Chapter 20

POWER SUPPLIES

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CHAPTER 20

POWER SUPPLIES

1. INTRODUCTION

Two main sources of power are generally required for operating thermionic valve circuits. They are (i) Cathode heating power, and (ii) Anode power. Biasing voltages are usually obtained either from (ii) or from a separate circuit similar to the one used for (ii).

(i) Cathode heating power

In radar circuits the cathode power is almost always derived from small heater windings on the input power transformers. It could also be provided by separate AC or DC generators, or by storage batteries.

(ii) Anode power

This may be supplied by

(a) Rectifier-filter circuits, operating from external mains or from motor alternators.

(b) DC generators.

(c) Vibrator packs operating from low tension storage batteries.

(d) High tension batteries.

(c) and (d) are normally used only for very low power purposes and have little application in Radar equipments save in small short-range portable sets or test equipment. For radar purposes (a) is nearly always used.

The first few sections of the chapter deal briefly with rectifier-filter circuits. A fuller account is given in Admiralty Handbook of Wireless Telegraphy Vol. II. Sec. H, and other standard works.

RECTIFIER CIRCUITS

2. General

Either high-vacuum tubes or hot-cathode mercury vapour rectifiers may be employed. Mercury are rectifiers are sometimes used where very heavy DC loads are taken, while copper-oxide rectifiers also have a limited application for small DC loads.

One of the chief advantages of the hard valve is that it can be built to withstand very high peak inverse voltages, yet still provide an anode current which is adequate for most purposes. The gas-filled valve, although more efficient and supplying greater currents than a hard valve of similar size, must not be subjected to large inverse voltages; other safeguards also are necessary, which make their use troublesome (see Chapter 6, Sec. 37).

3. Single-phase circuits

A simple diode half-wave rectifier operating from a single-phase supply is shown in Fig. 940(a). Since the current i can flow only during alternate half-cycles, in the direction shown, the output voltage v_o

developed across the load is far from constant unless adequate smoothing is provided. The available DC power output is correspondingly low. Also, since current flows only in one direction through the secondary of the transformer, the core is permanently magnetised, and is thus more readily saturated. This circuit is seldom used except for high-voltage

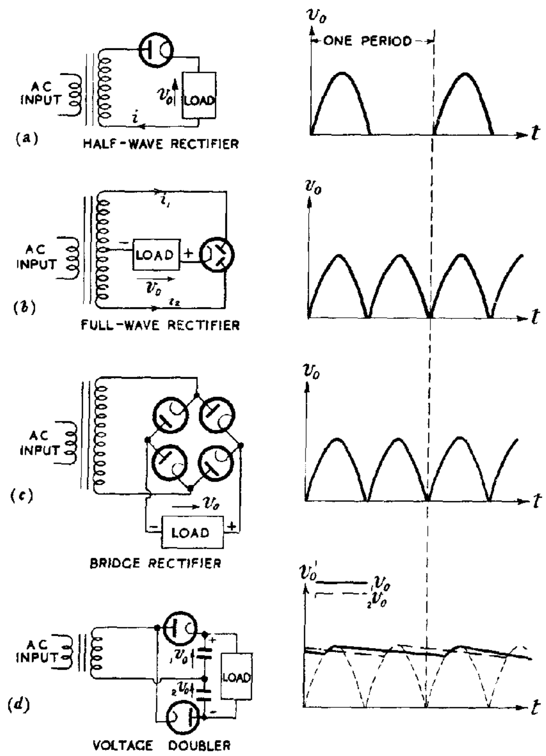

Fig. 940- Single-phase supply circuits.

low-current supplies such as are required for a cathode ray tube.

The most usual type of rectifier circuit is shown in Fig. 940(b) employing a centre-tapped secondary winding and either a double diode or two single diodes to give full-wave rectification. The ripple is at twice the input frequency, but the peak value of the output voltage v_0 is only one half that obtained from a half-wave rectifier using the same transformer. v_0 is, however, more constant and easier to filter, and since i_1 and i_2 flow in opposite directions through the transformer secondary, no permanent core magnetisation results.

A bridge full-wave rectifier is shown in Fig. 940(c). This gives the same peak value of v_0 for a given transformer as in (b), but four separate diodes are needed. Since the cathodes of these diodes are at greatly differing steady voltage levels, at least three separate heater supplies are necessary. This system is therefore most usually found in comparatively low-power circuits using four copper-oxide rectifiers instead of diodes.

Other circuits, such as the voltage doubler of Fig. 940(d), are sometimes used for special purposes. So long as only a small load current is taken the voltage doubler gives a peak output voltage which is approximately twice that of the half-wave rectifier using the same transformer. Because of the large output impedance and high degree of smoothing necessary its chief use is for supplying power to cathode ray tubes, or other high resistance loads, where long time-constant R-C filters are practicable.

4. Polyphase Circuits

As an example of the advantages and disadvantages of polyphase circuits, three-phase supplies will be discussed.

Of the enormous number of possible three-phase circuits only a few are commonly used, the three most important being shown in Fig. 941. A three-phase half-wave rectifier circuit is shown at (a), in which each leg of the three-phase transformer acts in the same way as the single secondary shown in Fig. 940(a). The ripple frequency is thus three times that of the input, and its amplitude is much less than in the single-phase case, so that filtering is simpler. A three-phase transformer is used instead of three single-phase transformers in order to avoid DC saturation, following permanent magnetisation of the cores.

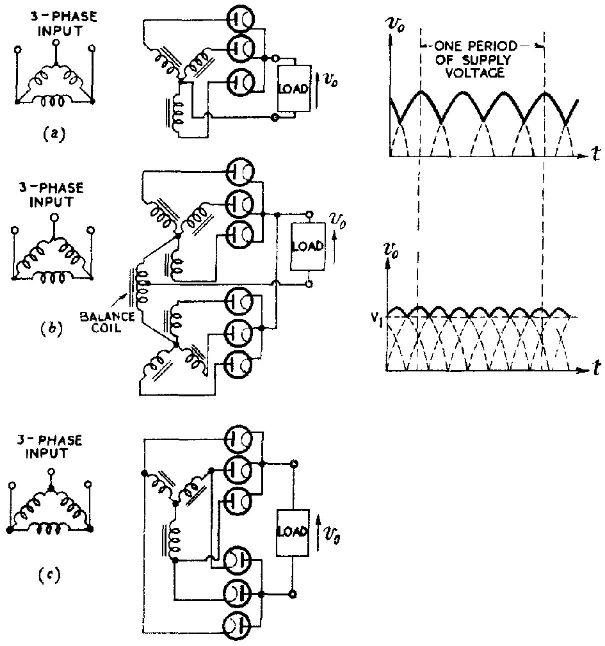

Fig. 941 - Three-phase rectifier circuits

The three-phase half-wave double-Y rectifier circuit shown at (b) consists of two circuits of the type shown at (a) connected in parallel with the load in such a way that when the output voltage of one three-phase unit is a maximum, that of the other is a minimum. The amplitude of the ripple is smaller than that for the circuit of Fig. 941(a) and its frequency is six times that of the input. The balance coil which connects the two units in effect enables each to operate independently of the other, so that one valve of each unit can conduct simultaneously. With a resistive load and no smoothing, two valves are then conducting all the time so that each valve supplies current for one-third of the operating time. Without the balance coil each valve would cease to conduct when its individual supply voltage fell below the level V_1, and would therefore supply current for only one-sixth of the operating time.

Fig. 941(c) shows a three-phase full-wave rectifier circuit in which each leg of the transformer secondary acts in the same way as the transformer secondary of Fig. 940(b). The output is the same as that obtained from the circuit of Fig. 941(b), but the transformer used is of simpler construction and no balance coil is necessary. The disadvantage is that four separate heater windings are needed on the filament transformer.

In general, the chief advantage of polyphase circuits is their superior output waveform, avoiding the use of intricate or bulky filter circuits. The main disadvantages are the more complex transformer systems and the large number of valves required.

FILTER CIRCUITS

5. General

The two principal types of filter circuit which will be considered are the series choke input filter and the shunt condenser input filter. C-R filters will be dealt with very briefly.

6. Series-choke input filter, (Fig. 942(a)

The alternating component of the output voltage from the rectifier is developed chiefly across L_1, whereas almost all of the steady voltage component is developed across C_1. Further smoothing is provided by L_2 and C_2. The main disadvantage of this method is that the output voltage is considerably smaller than the peak input to the filter, due to the voltage drop across L_1. The advantages are that the output voltage is steady, substantially independent of load current, and that the peak current supplied by the rectifier is not very large.

This type of filter is therefore most commonly used where good regulation is necessary because of varying load, and where a very high voltage is not needed.

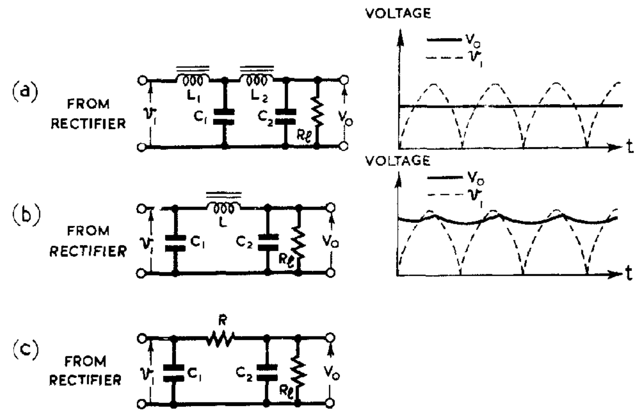

Fig. 942 - Filter circuits.

7. Shunt-Condenser Input Filter (Fig. 942(b))

In this type of filter the input condenser C_1 (because of its low impedance), charges very rapidly almost to the full peak voltage of the rectifier supply. This condenser voltage is very susceptible to changes in loading, however much smoothing is provided by L and C_2. If R_ℓ is substantially reduced the magnitude of the ripple across C_1 increases considerably, and the final voltage delivered to the load is much lower. In addition, the peak current supplied by the rectifier is much larger than in the circuit of Fig. 942(a) so that a larger rectifying valve is needed.

In three-phase circuits the main advantage of the shunt-condenser input filter is not nearly so pronounced because of the smaller ripple voltage, so that the choke input is much more largely used in polyphase circuits. In single-phase circuits the shunt-condenser input is more common, and if better regulation is required, some stabilising or regulating device is incorporated.

8. C-R Filter (Fig. 942(c))

Where the load impedance is very high, of the order of megohms, it becomes practicable to use C-R rather than L-C smoothing circuits, since the power dissipated in R (Fig. 942(c)) can be made negligible. The behaviour of this circuit is similar to that of the condenser-input filter described above, and it suffers from the same disadvantages. The amount of smoothing provided depends on the time constant CR, so that R should be chosen as large as possible without causing too severe a drop in output voltage.

STABILISING OR REGULATING CIRCUITS

9. Requirements

Radar circuits frequently require that one or more of the following conditions is maintained.

(i) The load voltage (or current) must be substantially independent of the fluctuations in amplitude of the generator supply.

(ii) The load voltage (or current) must be substantially independent of variations in load impedance.

Of these, voltage regulation is the more common requirement; and, since current regulation is usually limited to high power filament supplies and is provided by patent regulated transformer devices, it will be dealt with only very briefly.

Most generators are fitted with some form of electro-mechanical voltage regulator, of the make-and-break contact or carbon-pile types, and no treatment of these is given here. We are concerned mainly with regulating devices which receive their input from a DC supply source and provide a DC output to the load. The behaviour of these devices is considered with regard to variations in (i) supply and (ii) loading.

Either neon stabilisers or hard-valve circuits may be used. The neon valve possesses both characteristics required for (i) and (ii), namely an inherent "reference voltage" to which the load voltage is stabilised, and a low Differential Output Resistance (i.e., the change in voltage for unit change in current) for voltages above this value. Hard-valve stabilisers are essentially servo systems, (Chapter 19), in which the low differential resistance is provided by direct voltage feedback. There must be a reference voltage with which to compare the load voltage, and either a battery or a neon valve is usable, the latter being more common.

Instead of a valve being used a non-thermionic stabiliser may be employed. Examples of this are given in the thermistor circuits described below.

10. Neon Valve Stabilisers

The neon-valve-resistance combination shown in Fig. 943(a) is the simplest form of voltage stabiliser. Various loadlines are shown at (b), superimposed on the neon valve current-voltage characteristics, for different values of resistance and supply voltage. The anode voltage remains at the extinction voltage V_E provided:-

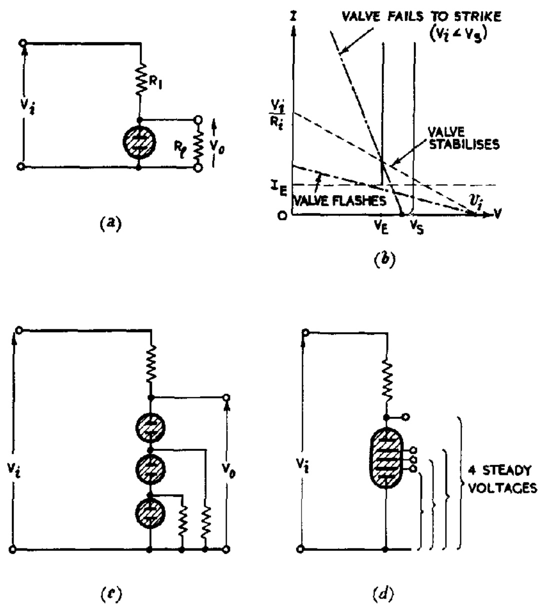

Fig. 943 - Neon valve-resistor stabilising circuits.

(i) The supply voltage is sufficiently high to cause the valve to strike, and

(ii) The load resistance is sufficiently small so that the valve current is not reduced below its extinction value (I_E). If this happens the valve ceases to conduct, the anode voltage rises to the striking value, at which the valve reconducts, and the familiar "flashing" of the neon valve occurs. Under these conditions the output voltage is anything but constant.

For a given load R_l and supply voltage V_i there are limits between which R_1 must lie in order to satisfy both of these requirements. A substantial change in either R_l or V_i may mean that one of the requirements is no longer fulfilled and the valve ceases to stabilise.

Within the working range determined by the chosen value of R_1, the neon valve satisfies both of the fundamental requirements of Sec. 9, but the range of operation is restricted by the invariability of the striking and extinction voltages.

For supplies of several hundreds of volts three or four neon valves may be used in series. To prevent instability due to one or more of the valves flashing, it is usual to shunt each valve with an extra resistance as shown at (c).

As was shown in the case of the resistive anode load R_1, the neon valve ceases to stabilise if R_1 is greater than or less than certain limiting values. If R_1 is replaced by another neon valve or by a neon valve in series with R_1, there is no longer any limit to the magnitude of the anode load, and continuous relaxation oscillations can arise between the two valves. If a suitable resistance is shunted across each of the valves it will act like the load resistance R_l of Fig. 943(a) and will also ensure that the other neons are not extinguished.

Instead of several valves in series, a stabilivolt, or multi-electrode neon, may be used. This contains, besides the anode and cold cathode, several (usually three) intermediate gridded electrodes, as shown at (d). The whole envelope is filled with neon gas at low pressure, and the effect is similar to that of having four separate neon valves in series, with the difference that the gas in all four sections must ionise (and de-ionise) at the same time. The stabilivolt is generally made with all five electrodes brought out as terminals so that the intermediate values, as well as the full output, can be used. As in the case of separate neon valves, each unused electrode should be connected to earth through a suitable resistance.

11. Thermistor Stabilisers

The chracteristics of thermistors are described in Chapter 6 Sec. 45, and Fig. 320(c) shows a typical current-voltage characteristic for one of these elements. Over a wide range of values of current the differential resistance is negative. If we connect in series with such a quasi-conductor a positive resistance equal to the negative differential resistance of the thermistor the voltage drop across the two is approximately constant; this is illustrated in Fig. 944(a).

Such an arrangement is usable in much the same way as a neon valve to stabilise a load voltage, as indicated at (b). Although the regulation is not nearly so good, in the simple circuit, as that provided by a neon valve, the element is much more robust, and is not affected, as is the valve, by limitations of striking and extinction voltages. Furthermore, by the use of more complicated bridge circuits, it is possible to reduce the load voltage variations to one part in a thousand over a wide range of load currents.

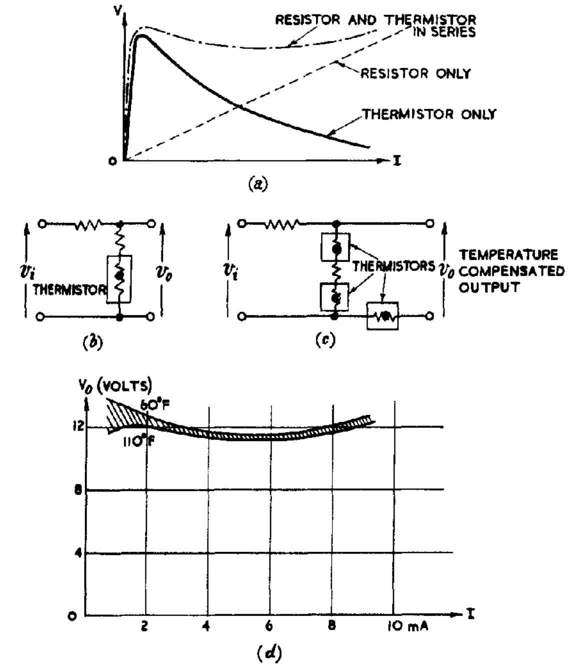

Fig. 944. - Thermistor stabilising circuits.

Thermistors are affected by changes in ambient temperature, but it is possible to compensate for this either by the use of thermostats or by employing additional elements with different temperature characteristics. Such a circuit is shown at (c), and the resultant stabilisation is illustrated by the two curves of Fig. 944(d), the voltage remaining between these values for all ambient temperatures between 60° and 110°F.

12. Hard-Valve Stabilisers

If a suitable constant reference voltage V_c is available, with which the output voltage can be compared, hard-valve circuits provide a means whereby the load voltage can be maintained at a given multiple or fraction of V_c. This is a definite advantage over the simple neon-valve circuit, where the output voltage is pre-determined at the extinction value, or over the stabilivolt, where there are only four "spot" values from which to choose.

The fundamental servo circuit for maintaining a constant load voltage is shown in schematic form in Fig. 945(a). This circuit is readily adaptable to the stabilisation of load current, as illustrated at (b). If the voltage across a small (constant-valued) resistor in series with the load is maintained at a fixed level, the current through it, and through the load, is kept constant.

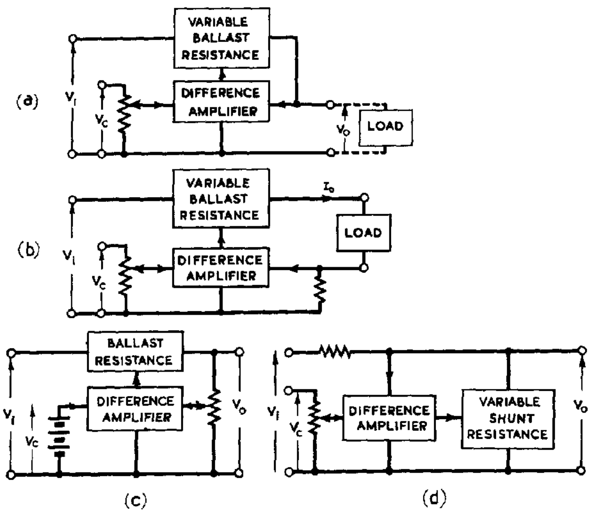

Fig. 945. - Hard-valve stabilisers; schematic arrangements.

In most cases the difference amplifier and the variable ballast resistance are thermionic devices, and the constant voltage is supplied by a neon valve fed from the variable supply. If the load voltage is greater than V_c, a reversal of the input networks to the difference amplifier, as shown at (c), will meet the case. By this means the neon may be replaced by a small constant-voltage battery.

An alternative arrangement to that shown at (a) is illustrated at (d). Here the ballast resistance is in parallel with the load, its magnitude being controlled by the difference amplifier, as before. This method is less economical than the former, the same power being taken from the supply for all values of load.

An arrangement corresponding to the schematic circuit of Fig. 945(a) is shown in Fig. 946(a). Two triodes, valves 1 and 2, fulfil the functions of difference amplifier and ballast resistance, respectively.

If the load voltage tends to rise, due either to a change in load resistance, or to an increase in supply voltage, the grid potential of valve 1 rises and its anode potential falls. This reduces the current in valve 2, thus increasing its resistance and causing a fall in the load voltage which partially offsets the initial rise.

An improvement may be effected by using a pentode in place of the triode as valve 1, the screen supply being taken from the input side of valve 2. A rise in input voltage increases the current in valve 1 and lowers the anode voltage as before, providing an additional stabilising effect. An additional advantage is the higher amplification provided by the pentode. The sensitivity of the stabiliser may be controlled by the insertion of a variable feedback resistor in the cathode load of valve 1. The larger this resistance is made without causing valve 1 to work on the curved portion of its characteristics the less sensitive is the regulation, but the larger is the range of voltage fluctuations over which the regulator will operate.

It is possible to dispense with the difference amplifier, but only at the expense of efficient regulation. The cathode follower circuit of Fig. 946(b) does this, and combines a fair degree of stabilisation with economy of material. A similar economy is provided by the direct voltage feedback circuit shown at (c). These circuits correspond to those of Fig. 945(a) and (c) respectively.

More elaborate, and more effective, circuits are illustrated by Figs. 946(d) and (e). At (d) the current through R_1 is governed by the control grid potential of valve 1, at which the full variations of the load voltage appear. These are offset by the corresponding variations of the resistance of valve 2. The screen voltage of valve 1 may be assumed to have little regulating effect.

By moving the slider of R_3 the constant output voltage may be varied within wide limits (raising the slider lowers the output voltage).

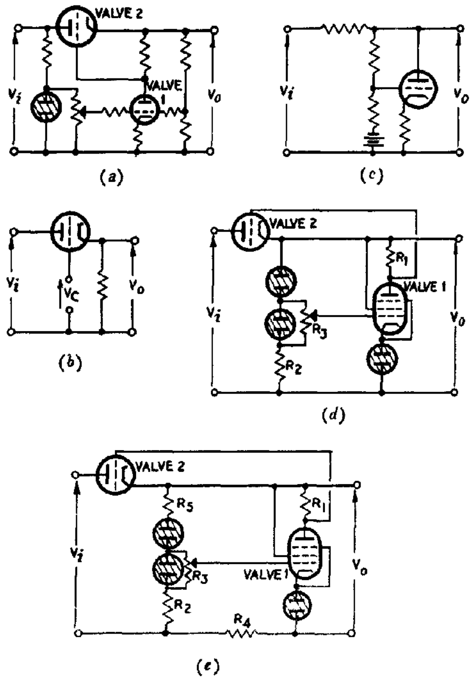

Fig. 946. - Hard-valve stabilisers: circuit diagrams.

If extra resistors R_4 and R_5 are added as at (e), the output impedance of the regulator may be reduced to zero, or even made negative, so that an increase in load current causes an increase in load voltage. It can be shown that provided the current taken by the shunt valve circuits is small compared with the load current, this output resistance is approximately equal to $\frac{2R_a}{k} - \frac{R_5 R_4}{R_2}$, where k is the attenuation, defined as the ratio of the input voltage variation to the output voltage variation. This attenuation is given approximately by

$$k = \frac{1G_{m.2}\,\mu.R_1R_2}{R_2 + R_5}$$

assuming valve 1 is a high gain pentode.

By a suitable choice of valves and components k can be made of the order of a million.

In practice, in each of the circuits of Fig. 946, it may be necessary to use several valves in parallel in place of valve 2 to carry the full load current.

REGULATED TRANSFORMERS AND AC STABILISATION

13. General

Where the stabilised output required is an alternating one, the circuits described in Secs. 9 to 12 are inapplicable and some other device of the type described below must be employed. These devices are usually reliable and simple to operate but are not so adaptable as the thermionic ones. Their use of saturable iron cores gives rise to powerful extraneous magnetic fields; the power factor of the supply may be poor and the output waveform far from sinusoidal. These defects may be minimised by suitable screening, power-factor-correcting and filter circuits, but only with considerable increase in bulk, weight and cost. The frequency range over which these devices are effective is often very limited. They are not suitable for use with rectifier circuits for stabilising DC output because good regulation against input voltage fluctuations and against variations in loading cannot be successfully accomplished by the same regulating transformer.

14. Alternating Current Regulator

The essential circuit is shown in schematic form in Fig. 947. This is a simple servo in which the motor or other device moves the input tap of the regulating transformer so as to maintain the current in the secondary circuit at some constant level. This level may, for example, be fixed as the current necessary to close or open a spring contact which forms the difference element of the servo. It is usually an on-off switch, the control circuit when switched on driving the motor until the contact ceases to operate.

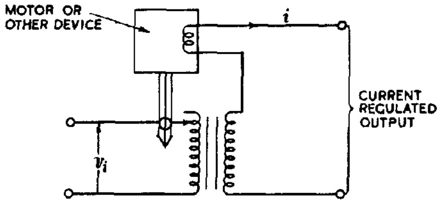

Fig. 947 - Current stabilisers.

In practice, the "motor or other device" may be a highly complicated system, depending upon the exact use to which the transformer is to be put.

15. Alternating Voltage Regulator: Motor Circuit

In this circuit, shown schematically in Fig. 948 the servo motor drives a tap on a large choke which shunts the AC input terminals. Between this tap and a fixed centre-tap is connected the primary of a transformer, the secondary of which is in series with the output line. This choke acts as an auto-transformer, reinforcing or reducing the output voltage according to the position of the variable tap, above or below the centre tap.

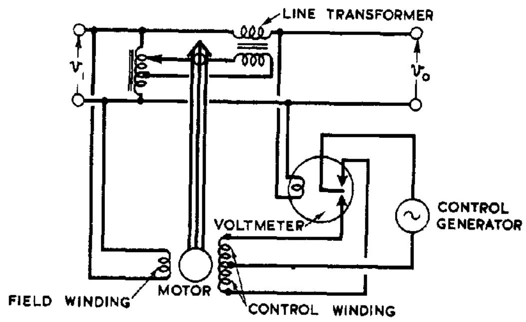

Fig. 948 - Motor regulator.

The AC servo motor may be driven by the field supplied by one of two control windings as shown. An AC voltmeter acts as difference element, and the servo is of the on-off type, the motor running at full speed in one direction or the other according to which of the two contacts is closed by the needle of the voltmeter. For smoother regulation multi-spring type contacts may be used, making the current in the control winding more smoothly variable.

16. Alternating Voltage Regulator: Saturable Reactor Circuit

Instead of the line transformer of Fig. 948 , a saturable reactor may be used, avoiding the relatively complicated motor circuit. The voltmeter difference element is replaced by a difference transformer circuit using a thermistor, for producing a constant reference voltage from the variable supply.

The circuit is shown in schematic form in Fig. 949 The reactor consists of a small laminated iron core on which are wound two coils, the line and saturating windings. The more direct current there is supplied to the latter, the more the core tends to saturate and the lower the impedance of the line winding. It is on this variation in output impedance that the regulation of the transformer depends.

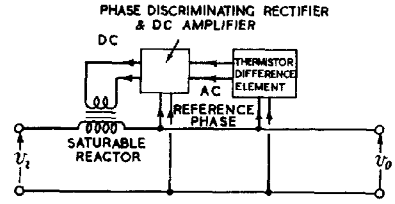

Fig. 949.- Saturable reactor regulator.

The thermistor difference element is connected across the output terminals and the magnitude and phase of its output is indicative of the amount by which the line voltage is too high or too low (the "error"). This is rectified in a phase discriminating circuit (see Chapter 19 Sec. 14) so that the direct output current depends in magnitude and direction on the size and sense of the error. This current is applied to the saturating winding of the reactor.

There are several disadvantages in this elementary circuit, notably the loss in output power due to the absorption in the reactor, and the variable power factor of the output supply. These may be minimised either by using a separate supply for the reactor, the output from which is added to the line by a transformer in parallel with the line, or else by including the saturable reactor in the field circuit of the alternator instead of in its output line. The former method is indicated in Fig. 950 . The latter is outside the scope of this chapter since it depends largely on the type of alternator field system used, and on other factors peculiar to the generator itself.

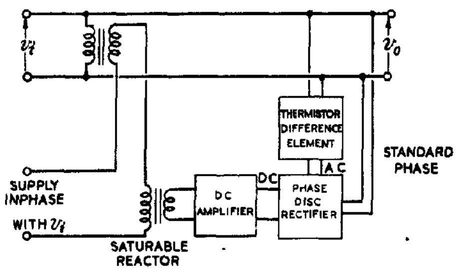

Fig. 950.- Alternative circuit using saturable reactor.

The reactor-thermistor arrangements are applicable over a wide frequency range and are thus usable where motor-circuits are inefficient. The reactor introduces a certain unavoidable amount of waveform distortion, but not usually to the extent of affecting the equipment used in radar.

17. AUTOMATIC POTENTIOMETER (ELECTRONIC POTENTIOMETER) EARTHING CIRCUIT.

In some radar equipments it is necessary to use a power supply which is not connected to earth at either the negative or the positive line or "rail". Generally, in such a case, it is sufficient to connect a potentiometer across the supply and to earth some point on this potentiometer. Provided the resistances between this point and the positive and negative lines remain constant and the supply voltage in unchanged, the lines remain at fixed potentials. If, however, leakage develops between either the positive or the negative supply line and earth, the resistance between this line and earth is reduced and the potential levels are upset; (Fig. 951). This is quite likely to occur with high-voltage supplies. The effect may be minimised by making the resistance of the potentiometer as small as possible, but heat losses limit the practicability of this method. What is required is a device for maintaining the chosen point on the potentiometer sufficiently close to earth potential without actually connecting it to earth. The leakage currents which flow from the positive or negative lines to earth do not then flow through the potentiometer, and the resistances of the two portions, and therefore the potentials of the supply lines, remain constant.

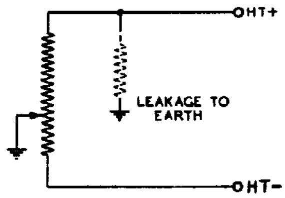

Fig. 951.- Direct earthing of the supply.

A device for producing the desired effect is the Automatic Potentiometer Circuit, or Electronic Potentiometer. A simple form of this circuit is shown in Fig. 952 . A cathode follower circuit is connected across the supply. Its control grid is connected to the required point on the potentiometer and the cathode is connected to earth. Large leakage currents may flow from either of the HT lines to earth without seriously affecting the action of the cathode follower, the grid-cathode voltage of which remains substantially constant. Hence the supply lines remain at reasonably constant potential levels with respect to earth.

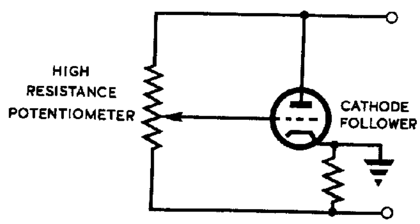

Fig. 952.- Use of cathode follower.

If the cathode load resistor is connected to earth at a point a few volts below the cathode the grid potential can be brought nearer to earth without the danger of grid current flowing and introducing a form of leakage which would produce the very effect which it is the object of the circuit to avoid.

An improvement in the simple arrangement can be affected by the substitution of a constant-current device for the cathode load resistor. Provided the cathode follower valve is a pentode, as shown in Fig .953 , variations of valve current with grid-cathode voltage are relatively independent of anode-cathode voltage. Hence, if the load is truly a constant-current device no variation in grid

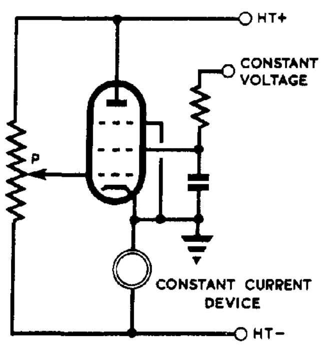

Fig. 953.- Use of constant current load.

voltage occurs however the position of the potentiometer tap P is varied. Leakage currents, however, still cause the grid-cathode voltage to vary.

A practical variant of the circuit of Fig.953 is shown in Fig.954. The lower valve is a Constant-Current Pentode, i.e., a pentode with the potentials at control and screen grids fixed with respect to cathode potential so that the valve operates above the knee of its $I_a - V_a$ characteristic. The screen grid of the upper valve is at a fixed potential relative to earth.

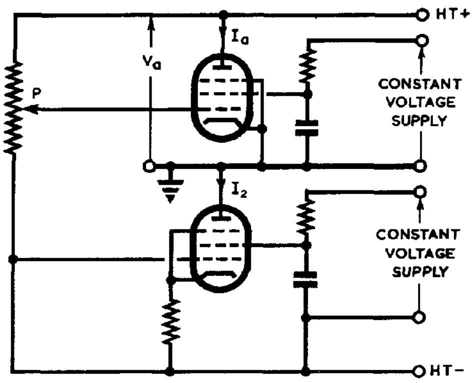

Fig.954.- Use of constant current pentode as load.

Let I_a denote the anode current of the cathode follower valve. In the absence of leakage this is also the current through the load. If a leakage current I_+ occurs from the positive line to earth the current I_2 through the load (lower valve) becomes $I_a + I_+$, whereas if a leakage current I_- flows from earth to the negative line,

$$I_2 = I_a - I_-$$

If the leakage is due to a resistor R_+ in the first case, I_+ is given by

$$I_+ = \frac{V_a}{R_+}\text{; whereas in the second case}$$

$$I_- = \frac{V_B - V_a}{R_-}$$

Fig. 955 shows the effect of leakage in a practical case in which it is necessary for P to vary over a wide range. If there is no leakage (curve A) the variation in grid-cathode voltage as V_a is varied from 1000 to 2400 volts, corresponding to different positions of the potentiometer tap P, is 0.3 volts. If there is a leakage resistance R_+ from the positive line to earth the current I_a is given by

$$I_a = I_2 - I_+$$
$$= I_2 - \frac{V_a}{R_+}$$

This is shown at curve B for R_+ = 20 MΩ. Similarly if there is a leakage resistance R_- from the negative line to earth the current I_a is given by

$$I_a = I_2 + I_-$$

$$= I_2 + \frac{V_B - V_a}{R_-}$$

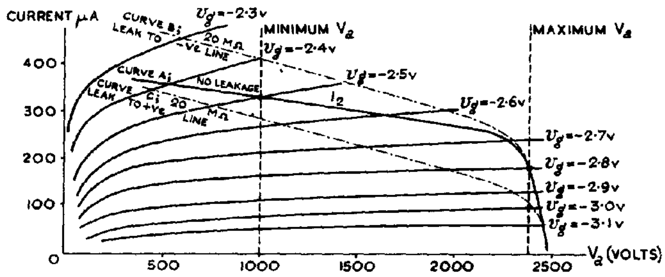

Fig. 955 - Effect of leakage.

This is shown at curve C for R_L = 20 MΩ. In neither case does the grid-cathode voltage variation over the required anode voltage range exceed 0·5 volts. Hence, whatever the position of P within the required range, the supply lines are always within 0·5 volts of their required values.

We may compare the above results with those which would be obtained by the arrangement of Fig. 951, for a potentiometer causing the same drain on the supply as the electronic potentiometer. The resistance of this potentiometer would be $\frac{2500}{300} \cdot 10^6 \Omega$; i.e., approximately 8 MΩ.

Without leakage the appropriate earthing point would be $\frac{1000}{2500} \times 8$ MΩ = 3·2 MΩ from the positive line for V_a = 1000 volts.

With 20 MΩ leakage resistance from the positive line to earth the 3·2 MΩ is modified to become

$$\frac{3{\cdot}2 \, . \, 20}{23{\cdot}2} \doteq 2{\cdot}76 \text{ M}\Omega.$$

The 2500 volts are therefore distributed about earth potential in the ratio

$$\frac{2{\cdot}76}{4{\cdot}8} \text{ instead of } \frac{3{\cdot}2}{4{\cdot}8},$$

so that the positive line is 913 volts above earth instead of 1000 volts.

Hence a shift of nearly 100 volts occurs in the potentials of the supply lines, compared with 0·5V in the electronic potentiometer circuit.