Jan. 19, 1943. S. E. MILLER 2,308,997

ELECTRIC WAVE TRANSLATION

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FIG. 1

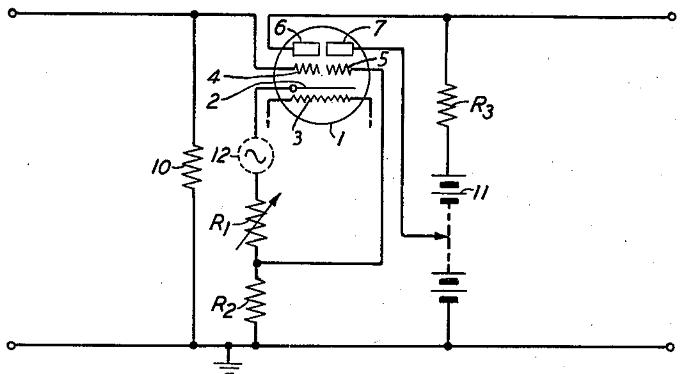



FIG. 2

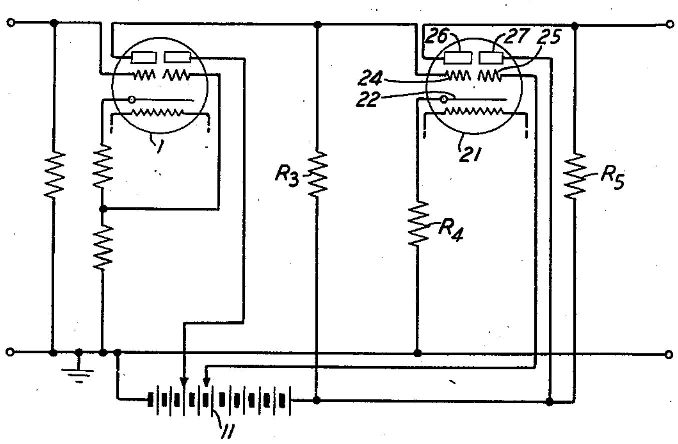
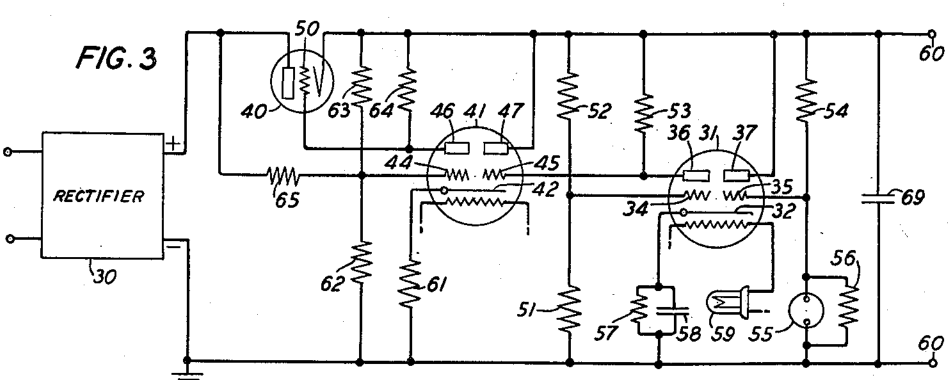



FIG. 3

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## ELECTRIC WAVE TRANSLATION

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13 Claims. (Cl. 179—171)

This invention relates to electric wave amplifiers and more particularly, although in its broader aspects not exclusively, to sensitive amplifiers adapted for the amplification of direct current or current of low frequency of the order of a few cycles per second.

In many fields where direct current amplifiers of high sensitivity are required, a troublesome effect commonly known as cathode drift is encountered. It manifests itself in a slow erratic fluctuation of output current or voltage, and it may be detected readily when the direct current voltage applied to the input for amplification is constant or zero. Various conflicting theories have been offered to account for the effect but it is rather generally agreed that it is associated with the cathodes of the amplifier discharge devices and that it accompanies assumed minute changes in cathode temperature. Cathode drift is especially important when it appears in or near the input stage of a multistage amplifier for its effect in that stage, although minute, may be comparable in magnitude with the quantity to be amplified and in any event it is greatly magnified by the gain of the amplifier. Such direct current amplifiers as those employed in so-called electronic voltage regulators, where extremely stable voltages are required, are among those suffering from cathode drift, and there are also others in which the quantity to be measured is alternating in character rather than unidirectional and of a frequency that may be of the order of a fraction of a cycle to a few cycles per second.

The principal object of the present invention is to eliminate or substantially reduce the effect of cathode drift.

Another object is to increase the accuracy and effectiveness of an electronic voltage regulator.

A further object of the invention is to provide an improved multistage amplifier adapted for the amplification of direct or low frequency currents.

In accordance with the present invention the principal objective of substantially reducing or eliminating cathode drift effect is achieved by associating with the cathode of a multielectrode amplifying discharge device in which cathode drift arises, a supplementary set of electrodes arranged to participate in the cathode drift effect arising from the common cathode, and by applying cathode drift currents derived from the discharge device in effectively opposing or neutralizing relation in the amplifier circuit.

The nature of the present invention and its various objects, features and advantages will appear more clearly from a consideration of the embodiments illustrated in the accompanying drawing and now to be described.

Fig. 1 illustrates schematically an embodiment of the invention comprising an amplifier stage in which cathode drift effect is substantially completely neutralized;

Fig. 2 illustrates a two-stage amplifier comprising an input stage of the kind shown in Fig. 1 and a second stage that is of a modified form adapted for substantial reduction of cathode drift effect; and it further illustrates an advantageous cascading of the two types of stages;

Fig. 3 illustrates an improved electronic voltage regulator in accordance with the invention embodying also a direct current amplifier with reduced cathode drift effect.

Referring more particularly now to Fig. 1, the specific circuit embodiment of the invention there shown may be understood as being a single-stage direct current amplifier or one stage, such as the input stage, of a multistage amplifier. The space discharge device 1 comprises a unitary straight cathode 2 that is uniformly heated throughout its length, as by means of a heater element 3 that is supplied with heating current from an accurately regulated constant voltage or constant current source (not shown). Opposite or surrounding different longitudinal portions of the cathode are the respective grids or control electrodes 4 and 5, and beyond or surrounding these are the respective anodes 6 and 7. It will be convenient to refer to grid 4 and anode 6 as comprising the amplifier section of the discharge device and to grid 5 and anode 7 as comprising the balancer section. In further explanation of the essential nature of the discharge device, it may be said that the latter provides for two discharge paths between the common cathode and the respective anodes and that the discharges or discharge paths are affected alike, either equally or in fixed proportion, by cathode drift. Although the two discharges are derived from different portions of the cathode, which conceivably might assume minutely different temperatures from time to time, it is concluded from the results obtained in practice that such temperature changes as do occur are precisely the same in the two portions. In any event substantially equal cathode drift effects are or may be observable in the two sections of the discharge device.

In the foregoing description of the discharge device 1, I have had particularly in mind a commercially available vacuum tube identified as RCA type 6SC7 which has been found to be moderately well suited for the purposes of the present invention. In this tube the amplifier and balancer sections are alike in size and proportions and the grid and anode of each section are spaced concentrically around a tubular thermionic cathode that is provided with an axial heater resistance.

The currents to be amplified are applied to the input of the amplifier across a coupling resistor 10. One input terminal is connected to the control grid 4, and the other input terminal, which may be grounded, is connected through series resistors R1 and R2 to cathode 2. Grid 5 is tied to the junction of resistors R1 and R2. Anode 6 is connected directly to one output terminal of the amplifier and it is connected through coupling resistor R3 to the positive terminal of a plate voltage source here represented as a battery 11, the negative terminal of which is grounded. Anode 7 is connected to an intermediate tap on battery 11.

For analytical purposes the cathode drift is represented by a fictitious voltage source 12 disposed in the lead to cathode 2. The voltage V of this source may be assumed to vary in such manner as to have the same effect on the potential of the cathode, relative to grids 4 and 5, as would the cathode drift which the source 12 represents. Implicit is the assumption that the parameters of the two sections of the discharge device are exactly alike so that the effective cathode drift voltage is the same for both sections, but this condition is unnecessary as will presently appear.

Let $\mu_1$ and $\mu_2$ represent the amplification factor of the amplifier and balancer sections, respectively, $r_1$ and $r_2$ the corresponding internal plate resistances of the respective sections, $g_1$ and $g_2$ their respective transconductances, $i_1$ and current that flows to anode 6 by virtue of the presence of source 12, and $i_2$ the current that flows to anode 7 by virtue of the presence of source 12. Then it will be found that

$$i_1=\frac{-(\mu_1+1)}{r_1+R3}[V+(i_1+i_2)(R1+R2)] \qquad (1)$$

$$i_2=\frac{-(\mu_2+1)V-(i_1+i_2)[R1(\mu_2+1)+R2]}{r_2} \qquad (2)$$

and, where $e$ is the voltage between cathode 2 and ground,

$$\frac{e}{V}=\frac{1-g_2R2}{1+g_2R1+\frac{\mu_1(R1+R2)}{r_1+R3}} \qquad (3)$$

if $\mu_1$ and $\mu_2$ are large in comparison with unity.

If the presence of source 12 is to have no net voltage effect on the amplifier, $e$ must be zero, a condition which Equation 3 shows on inspection is satisfied for

$$R2=\frac{1}{g_2} \qquad (4)$$

In other words, the effect of cathode drift in the circumstances assumed is completely neutralized if the resistance of R2 is made equal to the reciprocal of the transconductance of the balancer section.

If the two sections of the tube are unlike, the equivalent cathode drift voltage for one section may differ from that for the other section. This condition might well obtain if, for example, the amplifier section were designed as a pentode having high voltage amplification and the balancer section as a triode having high transconductance. If the equivalent cathode drift voltage $V_a$ for the amplifier section and the equivalent cathode drift voltage $V_b$ for the balancer section are proportional, however; that is, if

$$V_a=kV_b \qquad (5)$$

the cathode drift effect may nevertheless be neutralized by taking the proportionality into account. In this case

$$R2=k/g_2 \qquad (6)$$

Whereas Equation 4 or 6 may be used for establishing the proper value for R2, the choice of R1 involves a consideration of the fact that the voltage drop across R1 contributes to the grid bias of the balancer section and the fact that the grid bias in turn affects the transconductance of that section. In practice, R1 may be a rheostat or other variable resistance device, and the balancing of the circuit in accordance with Equation 4 or 6 may be effected by adjusting R1, and consequently $g_2$, rather than by predetermining $g_2$ and then calculating the proper value for R2.

The higher the transconductance $g_2$ of the balancer section, the smaller the value of R2 for neutralization. A high value for $g_2$ is advantageous inasmuch as R2 acts as a degenerative resistance in the amplifier stage. Moreover, the voltage drop across R2 largely contributes to the grid bias of the amplifier section, and in order to limit this voltage drop to the proper value the plate current in the balancer section should not be too large. With a triode the lower the anode voltage the lower the plate current, but on the other hand a certain minimum voltage on anode 7 is required to secure a large transconductance. An anode voltage of 60 to 80 volts has been found a good value in the case of the 6SC7 tube.

The effective voltage amplification G in the Fig. 1 circuit, where $\mu_1=\mu_2=\mu$, is given by the following equation:

$$G=\frac{\mu R3}{R3+r_1+r_2} \qquad (7)$$

Thus when the circuit is balanced the plate resistance is effectively the sum of the plate resistances of the amplifier and balancer sections.

In a particular case in practice employing a tube of the 6CS7 type in the Fig. 1 circuit, the circuit parameters were as follows: R1, 0 to 1,000 ohms, adjustable; R2, 1,000 ohms; R3 500,000 ohms; battery voltage for anode 6, 225 volts; battery voltage for anode 7, 75 volts.

When the circuit is balanced the resistance R1 has no net degenerative effect on the amplification of current supplied to the input. Only resistor R2 accounts for any net degenerative effect. Where R1 is an adjustable resistance it is especially easy to adjust the circuit for neutralization. From network theory it is known that changing a resistance R in a circuit by an amount ΔR is equivalent to placing a voltage in series with the resistance equal to $-i\Delta R$ where $i$ is the current flowing in R before the change. Referring to Fig. 1, the resistance R1 is directly in series with the voltage V of source 12. The condition that voltage V shall have no effect on the output, then, is that a small change in R1 shall have no effect on the output. This fact underlies a convenient and practicable method of balancing the stage: R1 is simply adjusted for maximum plate current in the amplifier section. In a multistage amplifier the current in the last stage may be used as an indicator, and in such case R1 is adjusted for maximum current if there are an odd number of stages, and for minimum current if there are an even number.

Instances may be found in practice where complete neutralization of the cathode drift effect may be unnecessary. In such cases, assuming R1 fixed, the value of R2 may be reduced below the prescribed value. Even with R2 completely removed, the circuit may afford a substantial reduction in the effect of cathode drift as will be explained with reference to Fig. 2.

In Fig. 2 there is illustrated schematically a two-stage amplifier, the first stage of which is designed in accordance with Fig. 1 for the neutralization of cathode drift effect and the second stage of which is a modified form in which the resistor R2 of Fig. 1 is omitted. The discharge device 21 in the second stage may be the same as the device 1 in the first stage, having a common cathode 22, and in the amplifier section a control grid 24 and anode 26, and in the balancer section control grid 25 and anode 27. Cathode 22 is connected to ground through a single resistor R4. Control grid 24 is conductively connected to anode 6 of the first stage with resistor R3 constituting an interstage coupling impedance. Anode 26 is connected to one output terminal of the second stage, and through coupling resistor R5 to the positive terminal of battery 11. Anode 27 is connected directly to the positive terminal of battery 11, and control grid 25 is connected to an intermediate tap on the battery.

Assuming for simplicity of exposition that the cathode drift effect is the same for both sections of discharge device 21, a fictitious voltage source corresponding to source 12 of Fig. 1 may be assumed to be interposed in the lead to cathode 22. As before, let V represent the effective cathode drift voltage and $e$ the resultant net voltage effective on the grid of the second stage. Two effects contribute to the reduction of $e$, one being the degenerative effect of resistor R4 due to the currents from anode 26 that traverse it. The other and more significant effect is due to the degenerative coupling of the balancer section through resistor R4 to the input of the stage. Even if the first effect were to be completely disregarded, the second effect alone would account for a reduction in the effect of cathode drift measured by the following equation:

$$\frac{e}{V}=\frac{1}{1+g_2R4} \qquad (8)$$

If the first effect is taken into account, that is, the degeneration in the amplifier section, the relation is approximately:

$$\frac{e}{V}=\frac{1}{1+\left(g_2+\frac{g_1}{1+\frac{R5}{r_1}}\right)R4} \qquad (9)$$

Where the discharge device 21 is of the 6SC7 type, illustrative values for the various circuit parameters may be as follows: R3, 500,000 ohms; R4, 50,000 ohms; and R5, 500,000 ohms. In the same example the battery voltage effective on balancer grid 25 may be approximately the same as the net biasing voltage at anode 6 of the first stage amplifier section.

It will be noted that in the Fig. 2 circuit the cathode 22 is operated at a potential above ground potential. Since this cathode may be operated at substantially the plate voltage of the first stage no separate biasing battery is required in series with grid 24. This is a substantial advantage inasmuch as slight variations occurring within such a battery would or might have a serious effect on the performance of the amplifier.

In so far as the second stage amplifier section is concerned, the degenerative resistance effectively presented by resistor R4 is given by the following expression:

$$\frac{R4/g_2}{R4+1/g_2} \qquad (10)$$

Referring now to Fig. 3 there is shown schematically an electronic voltage regulator in accordance with the invention incorporating a circuit arrangement like that in the second stage in Fig. 2 for reducing the effect of cathode drift, and other circuit features that will appear. The voltage to be regulated is represented in Fig. 3 as being the output of a full wave rectifier-filter 30 that is connected to an alternating current source to the left. The regulator proper comprises in general outline a space discharge device 40 interposed in the positive side of the line and having a grid electrode for varying the voltage drop. Voltage fluctuations that tend to appear at the output terminals 60 of the regulator are caused to develop a compensating change in the potential of grid electrode 50 and the voltage drop across discharge device 40. Regulators of this general type are discussed by Hunt and Hickman in an article, entitled "On electronic voltage stabilizers," appearing in the January, 1939, issue of Review of Scientific Instruments.

The circuit for translating output voltage fluctuations into compensating changes in the potential of grid electrode 50 comprises discharge devices 31 and 41 which may be of the general type described with reference to Fig. 1 but which will henceforward be treated as being specifically of the RCA type 6SC7. Two opposing voltages are effective on the grid 34 of tube 31, one being an invariable fraction of the regulator output voltage derived by means of potential dividing resitsors 51 and 52, and the other being an invariable voltage drop developed in the common lead to cathode 32 of that tube. The corresponding anode 36 is connected to the positive side of the line through a resistor 53. The other anode 37 is connected directly to the positive side of the line, and its associated control electrode 35 is connected on the one hand to the positive side of the line through a high resistance 54 and to the negative side of the line through a discharge device 55 shunted by a high resistance 56. Discharge device 55 is a diode having the property that the voltage drop across it is, without certain limits, independent of the current through it. It may be, for example of RCA type VR105-30. Cathode 32 of tube 31 is connected to the negative side of the line through a resistor 57 shunted by a condenser 58. Condenser 58 has been found advantageous to reduce the tendency of the circuit to generate self-oscillations.

By virtue of the constant voltage characteristic of tube 55 and the fact that the output voltage is accurately regulated, the potential of grid 35, the current through resistor 57 and the voltage drop across resistor 57 are substantially invariable, and the voltage drop is of such sense as to tend to bias grid 34 negatively with respect to cathode 32. By suitable proportioning of the various circuit parameters, the opposing grid biasing voltages developed across resistors 51 and 57, respectively, may be made approximately, although not quite, equal so that grid 34 receives a favorable negtaive bias plus potential variations corresponding to the fluctuations in the line voltage.

The amplified voltage fluctuations appearing at anode 36 are applied directly to control electrode 45 of tube 41. The associated anode 47 is connected directly to the positive side of the line and the common cathode 42 is connected through a resisotr 61 to the negative side of the line. The discharge between cathode 42 and anode 47 is accordingly varied, and across resistance 61 the voltage drop fluctuates in the same manner as the output voltage variations. This fluctuating voltage drop is applied to control electrode 44 by virtue of the connection of the latter to the junction of voltage dividing resistors 62 and 63 which are connected in series with each other across the line. The associated anode 46 is connected to the positive side of the line through resistor 64 and the amplified voltage fluctuations appearing across resistor 64 are applied as a variable bias to control electrode 50 of discharge device 40. The phase relations obtaining throughout the regulator are such that the variable bias applied to control electrode 50 is of proper phase to compensate or oppose any voltage variation tending to appear at the output of the regulator. Thus if the output voltage tends to rise above the value for which the regulator is set, a compensating negative bias increment would be applied to control grid 50.

The Fig. 3 regulator as described will reduce voltage variations appearing at the input by a factor of 2,000 or more. By the addition of a resistor 65 connecting control grid 44 with the positive side of the unregulated input an additional, forward-acting effect may be obtained which tends to produce a decrease of output voltage for an increase of input voltage or vice versa. If the proper value is chosen for resistor 65 there will be no sensible change in the output voltage for slight changes in input voltage. Where resistor 65 is used, it is desirable that the heaters for cathodes 32 and 42 be supplied through a ballast lamp 59 or other accurately regulated constant current source since the feedback gain in the circuit is large enough to obscure the rectified voltage variation as compared to changes in cathode emission. In practice, resistor 65 may be made variable in part and adjusted for zero or minimum hum at output terminals 60.

It is especially desirable that resistors 51 and 52 be of a highly stable type, for the regulated output voltage is equal to the product of the constant voltage across tube 55 and the quantity (R51+R52)/R51.

In one instance in practice in accordance with Fig. 3 where the discharge devices 31 and 41 were of RCA type 6SC7, the device 40 of RCA type 2A3, and the rectifier output voltage was 440 volts, the several circuit elements were proportioned as follows to secure a regulated output voltage of 315 volts: R51, 50,000 ohms; R52, 150,000 ohms; R53, 0.5 megohm; R54, 1 megohm; R56, 2 megohms; R57, 50,000 ohms; R61, R62 and R63, each 0.1 megohm; R64, 0.5 megohm; R65, 8 megohms; C68, 0.5 microfarad; and C69, 16 microfarads.

It is worthy of note that diode 55, which supplies the reference voltage, is not required to carry either a large or a fluctuating current, and it therefore may be maintained at the most favorable point on its operating characteristic. If desired, tube 55 may be replaced by a small dry cell battery, of 105 volts for the specific example set forth, in which case resistors 54 and 56 may be omitted. The battery is not required to supply any current since it simply biases grid 35, and such being the case it is capable of providing a stable source of reference voltage.

The regulated voltage supply shown in Fig. 3 may be employed advantageously in lieu of the battery indicated in Figs. 1 and 2, the several intermediate voltages being derived by separate sets of voltage dividing resistors connected across the output terminals of the regulator.

What is claimed is:

1. In a multistage amplifier adapted for amplification of electric currents approximating direct current in frequency, an input stage comprising a space discharge device that has a cathode, a control electrode and an output electrode, an input circuit for said stage comprising said cathode and control electrode, an output circuit for said stage comprising said output electrode, auxiliary electrode means within said discharge device and circuit means connected thereto for amplifying the effect of cathode drift associated with said cathode, and means for applying the amplified cathode drift effect in opposing relation to cathode drift effect tending to appear in said output circuit.

2. A combination in accordance with claim 1 in which said opposing relation is more particularly a neutralizing relation.

3. In a direct current amplifier, an amplifier stage comprising a discharge device having a thermionic cathode and a set of control and output electrodes associated therewith, means comprising said set of electrodes for amplifying unidirectional current applied to said amplifier stage, and means for substantially neutralizing cathode drift effects tending to appear in the amplified current comprising another set of control and output electrodes likewise associated with said thermionic cathode, and circuit means connected to said other set of electrodes for deriving a replica of the said cathode drift effects and applying the same to said amplifier in opposing relation to the said cathode drift effects tending to appear therein.

4. An amplifier stage adapted for the amplification of electric currents approximating direct current in frequency, said stage comprising a discharge device having separate sets of control and output electrodes and a thermionic cathode common to said sets of electrodes, means for applying current to be amplified to one of said control electrodes, means for deriving the amplified current from one of said output electrodes, and means for reducing cathode drift effect in said stage comprising circuit means connected to another of said control electrodes and another of said output electrodes for deriving a cathode drift opposing voltage.

5. In a conductively coupled amplifier, an amplifier stage comprising a discharge device having a pair of anodes and a common cathode, means for establishing separate and distinct space discharges between said cathode and said respective anodes, means for varying one of said discharges in accordance with current variations to be amplified, control electrode means for varying the other of said discharges in accordance with cathode drift effects associated with said

common cathode, and means for reducing cathode drift effects appearing in said one discharge comprising means for subjecting said one discharge to the control of variations in said other discharge.

6. An amplifier stage comprising a discharge device having two anodes and a cathode common to said anodes, means for establishing separate space discharges between said cathode and said respective anodes, a control electrode for controlling one of said discharges, means for varying the potential of said control electrode in accordance with a quantity to be amplified, means for varying the other of said discharges in accordance with cathode drift voltages effectively in series with said common cathode, and circuit means responsive to variations in said other discharge for neutralizing cathode drift effects tending to appear in said first discharge.

7. An amplifier stage comprising a discharge device having a first set of control grid and anode elements, a second set of control grid and anode elements, and a cathode common to said sets, means comprising said first set of elements for amplifying potentials applied to the input of said stage, said stage having an input and an output circuit each of which is grounded on one side, circuit means connecting said second control grid to said common cathode whereby the potential of said second grid is varied in accordance with the cathode drift effect associated with said cathode, and means for applying the cathode drift voltage appearing at said second anode to the input of said stage.

8. An amplifier stage comprising a device having a thermionic cathode and means including a pair of anodes and an anode voltage source therefor for maintaining two separate discharges from said cathode, a resistance in series with said cathode, means comprising an electrode for controlling one of said discharges, input circuit means for said stage comprising a connection to said electrode and a connection through said resistance to said cathode, an electrode controlling the other of said discharges, circuit means connecting said last-mentioned electrode through said resistance to said cathode, and means for introducing into said input circuit a voltage that varies in accordance with fluctuations in the other of said discharges.

9. In a direct current amplifier, an input stage comprising a discharge device having an amplifier section, a balancer section and a cathode common to said sections, an input circuit for said amplifier section including two resistances connected in series with each other to said cathode, said balancer section comprising a control electrode and an anode, circuit means connecting said control electrode to the junction of said two resistances, and circuit means connecting said anode to said cathode through said two resistances.

10. A combination in accordance with claim 9 in which one of said resistances is of such magnitude that a cathode drift neutralizing voltage is established in said input circuit.

11. In an amplifier adapted for a frequency of less than ten cycles per second, an input stage comprising a discharge device having two sets of electrically separate electrodes and a common cathode, means comprising one of said sets of electrodes for amplifying currents applied to the input of said stage, means comprising the other of said sets of electrodes for amplifying cathode drift effects associated with said common cathode, and means for degeneratively applying to the input of said stage the amplified cathode drift effects from said other set of electrodes.

12. The method of compensating for the effect of cathode drift in the amplification of direct and low frequency electric variables which comprises separately amplifying the effective cathode drift voltage and applying it as so amplified to the neutralization of cathode drift effect tending to appear in the amplified variable.

13. In an electric system subject to cathode drift, the method which comprises concurrently amplifying the effective cathode drift voltage and a variable to be amplified, separately translating the said effective cathode drift voltage with substantial discrimination against any component of the said variable that may be present, and applying the separately translated cathode drift voltage in neutralizing relation to the cathode drift effect tending to appear as a result of the aforesaid concurrent amplification of the effective cathode drift voltage and the variable to be amplified.

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