Aug. 17, 1948. E. K. STODOLA 2,447,040

MODULATION SYSTEM

Original Filed Nov. 17, 1942 3 Sheets-Sheet 1

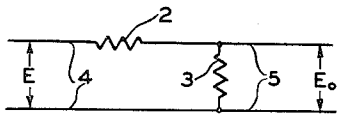


FIG.1.

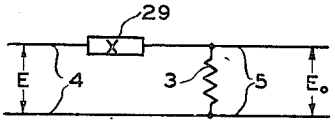


FIG.5.

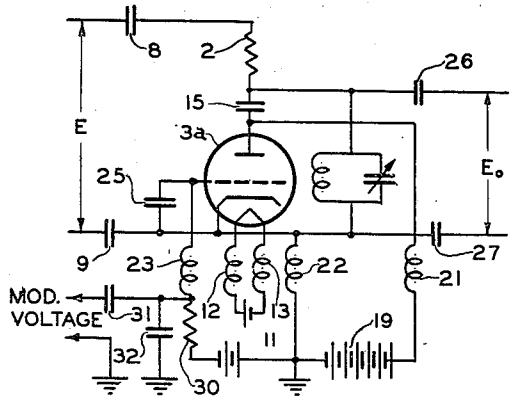


FIG. 3.

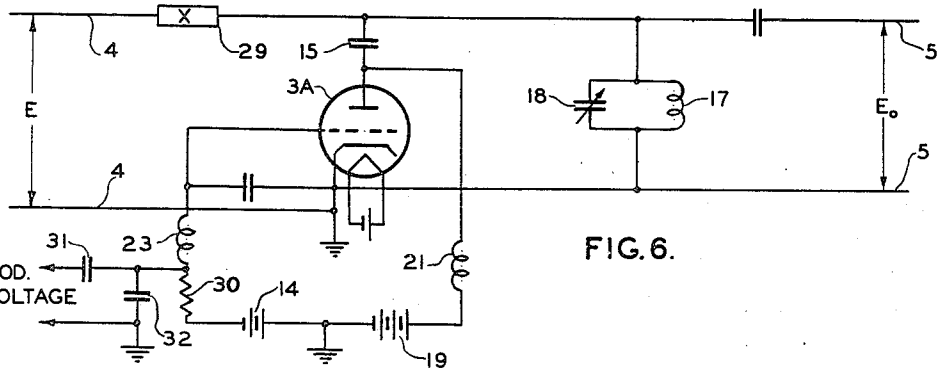


FIG. 6.

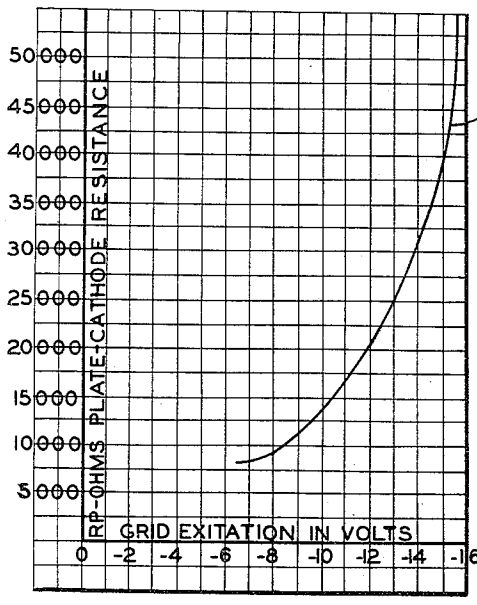


FIG. 2.

FROM DATA IN RCA
TUBE MANUAL RC13
RP FOR 6C5 TUBE
E_p = 250 VOLTS

Inventor
EDWIN K. STODOLA

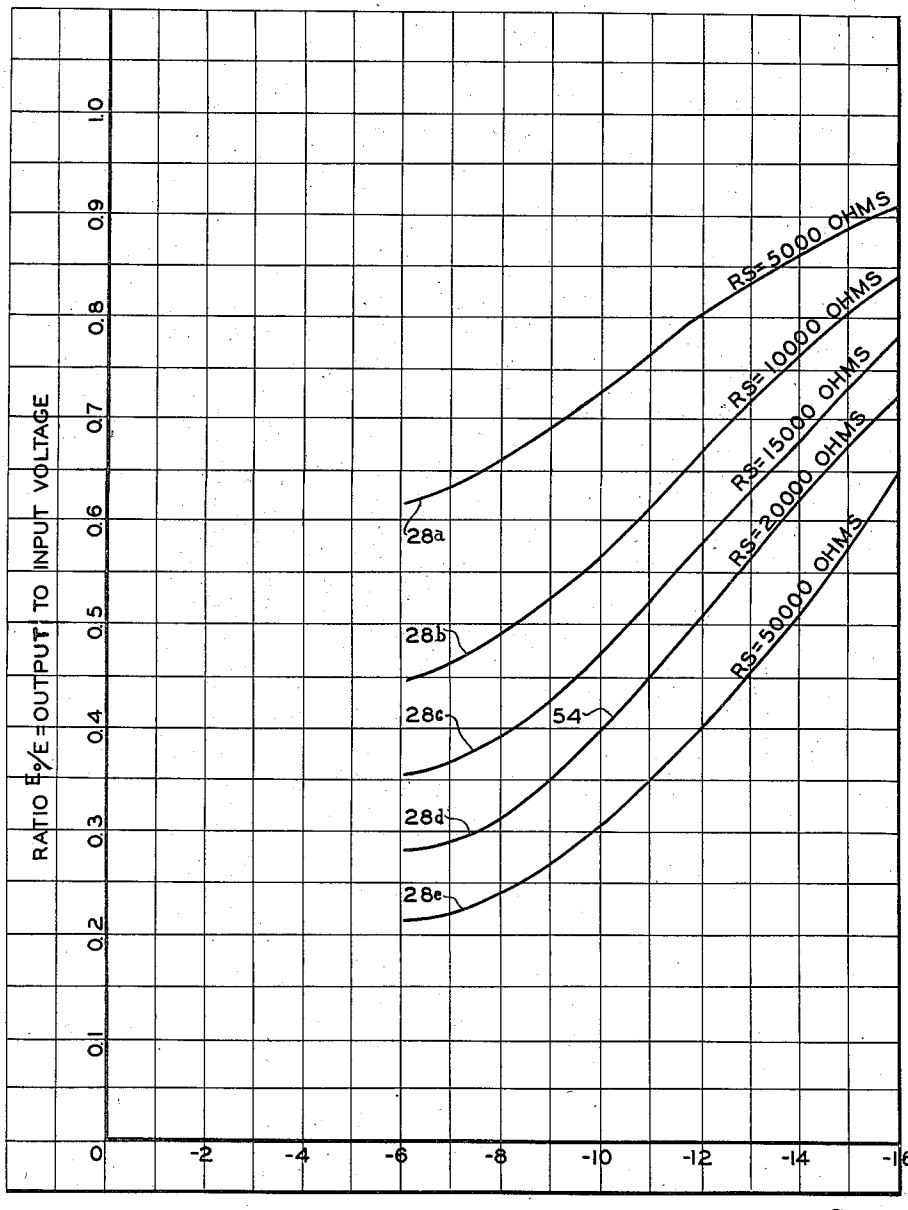
By William D. Hall.
Attorney

Aug. 17, 1948. E. K. STODOLA 2,447,040

MODULATION SYSTEM

Original Filed Nov. 17, 1942 3 Sheets-Sheet 2

FIG. 4.



Inventor
EDWIN K. STODOLA

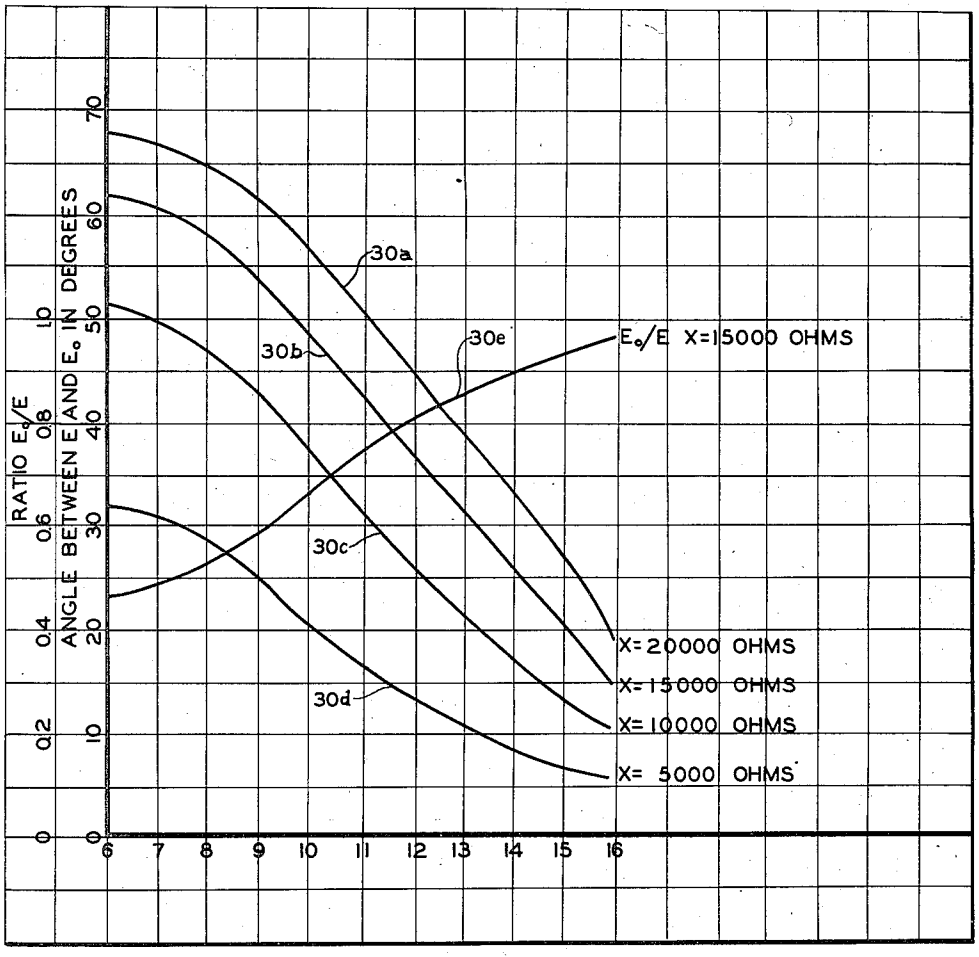
By William D. Hall.
Attorney

Aug. 17, 1948. E. K. STODOLA 2,447,040

MODULATION SYSTEM

Original Filed Nov. 17, 1942 3 Sheets-Sheet 3

FIG. 7.



Inventor
EDWIN K. STODOLA

By William D. Hall.
Attorney

Patented Aug. 17, 1948 2,447,040

UNITED STATES PATENT OFFICE

2,447,040

MODULATION SYSTEM

Edwin K. Stodola, Neptune, N. J.

Original application November 17, 1942, Serial No. 465,921. Divided and this application March 5, 1946, Serial No. 652,210

6 Claims. (Cl. 179—171.5)

(Granted under the act of March 3, 1883, as amended April 30, 1928; 370 O. G. 757)

1

The invention described herein may be manufactured and used by or for the Government for governmental purposes, without the payment to me of any royalty thereon.

My present invention relates to modulation systems, particularly such as are suitable for modulation of carrier waves. This application is a division of my copending application for "Electrical networks," Serial Number 465,921, filed November 17, 1942, which has matured into Patent No. 2,397,992, issued April 9, 1946.

In a signal system in which a source of energy is to be modulated in accordance with a signal, it is desirable to establish a linear relationship between the amplitude of the modulating signal and the desired modulating effect. It is a principal object of my invention to devise a simple and effective means for this purpose.

One object of my invention is to provide a modulation network for a source of carrier waves, said network including a nonlinear impedance adapted to be modulated and having such characteristics that a desired modulation characteristic of the potential across a portion of the network bears a linear relationship to the modulating potential.

Another object of my invention is to provide a network for producing a variable output from a source of input voltage in response to a control factor, variable over a predetermined range, said network comprising at least a pair of elements connected in series across said source, one element being an impedance which is preferably fixed, the other element being a resistance adapted to be varied in accordance with variation of said control energy, said elements being so related that the ratio of the magnitude of a given characteristic of the voltage across said output circuit with respect to the magnitude of a like characteristic of the voltage across said network is a substantially linear function of said control factor variation.

Another object of my invention is to provide a network for producing a variable phase output from a source of alternating current input voltage in response to a control factor variable over a predetermined range, said network comprising at least a pair of elements connected in series across said source, one element being a reactance which is preferably fixed, the other element being a resistance adapted to be varied in accordance with said control factor, and an output circuit connected across one of said elements, said elements being so related that the phase angle of the voltage across said output circuit is a substantially linear function of said control factor variation.

2

In accordance with my invention, a source of energy to be modulated is connected across a voltage divider including a pair of impedance elements, one of which may be fixed and the other of which is variable by means of a modulation potential, e. g., the space-current path of an electron tube. The modulated output is derived across one of said elements, preferably the one which is variable. I have discovered that by properly proportioning the value of the fixed impedance and properly choosing the relation between the impedance of said space-current path and its control factor, a desired characteristic of the modulated output with respect to the same characteristic of the input is a linear function of the modulating potential. If the input energy is constant, then the modulated characteristic of the output is a linear function of the modulating potential.

If the fixed impedance is resistive the network functions to produce linear amplitude modulation. If said fixed impedance is reactive, linear phase modulation is obtained.

For a better understanding of the invention, together with other objects thereof, reference is made to the following description, taken in connection with the accompanying drawings, wherein:

Figure 1 is a simplified diagram of an amplitude modulation circuit which forms the basis of my invention;

Figure 2 is a graph, illustrating the relationship between the grid voltage and the plate cathode resistance of a triode at present available on the market;

Figure 3 is a more detailed diagram of the circuit shown in Fig. 1;

Figure 4 is a family of curves showing the relationship between the grid voltage and the ratio between the tube voltage drop and total applied voltage across the tube and resistor in Fig. 3;

Figure 5 is a simplified diagram of a phase-modulation circuit including a reactor in series with the tube;

Figure 6 is a more detailed diagram of the circuit shown in Fig. 5, and includes a tube and reactor in series to constitute a linear phase-modulation circuit; and

Figure 7 is a graph showing a family of curves directed to the relationship of the phase angle between the voltage across the tube and the modulating potential on the grid in the circuit of Fig. 6.

Fig. 1 shows a voltage-divider circuit including two resistances 2 and 3 connected in series and energized by a voltage E from an input circuit 4. An output circuit 5 is connected across the terminals of the resistance 3. If resistances 2 and 3 are fixed, the voltage drop across each will always maintain the same proportion relative to the input voltage E, regardless of the variation of said voltage. If, however, the voltage E is kept constant and the resistances varied, the voltage drops thereacross will vary according to their relative values. The ratio of the output voltage E_0 to the input voltage E will vary according to the ratio of resistance 3 to the sum of the resistances 2 and 3.

Where the resistance 2 is kept at constant value and the resistance 3 is made variable, the drop in potential across resistance 3 will not vary directly in proportion to the variation of said resistance, but will vary according to the ratio of the resistance 3 to the total resistance of the voltage-dividing circuit. It will be obvious, therefore, that if resistance 3 was linearly modulated in accordance with a signal potential, the modulated output voltage would not be linear with respect to the signal potential.

In accordance with one aspect of my invention, linear amplitude modulation is obtained by varying resistance 3 in accordance with a modulating signal in such a manner that the ratio of said resistance with respect to the sum of both resistances 2 and 3 is always proportional to the instantaneous voltage of the modulating signal. Simple calculations show that the required rate of variation of resistance 3 with respect to the modulating voltage to obtain linear modulation is given by the following equation:

$$R_3 = \frac{R_2}{K} \cdot \frac{E_m}{K - E_m} \qquad (I)$$

Where:

R_3 is the resistance of resistance 3,
R_2 is the resistance of resistance 2,
E_m is the modulating factor which varies resistance 3, and
K is a constant of proportionality which establishes the extent of the modulating function necessary to produce a given effect.

I have found that at least a portion of the dynamic plate-resistance characteristic of an ordinary triode closely approximates the requirements of the above equation. Hence, by making resistance 3 the space-current path of a grid-controlled electron tube, the impedance of which varies nonlinearly with the modulation voltage, the requirements of the equation can be realized. The curve in Fig. 2 shows the variation of plate resistance with respect to grid potential of one type of commercially available triode, generally designated as the type 6C5, with a D. C. plate potential of 250 volts. By choosing the proper operating portion of this characteristic and a proper value for fixed resistance 2, it is possible to obtain linear amplitude modulation.

A more detailed embodiment of the elementary circuit of Fig. 1 is shown in Fig. 3, wherein the plate-cathode circuit of the tube 3*a* corresponds to the resistance 3 in Fig. 1. The input circuit 4 is shown connected to the voltage-dividing circuit, which includes the resistor 2 and the triode 3*a*, through coupling condensers 8 and 9 of low impedance to the impressed frequency of input potential E, which represents a source of carrier frequency currents.

The triode 3*a* is shown as a typical heater-type triode, in which the heater element is shown as energized from a source of heating energy, as a battery 11, connected to the heater element through two R. F. chokes 12 and 13. The cathode is connected to one conductor of the input circuit 4 through the condenser 9. The grid is provided with a biasing potential derived from a source indicated as a battery 14, connected to the grid through an R. F. choke 23 and a high series resistance 30. A modulation voltage is applied across resistance 30 and battery 14 to vary the grid bias. Blocking condenser 30 is of low impedance to the modulating currents. Shunt condenser 30 is of high impedance to the modulating currents but of low impedance to any residual radio frequency currents.

In order to balance out the interelectrode capacitance of the triode a parallel shunt, including an inductance 17 and a capacitance 18, is connected across the tube 3*a*. The constants of the shunt elements 17 and 18 are such, that, at the operating radio frequency, the tube capacity and the shunt are resonant to said frequency and constitute a substantially infinite impedance, non-reactive circuit, whereby the shunt resistance is very high at all times compared to the plate-cathode resistance. The plate voltage for the triode 3*a*, which in the present example operates at 250 volts, is provided by a source indicated as a battery 19, the negative terminal of which is grounded, and the positive terminal connected through an R. F. choke 21 to the plate. The cathode D. C. return path is provided by an R. F. choke 22. The grid biasing battery 14 is grounded at the positive terminal. The plate of the tube is connected to the resistor 2 through a blocking condenser 15 having negligible impedance at the operating radio frequency to prevent short circuiting of the plate battery 19 by the inductance 17.

The grid of triode 3*a* is shown provided with a by-pass condenser 25 to the cathode, to provide a low resistance path to any appreciable radio frequency voltage between the grid and the cathode while, at the same time, permitting the application of direct current biasing voltage and modulation voltage between the cathode and the grid.

The two condensers 8 and 9 in the input circuit, and two similar condensers 26 and 27 in the output circuit, connected to the terminals of the triode, are provided to isolate the direct current voltage within the voltage-divider assembly of Fig. 3, when that assembly is connected to the rest of a circuit. These condensers all have a negligible reactance to the impressed frequency.

In the arrangement shown in Fig. 3, as the grid voltage is varied, the resistance of the tube varies. As above pointed out, the ratio of the output voltage, representing the drop across the tube, to the input voltage, as applied to the voltage-dividing circuit, depends upon the value of the resistor 2, and the relationship of that value to the resistance characteristics of the tube 3*a*. Since the resistance of the tube 3*a* between the cathode and the anode, will vary with the excitation of the grid, the ratio of the output voltage to the input voltage will also vary with the grid excitation.

In Fig. 4, several curves 28*a* to 28*e* are shown, representing the relationship between the ratio of output voltage to input voltage and the cor-

responding grid voltage for different values of resistance in the series resistor **2** in Fig. 3.

The value of the resistor **2** corresponding to each curve **28***a* to **28***e* is shown at the upper end of each curve. The middle curve **28***c* corresponding to a resistance value of 15,000 ohms in series with the tube, shows a linear relationship between the ratio of output voltage to input voltage E_0/E and the grid voltage, between values of $E_0/E=0.795$ and $E_0/E=0.47$. Thus, with a circuit including a tube and a resistor having the proper resistance values corresponding to the characteristics of the tube, a direct linear voltage relationship may be established between modulating voltage on the grid of the tube and the output voltage over an extended range, provided that the input voltage is held constant.

While in the above circuit a tube has been used as a non-linear resistance, it is evident that any other known type of element which has a non-linear relation between its resistance or impedance and the controlling factor applied thereto can be used. In addition, all or part of resistance **2** in Figs. 1 and 3 can be constituted by the internal resistance of the source of voltage E.

Thus, by making the impressed voltage E, in Fig. 3, a source of carrier potential and placing a source of modulating potential in series with battery **14**, the output E_0 will be an amplitude-modulated carrier which will bear a linear relationship to the modulating voltage over a range depending upon the constants of the circuit.

Another object of my invention is the use of the principles above described to obtain linear phase modulation. It is well known that when an alternating voltage is applied to a circuit including a resistor and a reactance in series, the voltage across the reactance is phase displaced with respect to the voltage across the resistor, and that each such voltage is phase displaced with respect to the applied voltage. Such circuit arrangement is shown, for example, in Fig. 5, in which the applied voltage from an input circuit **4**, similar to that of Fig. 2, is applied to a circuit including the resistor **3** and reactance **29**. The circuit is similar to that shown in Fig. 1, except that either an inductive or capacitative reactance **29** is substituted for resistor **2**. It will be evident that the output voltage E_0 will be phase displaced with respect to the input voltage E, the direction of such phase-displacement depending on whether reactance **29** is capacitative or inductive. If the applied voltage E and the reactance **29** are held constant while the resistor **3** is varied in accordance with a modulation voltage, the phase displacement of output voltage E_0 will be modulated.

The required law of variation of resistance **3** with respect to the modulating voltage function to obtain linear phase modulation of the output E_0 with respect to the modulating voltage is given by the following equation:

$$R_3=\frac{X}{\tan KE_m} \qquad \text{(II)}$$

Where X is the reactance of reactor **29** and the other symbols are similar to those in Equation I.

As is the case with Equation I, the requirements of Equation II can also be closely approximated by making the resistance **3** the space-current path of an electron tube. Such a circuit is shown in Fig. 6 in which the space-current path of tube **3***a*, which may be of the 6C5 type, corresponds to resistance **3** of Fig. 5. In other respects the circuit is substantially similar to Fig. 3.

The modulation characteristics of the circuit in Fig. 6 are illustrated by the curves in Fig. 7. Curves **30***a*—**30***d* show the relationship between the grid voltage on tube **3***a* and the phase angle between the applied voltage E and the output voltage E_0 across the space-current path of the triode.

The curve **30***b*, corresponding to the case where a reactor **29** having 15,000 ohms reactance is used, shows a linear relationship between the grid voltage and the phase angle between the applied voltage and the output voltage for the range of values of the phase angle between 15° and 55°. Thus, by use of proper circuit constants in a voltage-dividing system such as shown in Fig. 6, a triode may be employed as a variable resistor, and an output voltage derived across the triode, whose phase relationship to the input voltage will be a linear function of the amplitude of the modulation voltage applied to the tube over a substantial range of that voltage.

It should be noted that curve **20***e* in Fig. 7 shows that amplitude modulation will accompany the phase modulation when reactance **29** has a value of 15,000 ohms. If this is considered undesirable it can be eliminated by conventional amplitude limiting or automatic volume control methods.

As is the case with Figs. 1 and 3, any other type of non-linear impedance can be used instead of tube **3***a* in Figs. 5 and 6. Also, all or part of reactance **29** can be constituted by the internal reactance of voltage source E.

Although in the above described circuits the linear relationships are functions of the grid voltage, the circuits can be arranged to make said relationships a function of the voltage impressed on another electrode or combination of electrodes.

The phase modulators above described can be used as components of conventional frequency modulation systems. It has been pointed out by Armstrong and others that pure frequency modulation is equivalent to phase modulation in which the maximum phase shift for a given modulating voltage is inversely proportional to the modulating frequency. Hence, any device which produces phase modulation will produce frequency modulation by making the modulating voltage inversely proportional to the modulating frequency. Of course, at any single modulating frequency there is no distinction between the two. Hence, in this application reference has been made to phase modulation with the understanding that by properly correcting the modulating voltage the same devices and methods will produce frequency modulation.

The specific circuits and constants above described are to be considered as illustrative of the principles of the invention. Numerous modifications can be made without departing from the spirit of the invention as set forth in the appended claims.

I claim:

1. A network for providing a variable-phase output from a source of alternating-current input voltage in response to a control factor variable over a predetermined range comprising: a reactance adapted to be coupled to said source in series with the space-current path of an electron tube, an output circuit coupled solely across said path, and means adapted to be controlled solely by said control factor to vary the resistance of said path, the resistance of said path over said range of variation of said control factor being a

non-linear function of said variation, the magnitude of said reactance being so related to said non-linear function that the phase angle between the voltage across said output circuit and the voltage across said network is a substantially linear function of said control factor variation.

2. A network for providing a variable-phase output from a source of fixed-frequency input voltage in response to a control voltage variable over a predetermined range comprising: a fixed reactance adapted to be connected across said source in series with the anode-cathode path of an electron tube, an output circuit coupled solely across said path, and a control grid in said electron tube adapted to be coupled solely to said control voltage to vary the resistance of said path, the resistance of said path over said range of variation of control voltage being a non-linear function of said control voltage, the magnitude of said fixed reactance being so related to the average resistance of said path over said range that the variation of the phase angle of the voltage across said output circuit is a substantially linear function of said control voltage variation over said range.

3. A network for varying the phase angle of the voltage of a source of alternating current in response to a control factor variable over a predetermined range, said network comprising an input circuit including a pair of impedances connected in series across said source, an output circuit coupled solely across one of said impedances, one impedance being predominantly reactive, the other impedance being predominantly resistive, the resistance of which is adapted to be controlled solely by said control factor, the variation of said resistance being a non-linear function of the variation of said control factor over said range, the magnitude of said reactive impedance being so related to the average resistance of said resistive impedance over said range that the ratio of the phase angle of the voltage across said input circuit relative to the phase angle of the voltage across said output circuit is a substantially linear function of the magnitude of said control factor over said range.

4. A network for varying the phase angle of the voltage of a source of alternating current in response to a control voltage variable over a predetermined range, said network comprising an input circuit including a pair of impedances connected in series across said source, an output circuit coupled solely across one of said impedances, one of said impedances being fixed and predominantly reactive, the other of said impedances being predominantly resistive and comprising the space-current path of an electron tube, a control grid in said electron tube adapted to be controlled solely by said control voltage, the resistance of said path being a non-linear function of the variation of said voltage over said range, the magnitude of said reactive impedance being so related to the average resistance of said path over said range that the ratio of the phase angle of the voltage across said input circuit relative to the phase angle of the voltage across said output circuit is a substantially linear function of the magnitude of said control voltage over said range.

5. A network as set forth in claim 4, including means to minimize the effect of the interelectrode capacitance of said electron tube.

6. A network as set forth in claim 5, wherein said means includes reactance shunted across said interelectrode path to form therewith a circuit which is parallel resonant to the frequency of said source.

EDWIN K. STODOLA.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,259,393	Van Roberts	Oct. 24, 1941
2,371,285	Crosby	Mar. 31, 1945
2,383,848	Crosby	Aug. 28, 1945