Feb. 23, 1932. F. E. TERMAN 1,846,043

ELECTRON TUBE CIRCUIT

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FIG. 1

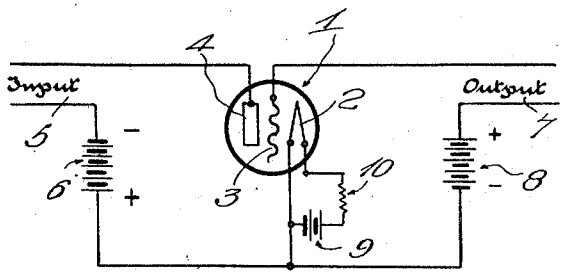


FIG. 2

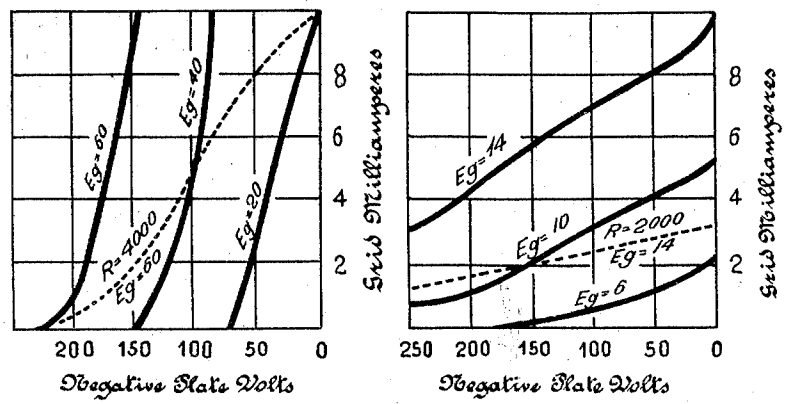
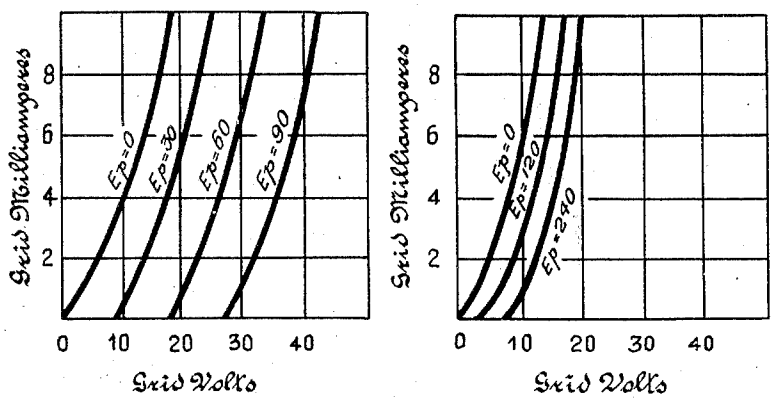


FIG. 3



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FIG. 4

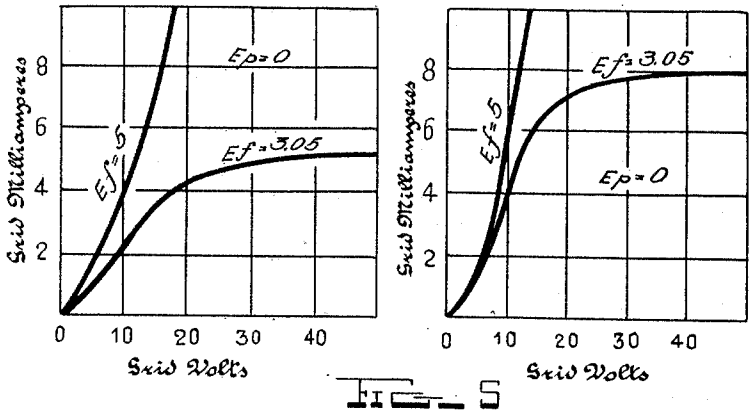


FIG. 5

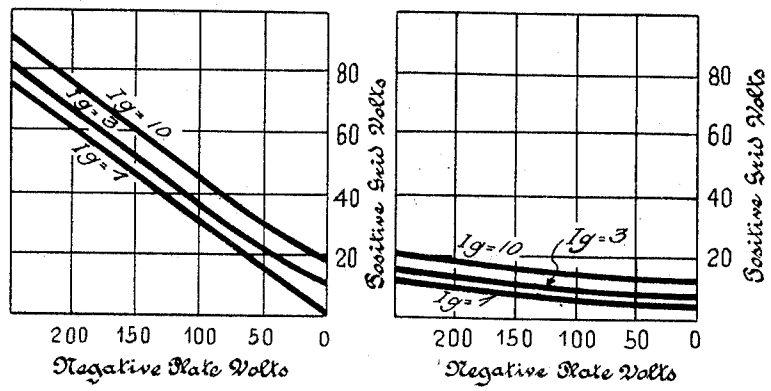


FIG. 6

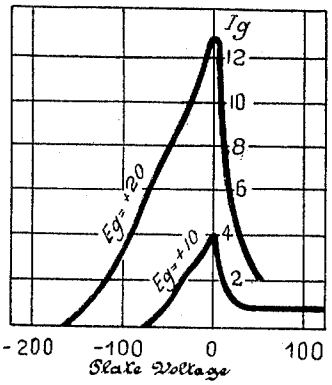


FIG. 8

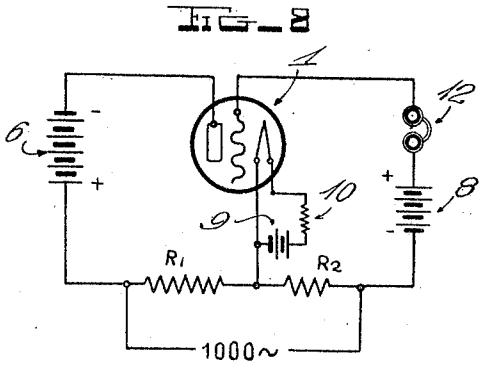
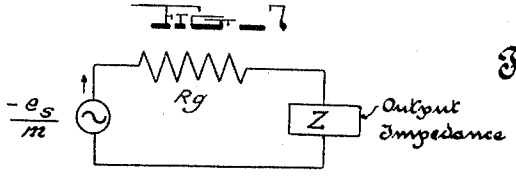


FIG. 7



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Fig. 9

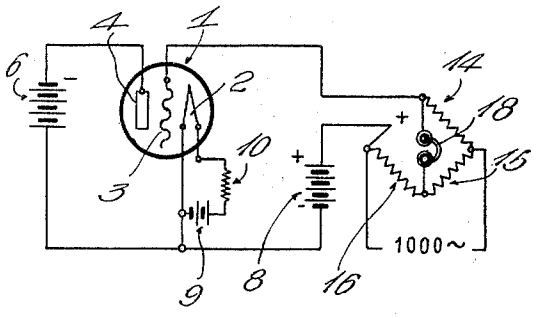


Fig. 10

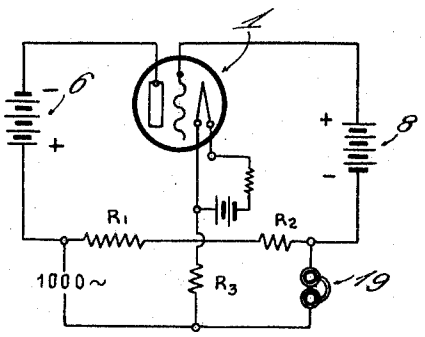


Fig. 11

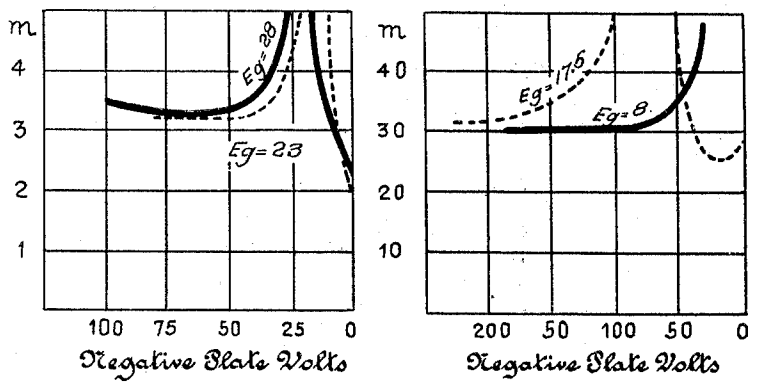
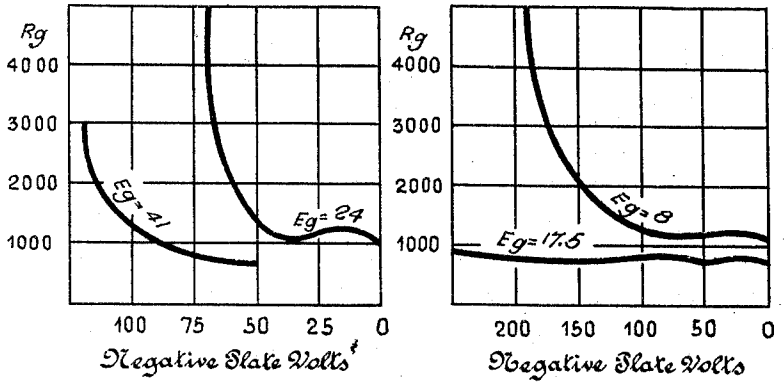


Fig. 12



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UNITED STATES PATENT OFFICE

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ELECTRON TUBE CIRCUIT

Application filed November 7, 1929. Serial No. 405,363.

My invention relates broadly to electron tube circuits and more particularly to an inverted vacuum tube system.

One of the objects of my invention is to provide an electron tube circuit operating as a voltage reducing power amplifier.

Another object of my invention is to provide an arrangement of electron tube circuit in which voltage applied to the input system may be reduced and delivered to the output system and in which a smaller voltage exists in the output system, according to a ratio dependent upon the amplification constant of the tube.

A further object of my invention is to provide an arrangement of electron tube circuit having the characteristic or voltage step-down as distinguished from a system in which the voltage amplitude is increased in successive stages.

My invention has various applications where the problem arises of reducing a high voltage to a smaller potential which will follow all of the voltage variations which are impressed thereon. The circuit arrangement of my invention is particularly adapted as an oscillograph or as a power transformer in a power distribution system where it is necessary to reduce potentials of hundreds of thousands of volts to relatively small voltages for distribution to circuits for domestic or commercial consumption.

The circuit arrangement of my invention is applicable in oscillator systems, frequency control systems, in circuits for measuring voltage, in rectifier circuits, in circuits employing multiple electron tubes and in numerous other instances, as will be more fully understood from the specification hereinafter following by reference to the accompanying drawings in which:

Figure 1 diagrammatically illustrates the elemental circuit arrangement for the electron tube system of my invention; Fig. 2 illustrates characteristic curves showing the relationship between plate voltage and grid current at constant grid voltage in two standard types of electron tube; Fig. 3 shows characteristic curves illustrating the relationship between grid current and grid voltage at constant plate voltage in two standard type tubes arranged in the circuit of my invention; Fig. 4 illustrates characteristic curves for the types of tubes on which measurements illustrated in Figs. 2 and 3 were taken and showing the effects of saturation; Fig. 5 shows a set of curves illustrating the relation of plate and grid voltages required for constant grid current in the circuit of my invention; Fig. 6 illustrates the static characteristic of the vacuum tube circuit of my invention; Fig. 7 is a theoretical diagram for more clearly explaining the operation of the circuit of my invention; Fig. 8 shows one arrangement of circuit which I have employed for measuring the step-down ratio obtainable in the vacuum tube circuit of my invention; Fig. 9 shows a circuit which I have employed for measuring the dynamic grid resistance of the inverted vacuum tube; Fig. 10 shows a circuit for measuring the reflex mutual conductance of the inverted vacuum tube; Fig. 11 shows characteristic curves for two standard forms of tube showing the step-down ratio in the tube circuit of my invention; and Fig. 12 illustrates in graphic form the dynamic grid resistance for tubes operated in accordance with my invention.

The basic circuit of the system of my invention is shown in Fig. 1. The essential features of this circuit are: (1) the grid is operated at a positive potential and so draws considerable current; (2) the plate is operated at a negative potential and so draws no current; and (3) the input circuit is the plate circuit, while the output circuit is the grid circuit. In Fig. 1 the electron tube 1 is shown including a cathode 2, a grid 3 and a plate 4. The input circuit is shown at 5 connected between plate 4 and cathode 2 through battery system 6. The negative side of battery system 6 connects to the input circuit. The output circuit is indicated at 7 disposed in series with the grid 3 and the cathode 2 with battery system 8 disposed therein, the positive terminal of the battery system 8 being connected to the input circuit. The cathode 2 is heated by battery 9, which may be suitably controlled by resistor 10.

The vacuum tube in the circuit of my invention acts as a voltage reducer, or voltage step-down device, because a voltage applied at the input, i. e., to the plate has the same effect on the grid current as though a similar but much smaller voltage had instead been added to the grid battery. If the vacuum tube used has a voltage amplification factor of μ, the step-down ratio will be approximately μ. The vacuum tube circuit of my invention acts as a power amplifier, for with the plate negative practically no energy is consumed in the plate circuit when a voltage is applied to the input, while at the same time this input voltage controls an appreciable grid current, thus controlling considerable energy in the grid, or output, circuit.

The operation of the vacuum tube circuit of my invention can best be visualized in terms of curves giving the relation between grid current and plate and grid voltages. A complete set of such curves for two representative tubes is given in Figs. 2, 3, 4, 5, and 6. One of these tubes has a μ of about 3 (step-down ratio of approximately 3) while the other has a μ of about 30 (step down ratio of approximately 30. As the two companion sets of curves are plotted to the same scales, and apply to tubes very similar to each other in general construction except for the value of μ, the effect of changing the step-down ratio can be readily visualized.

The charts on the left in Figs. 2, 3, 4, 5, 11 and 12 are all prepared by an investigation of the type of tube known as CX—371. The charts on the right in the above figures were all prepared by investigating the characteristics of the tube known as UX—240. All potentials in the figures are measured with respect to the negative filament lead.

The curves of Fig. 2 show the relation between grid current and negative plate voltage for various values of positive grid voltage. The results are seen to have a form similar to the E_g—I_p (grid-voltage plate current) curves of the usual vacuum-tube circuit. An important feature is that each curve in Fig. 2 has a straight line portion of more or less length. Variations of plate voltages within the boundaries of this straight line portion give rise to variations in grid current that are directly proportional to the plate voltage changes. When operating on this straight line part of the characteristic the grid current variations give a distortionless representation of any A. C. or D. C. voltage applied at the input shown in Fig. 1.

The dash lines in Fig. 2 give the characteristic when a resistance is inserted in series with the grid. The effect of this resistance is to straighten out the characteristic, and to extend greatly the range of plate voltage over which the grid current is proportional to changes in plate potential.

Fig. 3 gives the same information as Fig. 2 but in another form. The curves of Fig. 3 correspond to the usual E_p—I_p curves of the vacuum tube, and have the same form. The effects of limited electron emission from the filament are shown in Fig. 4. It is seen that as long as the filament temperature is sufficient to emit a small surplus above the number of electrons flowing to the positive grid, the filament temperature is unimportant. Portions of the curves in Fig. 4 where the electron emission is insufficient to furnish the necessary supply of electrons required for normal operation are flattened out as the figure indicates. The departure from normal takes place at lower and lower grid currents as the filament voltage is reduced because the electron emission drops rapidly with reduction in filament heating.

The curves in Fig. 5 are very important in the theory of operation of the vacuum tube circuit of my invention as will be explained hereinafter.

Fig. 6 differs from Fig. 2 only in showing the effect on the grid current of making the plate voltage positive. It is seen that as soon as the plate begins to take current, the grid circuit is robbed of a large part of its current. The very sudden change of curvature in the characteristics at zero plate volts indicates that this point gives a large rectifying effect.

The theory of the vacuum tube circuit of my invention rests upon the fundamental fact that the current flowing to the positive grid depends upon the electrostatic field existing between filament and grid, and is substantially independent of how the field is produced. Both the grid and plate potentials affect the magnitude of this field. It can be shown from the theory of electrostatics that the actual field is proportional to the quantity (E_g+E_p/m), where E_g and E_p are the potentials of the grid and plate respectively, and m is a constant that is determined by the geometrical proportions of the tube and is not affected by the electrode potentials. Stating that the field intensity between grid and filament is proportional to the quantity (E_g+E_p/m) is equivalent to saying that E_g volts applied to the grid produce the same field intensity as is produced by the application of mE_g volts on the plate. The constant m is usually larger than unity, ranging commonly from 3 to 40. The constant m is larger than unity because the grid is so constructed and located that it is in a better position to produce a high field intensity between filament and grid than is the plate.

The grid current is determined by the field intensity between filament and grid, and this field is proportional to the quantity (E_g+E_p/m). For constant grid current it follows that (E_g+E_p/m) must be constant. Fig. 5 shows a series of curves for different constant values of grid current. These

curves are practically straight lines that are substantially parallel. The equation of a straight line in Fig. 5 is:

$$(E_g+E_p/m)=\text{constant}$$

where (l/m) is the slope of the line. Since the lines are straight it follows that a constant grid current is obtained for all combinations of voltages that keep the quantity (E_g+E_p/m) constant. Since the factor m depends only on the slope of the lines in Fig. 5, and the lines are nearly parallel, it follows that m is a constant substantially independent of the tube voltages and current.

The lines in Fig. 5 depart a slight amount from perfect parallelism, and perfect straightness. To this extent the actual tube behavior departs from the simple theory that makes m a geometrical constant of the tube independent of electrode voltages, and that makes the grid current depend only on the value of the quantity (E_g+E_p/m).

The constant m is the same as the constant μ of the usual vacuum-tube circuit. Tests show that when the tube is used in the circuit of my invention, m and μ as determined from measurements are not exactly the same, m being in general slightly greater than μ. For this reason the symbol m is used for the μ of the vacuum tube circuit of my invention.

The constant m is the step-down ratio of the vacuum tube circuit of my invention. According to the theory, an increment of ΔE_p in plate potential will have an effect on the grid current equivalent to the effect of adding $\Delta E_p/m$ volts in the grid circuit. It follows from this that the effect on the grid circuit of an input voltage e_s in Fig. 1 is exactly the same as though this input voltage had been replaced by a fictitious generator of voltage e_s/m acting in the grid or output circuit.

The equivalent circuit of the vacuum tube system of my invention is given in Fig. 7. The effect of a signal voltage e_s applied to the input (plate) circuit is as though a generator having a voltage $-e_s/m$ was inserted between the grid and filament of the tube. The minus sign is present because of the direction in which this voltage is assumed to act in Fig. 7 which is the most convenient direction. The resistance R_g is the dynamic grid resistance, i. e. R_g is the resistance the grid circuit offers to an increment of voltage such as $-e_s/m$. It is the A. C. resistance of the grid circuit, and is analogous to the dynamic plate resistance R_p of the usual tube circuit. The value of R_g depends on the grid and plate-battery potentials, and can be determined by methods hereinafter explained. The voltage e_s that is applied to the input will generally be an A. C. voltage of magnitude E_s and frequency f. This voltage superimposed on the negative plate battery potential by being introduced at the point marked "Input" in Fig. 1, is equivalent to a voltage of amplitude $-E_s/m$ and of frequency f acting in the equivalent circuit. The current that this equivalent voltage produces depends upon the impedance of the equivalent circuit. This circuit consists of the dynamic grid resistance R_g in series with whatever impedance is inserted in the grid circuit at the point marked "Output" in Fig. 1. The grid current produced as a result of applying the A. C. input voltage of $e_s=E_s \sin \omega t$ is then

$$\text{A. C. grid current}=-\frac{(E_s/m)\sin \omega t}{R_g+Z}$$

where Z is the output impedance inserted in the grid circuit.

An important property of the vacuum tube circuit of my invention is the amount of change of grid current obtained with a given change of plate voltage, and with no load or output impedance present in the grid circuit. The constant expressing this property is the ratio dI_g/dE_p, and can be called the reflex mutual conductance of the vacuum tube circuit of my invention and given the symbol g. The reflex mutual conductance of the vacuum tube of my invention is analogous in all its properties to the mutual conductance g_m of the usual vacuum-tube circuit. In terms of m and R_g the reflex mutual conductance is

$$g_r=l/m\,R_g$$

When there is no load impedance inserted in the grid circuit the application of a small voltage E to the plate circuit causes a change of grid current of

$$E_{g_r}.$$

The voltage step-down ratio m of the vacuum tube circuit of my invention can be measured by means of the bridge circuit shown in Fig. 8. The electron tube 1, as shown in Fig. 8, has its electrodes connected similar to the circuit in Fig. 1, with the input circuit closed through resistance R_1 and the output circuit completed through high potential battery 8, telephones 12 and resistance R_2. R_1 and R_2 may serve as two arms of the grid circuit across which high frequency oscillations, such as oscillations of 1,000 cycles, are impressed. When no sound is heard in the telephones, an elementary application of the theory of the vacuum tube circuit of my invention shows the resistances R_1 and R_2 must be such that

$$m=R_1/R_2$$

Resistances for R_2 as low as ten ohms are satisfactory. Either of the resistances may be varied to establish the balance. The actual grid voltage to which the measurement applies is the battery voltage minus the voltage drop of the grid current in flowing through the telephones and R_2. To make this correction small, low resistance telephones and a moderately small value of R_2 are desirable.

The dynamic grid resistance R_g can be measured by the use of an alternating current bridge, as shown in Fig. 9. The electron tube 1 has its output circuit connected at X in one arm of the bridge. The other arms of the bridge are shown at 14, 15 and 16 with telephones 18 connected across the arms. High frequency energy of, for example, 1,000 cycles is impressed across arms 15—16. The method consists in making the grid filament resistance the X arm of the bridge. The grid potential to which the measurements apply is the battery voltage minus the voltage drop in the bridge of the grid current. By proper arrangement of bridge resistances the correction can be kept small.

The reflex mutual conductance g_r of the vacuum tube of my invention can be measured by the circuit shown in Fig. 10. The vacuum tube 1 may have its input and output circuits associated substantially as illustrated in Fig. 8, wherein the input and output circuits are coupled through resistances R_1 and R_2. The telephones 19 are connected between a point in the output circuit and the resistance R_3. The impressed energy is supplied across resistance R_3 and a point in the input circuit. When the resistances are such as to give no sound in the telephones, an elementary application of the vacuum tube according to my invention shows that

$$g_r = R_3/R_1R_2$$

Any one of the three resistances may be varied, although R_3 is generally most satisfactory for the variable element. Suitable values are $R_1 = 100$ ohms, $R_2 = 1000$ ohms, and R_3 variable up to 100 ohms in tenth ohm steps. Correction for the voltage drop in R_1 due to grid current must be made to get the grid voltage from the battery potential.

In all of these measurements it is desirable to make the A. C. input voltage to the measuring equipment small. With large inputs there is some second harmonic current generated, which masks the fundamental tone for which the bridge is to be balanced. A microphone hummer is a suitable source of audio-frequency energy for the measurements.

The constants of the vacuum tube circuit of my invention can also be derived from the static curves by methods analogous to those applied to static curves of ordinary vacuum tubes. The constants can also be determined by adding voltage increments in to the proper batteries, and reading the results on meters.

Results of measurements of m, and R_g for a low and a high μ tube are given in Figs. 11 and 12. Examination of Fig. 11 shows that the voltage step-down ratio m is subject to considerable fluctuations in value. Tests of a large number of tubes under different conditions indicate that the step-down ratio m varies in an erratic manner when the grid current is large, and particularly when the negative plate voltage is small. For large negative potentials on the plate, and where the grid current is relatively small, the step-down ratio m is practically constant at a value approximately equal to the μ of the tube.

The dynamic grid resistance of the vacuum tube circuit of my invention is rather low, even for very low grid voltages. This is because of the proximity of the grid and filament in standard tubes. For ordinary receiving tubes, resistances in the order of 1000 ohms are found for grid potentials of around 25 volts. The dimensions of the grid are not so very important, for Fig. 12 shows that two tubes with very different grid constructions have grid resistances in the same order of magnitude.

As heretofore noted the voltage reducing characteristic of the electron tube circuit of my invention renders the circuit particularly applicable in power transmission and distribution systems where the electron tube has its input circuit connected to high voltage lines, with its output circuit connected to the low voltage distribution lines operating as a power transformer.

The circuit arrangement is particularly useful for the operation of an oscillograph where it is desired to prevent consumption of current in the measuring device. The circuit arrangement of my invention is ideally suited for this purpose. The voltage wave to be photographed is applied directly to the plate using suitable plate bias battery. By the reducing action of the tube this high voltage is transformed into a smaller potential acting in the low impedance grid circuit, developing current variations that can be registered by the oscillograph.

I also employ the circuit of my invention as a constant frequency oscillator and as circuits for operating measuring instruments, such as a voltmeter. The circuit arrangement of my invention is also applicable for detection and rectification in signal receiving circuits.

The principles of my invention make the circuit highly desirable for numerous applications, and I have accordingly described my invention broadly, and desire that it be understood that the circuit thereof may be used whereever the principles of operation meet the conditions demanded by any particular problem.

While I have described the preferred embodiments of my invention, I desire that it be understood that modifications may be made and that no limitations upon my invention are intended other than are imposed by the scope of the appended claim.

What I claim as new and desire to secure by Letters Patent of the United States is as follows:

In an electron tube circuit, a thermionic tube including a cathode, a grid and an anode,

an input circuit comprising a source of potential disposed between said anode and cathode, an output circuit including a second source of potential and disposed between said grid and cathode, said source of potential in said input circuit being connected to subject said anode to a negative charge and said source of potential in said output circuit being adapted to subject said grid to a positive charge.

In testimony whereof I affix my signature.

FREDERICK E. TERMAN.