SWEEP CIRCUIT

Filed March 21, 1944

2 Sheets-Sheet 1

FIG. 1A

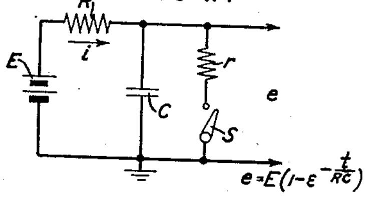


FIG. 1B

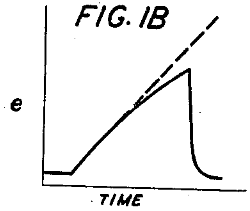


FIG. 1C

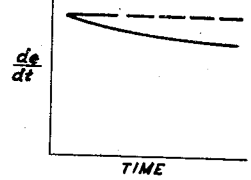


FIG. 2

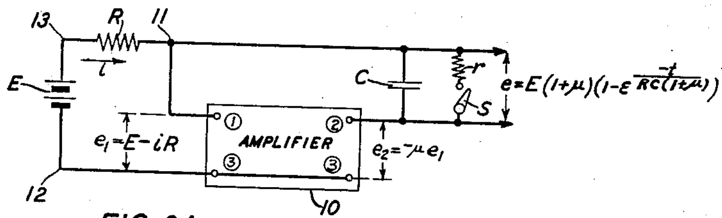


FIG. 3A

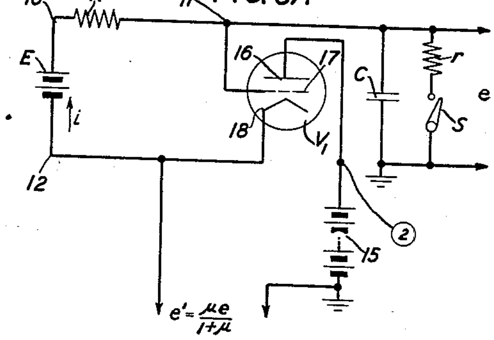


FIG. 3B

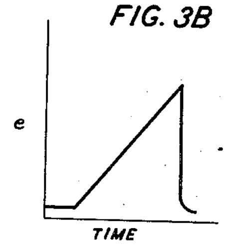


FIG. 3C

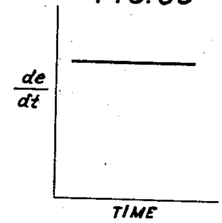
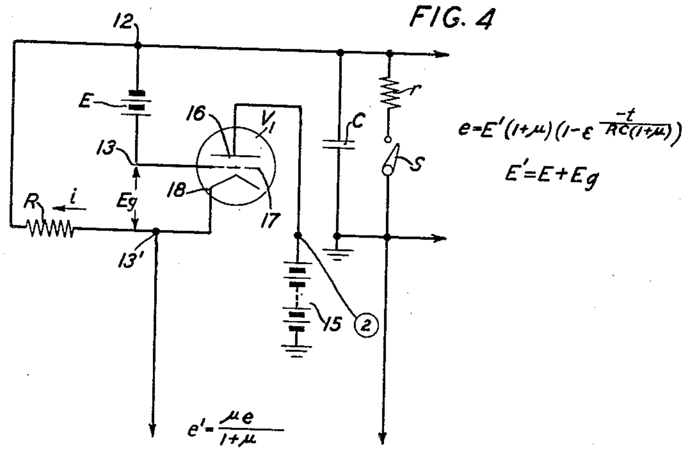


FIG. 4



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SWEEP CIRCUIT

Filed March 21, 1944 2 Sheets-Sheet 2

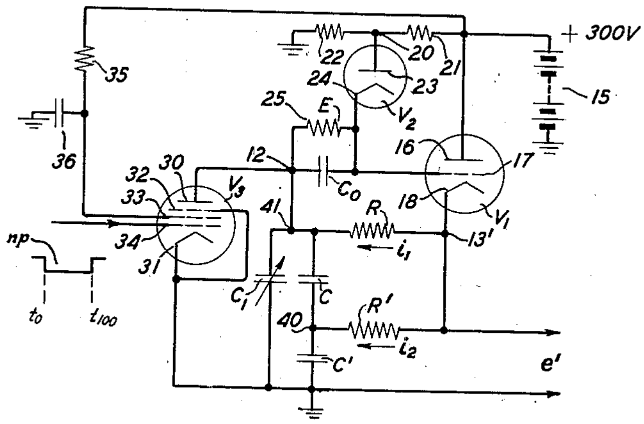


FIG. 5A

FIG. 5B

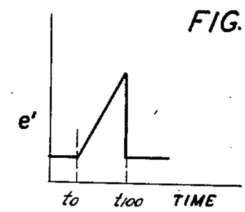
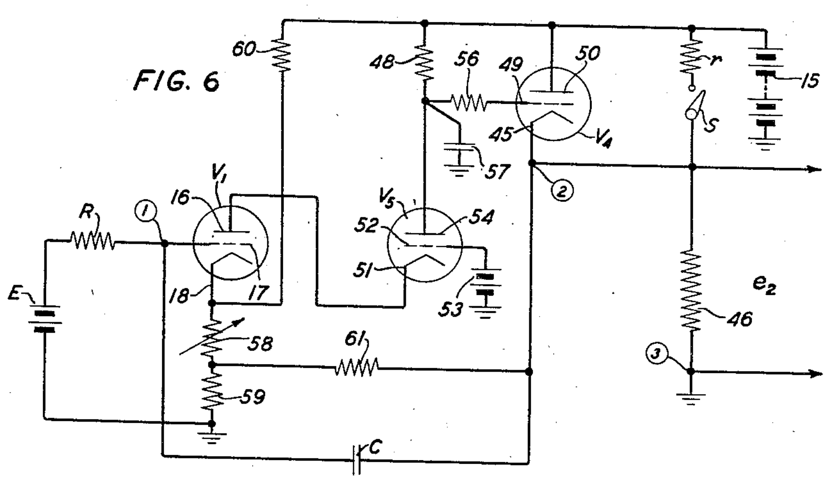


FIG. 6



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2,452,683

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SWEEP CIRCUIT

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Application March 21, 1944, Serial No. 527,457

2 Claims. (Cl. 250—36)

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This invention relates to an improvement in sweep circuits producing voltages of saw-tooth wave form, and is particularly useful when it is desired to obtain a voltage varying over a wide range linearly with time to a high degree.

The general object of the invention therefore is to provide an improved circuit for the generation of saw-tooth voltages.

The fundamental form of a saw-tooth voltage generator includes a sweep condenser which is rapidly charged from a source of voltage and then discharged at a controllable rate through a resistor. Alternatively, the condenser may be charged at a desired rate and then abruptly discharged. In this simple apparatus the variation in condenser voltage is never strictly linear with time, even over a short interval after the beginning of the controlled charge or discharge corresponding to a voltage change small in comparison to the maximum voltage of the condenser. Numerous circuits have been devised to improve the linearity of this voltage and several of these are described by O. S. Puckle in "Time Bases," chapter VII, published in 1943 by Chapman & Hall, Ltd.

The circuit of the present invention enables the desired linearity to be obtained throughout a total voltage change which is a large fraction of the maximum voltage on the sweep condenser and this enlargement of the useful range of the voltage variation is another object of the invention

In the circuit to be described, the optimum use is made of known expedients in a novel organization. By this organization there is made possible the attainment of substantially perfect linearity of time variation of voltage both for very rapid and for very slow rates of voltage change.

Accordingly, another object of the invention is to provide a sweep circuit capable of generating a voltage varying linearly with time over a wide range of voltage variation and over a wide range of time rates of such variation.

The invention is to be understood from the following description read with reference to the accompanying drawings, in which:

Fig. 1A is a diagram of a fundamental form of sweep circuit;

Figs. 1B and 1C exhibit respectively the variation with time of the voltage appearing across the sweep condenser of Fig. 1 as this condenser is being charged, and the variation with time of the rate of change of this voltage;

Fig. 2 is a circuit illustrative of the introduction of negative feedback for linearizing the voltage wave of Fig. 1B;

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Fig. 3A is a diagram of one form of the circuit embodying negative feedback;

Figs. 3B and 3C show, respectively, the voltage wave approximated by the circuit of Fig. 3A and the slope of this wave;

Fig. 4 is a diagram of a circuit electrically equivalent to the circuit of Fig. 3A but adapted to the introduction of further refinement;

Fig. 5A is a circuit including the refinement alluded to in connection with Fig. 4;

Fig. 5B is a graph of the time variation of voltage e' of Fig. 5A;

Fig. 6 is a circuit for producing a sweep voltage decreasing uniformly with time.

In all figures like elements are represented by like numerals and letters.

Referring first to Fig. 1A, at the time switch S is closed condenser C has been charged by battery E to a voltage appearing across the small resistance r. When switch S is opened condenser C begins to charge through resistance R and continues to charge until S is again closed. In Fig. 1B it is shown that the voltage e across condenser C rises at first approximately linearly but more and more slowly as the charge increases. The rate of voltage rise from the time t_1 when S is opened to t_2 when S is again closed is shown in Fig. 1C. Condenser C has at any instant between the opening and reclosing of S the voltage

$$e=E\left(1-\epsilon^{-\frac{t}{RC}}\right) \quad (1)$$

in which t is the charging time counted from the opening of switch S.

If e is a voltage used, for example, to position the electron spot on the screen of a cathode ray oscilloscope, successive positions of this spot may correspond linearly to successive values of e but not so to successive instants of time. There results a spot displacement error graphically shown by the curve of Fig. 55 on page 82 of Puckle's work, "Time Bases," above referred to. This curve shows that the error in spot velocity increases much more rapidly than the error in spot position. It is, of course, desired to render negligible the error in spot velocity, that is, to bring the curve

$$\frac{de}{dt}$$

in Fig. 1C nearly to a horizontal straight line, thus substantially eliminating the error in spot position even if condenser C is charged to a considerable fraction of the voltage of battery E.

Referring now to Fig. 2, amplifier 10 is introduced into the charging circuit, its input being connected in shunt across terminal 11 of resistance R and terminal 12 of battery E remote from junction 13 of battery E and resistance R. Amplifier 10 is understood to include an odd number of phase reversals between its input terminals 1, 3 and its output terminals 2, 3. Ground connection may be made at any of the terminals 1, 2 or 3. These numerals are encircled in all figures where they appear. If at any instant charging current i flows in resistance R, the input voltage to amplifier 10 is $e_1=E-iR$ resulting in an output voltage $e_2=-\mu e_1$, where μ is the amplification factor of amplifier 10. The plates of the condenser C are connected as shown in Fig. 2, namely, one plate to terminal 11 of resistance R, the other to output terminal 2 of amplifier 10. The output voltage of amplifier 10 is thus, so far as concerns condenser C, in series with that of battery E, and the voltage across condenser C when switch S is opened is given by the formula

$$e=E(1+\mu)\left(1-\epsilon^{-\frac{t}{RC(1+\mu)}}\right) \qquad (2)$$

which may be compred with the voltage of condenser C in Fig. 1A, namely,

$$e=E\left(1-\epsilon^{-\frac{t}{RC}}\right) \qquad (1)$$

The linearity improvement due to the negative feedback from amplifier 10 may be realized by rewriting the above formulae as follows:

Without feedback:

$$e=E\left(1-\epsilon^{-\frac{t}{RC}}\right) \qquad (1)$$

$$=E\left(\frac{t}{RC}-\frac{t^2}{2R^2C^2}+\frac{t^3}{6R^3C^3}-\cdots\right) \qquad (1a)$$

$$\frac{de}{dt}=\frac{E}{RC}\epsilon^{-\frac{t}{RC}}=\frac{E}{RC}\left(1-\frac{t}{RC}+\frac{t^2}{2R^2C^2}\cdots\right) \qquad (1b)$$

With negative feedback: since in Fig. 2

$$E=iR+\frac{1}{C}\int i\,dt-\mu(E-iR)$$

$$E(1+\mu)=iR(1+\mu)+\frac{1}{C}\int i\,dt$$

we have

$$e=E(1+\mu)\left(1-\epsilon^{-\frac{t}{RC(1+\mu)}}\right)$$

$$=E(1+\mu)\left(\frac{t}{RC(1+\mu)}-\frac{t^2}{2R^2C^2(1+\mu)^2}+\cdots\right) \qquad (2a)$$

$$\frac{de}{dt}=\frac{E}{RC}\epsilon^{-\frac{t}{RC(1+\mu)}}=$$

$$\frac{E}{RC}\left(1-\frac{t}{RC(1+\mu)}+\frac{t^2}{2R^2C^2(1+\mu)^2}\cdots\right) \qquad (2b)$$

Comparing the terms of the first order in the parentheses of Equations 1b and 2b, we see that for each case the initial rate of voltage rise is

$$\frac{de}{dt}=\frac{E}{RC}$$

and to a first approximation the distortion factor is

$$\frac{t}{RC}$$

without feedback and

$$\frac{t}{RC(1+\mu)}$$

with feedback.

Neglecting the second order distortion terms, if the distortion factor is required not to exceed Δ so that

$$\frac{de}{dt}=\frac{E}{RC}(1-\Delta)$$

the time of charge without feedback must be no greater than $t=\Delta RC$, whereas with feedback this charging time may be $t=\Delta RC\ (1+\mu)$. In the respective cases the maximum value of e is ΔE from Equation 1a, but ΔE $(1+\mu)$ from Equation 2a. The allowable change in condenser voltage for a prescribed non-linearity is thus greater in the ratio $1+\mu$ with negative feedback than without.

In Fig. 3A vacuum tube V1 is used as amplifier 10 of Fig. 2. Battery 15 supplies 300 volts to anode 16 of V1, of which grid 17 is connected to junction 11 of R and C. Cathode 18 of V1, heated by conventional means not shown, is connected to negative terminal 12 of battery E. It will be observed that points 1 and 3 of Fig. 2 correspond respectively to grid 17 and to cathode 18 in Fig. 3A, while the plate of condenser C remote from resistance R is grounded. For voltage variations at anode 16, this element is grounded through battery 15 and so is effectively connected to condenser C. The ground here corresponds to point 2 of Fig. 2. Such a circuit has been found useful for very rapid sweeps lasting for intervals of the order of 100 microseconds between opening and reclosing of switch S. Actually, switch S for such use is an electronic switch as will later appear.

Sweep voltage is obtainable from the circuit of Fig. 3A either across condenser C or between cathode 18 and ground. At the latter sweep terminals the variable voltage is

$$e'=\frac{\mu e}{1+\mu}$$

where e is the condenser voltage given by Equation 2.

Suitable values for the voltages and circuit elements in Fig. 3A are as follows: E=50 volts; R=200,000 ohms; C=250 micromicrofarads; μ=20. RC is here 50 microseconds and from the formula

$$\frac{de}{dt}=\frac{E}{RC}$$

the voltage e will rise when S is opened at the rate of about one volt per microsecond from its initial value, namely, the small voltage across r when S is closed. Tube V1 is suitably a triode, such as one-half of a 6SN7-GT, while r may be a few hundred ohms. If switch S is opened for 100 microseconds, e will rise to approximately 100 volts in this interval, falling short by some 4 per cent as shown by Equation 2a. The charging energy is, of course, supplied by battery 15 and E is relied on to fix the direction of flow of current i in resistor R and to control the rate of rise of the voltage across the sweep condenser.

In the circuit of Fig. 4 use is made of the fact last stated. Here negative terminal 12 of battery E is connected to the plate of condenser C remote from ground, positive terminal 13 is connected to grid 17 of tube V1. When switch S is closed, the current flowing in tube V1 biases cathode 18 some 15 volts positive to grid 17. The controlling voltage across resistor R then is the sum of E and the cathode to grid voltage E_g, or E'=50+15=65 volts. On the opening of switch S, the voltage across condenser C rises as in the case of Fig. 3A. In the circuit of Fig. 4 sweep voltages of nearly the same value are obtainable either across the sweep condenser or between cathode 18 and ground.

Neither the circuit of Fig. 3A nor that of Fig. 4 provides absolute linearity. The curves of Figs. 3B and 3C are ideal curves and are approached much more closely when limited amplification is available if the negative feedback improvement already described is supplemented by a circuit integrating the output sweep voltage.

Referring now to Fig. 5A, a pentode V3, suitably a 6AC7, replaces resistance r and switch S between point 12 and ground. Battery E is replaced by the voltage across condenser C_0, a voltage of 50 volts supplied from battery 15 through tap 20 on a voltage divider consisting of resistors 21 and 22 of resistances 100,000 and 20,000 ohms respectively. Condenser C_0 is charged to such voltage through diode V2 which may be one-half of a 6H6. Plate 23 of tube V2 is connected to tap 20 and cathode 24 is connected to one plate of condenser C_0 and to grid 17 of tube V1. Resistor 25, preferably of some 2 megohms resistance, shunts condenser C_0 and provides a conductive path over which anode voltage is supplied to anode 30 of tube V3.

Tube V3 is normally conducting, its cathode 31 being grounded and connected to its suppressor grid 32. The potential of screen grid 33 is controlled through 70,000-ohm resistor 35 from battery 15 and is shunted to ground through 0.1-microfarad condenser 36, which with resistor 35 constitutes a filtering circuit for the voltage of screen 33. A negative voltage pulse np, derived from whatever device is used for timing the start of the sweep voltage, is applied to grid 34 to annul the conductivity of tube V3 for a time interval which may be 100 microseconds from t_0 to t_{100}. The anode-cathode path of tube V3 absorbs, while V3 is conducting, a small fraction of the voltage between tap 20 and ground, corresponding to the drop across resistor r in Figs. 1A to 4, inclusive. Switch S, here replaced by tube V3, is abruptly opened at time t_0 and equally abruptly closed at time t_{100}.

At the moment of extinction of the conductivity of tube V3, the full voltage from tap 20 is effective to control the charging of condenser C through resistance R. Condenser C_0 is preferably of 0.006-microfarad capacitance, while resistor 25 is as stated of 2 megohms resistance so the time constant $R25C_0$ is more than 100 times the sweep interval, wherefore the voltage between grid 17 and point 12 is substantially constant. C_0, controlled in voltage by diode V2, thus replaces battery E of the preceding Figs. 1A to 4, inclusive. The charging of condenser C begins when tube V3 ceases to conduct and continues to the time of disappearance of the negative voltage pulse on grid 34. When tube V3 again conducts what small change in the voltage of condenser C_0 has taken place in the charging interval of condenser C is overcome practically instantly. C_0 is charged from diode V2 through the small resistance offered by tube V3, and this is a few hundred ohms making the time constant of this path a few microseconds. Cathode 18 of tube V1 is conductively grounded through resistor R and tube V3 when the latter is conducting, but is ungrounded during the sweep just as in Figs. 3A and 4, except when voltage e' is applied across a conductive load. During the sweep, cathode 24 is at a higher potential than anode 23, hence tube V_2 is not conducting.

There is added in Fig. 5A the integrating circuit R′ and C′. Condenser C′ is interposed between ground and condenser C and resistor R′ is connected between the junction of these condensers and cathode 18. The sweep voltage from the circuit of Fig. 5A is taken between cathode 18 and ground, which again corresponds to point 2 of Fig. 2. Trimming condenser C1 connected between ground and point 12 serves for final adjustment of the rate of rise of voltage e'.

To show the optimum relationship between the time constants RC and R′C′ when μ is the available amplification factor, the appropriate analysis treats the mesh R′C′ as charged by the voltage E′ across R′ while across R′C′ appears the voltage e'. If R is traversed by the current i_1 and R′ by the current i_2 as shown in Fig. 5A, then in operational terms

$$E'=i_1\left(R+R'+\frac{1}{pC}\right)-i_2R' \qquad (3)$$

$$e'-i_1R'+i_2\left(R'+\frac{1}{pC'}\right) \qquad (4)$$

$$=\frac{\mu}{1+\mu}\left(\frac{i_1}{pC}+\frac{i_2}{pC'}\right) \qquad (4a)$$

where p is the operator

$$\frac{d}{dt}$$

Equations 3 and 4 are the normal mesh equations, while Equation 4a relates the voltage of grid 17,

$$\frac{i_1}{pC}+\frac{i_2}{pC'}$$

to the voltage e' of cathode 18.

The detailed analysis is omitted here for the sake of brevity but it may be shown that

$$\frac{de'}{dt}=\frac{\mu}{1+\mu}\cdot\frac{C+C'}{RCC'}\cdot E'\left(1+\frac{1}{p}D_1+\frac{1}{p^2}D_2+\ .\ .\ .\right) \qquad (5)$$

when D_1 and D_2 are distortion terms, D_2 involving D_1 given by

$$D_1=\frac{1}{R'(C+C')}-\frac{1}{1+\mu}\cdot\frac{RC+R'(C+C')}{RCR'C'} \qquad (5a)$$

which is to be made zero to eliminate completely the first order of distortion in

$$\frac{de'}{dt}$$

When D_1 is made zero by choice of R′ and C′ for the preestablished values of R, C and μ, D_2 becomes

$$D_2=-\frac{1}{1+\mu}\cdot\frac{1}{RCR'C'} \qquad (5b)$$

$$(D_1=0)$$

and Equation 5 becomes

$$\frac{de'}{dt}=\frac{\mu}{1+\mu}\cdot\frac{C+C'}{RCC'}\cdot E\left(1-\frac{t^2}{2(1+\mu)RCR'C'}\ \cdot\cdot\cdot\right) \qquad (6)$$

If R, μ and C are already established, and it is desired to make $C'=n\times C$, the proper value of R′ is from Equation 5a.

$$R'=R\frac{\mu n-1}{(n+1)^2}R \qquad (7)$$

and

$$R'C'=\frac{n(\mu n-1)}{(n+1)^2}RC \qquad (8)$$

Equation 8 thus gives the appropriate relationship of R′ to R when for any reason R, μ and C are established and C′ has been arbitrarily chosen. In practice, n will be small for the sake of economy of condensers. If $n=1$, and $\mu=20$, $R'=4.75R$ and $R'C'=4.75RC$. A value of 5 for n will rarely be exceeded. In this case with R, μ and C as before

$$R'=\frac{100-1}{(1+5)^2}=2.75\ R$$

and $R'C'=13.75RC$ approximately,

In Equations 3, 5 and 6 the voltage E' is the sum of the voltage E, namely 50 volts, and the voltage of cathode 18 with respect to grid 17 which is 15 volts in the circuit illustrated in Fig. 5A.

From Equation 5, for an undistorted sweep,

$$\frac{de'}{dt}=\frac{\mu}{1+\mu}\cdot\frac{C+C'}{RCC'}\cdot E'$$

The first order distortion term is corrected by proper choice of R' if C and C' are equal, and the second order distortion term namely, the term in t^2 of Equation 6 is

$$-\frac{t^2}{2(1+\mu)}\cdot\frac{1}{RCR'C'}$$

If a sweep of 100 volts is desired, as illustrated in Fig. 5B, in 100 microseconds, one may take $\mu=20$; $C=C'=1000$ micromicrofarads, $R=124{,}000$ ohms, in which case

$$\frac{de'}{dt}$$

becomes 10^6 or one volt per microsecond, and $t=100\times10^{-6}$ seconds the sweep desired. In this case $R'=4.75R=590{,}000$ ohms and the second order term becomes one-third of one per cent. This is error in the rate of voltage rise at the end of the 100-microsecond interval and according to the customary definition measures the non-linearity of the voltage-time curve.

A feature of the circuit of Fig. 5A is the connection of diode V2 in such wise that a constant charge is maintained on condenser C_0 unaffected by the average charge of condenser C. I am aware that diodes have previously been used to supply constant potential to a condenser located as is C_0 in the circuit of Fig. 5A but in the circuits so far known the junction 41 of R and C is connected directly to grid 17 and condenser C_0 is inserted between R and cathode 18. The diode connection used in the present invention provides for the rapid restoration of any voltage lost by C_0 in the sweep, even if there is a variation in the repetition rate of the negative voltage pulse on grid 34 of tube V3, so that for each sweep the voltage on condenser C_0 shall be the same. In the circuit of Fig. 5A, when the negative signal passes from grid 34 of tube V3, the diode charges C_0 through the small resistance of tube V3. If this resistance is 1000 ohms and the capacity of C_0 is .006 microfarad, the time constant of 6 microseconds determines the recharging of C_0 whereas in some heretofore known circuits C_0 is charged through a large resistance connection between cathode 18 and ground, and its normal voltage may not be fully restored before the appearance of a succeeding negative pulse on grid 34.

The combination of an integrating circuit with negative feedback is most important where the available amplification is limited. When μ is sufficiently large, the integrating circuits R'C' (Fig. 5A) may be omitted. This is done in the circuit of Fig. 6 where tubes V_1 and V_5 constitute a direct current series amplifier succeeded by cathode follower tube V_4. Cathode 45 of tube V_4 is connected to ground through resistor 46, suitably of about 100,000 ohms resistance. Ground here is at point 3; condenser C is connected between point 2 (cathode 45 of tube V_4), and point 1 (grid 17 of tube V_1); and the sweep voltage is taken across resistor 46. As will appear, this sweep voltage may be regarded as a rising negative voltage progressively canceling an initial charge or condenser C.

In a particular application it was desired to cause the charge of condenser C to decrease from 200 to 100 volts in an interval varying from 100 to 400 seconds. With $R=3$ megohms, $C=4$ microfarads and $E=3$ volts, there is a cancellation of the initial charge of condenser C at the rate of one volt in four seconds. It has been found possible with the circuit of Fig. 6 to obtain a sweep of 100 volts in 400 seconds with a distortion of less than one per cent at the end of the sweep interval. It will be seen from Equation 2b that to reduce the first order distortion term to seven-tenths of one per cent with $RC=12$ and $t=400$ seconds, the value of μ required is 5000. For $E=12$, with $\mu=5000$, the 100-volt change across resistor 46 occupies 100 seconds and the distortion in

$$\frac{de_2}{dt}$$

becomes one-sixth of one per cent.

In Fig. 6 tubes V_1 and V_5 are two triodes, suitably the two parts of a 6SL7GT constituting with tube V_4 a direct current series amplifier. Voltage to anode 50 of tube V_4 is supplied directly from battery 15. Anode 16 of tube V_1 is connected directly to cathode 51 of tube V_5. Of the latter tube grid 52 is made positive with respect to cathode 51 by battery 53 which may conveniently be 45 volts derived through a voltage divider from battery 15, and anode 54 is supplied from battery 15 through resistor 48. From the end of resistor 48 remote from battery 15 anode 54 is connected through resistor 56 to grid 49 of tube V_4, a 6SN7. Condenser 57 is in circuit between the ground and the junction of resistors 48 and 56 and with resistor 56 serves to prevent oscillations of voltage on grid 49. Resistor 56 is of the order of 100 ohms while condenser 57 is about .00025 microfarad capacity. Through resistor 48 of about 10 megohms resistance, voltage is supplied from battery 15 to anode 54 of V_5 and thus from cathode 51 to anode 16 of V_1. Cathode 18 of V_1 is grounded through resistors 58 and 59 in series. Across these resistors between cathode 18 and ground is impressed a voltage derived through resistor 60 from battery 15 to provide a suitable biasing voltage for grid 17. Resistor 58 is made variable for this adjustment. Between ground and grid 17 are connected battery E and resistor R in series as in Fig. 1. Resistor 61 of about 80,000-ohms resistance provides positive feedback from cathode 45 of V_4 to the junction of resistors 58 and 59 which are conveniently 200 and 100 ohms respectively.

When switch S is closed battery 15 charges condenser C through the small resistance r and the low resistance to ground of resistors 58 and 59 and the grid-cathode path of V_1, grid 17 being now positive to cathode 18. The voltage now applied to charge condenser C is that across resistance 46, which is suitably chosen twice r. Condenser C is thus charged to 200 volts, positive toward point 2 and negative toward point 1, grid 17 becoming slightly positive with respect to cathode 18. The time constant RC is of the order of seconds for which reason the specifically described arrangement of Fig. 6 is adapted to slowly as well as to rapidly repeated operation. On the opening of switch S grid 17 tends to become negative to cathode 18, and battery E takes control of the circuit to discharge condenser C at a rate determined by the voltage drop across R. As the charge on condenser C begins to decrease the potential at point 2 begins also to fall. This results from a minute potential rise at grid 17 of V_1, which change is reversed at anode 16 wherefore the potential at cathode 51 of V_5 falls. Since grid 52 is maintained by battery 53 at a fixed voltage with respect to ground the fall of potential at cathode 51 is reflected as a fall also at anode 54. This potential fall at anode 54 appears also in grid 49 of V_4, a cathode follower tube of which cathode 45 follows closely in potential grid 49. The fall in potential in cathode 45 instigated by the rise of potential at grid 17 is returned through condenser C to oppose the change in potential at grid 17.

The negative feedback from cathode 45 to grid 17 thus checks nearly completely the tendency of grid 17 to rise in voltage. The amplification involved is that of the direct current amplifier consisting of tubes V_1 and V_5 in tandem and to raise this factor to the value $\mu=5000$ positive feedback is provided through resistor 61 from cathode 45 of V_4 to cathode 18 of V_1. Point 1 therefore remains at substantially constant potential, that of cathode 18, and E being constant there is a constant voltage drop across resistor R through which a constant current flows cancelling linearly with time the original charge on condenser C. Point 2 progressively falls in potential as C is discharged and this falling potential is the decreasing sweep voltage taken off across resistor 46. In practice, it has been found that the potential at grid 17 actually changes about .02 volt during a sweep over a range of 100 volts.

In such a sweep the first order distortion term from Equation 2b is

$$\frac{t}{RC(1+\mu)}$$

For $t=100$ seconds, $RC=12$ and $\mu=5000$, the distortion is .17 per cent. With the specified circuit elements of Fig. 7 the initial closing of switch S charges condenser C through grid 17 to about 200 volts and this voltage is reduced to 100 volts at a rate of decrease determined by the voltage of battery E. It is obvious that a faster cancellation of the voltage on condenser C may be obtained by the proper selection of R, C and E.

What is claimed is:

1. A circuit for the production of a sweep voltage varying linearly with time at a rate determined by a unidirectional control voltage comprising a first, a second and a third thermionic vacuum tube having each at least a cathode, a control grid and an anode, a first resistance connected between ground and the cathode of the first tube, a second resistance connected between ground and the cathode of the third tube, a direct connection between the anode of the first tube and the cathode of the second tube, a conductive connection between the anode of the second tube and the control grid of the third tube, power supply for said tubes including a source of unidirectional voltage conductively connected negatively to ground and positively to the cathode of the first tube and to the anodes of the second and third tubes, a sweep condenser connected between the cathode of the third tube and the control grid of the first tube, a source of unidirectional control voltage connected negatively to ground and positively through a third resistance to the control grid of the first tube, a fourth resistance connected between the cathode of the third tube and a point on the first resistance and a switching circuit connected between the cathode and the anode of the third tube operable directly to charge initially the sweep condenser and thereafter reversely to enable said condenser to be discharged at a rate determined by the magnitude of the control voltage, thereby providing across the second resistance a voltage decreasing substantially linearly with time.

2. A circuit for the production of a sweep voltage varying linearly with time at a rate determined by a unidirectional control voltage comprising a first, a second and a third thermionic vacuum tube having each at least a cathode, a control grid and an anode, a first resistance connected between ground and the cathode of the first tube, a second resistance connected between ground and the cathode of the third tube, a direct connection between the anode of the first tube and the cathode of the second tube, a conductive connection between the anode of the second tube and the control grid of the third tube, power supply for said tubes including a source of unidirectional voltage conductively connected negatively to ground and positively to the cathode of the first tube to the anodes of the second and third tubes, a sweep condenser connected between the cathode of the third tube and the control grid of the first tube, a source of unidirectional control voltage connected negatively to ground and positively through a third resistance to the control grid of the first tube and a switching circuit connected between the cathode and the anode of the third tube operable directly to charge initially the sweep condenser and thereafter reversely to enable said condenser to be discharged at a rate determined by the magnitude of the control voltage, thereby providing across the second resistance a voltage decreasing substantially linearly with time.

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