Aug. 12, 1952 L. A. MEACHAM 2,607,030

CURRENT REGULATION

Filed April 17, 1948 2 SHEETS—SHEET 1

FIG. 1

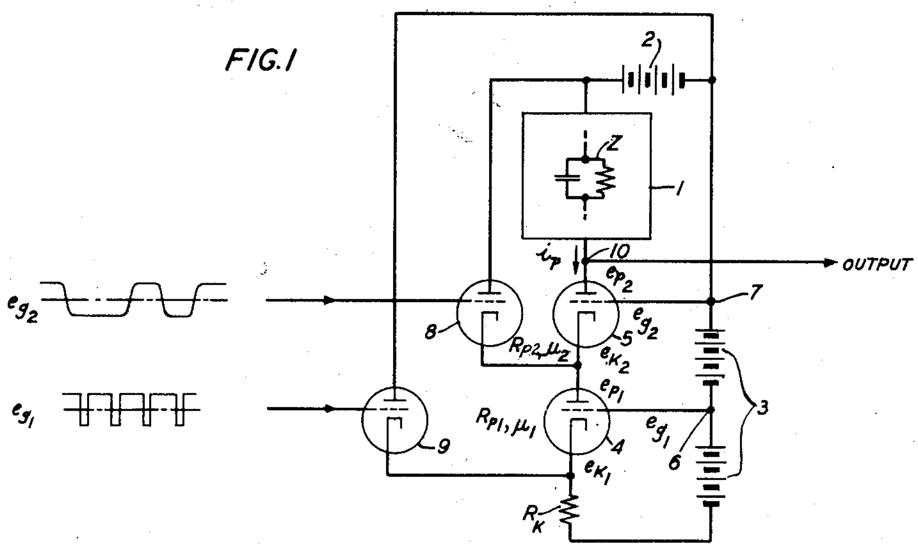
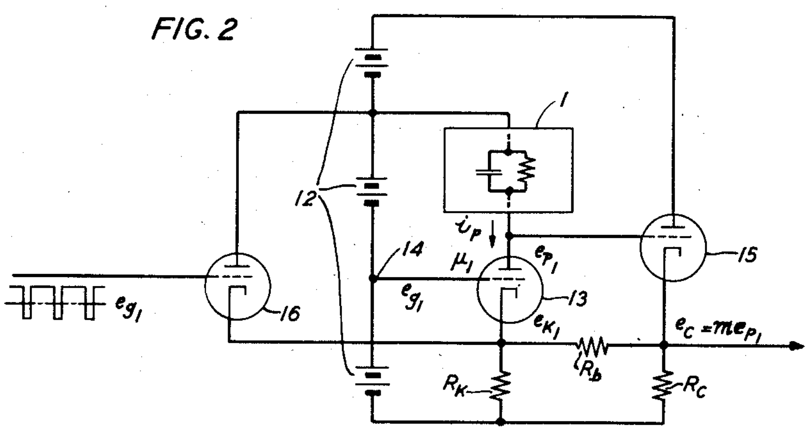


FIG. 2



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Filed April 17, 1948 2 SHEETS—SHEET 2

FIG. 3

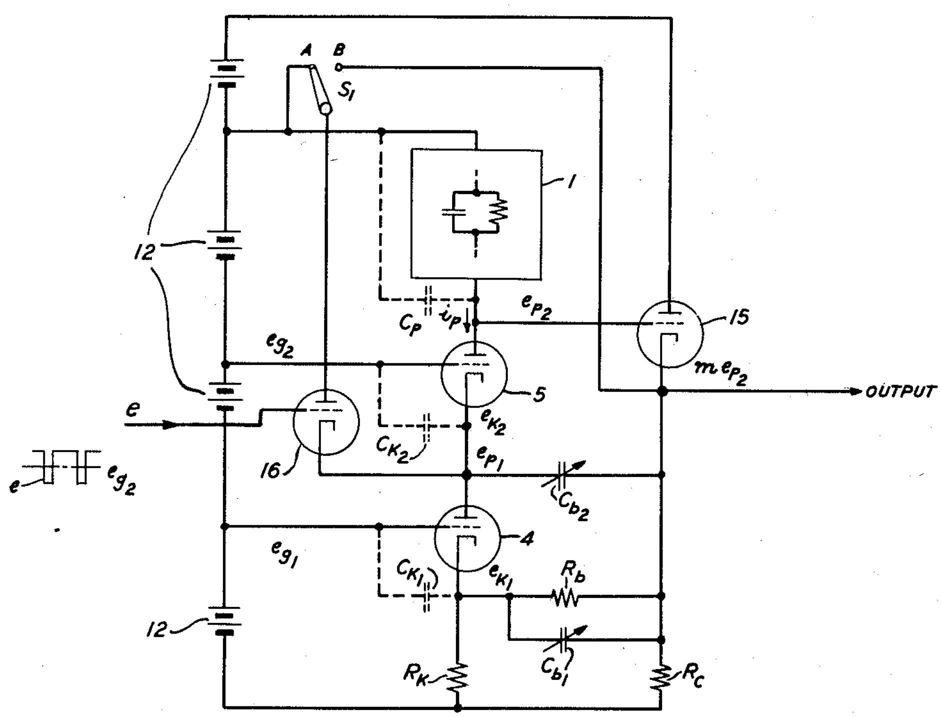
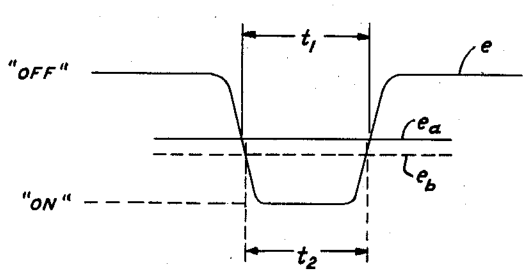


FIG. 4



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UNITED STATES PATENT OFFICE

2,607,030

CURRENT REGULATION

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Application April 17, 1948, Serial No. 21,651

12 Claims. (Cl. 323—22)

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This invention relates to current regulation.

The principle object of the invention is to render the current flowing from a source through a load to a great extent independent of load variations. A subsidiary object is to switch such a current on and off under the control of suitable pulses, thus making it a substantially two-valued function of time, the selection of one or other of the values being fully controlled, both as to its existence and as to the instant at which it comes into existence, while the magnitude of the particular value selected remains independent of past selections and other disturbing influences.

The invention is of use wherever it is required to draw through a network a current whose magnitude is independent of voltage variations across the network, but which is controllable as to the instants of its inception and termination. For example, in charge-measuring circuits of certain types, such a current of standard magnitude and controlled duration constitutes a measure of the charge accumulated on a condenser as a result of the current flow through it. The invention is equally of use in the generation of a sweep voltage wave of truly saw-tooth form for application to the deflecting elements of a beam tube and, generally, wherever a current is required to be precisely controlled as to the times of its inception and termination but otherwise independent of its environment.

The stated objects, and others as well, are attained by the provision, in series with a current source and a load in which the current is to be held constant independent of variations in the load, of a high resistor and two or more triodes connected for cathode feedback, the resistor constituting the cathode feedback resistance of one triode, and this triode and its cathode resistor together constituting the cathode feedback resistance of a second triode. In accordance with the well-known characteristic of the conventional cathode feedback connection which affords an effective plate circuit impedance approximately equal to the resistance of a cathode resistor increased by a factor $1+\mu$, where μ is the amplification factor of the tube, the effective increase which is consequent upon the interdependent tubes of the invention is multiplicative; that is, it is approximately $(1+\mu)^2$ for two tubes, $(1+\mu)^3$ for three, and so on. This affords a marked improvement over the series arrangement of independent cathode feedback tubes, wherein the effects are merely additive, i. e., $2(1+\mu)$ for two tubes, $3(1+\mu)$ for three tubes, and so on.

The foregoing arrangement is well adapted to be combined with a balancing circuit which, nominally, results in an infinite effective impedance, but with which serious deviations from the ideal follow from minor departures of the parameters from their nominal values. In combination with

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the interdependent triode arrangement, the sensitivity of the balance circuit to such departures is greatly reduced.

Whether the circuit be employed alone or in this or other combinations, the current, which as explained is constant while "on," may be freely switched "off" and "on" again by switching or gating pulses applied to it at a suitable point. When this application is made by way of a suitably energized gating tube, the switching instants, as well as the magnitudes of the switched currents, may be rendered substantially independent of load variations.

The invention will be fully apprehended from the following detailed description of certain preferred embodiments thereof, taken in connection with the appended drawings, in which:

Fig. 1 is a schematic circuit diagram illustrating the principles of one aspect of the invention;

Fig. 2 is a schematic circuit diagram illustrating the principles of another aspect of the invention;

Fig. 3 is a schematic circuit diagram of a preferred embodiment of the invention, combining the principles of Fig. 2 with those of Fig. 1; and,

Fig. 4 is a wave form diagram of assistance in the explanation of certain aspects of the invention.

Referring now to Fig. 1, a network of impedance Z, denoted by the block **1**, is shown connected in series with a current source which may be provided by batteries **2**, **3** and with two triodes **4**, **5** and a resistor R_k. The network **1** may, for example, include a condenser to which standard increments of charge are to be applied by passing through it currents of standard magnitudes which endure for standard times. The anode of the upper triode **5** is connected to the lower terminal of the network **1**. Its cathode is connected to the anode of the lower triode **4**. The cathode of the latter is connected to one end of the resistor R_k. The other end of the resistor R_k is connected to the negative terminal of the batteries **2**, **3** whose positive terminal is connected to the upper terminal of the network **1**, thus completing the series circuit.

The control electrode or grid of the lower triode **4** is maintained at a fixed potential, for example by connection to a tap **6** of the battery **3**. Current flowing through the lower tube **4** and the resistor R_k produces a voltage drop across the latter, thus raising the cathode to a potential slightly higher than that of the grid, by the action known as cathode feedback.

Disregarding, for the present, the action of the switching tubes **8**, **9**, that is, assuming them both to be cut off, if

i_p=current through lower triode,
e_{k_1}=cathode potential of lower triode,
e_{p_1}=anode potential of lower triode,

e_{g_1}=grid potential of lower triode,
μ_1=amplification factor of lower triode,
R_{p_1}=plate resistance of lower triode,

where all potentials are measured with respect to a common point, such as the lower end of the resistor R_k, then, from elementary circuit considerations,

$$i_p=\frac{e_{p_1}-e_{k_1}+\mu_1(e_{g_1}-e_{k_1})}{R_{p_1}} \quad (1)$$

Differentiating with respect to i_p, and solving for

$$\frac{di_p}{de_{p_1}}$$

gives

$$\frac{di_p}{de_{p_1}}=\frac{1}{R_{p_1}+(1+\mu_1)\frac{de_{k_1}}{di_p}} \quad (2)$$

But the variation of the cathode potential with the tube current is simply

$$\frac{de_{k_1}}{di_p}=R_k \quad (3)$$

and therefore (2) becomes

$$\frac{di_p}{de_{p_1}}=\frac{1}{R_{p_1}+(1+\mu_1)R_k} \quad (4)$$

This quantity, in turn, is simply the reciprocal of the apparent resistance R_1 looking into the anode of the lower tube; and therefore

$$R_1=\frac{1}{\frac{di_p}{de_{p_1}}}=R_{p_1}+(1+\mu_1)R_k \quad (5)$$

Evidently, for best results in obtaining a high apparent resistance, both μ_1 and R_k should have large values. In other words, the lower triode should have high gain and its cathode resistor should be of high resistance.

The potential e_{p_1} of the anode of the lower tube is then

$$e_{p_1}=R_1 i_p \quad (6)$$

where R_1 is defined by Equation 5.

Now the grid of the upper tube is likewise supplied with a fixed potential with respect to the lower end of the resistor R_k as by connection to the common point 7 of the batteries 2 and 3. Thus the upper tube too is connected for cathode feedback, its feedback resistor being furnished by the discharge path of the lower tube and the resistor R_k together. Equations of the same form as the foregoing ones may therefore be written for the upper tube, in which:

i_p is the current through it,
e_{p_2} is its anode voltage,
e_{k_2} is its cathode voltage,
e_{g_2} is its grid voltage,
μ_2 is its amplification factor,
R_{p_2} is its plate resistance,

and R_1, as given by (5) above is its cathode feedback resistance. Thus, by analogy with (2),

$$\frac{di_p}{de_{p_2}}=\frac{1}{R_{p_2}+(1+\mu_2)\frac{de_{k_2}}{di_p}} \quad (7)$$

Because the cathode of the upper tube is connected directly to the anode of the lower one,

$$e_{k_2}=e_{p_1} \quad (8)$$

$$\frac{de_{k_2}}{di_p}=\frac{de_{p_1}}{di_p} \quad (9)$$

Substitution of (9) and (4) into (7) gives

$$\frac{1}{R_2}=\frac{di_p}{de_{p_2}}=\frac{1}{R_{p_2}+(1+\mu_2)R_{p_1}+(1+\mu_1)(1+\mu_2)R_k} \quad (10)$$

where R_2 is now the apparent resistance of the two tubes and the cathode resistor acting in combination.

If R_k is of substantial magnitude as compared with the plate resistances, and if μ_1 and μ_2 are substantially greater than unity, (10) becomes, approximately

$$R_2=(1+\mu_1)(1+\mu_2)R_k \quad (11)$$

If, in turn, the tubes are alike,

$$\mu_1=\mu_2$$

so that

$$R_2=(1+\mu)^2R_k \quad (12)$$

Thus the circuit arrangement of the invention results in a multiplicative increase in the effect produced by a single cathode feedback tube by itself. It is, indeed, equal to that which would be obtained by use of a very large number of individually independent cathode feedback tubes in series, and is obtained without resorting to a current source of excessive voltage which would be required for such an arrangement. Any variations in the impedance Z of the network 1 or in the voltage across it, such as an inductive voltage due to suddent application or interruption of the regulated current, or the voltage due to an accumulation of charge on a condenser, are prevented from causing changes in the current through this network by the much higher impedance of the intercoupled cathode feedback triodes.

The current through the circuit which, when it exists, is substantially constant as described above, may be switched on and off by gating pulses derived from sources not shown and applied to the cathode of the lower tube, the cathode of the upper tube, or elsewhere. By way of example, two sequences of gating pulses are shown in the figure as being applied by way of gating tubes 8, 9, the first sequence being an irregular sequence of relatively long pulses and the second a regular sequence of short ones. With proper selection of the grid potentials of the gating tubes with respect to those of the series triodes, either of the gating tubes robs the network 1 of all current until the simultaneous arrival of pulses at both gating points driving the gating tubes below cut-off. Thereupon current flows through the network 1 and the series triodes during their joint presence and ceases when either of them terminates. With a different selection of the tapping points 6, 7, and opposite polarity of the pulses, the gating tubes may be arranged to turn the circuit "off" instead of "on." In this case, the current is interrupted when a pulse occurs at either of the gating points.

The principle of operation here is similar to that described in application of L. A. Meacham, Serial No. 772,913, filed September 9, 1947, now Patent 2,537,843, issued January 9, 1951.

The voltage at an output point, such as a terminal 10 of the impedance network, is a precise measure of the charge which has been accumulated on a condenser contained therein by the flow of constant current in response to the gating pulses.

The arrangement may obviously be extended to three or more stages, it being only necessary to connect a desired number of triodes in series, the anode of each to the cathode of the next, to provide a high resistance cathode resistor for the first in the conventional fashion, and to connect the control grids of all of them to points of fixed potential of appropriate value.

Fig. 2 shows a circuit arrangement in which the problem of maintaining constancy of current through the load impedance network **1** is approached in a different manner. The impedance network **1** is connected in series with a potential source such as a battery **12**, a triode **13** and a high resistor R_k connected from the cathode of the triode to the negative terminal of the battery **12**. The control grid of the triode is supplied with a fixed potential as by connection to a tap **14** of the battery **12**. As above explained, these connections provide inverse feedback by way of the cathode resistor R_k so that the effective impedance in series with the network **1** is given by Equation 5. A second cathode feedback triode **15** has its anode connected directly to a suitable fixed positive potential point of the battery **12** and its cathode resistor R_c from its cathode to the negative battery terminal. Output voltage may be taken from the cathode of this triode **15**, which is thus connected as a cathode follower, while input switching pulses may be applied by way of a buffer amplifier **16** to the cathode of the first triode, or otherwise, as desired. A resistor R_b is connected from the cathode of the first triode **13** to that of the second. With this arrangement and proper choice of the value of the resistor R_b, it is possible to reduce the value of

$$\frac{di_p}{de_{p_1}}$$

to zero, thus placing an effectively infinite variational impedance in series with the network **1**. This will be evident from the following:

It is a consequence of the behavior of the cathode follower tube **15** that, when the voltage e_{p_1} of the left-hand triode **13** is applied to its grid, its cathode voltage will be

$$e_c = me_{p_1} \qquad (13)$$

where m is a constant which may be made to have a value only slightly smaller than 1 by suitable choice of the tube and the resistor R_c. From elementary circuit analysis considerations,

$$e_{k_1} = i_p \frac{R_d R_b}{R_k + R_b} + me_{p_1} \frac{R_k}{R_k + R_b} \qquad (14)$$

Differentiating,

$$\frac{de_{k_1}}{di_p} = \frac{R_k R_b}{R_k + R_b}\left(1 + \frac{m}{R_b} \cdot \frac{de_{p_1}}{di_p}\right) \qquad (15)$$

Substituting this expression into Equation 2, and collecting terms, gives

$$\frac{di_p}{de_{p_1}} = \frac{1 - (1+\mu_1)\frac{mR_k}{R_k + R_b}}{R_{p_1} + (1+\mu_1)\frac{R_k R_b}{R_k + R_b}} \qquad (16)$$

The numerator of this expression, and consequently the expression as a whole, vanishes when the resistor R_b is chosen to satisfy the relation

$$R_b = R_k[(1+\mu_1)m - 1] \qquad (17)$$

Here, for a qualitative explanation, the fundamental relation of the triode **13**, assuming constant plate current, namely

$$\Delta e_{k_1} = \frac{\Delta e_{p_1}}{1+\mu} \qquad (18)$$

may be taken as a starting point. If i_p is to remain constant, any increase in e_{p_1} must be accompanied by a smaller increase in e_{k_1} such that Equation 18 is satisfied. But, if R_k is finite, the increase in e_{k_1} must be accompanied by a small increase in current through R_k. This additional current must not be supplied by way of the triode **13**, or the initial assumption will be violated. Therefore, the proper amount of current is supplied from the cathode follower **15** to R_k through the added high resistor R_b. Effectively, the cathode impedance of tube **13** is thus made to behave as though it were infinite.

Since μ_1 and (to a lesser extent) m depend upon the tubes themselves, the optimum value of R_b may change from time to time; but comparison of (16) with (5) shows that even a moderate degree of balance affords improvement over the results obtainable by use of a single cathode feedback tube as a current regulator for the impedance network.

For example, with $\mu_1=38$, $R_1=7000$, $R_k=30{,}000$, and $m=0.95$, it turns out that for true balance $R_b=1.082$ megohms. If R_b actually misses this value by as much as $\pm10\%$,

$$\frac{di_p}{de_p}$$

has a value in the range ±0.09 micromho, corresponding to a series variational resistance of 11 megohms.

Fig. 3 is a schematic circuit diagram of a system in which balance is used to minimize residual variations not only in the magnitude of the current, in accordance with the principles of Fig. 2, but also in the instants at which the current is switched on or off. As in Fig. 1, an impedance network through which the current is to be held constant is shown connected in series with a source **12**, two triodes, **4**, **5**, and a high resistor R_k, the anode of the lower triode **4** being connected to the cathode of the upper one **5**, and the cathode of the lower one **4** to the resistor R_k. As before, the other end of the resistor is connected to the negative terminal of the source **12** of which a suitable positive point is connected to the impedance network **1**. The control grids of the two triodes **4**, **5** are supplied with fixed potential as by connection to suitable taps of the source. The output is taken from the anode of the upper triode **5** and is applied to the control grid of a buffer amplifier tube **15** whose anode is supplied from the positive terminal of the source. This tube may appropriately be connected as a cathode follower, in order to make the output voltage which appears across the impedance network **1** available to succeeding circuits at a low impedance level. Thus a resistance R_c is connected from the cathode of the follower tube **15** to the negative terminal of the source **12**. The circuit as thus far described operates like that of Fig. 1, to produce a very high effective impedance in series with the impedance network and the source. In addition, a resistor R_b interconnects the upper ends of the two resistors R_k and R_c, as in Fig. 2.

Switching or gating pulses may be applied to the cathode of either one of the series triodes **4**, **5**, as suggested in connection with Fig. 1, or to both of them together as shown in Fig. 1. In the present example, they are applied, by way of a buffer tube **16**, to the cathode of the upper triode **5**. This buffer tube **16** is shown as being supplied with anode potential either from a fixed potential point of the source **12** with the switch in position A or, with the switch in position B, from the cathode of the cathode follower tube 15. The significance of the latter connection will appear below.

The resistor R_b serves in Fig. 3 just as it does in Fig. 2. Thus Equations 14 and 15 apply in terms; that is, with e_{p_2} replacing e_{p_1}. But, from Equations 10 and 3

$$\frac{1}{R_2}=\frac{di_p}{de_{p_2}}=\frac{1}{R_{p_2}+(1+\mu_2)R_{p_1}+(1+\mu_1)(1+\mu_2)\frac{de_{k_1}}{di_p}} \tag{10a}$$

Substituting 15 into $10a$ and solving for

$$\frac{di_p}{de_{p_2}}$$

gives

$$\frac{di_p}{de_{p_2}}=\frac{1-(1+\mu_1)(1+\mu_2)\frac{mR_k}{R_k+R_b}}{R_{p_2}+(1+\mu_2)R_{p_1}+(1+\mu_1)(1+\mu_2)\frac{R_kR_b}{R_k+R_b}} \tag{19}$$

The numerator goes to zero when

$$R_b=R_k[(1+\mu_1)(1+\mu_2)m-1] \tag{20}$$

By choosing R_b to have the value given by 20 which evidently depends on μ_1, μ_2, m and R_k, the effective admittance of the circuit as given by 19 is reduced to zero. It is for this reason that the resistance R_b may be termed a balancing resistor. As a practical matter, however, this perfect balance cannot be maintained, because of deviations or fluctuations in the values of the parameters on which it depends. But, because of the high value of the denominator of 19, due in turn to the action of the series cathode feedback tubes, minor departures from perfect balance still leave a very low value for the admittance of the circuit. In one example, with

$$R_{p_1}=R_{p_2}=7{,}000 \text{ ohms}$$
$$\mu_1=\mu_2=38$$
$$R_k=10{,}000 \text{ ohms}$$
$$m=0.05$$

the value of R_b for balance is 14.44 megohms. For a ten per cent error in the value of this resistor, the admittance

$$\frac{di_p}{de_p}$$

as given by Equation 19 lies in the range of ± 0.0065 micromho, corresponding to an effective resistance R_2 for the circuit as a whole of 150 megohms. This evidently represents a marked improvement over the stability of the simpler balancing arrangement of Fig. 2.

In the foregoing analysis reactive currents such as might be drawn by interelectrode capacitances have not been taken into account. The balance of Figs. 2 and 3 can be extended to these as well, thus making the reactive component of

$$\frac{di_p}{de_p}$$

extremely small, as well as the conductive component. For example, in Fig. 3, C_p, C_{k_1} and C_{k_2} represent the principal interelectrode capacitances involved with the series cathode feedback triodes.

C_p can be lumped with the impedance network. C_{k_2} can be balanced by a condenser C_{b_2} on condition that the frequencies of interest do not extend above the range in which the transmission m through the follower tube is substantially a real number so that e_{k_2} and me_{p_2} are approximately in phase. To determine the required magnitude of the balancing condenser, the currents flowing through these two capacitances may be equated. Thus

$$C_{k_2}\frac{de_{k_2}}{dt}=C_{b_2}\left(m\frac{de_{p_2}}{dt}-\frac{de_{k_2}}{dt}\right) \tag{21}$$

or

$$C_{k_2}=C_{b_2}\left(m\frac{de_{p_2}}{de_{k_2}}-1\right) \tag{22}$$

When R_b is adjusted for conductive balance in accordance with Equation 20,

$$\frac{di_p}{de_{p_2}}=0$$

and in this case Equation 18 may be applied. This may be written, for the upper series triode, as

$$\frac{de_{p_2}}{de_{k_2}}=1+\mu_2 \tag{18a}$$

Hence

$$C_{b_2}=\frac{C_{k_2}}{m(1+\mu_2)-1} \tag{23}$$

Similarly, C_{k_1} may be balanced by a small condenser C_{b_1}, whose magnitude may be determined by equating currents as above. Thus

$$C_{k_1}=C_{b_1}\left(m\frac{de_{p_2}}{de_{k_1}}-1\right) \tag{24}$$

From Equation 10

$$de_{p_2}=[R_{p_2}+(1+\mu_2)R_{p_1}]di_p+(1+\mu_2)(1+\mu_1)de_{k_1} \tag{25}$$

If, as above,

$$\frac{di_p}{de_2}=0$$

$$\frac{de_{p_2}}{de_{k_1}}=(1+\mu_1)(1+\mu_2) \tag{18b}$$

and therefore the value of C_{b_1} for balance is, from (24)

$$C_{b_1}=\frac{C_{k_1}}{m(1+\mu_1)(1+\mu_2)-1} \tag{26}$$

The circuit of Fig. 3 as thus far described results in a current of a high degree of constancy through the impedance network 1 and the series triodes 4, 5 when the circuit is switched "on." As in Fig. 2, the switching may be carried out by the application of pulses to a buffer tube 16 whose cathode is directly connected to the cathode of the upper series triode. When the control grid of this buffer tube is sufficiently positive, all of the current through the lower series triode flows through the buffer tube so that the current through the upper series triode 5 and the impedance network is cut off. A typical control pulse e as applied to the control grid of the buffer tube is shown in Fig. 4. Assume that the steady bias of this grid is so chosen that the transfer of anode current from the buffer 16 to the upper series triode 5 is just half completed when the pulse is at potential e_a, that is e_a represents the grid potential of the buffer tube 16 at which half the regulated current flows through it and half through the upper series triode 5. This is merely a convenient way of denoting the point at which the switching nominally takes effect, and gives a corresponding "on" time t_1.

If the upper series triode 5 and the buffer tube are alike in characteristics and have the same anode potential, the voltage e_a will be equal to the potential of the grid of the upper series triode 5, regardless of the value of the common anode potential. But suppose the anode potential of the buffer tube 16 is fixed, for example, by throwing the switch S_1 to position A. When the anode potential e_{p_2} of the upper series triode 5 is reduced below this fixed potential, for example in the course of the addition of successive incremental charges to the condenser of the impedance network 1, the normal current regulation by the action of the series triode arrangement during the "on" condition drives the cathode of the upper series triode 5 to a lower potential. Accordingly the transfer potential of the switching action is reduced from the value e_a to another value such as e_b. Inasmuch as the leading and trailing edges of the switching pulse e are not infinitely steep; the duration of the "on" time is diminished from its proper value t_1 to a different and incorrect value t_2. Such a variation of "on" time with e_{p_2} is objectionable in many cases. For example, in any circuit in which a current which endures for a pre-assigned time is used as a measure of a charge, constancy of the time during which the current flows is of equal importance with constancy of the current.

This effect is overcome with the switch in position B in which the anode potential of the buffer tube is supplied, not from a fixed point of the source 12, but from the cathode of the output tube 15 which, as above stated, is connected as a cathode follower. It is characteristic of the cathode follower circuit that its cathode "follows" its control grid in potential, differing therefrom only by a small margin. Inasmuch as the grid potential of the output tube 15 is identical with the anode potential of the upper series triode 5, it results from this connection that the anode of the upper series triode 5 and the anode of the buffer tube 15 undergo substantially identical potential variations. Hence the transfer point in Fig. 1 remains at voltage e_a regardless of the value of e_{p_2}.

Various departures in detail from the circuit arrangements described above may be made without departing from the invention whose scope is defined in the appended claims.

What is claimed is:

1. The series combination which comprises a current source, a load in which the current of the source is to be held substantially constant independent of variations in the load, and a constant current path which comprises a first discharge device having an anode, a cathode and a control electrode, a second discharge device having an anode, a cathode and a control electrode, the anode of the first device being connected to the cathode of the second device, a resistor having one end connected to the cathode of the first device, the control electrodes of both devices being maintained at fixed potentials with respect to the other end of said resistor, means comprising a switching tube for depriving said load of said constant current, a cathode follower stage comprising another discharge device and a high cathode resistor, a connection from the anode of the second series device to the grid of said follower, and a connection from the cathode of said follower for supplying anode potential to said switching tube.

2. In combination with a current source and a network, apparatus for holding constant the current flowing from said source through said network which comprises a first discharge device connected for cathode feedback with its discharge path in series with the network, a second discharge device connected for cathode feedback with its discharge path in shunt with the series combination of the network and the first device, a connection for applying the anode voltage of the first device as a signal to a control electrode of the second device, and a balancing impedance element connecting the cathode of the first device to the cathode of the second device.

3. In combination with a current source and a network, apparatus for holding constant the current flowing from said source through said network which comprises a first discharge device connected for cathode feedback with its discharge path in series with the network, a second discharge device connected for cathode feedback with its discharge path in shunt with the series combination of the network and the first device, a connection for applying the anode voltage of the first device as a signal to a control electrode of the second device, and a balancing impedance element connecting the cathode of the first device to the cathode of the second device, said impedance element having a value such as to reduce the variational admittance of the discharge path of the first device to zero.

4. In combination with a current source and a network, apparatus for holding constant the current flowing from said source through said network which comprises a first discharge device connected for cathode feedback with its discharge path in series with the network, a second discharge device connected for cathode feedback with its discharge path in shunt with the series combination of the network and the first device, a connection for applying the anode voltage of the first device as a signal to a control electrode of the second device, a balancing impedance element connecting the cathode of the first device to the cathode of the second device, said impedance element having a value such as to reduce the variational admittance of the discharge path of the first device to zero, a by-pass tube, and means for switching the current from said network to said by-pass tube under control of switching pulses.

5. The combination in series with a current source and a load in which the current is to be held constant, of two discharge devices and a resistor, each device being connected for cathode feedback, the resistor serving as the feedback resistance of the first device, and this device and the resistor together serving as the feedback resistance of the second device, and means for balancing residual current variations not eliminated by said devices, which comprises a third discharge device connected for cathode feedback with its discharge path in shunt with the series combination of the load and the first two devices, a connection for applying anode voltage of the second device as a signal to the grid of the third device, and a balancing impedance element connecting the cathode of the first device to the cathode of the third device.

6. The series combination which comprises a current source, a load in which the current of the source is to be held substantially constant independent of variations in the load, and a constant current path which comprises a discharge device having an anode, a cathode and a control electrode, and a resistance element having one terminal connected to the cathode of said device, the control electrode of said device being maintained at a fixed potential with respect to the other end of said resistance element, means comprising a switching tube for depriving said load of said

constant current, a cathode follower stage comprising another discharge device and a high cathode resistor, a connection from the anode of the first-named device to the grid of said follower, and a connection from the cathode of said follower for supplying anode potential to said switching tube.

7. In combination with a current source and a network, apparatus for holding constant the current flowing from said source through said network, which comprises a first discharge device connected for cathode feedback with its discharge path in series with the network, a second discharge device connected for cathode feedback with its discharge path in shunt with the series combination of the network and the first device, a connection for applying the anode voltage of the first device as a signal to a control electrode of the second device, and a feedback path coupling the cathode of the first device to the cathode of the second device, said feedback path including an impedance element of a value such as to reduce the variational admittance of the discharge path of the first device to zero.

8. In combination with a current source and a network, apparatus for holding constant the current flowing from said source through said network which comprises a first triode and a resistor R_k connected for cathode feedback with the discharge path of the triode in series with the network, a second triode and a resistor R_c connected for cathode feedback with the discharge path of said second triode in shunt with the series combination of the network and the first triode, a connection for applying the anode voltage of the first triode as a signal to the grid of the second triode, and a balancing impedance element R_b connecting the cathode of the first triode to the cathode of the second triode, said impedance element being proportioned according to the formulae

$$R_b=R_k[(1+\mu_1)m-1]$$

$$m=\frac{e_c}{e_{p_1}}$$

where

μ_1 is the amplification factor of the first triode,
e_{p_1} is the anode voltage of the first triode, and
e_c is the cathode voltage of the second triode.

9. In combination with apparatus as defined in claim 8, a by-pass tube, and means for switching the current from said network to said by-pass tube under control of switching pulses.

10. The combination in series with a current source and a load in which the current is to be held constant of two triodes and a resistor R_k, each triode being connected for cathode feedback, the resistor serving as the feedback resistance of the first triode and this triode and the resistor together serving as the feedback resistance of the second triode, and means for balancing residual current variations not eliminated by said triodes, which comprises a third triode connected for cathode feedback with its discharge path in shunt with the series combination of the load and the first two triodes, a connection for applying anode voltage of the second triode as a signal to the grid of the third triode, and a balancing impedance element R_b connecting the cathode of the first triode to the cathode of the third triode, said impedance element being proportioned according to the formulae

$$R_b=R_k[(1+\mu_1)(1+\mu_2)m-1]$$

$$m=\frac{e_c}{e_{p_1}}$$

where

μ_1 is the amplification factor of the first triode,
μ_2 is the voltage amplification factor of the second triode,
e_{p_1} is the anode voltage of the first triode, and
e_c is the cathode voltage of the third triode.

11. The series combination which comprises a current source, a load in which the current of the source is to be held substantially constant independent of load variations, and a constant current path which comprises a first discharge device having an anode, a cathode and a single control electrode, a second discharge device having an anode, a cathode and a single control electrode, the anode of the first device being connected to the cathode of the second device, a fixed potential point, a resistor having one end connected to the cathode of the first device and the other end connected to said fixed potential point, means comprising a potential source and connections of insubstantial impedance for maintaining the control electrodes of both devices at potentials which are fixed with respect to said fixed potential point, a pulse source having two output terminals, a connection from one of said terminals to said fixed potential point, and a connection from the other of said terminals to the cathode of one of said devices, whereby pulses of said source operate to switch the current in said path.

12. The series combination which comprises a current source, a load in which the current of the source is to be held substantially constant independent of load variations, and a constant current path which comprises a first discharge device having an anode, a cathode and a single control electrode, a second discharge device having an anode, a cathode and a single control electrode, the anode of the first device being connected to the cathode of the second device, a fixed potential point, a resistor having one end connected to the cathode of the first device and the other end connected to said fixed potential point, means comprising a potential source and connections of insubstantial impedance for maintaining the control electrodes of both devices at potentials which are fixed with respect to said fixed potential point, means for depriving said load of said constant current, which depriving means comprises a switching tube having a cathode connected to the cathode of one of said devices, an anode connected to said source and a control electrode, a pulse source having two output terminals, a connection from one of said terminals to said fixed potential point, and a connection from the other of said terminals to the control electrode of said switching tube.

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