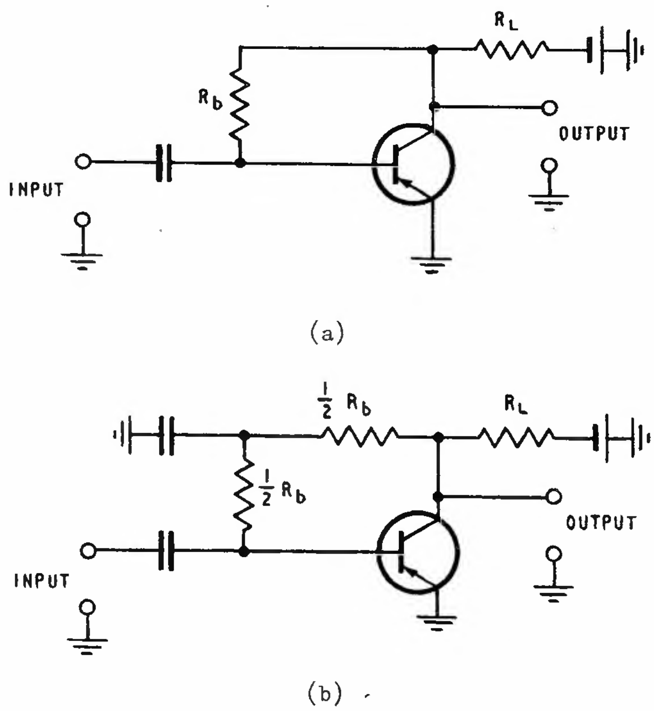
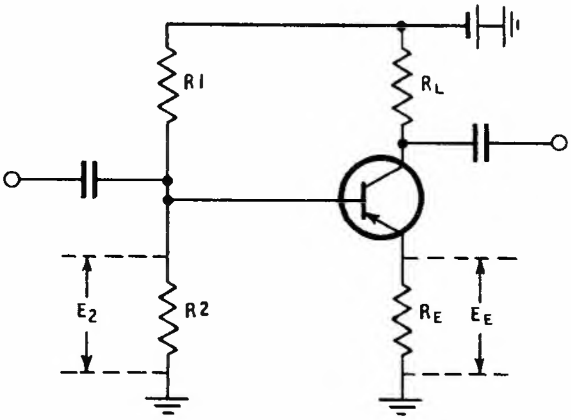


FIG. 24. COLLECTOR BIAS.

5.4 One important factor which induces instability in the simple circuits of Figs. 23 and 24 is that the whole of the collector-to-base leakage current finds its way to earth via the base-emitter junction where, being in the same direction as the bias current, it gives rise to a collector current of its own by normal transistor action. In other words (and as mentioned previously in paragraph 4.11), the I_{CO}' of common emitter circuits is much higher than I_{CO} of common base circuits simply because I_{CO} is amplified; changes in I_{CO} are likewise amplified. When some of the collector-to-base leakage passes to earth via the base instead of the emitter, this portion is not amplified and I_{CO}' is reduced.

Combination Bias or Voltage Divider bias is arranged as shown in Fig. 25 and is the usual arrangement for common emitter circuits with either resistance or transformer coupling. A voltage divider R1, R2 is bridged across the supply and the potential across R2 is applied to the base. A resistor R_E is inserted between emitter and ground which drops a voltage equal to R_E times the emitter current: $(I_C + I_B)\ R_E$. The actual bias voltage and hence the base current is therefore determined by the difference between the voltage drops across R2 and R_E; that is $(E_2 - E_E)$.



COMBINATION BIAS.

FIG. 25.

Stabilisation. If the no signal value of I_C increases slightly, E_E rises and this lowers the bias voltage $(E_2 - E_E)$. This effect regulates the tendency for I_C to change, and in a well designed circuit keeps any change within small limits. This is actually D.C. negative feedback.

Variations of base current with signal will cause A.C. negative feedback also, owing to variations in E_E. If R_E is bypassed for the A.C. signal with a capacitor, loss of gain from this feedback will be minimised. This is shown in Fig. 26 which has typical values for a low power A.F. amplifier.

Choice of values for R_E, R2 and R1 is a compromise since values which give maximum stabilisation may adversely affect input impedance and the gain. For stability considerations alone, R_E should be as high as possible and R2 as low as possible so that the feedback voltage changes across R_E can have sufficient effect on the base current; a low value of R2 also allows a greater proportion of leakage current to reach earth via the base. However, too high a value of R_E wastes energy and reduces the available collector to emitter voltage. Too low a value of R2 may severly shunt the signal; R1 would then also be low and the bleed current via R1 and R2 wasteful of energy.

The circuit of Fig. 26 is used as monitoring amplifier in some trunk switchboards. The 9V supply is derived from a voltage divider across 50V.

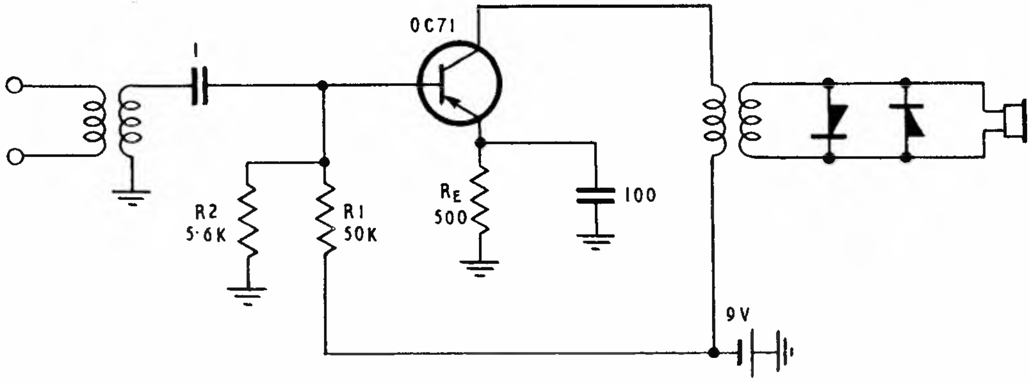


FIG. 26.

Choice of working point depends largely on the magnitude of the input signal. With small signals, bias currents of less than 10µA are common, with larger signals low and medium power transistors generally require bias currents of the order of 50µA to about 1mA. Because of the low impedance of the base-emitter junction, the difference in bias voltage to increase the bias current from 10 to 100µA is very small - often less than 0.1V as can be seen from the curves in Fig. 22. Selection of values for a circuit stabilised to a specified working point is therefore quite critical and requires more lengthy calculations than for tube circuits. Maker's data often includes values for typical applications.

5.5 Power Amplifiers. Like their tube counterparts, transistor power amplifiers operate with higher currents than the low power stages. Medium power transistors can safely carry collector currents of 50 - 100mA while some higher power types have collector currents of from 1-3A for continuous operation. (Some high power pulse circuits can handle collector currents of hundreds of amperes for short periods of a few microseconds.)

Fig. 27 shows two medium power transistors in push-pull as used in some hearing aid telephones. This amplifier gives gain of up to 27db at 1kc/s although a protection network and volume control on the input reduce usable gain to about 20db. The 10k resistor gives negative feedback to reduce distortion.

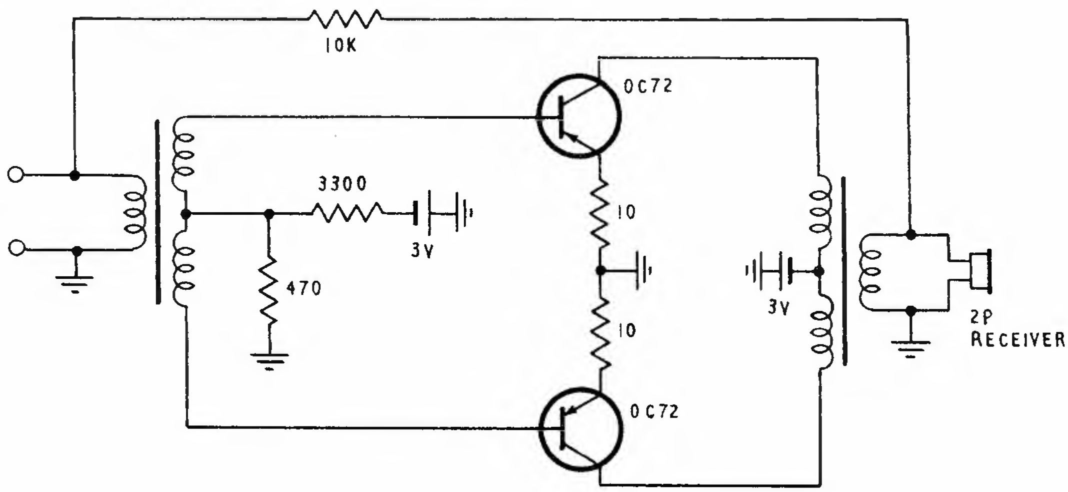


FIG. 27.

Fig. 28a shows the circuit of a typical single ended power stage capable of an output of just over 2W. The no-signal collector current is about 1A. Note the low resistance values compared to Figs. 26 and 27 and also the large capacitors needed to bypass these resistors effectively. Note also that the bias current is fed via the secondary of the input transformer because with direct feed to the base, R2 would shunt out most of the signal.

Correct bias current is obtained by adjusting R1 which is then fixed to establish working point.

Very accurate stabilisation is possible if resistor R2 is made up of two parallel elements (Fig. 28b) one of which is a suitable thermistor mounted to operate at the temperature of the transistor itself. A rise in temperature then lowers the value of R2 and consequently the bias current. Thermistors are dealt with in Section 8.

Because of the fairly high currents of up to 3A or more, operation from primary cells is not economical and circuits of this type generally operate from secondary batteries. Fig. 28a is a typical output stage as used in car radios.

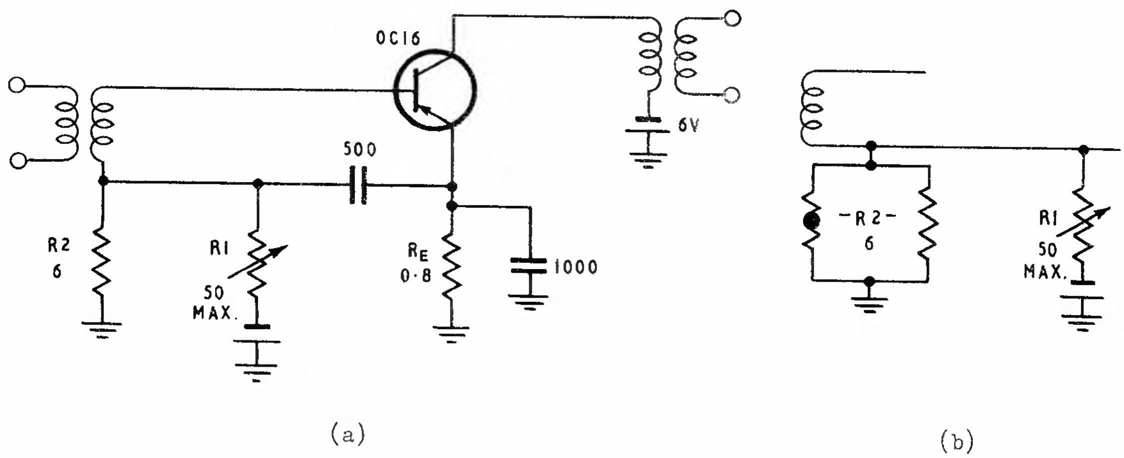


FIG. 28.

5.7 Oscillators using transistors may be made by adapting most of the popular valve oscillator circuits. Fig. 29 shows a simple 1kc/s oscillator circuit which includes an amplifier stage to increase the output power and to isolate the oscillator itself from load variations which would alter the frequency.

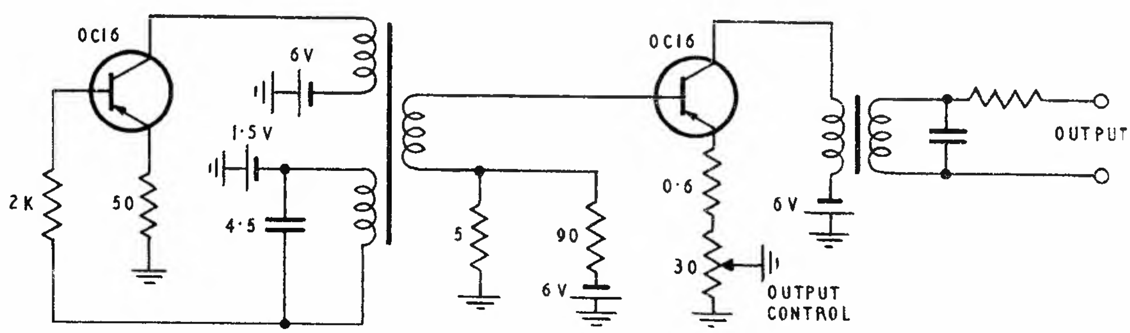


FIG. 29.

5.8 Switching Circuits. The term 'switching' applied to electronics covers a very wide field. For example, operation of counting or similar recording devices in response to very small input powers (D.C. up to high frequency A.C.) is a very common requirement in automatic machine control and processing, electronic computers and decade and binary counters. Transistors have virtually superseded valves in this field because of their greater reliability and compactness.

A dial speed checking circuit used in some crossbar exchanges includes a binary counter with successive stages of bistable ("flip-flop") circuits. The elements of one stage are shown in Fig. 30. During the receipt of 10 dialled pulses, the seven stage counter actually counts the number of 100 c/s pulses derived from the mains supply. (Binary notation is counting in twos and bistable circuits are those which remain in either one of two states until altered to the other state by an external signal.)

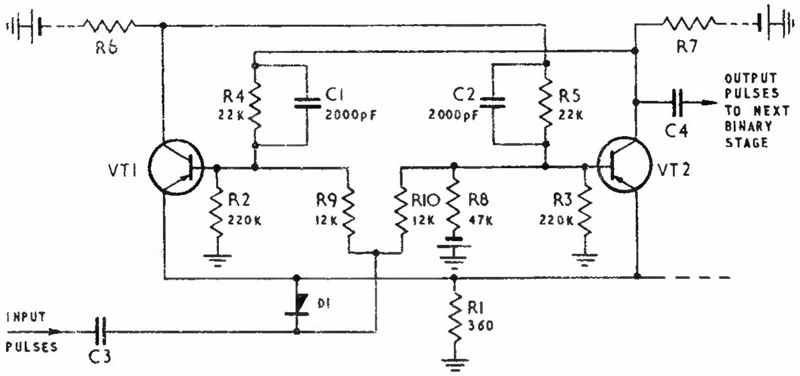


FIG. 30.

In the normal condition VT2 has negative base bias and is conducting while VT1 is cut off by a positive base-to-emitter potential. Both emitters are kept negative with respect to earth by the P.D. across R1 (which carries the emitter currents of 7 stages). The base of VT1 is positive with respect to the emitter, being connected to earth via R2. This positive bias is greater at this stage than the opposing negative potential applied via R4 from the collector of VT2; the collector-to-emitter voltage of VT2 is low, the greater part of the collector supply voltage being dropped across R7. As VT1 is not conducting there is negligible voltage drop across R6, and the potential fed via R5 is great enough to keep the VT2 base negative with respect to the emitter (which is also negative to earth because of R1).

A positive going pulse of short duration is applied to both bases via C3. This does not affect the collector current of VT1 which is already cut off, but reduces the collector current of VT2. This reduces the drop across R7 and therefore applies a higher negative potential to the base of VT1 via R4, which at the end of the signal pulse is enough to allow collector current in VT1 and R6. The drop in R6 reduces the negative potential applied to VT2 base via R5 - further reducing collector current in VT2 and R7 resulting in a further increase in negative bias for VT1 via R4. This regenerative action continues until VT1 is fully conducting and VT2 is cut off. This stable state is then maintained until another positive signal pulse restarts the regenerative action to restore the original state with VT2 conducting; a pulse is then fed to the next stage. With this "flip-flop" action there is one output pulse for every two input pulses.

The diode D1 allows C3 to assume the correct state of charge between pulses. Negative potential applied via R8 is only to ensure that VT2 is first to conduct when the circuit is switched on. The diode shunts this potential from the base of VT1. The capacitors C1 and C2 improve the switching time by bypassing the high frequency components of the rapidly changing voltages.

6. USING TRANSISTORS.

6.1 Compared to electron tubes, transistors have a number of advantages and disadvantages. When using transistors the differences must be kept in mind even when one is very familiar with wiring and testing valve circuits. The advantages of transistors are -

- Small size,
- Low operating voltages,
- No heaters,
- Small energy requirements,
- Robust,
- Long reliable service life - providing circuit design and handling precautions are observed.

The disadvantages are -

- Very temperature sensitive,
- Susceptible to electrical overloads even of very short duration,
- Internal feedback.

As we have seen, the drift of characteristics with changes of junction temperature complicates circuit design as stabilisation not usual with tube circuits is generally necessary for transistors.

Electrical overloads result in local overheating which can destroy or impair the performance. Care in design and servicing are especially important as damaging overloads can arise from hitherto disregarded sources.

Voltage surges and other damaging transients may be set up by steep signal wave forms. switching of operating potentials, inductive "kicks", etc.

6.2 Absolute Maximum Ratings are specified by the makers primarily to limit junction temperature which in most cases should not exceed about 85° C. for germanium and 150° for silicon. Preferably junction temperatures should be a good deal less than these figures as it has been found that deterioration of transistors and diodes, normally an extremely gradual process, is much accelerated at the upper temperature limits. Deterioration of transistors becomes evident usually as reduced gain and higher leakage current.

Typical Ratings for a medium gain, P-N-P audio frequency transistor (OC71) are listed below.

Absolute Maximum Ratings:

Collector -

Voltage (C - E)
- Peak - max. 30V.
- Average - max. 30V.

Current
- Average - max. 10mA
- Peak - max. 50mA

Dissipation in free air
- Ambient T 25° C. - 125mW (77° F.)
- " T 50° C. - 50mW (122° F.)
- " T 65° C. - 25mW (149° F.)

Emitter -

Current
- Average - max. 12mA
- Peak - max. 55mA

Base -

Current
- Average - max. 2mA
- Peak - max. 5mA

Thermal Data:

Junction Temperature (continuous operation)	- max. 75° C.
Junction Temperature (intermittent operation)	- max. 90° C.
Junction Temperature rise in free air	- 0.4° C/mW.
Storage Temperature	- -55 to +75° C.

When inductive loads are used, as in transformer or impedance coupled stages, the usual safeguard against high induced e.m.fs. is to limit the collector supply battery voltage to no more than half the specified maximum. For example, a transistor having a specified maximum collector voltage of 10V would commonly be used with batteries of up to 9V with resistive loads and with 4.5V supply for inductive loads.

6.3 Wiring up Precautions. Since their reliability is of the same order as most other small components - resistors, capacitors, coils, etc. (and greater than that of most electrolytic capacitors), transistors are generally soldered into the circuit directly. Miniature sockets may be used on some occasions but soldered connections or "printed" circuitry is preferred.

When soldering great care must be taken not to allow overheating of the transistor. Soldering techniques are not difficult but the following precautions must be observed:-

- Keep the soldering bit and body of the iron well away from the case of the transistor or any other transistor or crystal diode near by.

- Grip the pigtail tightly with a pair of pliers between the end being soldered and the transistor itself. The greater mass of the pliers acts as a heat shunt and prevents excessive heat being conducted up the lead. See Fig. 31.

- Hold the pliers in place for a few seconds after the soldering bit is removed and the joint is cooling.

- Work quickly and avoid prolonged or excessive heating.

- When doing a lot of soldering make sure that the pliers do not become hot and thus less effective as a heat shunt. Do not put them down close to the soldering iron.

- Keep the pigtails as long as practicable.

- When bending pigtails grip them with the pliers and avoid bending them at the point of entry into the transistor as this could possibly damage the hermetic seal or disturb the internal mounting.

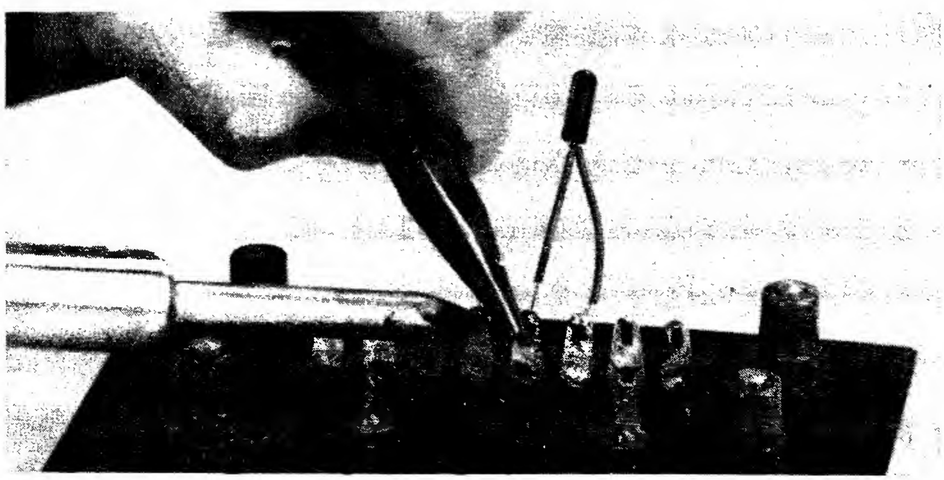


FIG. 31.

6.4 Heat Sinks are provided for some medium power and all high power transistors. These are simply a body of metal to absorb and radiate heat generated in the transistor. Their use allows higher collector dissipations to be used while keeping junction temperature within the desired limits.

The usual forms of heat sink are either the metal chassis of the equipment, or blocks of metal with holes into which the transistors fit snugly. When the chassis is the heat sink for power transistors the metal case is bolted firmly to it so that a good thermal contact is obtained either direct or via mica insulating washers (mica is a fairly good conductor of heat). Sheet metal clips can be obtained for medium power transistors; these are shaped to fit snugly over the case and have a fin extending about $\frac{3}{4}$ inch to one side. This may be bolted to the chassis.

When mounting transistors so that the chassis serves as a heat sink make sure it is clean and free from paint or varnish at the point of attachment. The bolted connection should be tight and shakeproof washers are recommended.

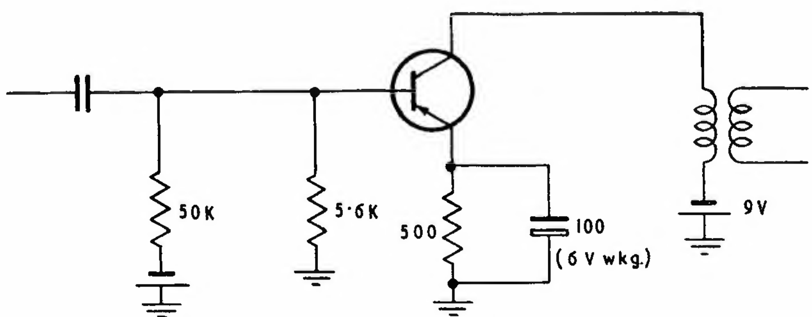
6.5 Testing and Servicing Precautions. Considerably greater care is needed when locating faults in transistor circuits than in valve circuits. Although voltages are low, accidental short circuits must be avoided.

Remember that the base-emitter resistance is low, yet the base current is frequently less than 100μA. An accidental short circuit of any negative potential to the base can increase the base and collector current many times (positive potential for N-P-N).

Short circuits or earths in transformer coupled circuits may result in damaging induced e.m.fs. when the short circuits are removed.

Remember that the high value electrolytic capacitors used for bypassing have a low peak voltage; any large increase in current through the resistor being bypassed may raise the voltage and break down the capacitor. If an emitter resistance bypass capacitor goes short circuit the base bias current and collector current become excessive.

For example, consider the effect of clumsy probing in the circuit of Fig. 32.



What could happen if -

(i) the collector and base leads where short circuited?

(ii) the emitter were shorted to earth?

(iii) the 50 k resistor were shorted out?

FIG. 32.

Never disconnect or remake connections, or extract transistors from sockets with the supply switched on.

To avoid unsoldering it is a good plan to calculate current values by the voltage drop across resistors of known value (applying Ohm's Law). Use a sensitive voltmeter which will not appreciably alter the circuit conditions when placed in parallel with resistor. (at least 10,000 ohms per volt is advisable).

When using ohmmeters (these have an internal battery) check the polarity and maximum current with another meter first. Quite often the ohmmeter section of multimeters gives lead polarities opposite to that indicated for voltage and current measurements. On the low ohms scales currents of 10 and 100mA are common and such currents can be excessive in many transistors.

When working on a circuit having earthed components it is advisable to use a soldering iron having an earthed body. A soldering iron with only very slight leakage from the element to an unearthed body could cause damaging currents in some transistor circuits.

Unlike electron tubes, transistors do not become open circuit internally with the supply switched off but present non-linear resistance paths between terminals which can give misleading measurements when other components are being tested with the transistor in circuit. Should it become necessary to disconnect one or more leads of the transistor or another component sharing a tag with the transistor - don't forget the soldering precautions.

Never replace a faulty transistor with a new one without first checking the associated circuit also. As they are very reliable in themselves, it is very likely the transistor failed because of a fault in another component.

When a transistor test set is not available, doubtful transistors (and new transistors) may be tested quite well using the experimental hook up of Fig. 20 on page 16. If two meters are not available a good indication can be obtained by using one meter as shown in Fig. 33.

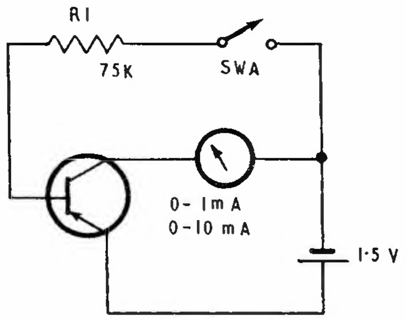


FIG. 33.

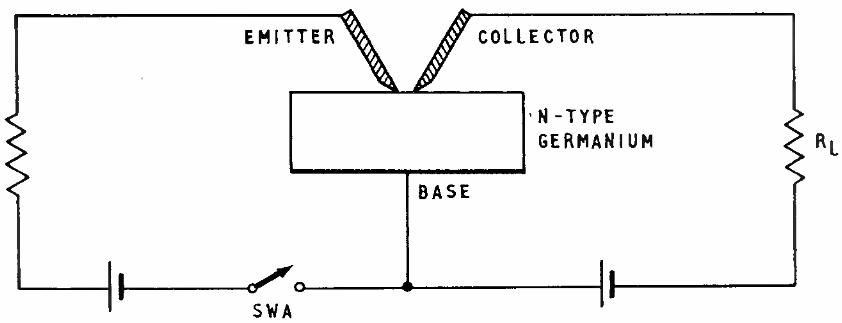
With switch SWA open, the I_{CO}' should be within the range specified by the maker or from about 100 to 300μA. When the switch is closed, base current will rise from 0 to about 20μA $\left(\frac{1.5 \times 10^6}{75,000}\right)$. The rise in collector current indicated on the meter divided by 20μA will be the approximate current gain β. For example, a rise from 0.2mA to 1mA means a β of $\frac{1000 - 200}{20} = 40$. Fig. 33 shows values suitable for typical low power transistors. R1 may be any value between 20kΩ and 100kΩ as long as its resistance is known with reasonable accuracy.

Medium power and power transistors require greater currents and suitable values for the test circuit may be readily calculated from the maker's data. Testing should not be prolonged unless these transistors are firmly secured to some form of heat sink.

7. OTHER TYPES OF TRANSISTORS.

7.1 The Point Contact Transistor. Point contact transistors consist of a base material of N-type or P-type germanium with sharply pointed metallic leads pressing on the base slab to form the emitter and collector. The two points are only a few mils apart.

Fig. 34 represents a point contact transistor with N-type base material which is the most commonly used. As far as the polarity of external voltages is concerned, this corresponds to the P-N-P junction transistors. P-type base point contact transistors are connected as for N-P-N junction transistors.



POINT CONTACT TRANSISTOR.

FIG. 34.

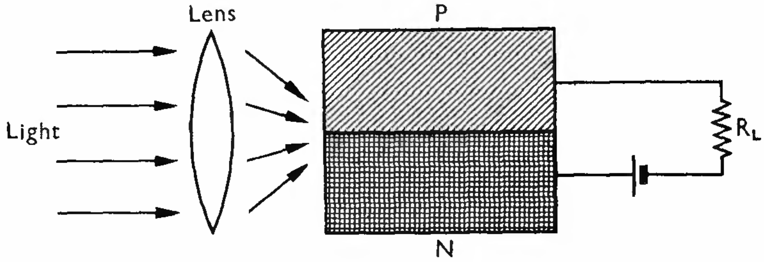
When connected in a common base circuit as in Fig. 34, collector current does not flow (except for leakage current) until the emitter-base circuit is completed. Then however, collector current rises to a value from 2 to 4 times greater than the emitter current. Point contact transistors therefore have current gain alpha (α) greater than 1. Input impedance is low and output impedance is fairly high which allows considerable voltage gain to be achieved.

A number of theories have been advanced to explain why the emitter current changes can produce and control greater collector current changes. It is known that the sharp points of emitter and collector give an intense electric field in a small area. It is thought that this field creates holes near the emitter by stripping valence electrons from their covalent bonds. Most of these pass to the collector to recombine with electrons and at the same time promote an additional and proportional electron flow from collector to base.

After assembly, point contact transistors are given a forming process involving the passage of a high current pulse. The point contact wires are alloys of copper and other metals and one theory suggests that during the forming process, the two metals fuse into the germanium differently to give an N region near the point and a P region farther away, creating the effect of a transistor within a transistor.

Point contact transistors are generally confined to common base circuits as the other arrangements are apt to become unstable. This is because internal feedback is increased with external resistance in the base circuit.

7.2 A Photo Diode is essentially a junction or point contact diode arranged so that light falling on it releases carriers to allow conduction in the otherwise non-conducting direction. Fig. 35 shows the principle of a junction photo diode. In darkness, only the leakage current (called dark current) flows in the load. When light falls on the junction, a current approximately proportional to the light intensity flows in the load. A lens is often used to focus the light.



PRINCIPLE OF JUNCTION PHOTO-DIODE.

FIG. 35.

7.3 A Photo-transistor is a junction transistor arranged so that light falls on the light-sensitive base region. The advantage over the photo-diode or earlier photo cell is that amplification increases the output. In practice, photo-transistors can be connected to operate a relay directly without an intermediate amplifying stage. Fig. 36 shows such a circuit.

With the base connection left open circuit there is a slight voltage between base and emitter owing to the leakage current. Light generates a bias current which is amplified in the collector circuit to operate the relay.

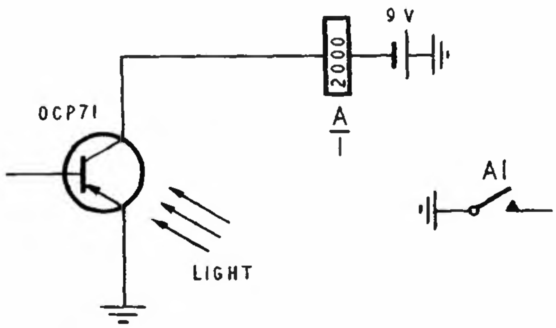


PHOTO-TRANSISTOR - TYPICAL CIRCUIT.

FIG. 36.

7.4 The high frequency performance of transistors is limited by several factors. The main one is the time it takes for a hole or electron to travel through the base. This is called the base transit time.

7.5 The Drift Transistor accelerates the carriers through the base by establishing an internal electric field to assist their passage. This is done by varying the distribution of impurity atoms in the base region during manufacture to give high conductivity near the emitter and low conductivity near the collector. With this non-uniform conductivity the electron density (in N type base for example) is greatest near the emitter. The electrons tend to drift out of the high conductivity region but in so doing produce a positive charge on the atoms from which the electrons left.

The positive charge of the drift field tends to keep the remaining electrons near the emitter side of the base. The holes injected by the emitter are accelerated toward the collector by the drift field, reducing transit time in the base to about a quarter of that in conventional alloyed transistors. Also, the high conductivity near the emitter reduces the input resistance and the low conductivity near the collector reduces the collector capacitance; these two features also improve the high frequency performance. Drift transistors are capable of operating at frequencies up to about 300 Mc/s.

7.6 The Tetrode Transistor has an additional lead attached to the base region making four leads in all - hence the name tetrode. A bias voltage is connected between the two base leads, and as shown in Fig. 37, this creates an electric field of sufficient strength to restrict the carriers to a narrow part of the base region. This lowers the base resistance and the emitter and collector capacitances thus greatly improving the high frequency performance. Power handling capabilities are reduced but this is not generally important at radio frequencies; gain is also reduced.

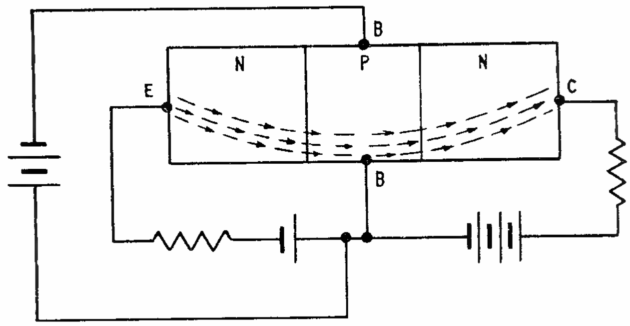


FIG. 37. TETRODE TRANSISTOR.

7.7 Tunnel Diodes. A new semiconductor phenomena was discovered in Japan in 1958. From the discovery a device called the tunnel diode has been developed. The main feature of tunnel diodes is a negative resistance characteristic which can be made use of at super-high frequencies of up to 10,000 Mc/s and probably higher.

These diodes consist of P and N regions having high impurity content and a very abrupt change from P to N. When a conducting direction voltage is gradually raised, the forward current first increases with increasing voltage, and then at a potential of a few hundred millivolts decreases before finally increasing again as in an ordinary conducting diode. (Fig. 38.)

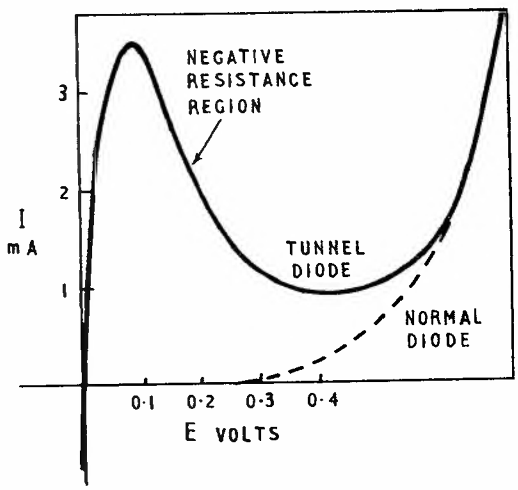


FIG. 38.

When biassed to the negative resistance region the device can be used in oscillators and amplifiers, although separating the input and output of a two terminal amplifier presents some difficulties. After further development, it may supersede more conventional transistors in many applications particularly at high frequencies.

The name "tunnel" is derived from the theory of operation which cannot be explained by the theory for junction diodes and transistors outlined in Sections 3 and 4 and is beyond the scope of this paper. (See para. 9.4 however.

Simply explained, current carriers in any conducting medium can travel either in the guise of waves or particles; in tunnel diodes the majority carriers are believed to "tunnel" through the depletion layer as waves even when as particles they have insufficient energy to surmount its potential barrier. In transistors, the base transit time of minority carriers limits their high frequency performance, but since tunnel diodes use the majority carriers at the operating point, this difficulty is avoided entirely.

8. OTHER SEMICONDUCTOR DEVICES.

8.1 Negative Temperature Co-efficient Resistors. "Thermistors" or "N.T.C. Resistors" are thermally sensitive resistors whose temperature co-efficient is negative and many times greater than that of metals at room temperature. A typical thermistor may have a co-efficient of −4 per cent. per degree centigrade at room temperature whereas that of copper is only +0.39 per cent. at that temperature.

Thermistors may be divided into two main groups; directly heated and indirectly heated. The directly heated types are simply the N.T.C. element with two leads. The indirectly heated types have a metallic heater surrounding the element. Separate leads are provided for the heater and element which allows separate controlling and controlled circuits. Thermistors are non-reactive and non-polarised so are suitable for use in either A.C. or D.C. circuits.

The resistance material consists of metal oxide compounds prepared by special processes. It is formed into small bead type elements, rods, blocks or tubes and sealed for protection in glass or metal envelopes to suit a wide variety of applications.

Thermistors are available covering a very wide range, from cold values of 0.5MΩ to a few hundred ohms, falling to a range of about 1000Ω to fractions of an ohm when heated. Fig. 39 shows typical thermistor curves (for one particular maker's "type A" thermistors which consist of a directly heated bead in an evacuated glass bulb less than one inch in length).

Thermistors are widely used in industry for temperature measurement and control, suppression of current surges and many other applications. In Departmental equipment they are used for surge suppression to prevent tinkling of bells in duplex telephones and false operation of shutters in some C.B. P.B.Xs. Temperature stabilisation of transistor amplifiers is another important application described in Section 5 of this paper.

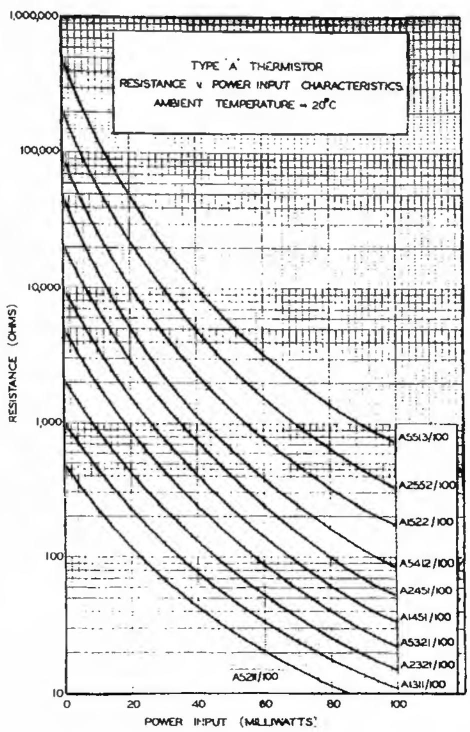


FIG. 39. TYPICAL THERMISTOR CHARACTERISTICS.

8.2 Voltage Dependent Resistors, Non-Linear Resistors or "Varistors" are another semiconductor product used mainly for the suppression of voltage surges. The characteristic of these resistors is a sharp drop in resistance as the applied voltage rises.

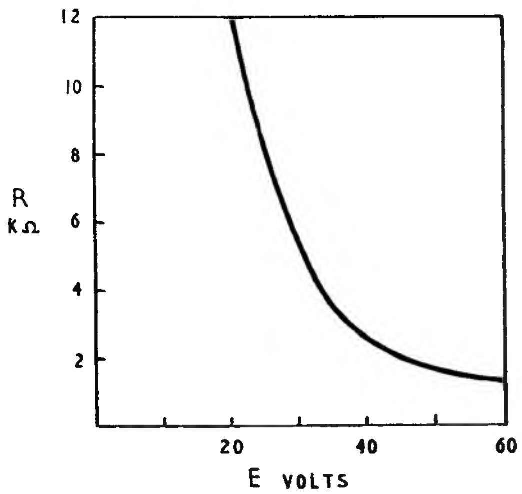


FIG. 40.

VARISTOR, TYPICAL CHARACTERISTIC CURVE.

Varistors are made covering a wide range of voltage and resistance values. Fig. 40 shows a typical curve for a varistor as used to suppress inductive voltages across some magnet coils in crossbar exchanges; when the circuit to the coil is opened, an effective spark quench is provided as the resistor becomes a low resistance non-inductive shunt across the coil. At normal working voltages the shunt resistance is very high.

Varistors are composed of silicon carbide and a ceramic bonding material, the voltage dependency being caused by the contact between the carbide crystals. They are made in the form of discs from ½ to 1½ inches in diameter and in rods less than 1 inch in length. They are not very susceptible to contamination from water vapour or gases and protective casings are not used except for severe conditions when a lacquer coating is sufficient protection.

9. FUTURE TRENDS.

9.1 New Applications. Transistors are more versatile than valves and are being used in ways not practicable with valves. Converters of D.C. to A.C. and D.C. to D.C. have been produced and as development of higher power transistors proceeds these may have many Departmental applications. One likely use is the provision of 130V D.C. supply from a 50V exchange battery at combined Telephone and Long Line stations. Transistorised ringing generators operating from a 12V battery have already been provided at some country exchanges.

9.2 New Devices. Sections 7 and 8 make no attempt to cover all the available semiconductor devices. Development is proceeding rapidly and in technical periodicals new devices are announced almost every month. New names are continually being added to the vocabulary of electronics; Field-effect transistor, Tandem transistor, Technetron P-N-I-P transistor, Spacistor, Thyristor and Tunnel diode are a few examples. It can be expected that further advances will bring new devices into prominence and perhaps reduce the importance of some now in use.

Germanium has been the most popular semiconductor material as its purification and processing presented fewer problems than those of silicon. These difficulties have been largely overcome and, because silicon has advantages in many applications, it is being used to a greater extent.

9.3 Miniaturization. The advent of the transistor has made possible true miniaturization of equipment (valves require airspace to dissipate their heat). Resistors, capacitors, transformers, etc. have been miniaturized to take full advantage of the possibilities for compact equipment. Recent manufacturing techniques overseas have introduced a new concept called micro-miniaturization where a 10 to 15 times further reduction in size is being achieved mainly for low power high frequency equipment. With very compact miniature valve equipment a component 'density' of 8,000 per cubic foot was about the limit (1950). Some recent experimental circuits are so small that the equivalent component density is from 5 to 10 million per cubic foot (1960)!

9.4 Difficulties in Explaining Basic Concepts. Convincing explanations of the operation of electronic devices has always presented a problem. The diagrams of atomic 'structure' found useful in the study of chemical combination (such as Figs. 1 to 5 of this paper) have so far been reasonably adequate as a starting point. The Science of Physics has shown for some time, however, that the concept of the atom as a 'mechanism' with component 'particles' is not valid for all circumstances. The recently developed Tunnel diode has highlighted this problem since it seems that no visual model of an arrangement of particles can be conceived to account for its behaviour. The following extract from a periodical (Wireless World - February, 1960) illustrates this:-

"Using the picture of atomic particles as waves of probability, tunnelling may be looked upon as due to the fact that waves of a charged particle can penetrate partially a potential barrier even when the particle does not have enough energy to surmount the barrier. Now a wave on the other side of the barrier represents a finite probability of finding a particle on the other side of the barrier. If and when this probability is realised, the particle is said to have tunnelled through the barrier ......"

We see from this that with words the problem remains, as words attempt to suggest pictures that are too abstract to be visualised. The principal tool in exploring sub-atomic phenomena is mathematics and this does not translate readily into words and pictures, being mainly an abstract form of expression.

Strictly speaking, therefore, the 'microcosm' (the world of protons, electrons, etc.) does not allow accurate description using visual models or diagrams or even words. However, several distinguished scientists have endeavoured to express these difficult ideas in language comprehensible to others. The following paragraphs were prepared from writings on this subject by Dr. R.C. Johnson, M.A., Ph.D., D.Sc., Master of Queens College, University of Melbourne; quotations are used with the kind permission of the author.

During the early part of this century, experiments into the nature of light yielded very perplexing results. Following this, "...numerous carefully conducted experiments showed what no one had hitherto suspected, that even our authentic corpuscles (electrons, etc.) sometimes behave like wave groups!" Now, as ideas of particles and waves are based on the assumption that distance and time as we think of them are just as applicable in the microcosm, the problem then became "...a question of whether the fundamental assumptions with which we approached this field...are applicable at all."

"About 1925, this highly unsatisfactory situation in atomic physics was subjected to careful examination by several brilliant mathematical physicists. The attempt to provide a model of any sort was definitely ruled out by all these investigators...; distance and time seem to be indeterminate...and the terms electron, proton, light quantum are really no more than x, y, and z - symbols for unknowns."

The present conclusion therefore is that with the probable exception of mathematics, "...none of our mental concepts (colour, position, shape, sound, resistance to touch, etc.) apply, and even Space and Time which seem to dominate our familiar world are quite elusive in the microcosm. They are concepts which have proved very helpful in the understanding of the familiar world, and which we ourselves have introduced into it - but only because we found ourselves built on a very large scale compared with atoms and molecules."

However, this need not bother us from a practical point of view. The mysteries surrounding the nature of matter need in no way limit our ability to apply the well demonstrated laws governing the behaviour of conductors, insulators, vacuum tubes, semiconductor devices, coils, capacitors, magnets, etc. We should realise, however, that having used our pictures of sub-atomic 'particles' as a starting point for an understanding of electrical fundamentals, the ideas and laws developed become self-supporting; the pictures, like all visual aids, have served their purpose and need not be regarded as a true representation of the foundations of the visible world.

10. TEST QUESTIONS.

1. List the main characteristics of semiconductors which distinguish them from conductors and insulators.

2. (a) Explain the term 'shells' as applied to imaginary models of atomic structure.
   (b) With reference to these shells, describe how some elements possess a stable atomic state.

3. Under what atomic conditions do substances have a crystalline structure?

4. Describe the motion of current carriers under the influence of an applied e.m.f. in -
   (a) Pure germanium crystal at room temperature.
   (b) N-type germanium crystal.
   (c) P-type germanium crystal.

5. What are minority current carriers?

6. (a) What is the effect of an increase in temperature on semiconductor crystals?
   (b) How do you account for this?

7. Briefly describe the formation of the depletion layer at a P-N junction.

8. Why does the reverse current in a crystal diode show a marked increase with temperature rise.

9. What is the main application of Zener diodes?

10. By means of a simple diagram, show how evidence of "transistor action" can be obtained using a common base circuit.

11. Draw the basic circuit of a common emitter, transformer coupled transistor amplifier and briefly describe its operation.

12. Why is the common base amplifier unsuitable for resistance coupling?

13. Why are large value capacitors used for coupling and bypassing in transistor circuits.

14. (a) With the aid of a diagram, describe the simplest method of obtaining base bias in a common emitter amplifier.
    (b) Explain why this method finds very limited practical use.

15. Explain how collector bias tends to overcome the shortcomings of the circuit of Ques. 14a.

16. With the aid of a diagram explain the action of the bias circuit most generally used for common emitter amplifiers.

17. A "thermistor" is sometimes incorporated in the bias circuit of a transistor amplifier. Explain the reason for this.

18. What is the principal reason for specifying "absolute maximum ratings" for transistors.

19. List the main precautions to be observed during soldering of transistors into circuits.

20. Show how a transistor may be tested simply when more elaborate test gear is not available.

21. What is the most significant difference between the characteristics of point-contact and junction transistors when both are tested in common base circuits?

22. Explain the principle of - (a) a junction photo diode.
    (b) a simple photo transistor circuit capable of operating a relay.

23. (a) What are the two main types of "thermistor"?
    (b) Name typical applications of "thermistors".

24. (a) What is the chief characteristic of "varistors"?
    (b) Explain the action of a varistor used as a spark quench.

END OF PAPER.

USE OF FOUR FIGURE LOGARITHM TABLES.

The logarithm of a number consists of an integral part called "the characteristic" or index and a decimal part called "the mantissa".

Mantissa. Referring to the tables on page 2, four numbers forming the mantissa are shown in rows beside each of the numbers from 10 to 99.

Characteristic. The characteristic has to be determined from the number in each case. The characteristic of any number greater than unity is positive and is less by one than the number of figures to the left of the decimal point. The characteristic of a number less than unity is negative and is greater by one than the number of zeros which follow the decimal point. For example:-

Characteristic of 7372 is 3	Characteristic of 737.2 is 2
Characteristic of 73.72 is 1	Characteristic of 7.372 is 0
Characteristic of 0.7372 is $\bar{1}$	Characteristic of 0.07372 is $\bar{2}$

Negative characteristics are usually designated as bar 1; bar 2, etc.

To find the logarithm of a given number.

Example 1. To find log 73.

In the column opposite the number 73 is found the mantissa 8633; the characteristic is 1.

$\therefore$ log 73 = 1.8633

Similarly log 7.3 = 0.8633; log 7300 = 3.8633

Example 2. To find log 737.

Referring to the tables, find the first two numbers at the extreme left; then passing along the horizontal line to the number in the vertical column headed by the figure 7, the number 8675 is obtained

log 737 = 2.8675

To obtain the logarithm of a number consisting of four figures use the mean difference columns at the extreme right of the page.

Example 3. To find log 737.5.

Characteristic of 737 = 2

Mantissa of log 737 = 0.8675

Mean difference for 5 = 0.0003

$\therefore$ log 737.5 = 2.8678

Similarly log 7.375 = 0.8678; log .007375 = $\bar{3}$.8678

Antilogarithms. The number corresponding to a given logarithm is found by using the table of Antilogarithms.

Example 4. To find the number whose log is 1.5958.

Antilog 595 = 0.3936

Mean difference for 8 = 7

Antilog .5958 = 0.3943

$\therefore$ The number whose log is 1.5958 is 39.43.

Multiplication. Add the logarithms of the numbers; the sum is the logarithm of the product.

Division. Subtract the logarithms of the divisor from the logarithm of the dividend; the difference is the logarithm of the quotient.

Note:- In logarithms of decimal numbers, only the characteristic is negative; the mantissa is positive. For example, in log $\bar{3}$.5958 only the $\bar{3}$, called bar 3, is negative, the remaining figures .5958 are positive.

LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

ANTI-LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9

ANTI-LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9

ANTI-LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

ANTI-LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	Differences. 1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5967	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

Squares of Numbers from 1 to 10,000, Correct to Four Significant Figures.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	1000	1020	1040	1061	1082	1102	1124	1145	1166	1188	3	5	7	9	11	13	15	17	19
11	1210	1232	1254	1277	1300	1323	1346	1369	1392	1416	3	5	7	10	12	14	17	19	21
12	1440	1464	1488	1513	1538	1563	1588	1613	1638	1664	3	5	8	10	13	15	18	20	23
13	1690	1716	1742	1769	1796	1823	1850	1877	1904	1932	3	6	9	11	14	17	19	22	25
14	1960	1988	2016	2045	2074	2103	2132	2161	2190	2220	3	6	9	12	15	18	21	24	27
15	2250	2280	2310	2341	2372	2403	2434	2465	2496	2528	4	7	10	13	16	19	22	25	28
16	2560	2592	2624	2657	2690	2723	2756	2789	2822	2856	4	7	10	14	17	20	24	27	30
17	2890	2924	2958	2993	3028	3063	3098	3133	3168	3204	4	7	11	14	18	21	25	28	32
18	3240	3276	3312	3349	3386	3423	3460	3497	3534	3572	4	8	12	15	19	23	26	30	34
19	3610	3648	3686	3725	3764	3803	3842	3881	3920	3960	4	8	12	16	20	24	28	32	36
20	4000	4040	4080	4121	4162	4203	4244	4285	4326	4368	5	9	13	17	21	25	29	33	37
21	4410	4452	4494	4537	4580	4623	4666	4709	4752	4796	5	9	13	18	22	26	31	34	39
22	4840	4884	4928	4973	5018	5063	5108	5153	5198	5244	5	9	14	18	23	27	32	36	41
23	5290	5336	5382	5429	5476	5523	5570	5617	5664	5712	5	10	15	19	24	27	33	38	43
24	5760	5808	5856	5905	5954	6003	6052	6101	6150	6200	5	10	15	20	25	30	35	40	45
25	6250	6300	6350	6401	6452	6503	6554	6605	6656	6708	6	11	16	21	26	31	36	41	46
26	6760	6812	6864	6917	6970	7023	7076	7129	7182	7236	6	11	16	22	27	32	38	43	48
27	7290	7344	7398	7453	7508	7563	7618	7673	7728	7784	6	11	17	22	28	33	39	44	50
28	7840	7896	7952	8009	8066	8123	8180	8237	8294	8352	6	12	18	23	29	35	40	46	52
29	8410	8468	8526	8585	8644	8703	8762	8821	8880	8940	6	12	18	24	30	36	42	48	54
30	9000	9060	9120	9181	9242	9303	9364	9425	9486	9548	7	13	19	25	31	37	43	49	55
31	9610	9672	9734	9797	9860	9923	9986	1005[1]	1011[1]	1018[1]	7	13	19	26	32	38	45	51	57
32	1024	1030	1037	1043	1050	1056	1063	1069	1076	1082	1	1	2	3	3	4	5	5	6
33	1089	1096	1102	1109	1116	1122	1129	1136	1142	1149	1	1	2	3	4	4	5	6	6
34	1156	1163	1170	1176	1183	1190	1197	1204	1211	1218	1	2	2	3	4	4	5	6	6
35	1225	1232	1239	1246	1253	1260	1267	1273	1282	1289	1	2	2	3	4	4	5	6	7
36	1296	1303	1310	1318	1325	1332	1340	1347	1354	1362	1	2	2	3	4	5	5	6	7
37	1369	1376	1384	1391	1399	1406	1414	1421	1429	1436	1	2	2	3	4	5	5	6	7
38	1444	1452	1459	1467	1475	1482	1490	1498	1505	1513	1	2	2	3	4	5	6	6	7
39	1521	1529	1537	1544	1552	1560	1568	1576	1584	1592	1	2	3	3	4	5	6	6	7
40	1600	1608	1616	1624	1632	1640	1648	1656	1665	1673	1	2	3	3	4	5	6	7	7
41	1681	1689	1697	1706	1714	1722	1731	1739	1747	1756	1	2	3	3	4	5	6	7	8
42	1764	1772	1781	1789	1798	1806	1815	1823	1832	1840	1	2	3	4	4	5	6	7	8
43	1849	1858	1866	1875	1884	1892	1901	1910	1918	1927	1	2	3	4	5	5	6	7	8
44	1936	1945	1954	1962	1971	1980	1989	1998	2007	2016	1	2	3	4	5	5	6	7	8
45	2025	2034	2043	2052	2061	2070	2079	2088	2098	2107	1	2	3	4	5	6	7	7	8
46	2116	2125	2134	2144	2153	2163	2172	2181	2190	2200	1	2	3	4	5	6	7	8	9
47	2209	2218	2228	2237	2247	2256	2266	2275	2285	2294	1	2	3	4	5	6	7	8	9
48	2304	2314	2323	2333	2343	2352	2362	2372	2381	2391	1	2	3	4	5	6	7	8	9
49	2401	2411	2421	2430	2440	2450	2460	2470	2480	2490	1	2	3	4	5	6	7	8	9
50	2500	2510	2520	2530	2540	2550	2560	2570	2581	2591	1	2	3	4	5	6	7	8	9
51	2601	2611	2621	2632	2642	2652	2663	2673	2683	2694	1	2	3	4	5	6	7	8	9
52	2704	2714	2725	2735	2746	2756	2767	2777	2788	2798	1	2	3	4	5	6	8	9	10
53	2809	2820	2830	2841	2852	2862	2873	2884	2894	2905	1	2	3	4	6	7	8	9	10
54	2916	2927	2938	2948	2959	2970	2981	2992	3003	3014	1	2	3	5	6	7	8	9	10

Squares from	1 to 3 contain 1 figure.	Squares from	100 to 316 contain 5 figures.
,, ,,	4 to 9 ,, 2 figures.	,, ,,	317 to 999 ,, 6 ,,
,, ,,	10 to 31 ,, 3 ,,	,, ,,	1000 to 3162 ,, 7 ,,
,, ,,	32 to 99 ,, 4 ,,	,, ,,	3163 to 10000 ,, 8 ,,

[1] The differences for squares from 3171 to 3199 are 1, 1, 2, 3, 3, 4, 5, 5, 6.

Squares of Numbers from 1 to 10,000, Correct to Four Significant Figures.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	3025	3036	3047	3058	3069	3080	3091	3102	3114	3125	1	2	3	5	6	7	8	9	10
56	3136	3147	3158	3170	3181	3192	3204	3215	3226	3238	1	2	4	5	6	7	8	9	10
57	3249	3260	3272	3283	3295	3306	3318	3329	3341	3352	1	2	4	5	6	7	8	9	11
58	3364	3376	3387	3399	3411	3422	3434	3446	3457	3469	1	2	4	5	6	7	8	10	11
59	3481	3493	3505	3516	3528	3540	3552	3564	3576	3588	1	3	4	5	6	7	8	10	11
60	3600	3612	3624	3636	3648	3660	3672	3684	3697	3709	1	3	4	5	6	7	9	10	11
61	3721	3733	3745	3758	3770	3782	3795	3807	3819	3832	1	3	4	5	6	8	9	10	11
62	3844	3856	3869	3881	3894	3906	3919	3931	3944	3956	1	3	4	5	6	8	9	10	11
63	3969	3982	3994	4007	4020	4032	4045	4058	4070	4083	1	3	4	5	7	8	9	10	12
64	4096	4109	4122	4134	4147	4160	4173	4186	4199	4212	1	3	4	5	7	8	9	10	12
65	4225	4238	4251	4264	4277	4290	4303	4316	4330	4343	1	3	4	5	7	8	9	11	12
66	4356	4369	4382	4396	4409	4422	4436	4449	4462	4476	1	3	4	5	7	8	9	11	12
67	4489	4502	4516	4529	4543	4556	4570	4583	4597	4610	2	3	4	6	7	8	10	11	12
68	4624	4638	4651	4665	4679	4692	4706	4720	4733	4747	2	3	4	6	7	8	10	11	12
69	4761	4775	4789	4602	4816	4830	4844	4858	4872	4886	2	3	4	6	7	8	10	11	13
70	4900	4914	4928	4942	4956	4970	4984	4998	5013	5027	2	3	4	6	7	9	10	11	13
71	5041	5055	5069	5084	5098	5112	5127	5141	5155	5170	2	3	4	6	7	9	10	12	13
72	5184	5198	5213	5227	5242	5256	5271	5285	5300	5314	2	3	5	6	7	9	10	12	13
73	5329	5344	5358	5373	5388	5402	5417	5432	5446	5461	2	3	5	6	8	9	10	12	13
74	5476	5491	5506	5520	5535	5550	5565	5580	5595	5610	2	3	5	6	8	9	11	12	14
75	5625	5640	5655	5670	5685	5700	5715	5730	5746	5761	2	3	5	6	8	9	11	12	14
76	5776	5791	5806	5822	5837	5852	5868	5883	5898	5914	2	3	5	6	8	9	11	12	14
77	5929	5944	5960	5975	5991	6006	6022	6037	6053	6068	2	3	5	6	8	9	11	13	14
78	6084	6100	6115	6131	6147	6162	6178	6194	6209	6225	2	3	5	6	8	10	11	13	14
79	6241	6257	6273	6288	6304	6320	6336	6352	6368	6384	2	3	5	7	8	10	11	13	14
80	6400	6416	6432	6448	6464	6480	6496	6512	6529	6545	2	3	5	7	8	10	11	13	15
81	6561	6577	6593	6610	6626	6642	6659	6675	6691	6708	2	3	5	7	8	10	12	13	15
82	6724	6740	6757	6773	6790	6806	6823	6839	6856	6872	2	3	5	7	8	10	12	13	15
83	6889	6906	6922	6930	6956	6972	6989	7006	7022	7039	2	3	5	7	9	10	12	14	15
84	7056	7073	7090	7106	7123	7140	7157	7174	7191	7208	2	4	5	7	9	10	12	14	15
85	7225	7242	7259	7276	7293	7310	7327	7344	7362	7379	2	4	5	7	9	10	12	14	16
86	7396	7413	7430	7448	7465	7482	7500	7517	7534	7552	2	4	5	7	9	11	12	14	16
87	7569	7586	7604	7621	7639	7656	7674	7691	7709	7726	2	4	5	7	9	11	12	14	16
88	7744	7762	7779	7797	7815	7832	7850	7868	7885	7903	2	4	5	7	9	11	13	14	16
89	7921	7939	7957	7974	7992	8010	8028	8046	8064	8082	2	4	6	7	9	11	13	14	16
90	8100	8118	8136	8154	8172	8190	8208	8226	8245	8263	2	4	6	7	9	11	13	15	16
91	8281	8209	8317	8336	8354	8372	8391	8409	8427	8446	2	4	6	7	9	11	13	15	17
92	8464	8482	8501	8519	8538	8556	8575	8593	8612	8630	2	4	6	8	9	11	13	15	17
93	8649	8668	8686	8705	8724	8742	8761	8780	8798	8817	2	4	6	8	10	11	13	15	17
94	8836	8855	8874	8892	8911	8930	8949	8968	8987	9006	2	4	6	8	10	11	13	15	17
95	9025	9044	9063	9082	9101	9120	9139	9158	9178	9197	2	4	6	8	10	12	14	15	17
96	9216	9235	9254	9274	9293	9312	9332	9351	9370	9390	2	4	6	8	10	12	14	16	18
97	9409	9428	9448	9467	9487	9505	9526	9545	9565	9584	2	4	6	8	10	12	14	16	18
98	9604	9624	9643	9663	9683	9702	9722	9742	9761	9781	2	4	6	8	10	12	14	16	18
99	9801	9821	9841	9860	9880	9900	9920	9940	9960	9980	2	4	6	8	10	12	14	16	18

Squares from	1 to 3 contain 1 figure.	Squares from	100 to 316 contain 5 figures.
,, ,,	4 to 9 ,, 2 figures.	,, ,,	317 to 999 ,, 6 ,,
,, ,,	10 to 31 ,, 3 ,,	,, ,,	1000 to 3162 ,, 7 ,,
,, ,,	32 to 99 ,, 4 ,,	,, ,,	3163 to 10000 ,, 8 ,,

TABLES GIVING THE SQUARES OF NUMBERS FROM 1 TO 10,000.

(Correct to four significant figures.)

RECIPROCALS OF NUMBERS FROM 1 TO 9999.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	$\bar{9}901$	$\bar{9}804$	$\bar{9}709$	$\bar{9}615$	$\bar{9}524$	$\bar{9}434$	$\bar{9}346$	$\bar{9}259$	$\bar{9}174$	9	18	27	36	45	54	63	72	81
11	9091	9009	8929	8850	8772	8696	8621	8547	8475	8403	8	16	23	31	38	46	53	61	68
12	8333	8264	8197	8130	8065	8000	7937	7874	7813	7752	6	13	19	26	32	38	45	51	57
13	7692	7634	7576	7519	7463	7407	7353	7299	7246	7194	5	11	16	22	27	32	38	43	49
14	7143	7092	7042	6993	6944	6897	6849	6803	6757	6711	5	9	14	19	23	28	33	37	42
15	6667	6623	6579	6536	6494	6452	6410	6369	6329	6289	5	9	13	17	21	25	29	34	38
16	6250	6211	6173	6135	6098	6061	6024	5988	5952	5917	4	8	11	15	19	22	26	30	33
17	5882	5848	5814	5780	5747	5714	5682	5650	5618	5587	3	6	10	13	16	19	23	26	29
18	5556	5525	5495	5464	5435	5405	5376	5348	5319	5291	3	6	8	11	14	17	20	23	26
19	5263	5236	5208	5181	5155	5128	5102	5076	5051	5025	3	5	8	10	13	16	18	21	23
20	5000	4975	4950	4926	4902	4878	4854	4831	4808	4785	2	5	7	10	12	14	17	19	21
21	4762	4739	4717	4695	4673	4651	4630	4608	4587	4566	2	4	6	9	11	13	15	17	19
22	4545	4525	4505	4484	4464	4444	4425	4405	4386	4367	2	4	6	8	10	11	13	15	17
23	4348	4329	4310	4292	4274	4255	4237	4219	4202	4184	2	3	5	7	9	11	12	14	16
24	4167	4149	4132	4115	4098	4082	4065	4049	4032	4016	2	4	5	7	9	10	12	14	15
25	4000	3984	3968	3953	3937	3921	3906	3891	3876	3861	1	3	4	6	7	9	10	12	13
26	3846	3831	3817	3802	3788	3774	3759	3745	3731	3717	1	2	4	5	7	8	9	11	12
27	3704	3690	3676	3663	3650	3636	3623	3610	3597	3584	1	2	4	5	6	8	9	10	12
28	3571	3559	3546	3534	3521	3509	3497	3484	3472	3460	2	3	4	5	6	8	9	10	11
29	3448	3436	3425	3413	3401	3390	3378	3367	3356	3344	1	3	4	5	6	7	8	9	11
30	3333	3322	3311	3300	3289	3279	3268	3257	3247	3237	1	3	4	5	6	7	8	9	10
31	3226	3215	3205	3195	3185	3175	3165	3155	3145	3135	2	3	4	5	6	7	8	9	10
32	3125	3115	3106	3096	3086	3077	3067	3058	3049	3040	1	2	3	4	5	6	7	8	9
33	3030	3021	3012	3003	2994	2985	2976	2967	2959	2950	1	2	3	4	4	5	6	7	8
34	2941	2933	2924	2915	2907	2899	2890	2882	2874	2865	0	1	2	3	4	5	5	6	7
35	2857	2849	2841	2833	2825	2817	2809	2801	2793	2785	1	2	3	3	4	5	6	7	7
36	2778	2770	2762	2755	2747	2740	2732	2725	2717	2710	1	2	3	3	4	5	6	6	7
37	2703	2695	2688	2681	2674	2667	2660	2653	2646	2639	1	2	3	3	4	5	5	6	7
38	2632	2625	2618	2611	2604	2597	2591	2584	2577	2571	0	1	2	2	3	4	4	5	6
39	2564	2558	2551	2545	2538	2532	2525	2519	2513	2506	1	2	2	3	4	4	5	6	6
40	2500	2494	2488	2481	2475	2469	2463	2457	2451	2445	1	1	2	2	3	4	4	5	5
41	2439	2433	2427	2421	2415	2410	2404	2398	2392	2387	1	2	2	3	3	4	5	5	6
42	2381	2375	2370	2364	2358	2353	2347	2342	2336	2331	1	1	2	2	3	3	4	5	5
43	2326	2320	2315	2309	2304	2299	2294	2288	2283	2278	1	1	2	2	3	3	4	4	5
44	2273	2268	2262	2257	2252	2247	2242	2237	2232	2227	0	1	1	2	2	3	3	4	4
45	2222	2217	2212	2208	2203	2198	2193	2188	2183	2179	1	1	2	2	3	3	4	4	5
46	2174	2169	2165	2160	2155	2151	2146	2141	2137	2132	0	0	1	1	2	2	3	3	4
47	2128	2123	2119	2114	2110	2105	2101	2096	2092	2088	0	1	1	2	2	2	3	3	4
48	2083	2079	2075	2070	2066	2062	2058	2053	2049	2045	1	1	2	2	2	3	3	4	4
49	2041	2037	2033	2028	2024	2020	2016	2012	2008	2004	0	1	1	2	2	2	3	3	4
50	2000	1996	1992	1988	1984	1980	1976	1972	1969	1965	0	1	1	1	2	2	3	3	3
51	1961	1957	1953	1949	1946	1942	1938	1934	1931	1927	1	1	1	2	2	3	3	3	4
52	1923	1919	1916	1912	1908	1905	1901	1898	1894	1890	1	1	1	2	2	3	3	3	4
53	1887	1883	1880	1876	1873	1869	1866	1862	1859	1855	0	1	1	1	2	2	2	3	3
54	1852	1848	1845	1842	1838	1835	1832	1828	1825	1821	1	1	1	2	2	2	3	3	3

Reciprocals from 2 to 10 = 0· | Reciprocals from 101 to 1000 = 0·00
" " to 100 = 0·0 | " " 1001 to 9999 = 0·000

NOTE.—Numbers in difference columns to be subtracted, not added.

RECIPROCALS OF NUMBERS FROM 1 TO 9999.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	1818	1815	1812	1808	1805	1802	1799	1795	1792	1789	1	1	1	2	2	2	3	3	3
56	1786	1783	1779	1776	1773	1770	1767	1764	1761	1757	1	1	1	1	2	2	2	3	3
57	1754	1751	1748	1745	1742	1739	1736	1733	1730	1727	0	1	1	1	1	2	2	2	3
58	1724	1721	1718	1715	1712	1709	1706	1704	1701	1698	0	0	1	1	1	1	2	2	2
59	1695	1692	1689	1686	1684	1681	1678	1675	1672	1669	1	1	1	2	2	2	2	3	3
60	1667	1664	1661	1658	1656	1653	1650	1647	1645	1642	0	1	1	1	2	2	2	2	3
61	1639	1637	1634	1631	1629	1626	1623	1621	1618	1616	0	1	1	1	1	2	2	2	2
62	1613	1610	1608	1605	1603	1600	1597	1595	1592	1590	0	1	1	1	1	2	2	2	2
63	1587	1585	1582	1580	1577	1575	1572	1570	1567	1565	1	1	1	1	2	2	2	2	3
64	1563	1560	1558	1555	1553	1550	1548	1546	1543	1541	0	0	0	1	1	1	1	2	2
65	1538	1536	1534	1531	1529	1527	1524	1522	1520	1517	1	1	1	1	2	2	2	2	2
66	1515	1513	1511	1508	1506	1504	1502	1499	1497	1495	1	1	1	1	1	2	2	2	2
67	1493	1490	1488	1486	1484	1481	1479	1477	1475	1473	0	0	0	0	1	1	1	1	2
68	1471	1468	1466	1464	1462	1460	1458	1456	1453	1451	0	1	1	1	1	2	2	2	2
69	1449	1447	1445	1443	1441	1439	1437	1435	1433	1431	0	1	1	1	1	1	2	2	2
70	1428	1427	1425	1422	1420	1418	1416	1414	1412	1410	0	0	0	0	1	1	1	1	1
71	1408	1406	1404	1403	1401	1399	1397	1395	1393	1391	1	1	1	1	1	2	2	2	2
72	1389	1387	1385	1383	1381	1379	1377	1376	1374	1372	0	0	0	1	1	1	1	1	1
73	1370	1368	1366	1364	1362	1361	1359	1357	1355	1353	0	0	0	0	0	1	1	1	1
74	1351	1350	1348	1346	1344	1342	1340	1339	1337	1335	0	0	0	1	1	1	1	1	1
75	1333	1332	1330	1328	1326	1325	1323	1321	1319	1317	0	0	0	0	0	1	1	1	1
76	1316	1314	1312	1311	1309	1307	1305	1304	1302	1300	0	0	0	1	1	1	1	1	1
77	1299	1297	1295	1294	1292	1290	1289	1287	1285	1284	0	0	0	0	1	1	1	1	1
78	1282	1280	1279	1277	1276	1274	1272	1271	1269	1267	0	1	1	1	1	1	1	2	2
79	1266	1264	1263	1261	1259	1258	1256	1255	1253	1252	0	1	1	1	1	1	1	2	2
80	1250	1248	1247	1245	1244	1242	1241	1239	1238	1236	0	0	0	0	1	1	1	1	1
81	1235	1233	1232	1230	1229	1227	1225	1224	1222	1221	0	0	1	1	1	1	1	1	1
82	1220	1218	1217	1215	1214	1212	1211	1209	1208	1206	0	0	0	1	1	1	1	1	1
83	1205	1203	1202	1200	1199	1198	1196	1195	1193	1192	1	1	1	1	1	1	1	2	2
84	1190	1189	1188	1186	1185	1183	1182	1181	1179	1178	0	0	0	0	0	1	1	1	1
85	1176	1175	1174	1172	1171	1170	1168	1167	1166	1164	0	0	0	0	0	0	0	1	1
86	1163	1161	1160	1159	1157	1156	1155	1153	1152	1151	0	0	0	1	1	1	1	1	1
87	1149	1148	1147	1145	1144	1143	1142	1140	1139	1138	0	1	1	1	1	1	1	1	1
88	1136	1135	1134	1133	1131	1130	1129	1127	1126	1125	0	0	1	1	1	1	1	1	1
89	1124	1122	1121	1120	1119	1117	1116	1115	1114	1112	0	0	0	0	0	1	1	1	1
90	1111	1110	1109	1107	1106	1105	1104	1103	1101	1100	0	0	0	1	1	1	1	1	1
91	1099	1098	1096	1095	1094	1093	1092	1091	1089	1088	0	0	1	1	1	1	1	1	1
92	1087	1086	1085	1083	1082	1081	1080	1079	1078	1076	0	0	0	0	1	1	1	1	1
93	1075	1074	1073	1072	1071	1070	1068	1067	1066	1065	0	0	0	0	0	0	0	0	1
94	1064	1063	1062	1060	1059	1058	1057	1056	1055	1054	0	0	0	0	0	1	1	1	1
95	1053	1052	1050	1049	1048	1047	1046	1045	1044	1043	0	0	0	0	1	1	1	1	1
96	1042	1041	1040	1038	1037	1036	1035	1034	1033	1032	0	0	0	0	0	0	1	1	1
97	1031	1030	1029	1028	1027	1026	1025	1024	1022	1021	1	1	1	1	1	1	1	1	1
98	1020	1019	1018	1017	1016	1015	1014	1013	1012	1011	0	0	0	0	0	0	1	1	1
99	1010	1009	1008	1007	1006	1005	1004	1003	1002	1001	0	0	0	0	1	1	1	1	1

Reciprocals from 2 to 10 = 0 | Reciprocals from 101 to 1000 = 0·00
" " 11 to 100 = 0·0 | " " 1001 to 9999 = 0·000

NOTE.—Numbers in difference columns to be subtracted, not added.

RECIPROCALS OF NUMBERS FROM 1 TO 9999.

EXAMPLE. THE RECIPROCAL OF 35.5 = $\frac{1}{35.5}$ = (FROM TABLES) 0.02817.

NATURAL SINES.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Differences. 1′	2′	3′	4′	5′
0°	0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
1	0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
2	0349	0366	0384	0401	0419	0436	0454	0471	0488	0506	3	6	9	12	15
3	0523	0541	0558	0576	0593	0610	0628	0645	0663	0680	3	6	9	12	15
4	0698	0715	0732	0750	0767	0785	0802	0819	0837	0854	3	6	9	12	14
5	0872	0889	0906	0924	0941	0958	0976	0993	1011	1028	3	6	9	12	14
6	1045	1063	1080	1097	1115	1132	1149	1167	1184	1201	3	6	9	12	14
7	1219	1236	1253	1271	1288	1305	1323	1340	1357	1374	3	6	9	12	14
8	1392	1409	1426	1444	1461	1478	1495	1513	1530	1547	3	6	9	12	14
9	1564	1582	1599	1616	1633	1650	1668	1685	1702	1719	3	6	9	12	14
10	1736	1754	1771	1788	1805	1822	1840	1857	1874	1891	3	6	9	11	14
11	1908	1925	1942	1959	1977	1994	2011	2028	2045	2062	3	6	9	11	14
12	2079	2096	2113	2130	2147	2164	2181	2198	2215	2233	3	6	9	11	14
13	2250	2267	2284	2300	2317	2334	2351	2368	2385	2402	3	6	8	11	14
14	2419	2436	2453	2470	2487	2504	2521	2538	2554	2571	3	6	8	11	14
15	2588	2605	2622	2639	2656	2672	2689	2706	2723	2740	3	6	8	11	14
16	2756	2773	2790	2807	2823	2840	2857	2874	2890	2907	3	6	8	11	14
17	2924	2940	2957	2974	2990	3007	3024	3040	3057	3074	3	6	8	11	14
18	3090	3107	3123	3140	3156	3173	3190	3206	3223	3239	3	6	8	11	14
19	3256	3272	3289	3305	3322	3338	3355	3371	3387	3404	3	5	8	11	14
20	3420	3437	3453	3469	3486	3502	3518	3535	3551	3567	3	5	8	11	14
21	3584	3600	3616	3633	3649	3665	3681	3697	3714	3730	3	5	8	11	14
22	3746	3762	3778	3795	3811	3827	3843	3859	3875	3891	3	5	8	11	14
23	3907	3923	3939	3955	3971	3987	4003	4019	4035	4051	3	5	8	11	14
24	4067	4083	4099	4115	4131	4147	4163	4179	4195	4210	3	5	8	11	13
25	4226	4242	4258	4274	4289	4305	4321	4337	4352	4368	3	5	8	11	13
26	4384	4399	4415	4431	4446	4462	4478	4493	4509	4524	3	5	8	10	13
27	4540	4555	4571	4586	4602	4617	4633	4648	4664	4679	3	5	8	10	13
28	4695	4710	4726	4741	4756	4772	4787	4802	4818	4833	3	5	8	10	13
29	4848	4863	4879	4894	4909	4924	4939	4955	4970	4985	3	5	8	10	13
30	5000	5015	5030	5045	5060	5075	5090	5105	5120	5135	3	5	8	10	13
31	5150	5165	5180	5195	5210	5225	5240	5255	5270	5284	2	5	7	10	12
32	5299	5314	5329	5344	5358	5373	5388	5402	5417	5432	2	5	7	10	12
33	5446	5461	5476	5490	5505	5519	5534	5548	5563	5577	2	5	7	10	12
34	5592	5606	5621	5635	5650	5664	5678	5693	5707	5721	2	5	7	10	12
35	5736	5750	5764	5779	5793	5807	5821	5835	5850	5864	2	5	7	9	12
36	5878	5892	5906	5920	5934	5948	5962	5976	5990	6004	2	5	7	9	12
37	6018	6032	6046	6060	6074	6088	6101	6115	6129	6143	2	5	7	9	12
38	6157	6170	6184	6198	6211	6225	6239	6252	6266	6280	2	5	7	9	11
39	6293	6307	6320	6334	6347	6361	6374	6388	6401	6414	2	4	7	9	11
40	6428	6441	6455	6468	6481	6494	6508	6521	6534	6547	2	4	7	9	11
41	6561	6574	6587	6600	6613	6626	6639	6652	6665	6678	2	4	7	9	11
42	6691	6704	6717	6730	6743	6756	6769	6782	6794	6807	2	4	6	9	11
43	6820	6833	6845	6858	6871	6884	6896	6909	6921	6934	2	4	6	8	11
44	6947	6959	6972	6984	6997	7009	7022	7034	7046	7059	2	4	6	8	10
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′ Differences.

NATURAL SINES.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Differences. 1′	2′	3′	4′	5′
45°	7071	7083	7096	7108	7120	7133	7145	7157	7169	7181	2	4	6	8	10
46	7193	7206	7218	7230	7242	7254	7266	7278	7290	7302	2	4	6	8	10
47	7314	7325	7337	7349	7361	7373	7385	7396	7408	7420	2	4	6	8	10
48	7431	7443	7455	7466	7478	7490	7501	7513	7524	7536	2	4	6	8	10
49	7547	7559	7570	7581	7593	7604	7615	7627	7638	7649	2	4	6	8	9
50	7660	7672	7683	7694	7705	7716	7727	7738	7749	7760	2	4	6	7	9
51	7771	7782	7793	7804	7815	7826	7837	7848	7859	7869	2	4	5	7	9
52	7880	7891	7902	7912	7923	7934	7944	7955	7965	7976	2	4	5	7	9
53	7986	7997	8007	8018	8028	8039	8049	8059	8070	8080	2	3	5	7	9
54	8090	8100	8111	8121	8131	8141	8151	8161	8171	8181	2	3	5	7	8
55	8192	8202	8211	8221	8231	8241	8251	8261	8271	8281	2	3	5	7	8
56	8290	8300	8310	8320	8329	8339	8348	8358	8368	8377	2	3	5	6	8
57	8387	8396	8406	8415	8425	8434	8443	8453	8462	8471	2	3	5	6	8
58	8480	8490	8499	8508	8517	8526	8536	8545	8554	8563	2	3	5	6	8
59	8572	8581	8590	8599	8607	8616	8625	8634	8643	8652	1	3	4	6	7
60	8660	8669	8678	8686	8695	8704	8712	8721	8729	8738	1	3	4	6	7
61	8746	8755	8763	8771	8780	8788	8796	8805	8813	8821	1	3	4	6	7
62	8829	8838	8846	8854	8862	8870	8878	8886	8894	8902	1	3	4	5	7
63	8910	8918	8926	8934	8942	8949	8957	8965	8973	8980	1	3	4	5	6
64	8988	8996	9003	9011	9018	9026	9033	9041	9048	9056	1	3	4	5	6
65	9063	9070	9078	9085	9092	9100	9107	9114	9121	9128	1	2	4	5	6
66	9135	9143	9150	9157	9164	9171	9178	9184	9191	9198	1	2	3	5	6
67	9205	9212	9219	9225	9232	9239	9245	9252	9259	9265	1	2	3	4	6
68	9272	9278	9285	9291	9298	9304	9311	9317	9323	9330	1	2	3	4	5
69	9336	9342	9348	9354	9361	9367	9373	9379	9385	9391	1	2	3	4	5
70	9397	9403	9409	9415	9421	9426	9432	9438	9444	9449	1	2	3	4	5
71	9455	9461	9466	9472	9478	9483	9489	9494	9500	9505	1	2	3	4	5
72	9511	9516	9521	9527	9532	9537	9542	9548	9553	9558	1	2	3	3	4
73	9563	9568	9573	9578	9583	9588	9593	9598	9603	9608	1	2	2	3	4
74	9613	9617	9622	9627	9632	9636	9641	9646	9650	9655	1	2	2	3	4
75	9659	9664	9668	9673	9677	9681	9686	9690	9694	9699	1	1	2	3	4
76	9703	9707	9711	9715	9720	9724	9728	9732	9736	9740	1	1	2	3	3
77	9744	9748	9751	9755	9759	9763	9767	9770	9774	9778	1	1	2	3	3
78	9781	9785	9789	9792	9796	9799	9803	9806	9810	9813	1	1	2	2	3
79	9816	9820	9823	9826	9829	9833	9836	9839	9842	9845	1	1	2	2	3
80	9848	9851	9854	9857	9860	9863	9866	9869	9871	9874	0	1	1	2	2
81	9877	9880	9882	9885	9888	9890	9893	9895	9898	9900	0	1	1	2	2
82	9903	9905	9907	9910	9912	9914	9917	9919	9921	9923	0	1	1	2	2
83	9925	9928	9930	9932	9934	9936	9938	9940	9942	9943	0	1	1	1	2
84	9945	9947	9949	9951	9952	9954	9956	9957	9959	9960	0	1	1	1	2
85	9962	9963	9965	9966	9968	9969	9971	9972	9973	9974	0	0	1	1	1
86	9976	9977	9978	9979	9980	9981	9982	9983	9984	9985	0	0	1	1	1
87	9986	9987	9988	9989	9990	9990	9991	9992	9993	9993	0	0	0	1	1
88	9994	9995	9995	9996	9996	9997	9997	9997	9998	9998	0	0	0	0	0
89	9998	9999	9999	9999	9999	1·000	1·000	1·000	1·000	1·000	0	0	0	0	0
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′ Differences.

NATURAL COSINES.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Differences. 1′	2′	3′	4′	5′
0°	1·000	1·000	1·000	1·000	1·000	1·000	9999	9999	9999	9999	0	0	0	0	0
1	9998	9998	9998	9997	9997	9997	9996	9996	9995	9995	0	0	0	0	0
2	9994	9993	9993	9992	9991	9990	9990	9989	9988	9987	0	0	0	1	1
3	9986	9985	9984	9983	9982	9981	9980	9979	9978	9977	0	0	1	1	1
4	9976	9974	9973	9972	9971	9969	9968	9966	9965	9963	0	0	1	1	1
5	9962	9960	9959	9957	9956	9954	9952	9951	9949	9947	0	1	1	1	2
6	9945	9943	9942	9940	9938	9936	9934	9932	9930	9928	0	1	1	1	2
7	9925	9923	9921	9919	9917	9914	9912	9910	9907	9905	0	1	1	2	2
8	9903	9900	9898	9895	9893	9890	9888	9885	9882	9880	0	1	1	2	2
9	9877	9874	9871	9869	9866	9863	9860	9857	9854	9851	0	1	1	2	2
10	9848	9845	9842	9839	9836	9833	9829	9826	9823	9820	1	1	2	2	3
11	9816	9813	9810	9806	9803	9799	9796	9792	9789	9785	1	1	2	2	3
12	9781	9778	9774	9770	9767	9763	9759	9755	9751	9748	1	1	2	3	3
13	9744	9740	9736	9732	9728	9724	9720	9715	9711	9707	1	1	2	3	3
14	9703	9699	9694	9690	9686	9681	9677	9673	9668	9664	1	1	2	3	4
15	9659	9655	9650	9646	9641	9636	9632	9627	9622	9617	1	2	2	3	4
16	9613	9608	9603	9598	9593	9588	9583	9578	9573	9568	1	2	2	3	4
17	9563	9558	9553	9548	9542	9537	9532	9527	9521	9516	1	2	3	3	4
18	9511	9505	9500	9494	9489	9483	9478	9472	9466	9461	1	2	3	4	5
19	9455	9449	9444	9438	9432	9426	9421	9415	9409	9403	1	2	3	4	5
20	9397	9391	9385	9379	9373	9367	9361	9354	9348	9342	1	2	3	4	5
21	9336	9330	9323	9317	9311	9304	9298	9291	9285	9278	1	2	3	4	5
22	9272	9265	9259	9252	9245	9239	9232	9225	9219	9212	1	2	3	4	6
23	9205	9198	9191	9184	9178	9171	9164	9157	9150	9143	1	2	3	5	6
24	9135	9128	9121	9114	9107	9100	9092	9085	9078	9070	1	2	4	5	6
25	9063	9056	9048	9041	9033	9026	9018	9011	9003	8996	1	3	4	5	6
26	8988	8980	8973	8965	8957	8949	8942	8934	8926	8918	1	3	4	5	6
27	8910	8902	8894	8886	8878	8870	8862	8854	8846	8838	1	3	4	5	7
28	8829	8821	8813	8805	8796	8788	8780	8771	8763	8755	1	3	4	6	7
29	8746	8738	8729	8721	8712	8704	8695	8686	8678	8669	1	3	4	6	7
30	8660	8652	8643	8634	8625	8616	8607	8599	8590	8581	1	3	4	6	7
31	8572	8563	8554	8545	8536	8526	8517	8508	8499	8490	2	3	5	6	8
32	8480	8471	8462	8453	8443	8434	8425	8415	8406	8396	2	3	5	6	8
33	8387	8377	8368	8358	8348	8339	8329	8320	8310	8300	2	3	5	6	8
34	8290	8281	8271	8261	8251	8241	8231	8221	8211	8202	2	3	5	7	8
35	8192	8181	8171	8161	8151	8141	8131	8121	8111	8100	2	3	5	7	8
36	8090	8080	8070	8059	8049	8039	8028	8018	8007	7997	2	3	5	7	9
37	7986	7976	7965	7955	7944	7934	7923	7912	7902	7891	2	4	5	7	9
38	7880	7869	7859	7848	7837	7826	7815	7804	7793	7782	2	4	5	7	9
39	7771	7760	7749	7738	7727	7716	7705	7694	7683	7672	2	4	6	7	9
40	7660	7649	7638	7627	7615	7604	7593	7581	7570	7559	2	4	6	8	9
41	7547	7536	7524	7513	7501	7490	7478	7466	7455	7443	2	4	6	8	10
42	7431	7420	7408	7396	7385	7373	7361	7349	7337	7325	2	4	6	8	10
43	7314	7302	7290	7278	7266	7254	7242	7230	7218	7206	2	4	6	8	10
44	7193	7181	7169	7157	7145	7133	7120	7108	7096	7083	2	4	6	8	10
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′ Differences.

Note.—Numbers in difference columns to be subtracted, not added.

NATURAL COSINES.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Differences. 1′	2′	3′	4′	5′
45°	7071	7059	7046	7034	7022	7009	6997	6984	6972	6959	2	4	6	8	10
46	6947	6934	6921	6909	6896	6884	6871	6858	6845	6833	2	4	6	8	11
47	6820	6807	6794	6782	6769	6756	6743	6730	6717	6704	2	4	6	9	11
48	6691	6678	6665	6652	6639	6626	6613	6600	6587	6574	2	4	7	9	11
49	6561	6547	6534	6521	6503	6494	6481	6468	6455	6441	2	4	7	9	11
50	6428	6414	6401	6388	6374	6361	6347	6334	6320	6307	2	4	7	9	11
51	6293	6280	6266	6252	6239	6225	6211	6198	6184	6170	2	5	7	9	11
52	6157	6143	6129	6115	6101	6088	6074	6060	6046	6032	2	5	7	9	12
53	6018	6004	5990	5976	5962	5948	5934	5920	5906	5892	2	5	7	9	12
54	5878	5864	5850	5835	5821	5807	5793	5779	5764	5750	2	5	7	9	12
55	5736	5721	5707	5693	5678	5664	5650	5635	5621	5606	2	5	7	10	12
56	5592	5577	5563	5548	5534	5519	5505	5490	5476	5461	2	5	7	10	12
57	5446	5432	5417	5402	5388	5373	5358	5344	5329	5314	2	5	7	10	12
58	5299	5284	5270	5255	5240	5225	5210	5195	5180	5165	2	5	7	10	12
59	5150	5135	5120	5105	5090	5075	5060	5045	5030	5015	3	5	8	10	13
60	5000	4985	4970	4955	4939	4924	4909	4894	4879	4863	3	5	8	10	13
61	4848	4833	4818	4802	4787	4772	4756	4741	4726	4710	3	5	8	10	13
62	4695	4679	4664	4648	4633	4617	4602	4586	4571	4555	3	5	8	10	13
63	4540	4524	4509	4493	4478	4462	4446	4431	4415	4399	3	5	8	10	13
64	4384	4368	4352	4337	4321	4305	4289	4274	4258	4242	3	5	8	11	13
65	4226	4210	4195	4179	4163	4147	4131	4115	4099	4083	3	5	8	11	13
66	4067	4051	4035	4019	4003	3987	3971	3955	3939	3923	3	5	8	11	14
67	3907	3891	3875	3859	3843	3827	3811	3795	3778	3762	3	5	8	11	14
68	3746	3730	3714	3697	3681	3665	3649	3633	3616	3600	3	5	8	11	14
69	3584	3567	3551	3535	3518	3502	3486	3469	3453	3437	3	5	8	11	14
70	3420	3404	3387	3371	3355	3338	3322	3305	3289	3272	3	5	8	11	14
71	3256	3239	3223	3206	3190	3173	3156	3140	3123	3107	3	6	8	11	14
72	3090	3074	3057	3040	3024	3007	2990	2974	2957	2940	3	6	8	11	14
73	2924	2907	2890	2874	2857	2840	2823	2807	2790	2773	3	6	8	11	14
74	2756	2740	2723	2706	2689	2672	2656	2639	2622	2605	3	6	8	11	14
75	2588	2571	2554	2538	2521	2504	2487	2470	2453	2436	3	6	8	11	14
76	2419	2402	2385	2368	2351	2334	2317	2300	2284	2267	3	6	8	11	14
77	2250	2233	2215	2198	2181	2164	2147	2130	2113	2096	3	6	9	11	14
78	2079	2062	2045	2028	2011	1994	1977	1959	1942	1925	3	6	9	11	14
79	1908	1891	1874	1857	1840	1822	1805	1788	1771	1754	3	6	9	11	14
80	1736	1719	1702	1685	1668	1650	1633	1616	1599	1582	3	6	9	12	14
81	1564	1547	1530	1513	1495	1478	1461	1444	1426	1409	3	6	9	12	14
82	1392	1374	1357	1340	1323	1305	1288	1271	1253	1236	3	6	9	12	14
83	1219	1201	1184	1167	1149	1132	1115	1097	1080	1063	3	6	9	12	14
84	1045	1028	1011	0993	0976	0958	0941	0924	0906	0889	3	6	9	12	14
85	0872	0854	0837	0819	0802	0785	0767	0750	0732	0715	3	6	9	12	14
86	0698	0680	0663	0645	0628	0610	0593	0576	0558	0541	3	6	9	12	15
87	0523	0506	0488	0471	0454	0436	0419	0401	0384	0366	3	6	9	12	15
88	0349	0332	0314	0297	0279	0262	0244	0227	0209	0192	3	6	9	12	15
89	0175	0157	0140	0122	0105	0087	0070	0052	0035	0017	3	6	9	12	15
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′ Differences.

Note.—Numbers in difference columns to be subtracted, not added.

NATURAL TANGENTS.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Diff. 1′	2′	3′	4′	5′
0°	·0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
1	·0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
2	·0349	0367	0384	0402	0419	0437	0454	0472	0489	0507	3	6	9	12	15
3	·0524	0542	0559	0577	0594	0612	0629	0647	0664	0682	3	6	9	12	15
4	·0699	0717	0734	0752	0769	0787	0805	0822	0840	0857	3	6	9	12	15
5	·0875	0892	0910	0928	0945	0963	0981	0998	1016	1033	3	6	9	12	15
6	·1051	1069	1086	1104	1122	1139	1157	1175	1192	1210	3	6	9	12	15
7	·1228	1246	1263	1281	1299	1317	1334	1352	1370	1388	3	6	9	12	15
8	·1405	1423	1441	1459	1477	1495	1512	1530	1548	1566	3	6	9	12	15
9	·1584	1602	1620	1638	1655	1673	1691	1709	1727	1745	3	6	9	12	15
10	·1763	1781	1799	1817	1835	1853	1871	1890	1908	1926	3	6	9	12	15
11	·1944	1962	1980	1998	2016	2035	2053	2071	2089	2107	3	6	9	12	15
12	·2126	2144	2162	2180	2199	2217	2235	2254	2272	2290	3	6	9	12	15
13	·2309	2327	2345	2364	2382	2401	2419	2438	2456	2475	3	6	9	12	15
14	·2493	2512	2530	2549	2568	2586	2605	2623	2642	2661	3	6	9	12	16
15	·2679	2698	2717	2736	2754	2773	2792	2811	2830	2849	3	6	9	13	16
16	·2867	2886	2905	2924	2943	2962	2981	3000	3019	3038	3	6	9	13	16
17	·3057	3076	3096	3115	3134	3153	3172	3191	3211	3230	3	6	10	13	16
18	·3249	3269	3288	3307	3327	3346	3365	3385	3404	3424	3	6	10	13	16
19	·3443	3463	3482	3502	3522	3541	3561	3581	3600	3620	3	7	10	13	16
20	3640	3659	3679	3699	3719	3739	3759	3779	3799	3819	3	7	10	13	17
21	·3839	3859	3879	3899	3919	3939	3959	3979	4000	4020	3	7	10	13	17
22	·4040	4061	4081	4101	4122	4142	4163	4183	4204	4224	3	7	10	14	17
23	·4245	4265	4286	4307	4327	4348	4369	4390	4411	4431	3	7	10	14	17
24	·4452	4473	4494	4515	4536	4557	4578	4599	4621	4642	4	7	11	14	18
25	·4663	4684	4706	4727	4748	4770	4791	4813	4834	4856	4	7	11	14	18
26	·4877	4899	4921	4942	4964	4986	5008	5029	5051	5073	4	7	11	15	18
27	·5095	5117	5139	5161	5184	5206	5228	5250	5272	5295	4	7	11	15	18
28	·5317	5340	5362	5384	5407	5430	5452	5475	5498	5520	4	8	11	15	19
29	·5543	5566	5589	5612	5635	5658	5681	5704	5727	5750	4	8	12	15	19
30	·5774	5797	5820	5844	5867	5890	5914	5938	5961	5985	4	8	12	16	20
31	·6009	6032	6056	6080	6104	6128	6152	6176	6200	6224	4	8	12	16	20
32	·6249	6273	6297	6322	6346	6371	6395	6420	6445	6469	4	8	12	16	20
33	·6494	6519	6544	6569	6594	6619	6644	6669	6694	6720	4	8	13	17	21
34	·6745	6771	6796	6822	6847	6873	6899	6924	6950	6976	4	9	13	17	21
35	·7002	7028	7054	7080	7107	7133	7159	7186	7212	7239	4	9	13	18	22
36	7265	7292	7319	7346	7373	7400	7427	7454	7481	7508	5	9	14	18	23
37	·7536	7563	7590	7618	7646	7673	7701	7729	7757	7785	5	9	14	18	23
38	·7813	7841	7869	7898	7926	7954	7983	8012	8040	8069	5	9	14	19	24
39	·8098	8127	8156	8185	8214	8243	8273	8302	8332	8361	5	10	15	20	24
40	·8391	8421	8451	8481	8511	8541	8571	8601	8632	8662	5	10	15	20	25
41	·8693	8724	8754	8785	8816	8847	8878	8910	8941	8972	5	10	16	21	26
42	·9004	9036	9067	9099	9131	9163	9195	9228	9260	9293	5	11	16	21	27
43	·9325	9358	9391	9424	9457	9490	9523	9556	9590	9623	6	11	17	22	28
44	·9657	9691	9725	9759	9793	9827	9861	9896	9930	9965	6	11	17	23	29
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′

NATURAL TANGENTS.

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Diff. 1′	2′	3′	4′	5′
45°	1·0000	0035	0070	0105	0141	0176	0212	0247	0283	0319	6	12	18	24	30
46	1·0355	0392	0428	0464	0501	0538	0575	0612	0649	0686	6	12	18	25	31
47	1·0724	0761	0799	0837	0875	0913	0951	0990	1028	1067	6	13	19	25	32
48	1·1106	1145	1184	1224	1263	1303	1343	1383	1423	1463	7	13	20	27	33
49	1·1504	1544	1585	1626	1667	1708	1750	1792	1833	1875	7	14	21	28	34
50	1·1918	1960	2002	2045	2088	2131	2174	2218	2261	2305	7	14	22	29	36
51	1·2349	2393	2437	2482	2527	2572	2617	2662	2708	2753	8	15	23	30	38
52	1·2799	2846	2892	2938	2985	3032	3079	3127	3175	3222	8	16	24	31	39
53	1·3270	3319	3367	3416	3465	3514	3564	3613	3663	3713	8	16	25	33	41
54	1·3764	3814	3865	3916	3968	4019	4071	4124	4176	4229	9	17	26	34	43
55	1·4281	4335	4388	4442	4496	4550	4605	4659	4715	4770	9	18	27	36	45
56	1·4826	4882	4938	4994	5051	5108	5166	5224	5282	5340	10	19	29	38	48
57	1·5399	5458	5517	5577	5637	5697	5757	5818	5880	5941	10	20	30	40	50
58	1·6003	6066	6128	6191	6255	6319	6383	6447	6512	6577	11	21	32	43	53
59	1·6643	6709	6775	6842	6909	6977	7045	7113	7182	7251	11	23	34	45	56
60	1·7321	7391	7461	7532	7603	7675	7747	7820	7893	7966	12	24	36	48	60
61	1·8040	8115	8190	8265	8341	8418	8495	8572	8650	8728	13	26	38	51	64
62	1·8807	8887	8967	9047	9128	9210	9292	9375	9458	9542	14	27	41	55	68
63	1·9626	9711	9797	9883	9970	0057	0145	0233	0323	0413	15	29	44	58	73
64	2·0503	0594	0686	0778	0872	0965	1060	1155	1251	1348	16	31	47	63	78
65	2·1445	1543	1642	1742	1842	1943	2045	2148	2251	2355	17	34	51	68	85
66	2·2460	2566	2673	2781	2889	2998	3109	3220	3332	3445	18	37	55	73	92
67	2·3559	3673	3789	3906	4023	4142	4262	4383	4504	4627	20	40	60	79	99
68	2·4751	4876	5002	5129	5257	5386	5517	5649	5782	5916	22	43	65	87	108
69	2·6051	6187	6325	6464	6605	6746	6889	7034	7179	7326	24	47	71	95	118
70	2·7475	7625	7776	7929	8083	8239	8397	8556	8716	8878	26	52	78	104	131
71	2·9042	9208	9375	9544	9714	9887	0061	0237	0415	0595	29	58	87	115	144
72	3·0777	0961	1146	1334	1524	1716	1910	2106	2305	2506	32	64	96	129	161
73	3·2709	2914	3122	3332	3544	3759	3977	4197	4420	4646	36	72	108	144	180
74	3·4874	5105	5339	5576	5816	6059	6305	6554	6806	7062	41	81	122	162	203
75	3·7321	7583	7848	8118	8391	8667	8947	9232	9520	9812	46	93	139	186	232
76	4·0108	0408	0713	1022	1335	1653	1976	2303	2635	2972	53	107	160	213	267
77	4·3315	3662	4015	4374	4737	5107	5483	5864	6252	6646					
78	4·7046	7453	7867	8288	8716	9152	9594	0045	0504	0970					
79	5·1446	1929	2422	2924	3435	3955	4486	5026	5578	6140					
80	5·6713	7297	7894	8502	9124	9758	0405	1066	1742	2432					
81	6·3138	3859	4596	5350	6122	6912	7720	8548	9395	0264					
82	7·1154	2066	3002	3962	4947	5958	6996	8062	9158	0285					
83	8·1443	2636	3863	5126	6427	7769	9152	0579	2052	3572					
84	9·5144	9·677	9·845	10·02	10·20	10·39	10·58	10·78	10·99	11·20					
85	11·43	11·66	11·91	12·16	12·43	12·71	13·00	13·30	13·62	13·95					
86	14·30	14·67	15·06	15·46	15·89	16·35	16·83	17·34	17·89	18·46					
87	19·08	19·74	20·45	21·20	22·02	22·90	23·86	24·90	26·03	27·27					
88	28·64	30·14	31·82	33·69	35·80	38·19	40·92	44·07	47·74	52·08					
89	57·29	63·66	71·62	81·85	95·49	114·6	143·2	191·0	286·5	573·0					
	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′

Differences.

INDEX

INDEX.