

Aug. 14, 1934.

J. G. KREER, JR

1,970,325

REDUCTION OF DISTORTION IN VACUUM TUBE CIRCUITS

Filed Feb. 27, 1932

FIG. 1

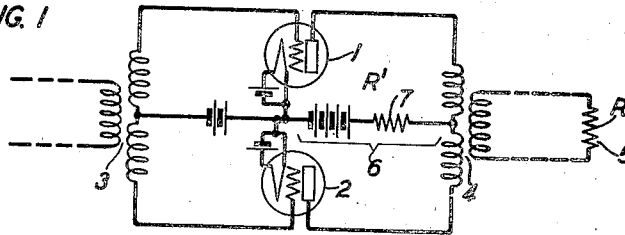


FIG. 2

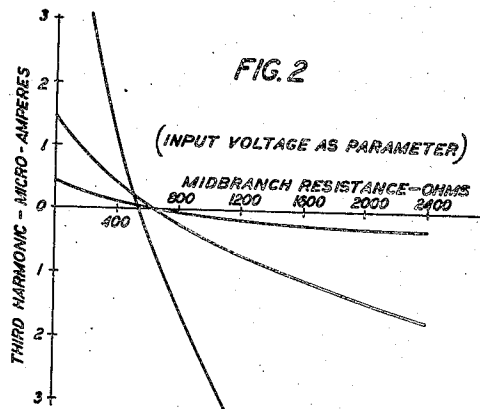


FIG. 3

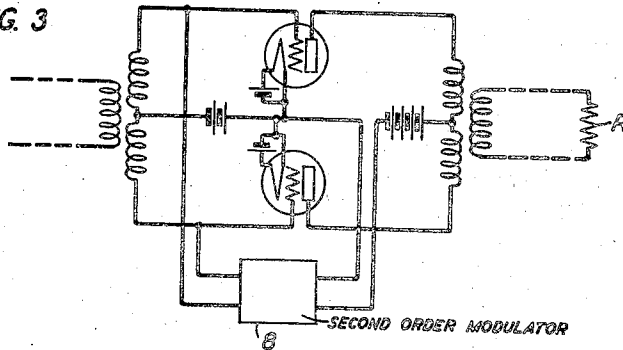
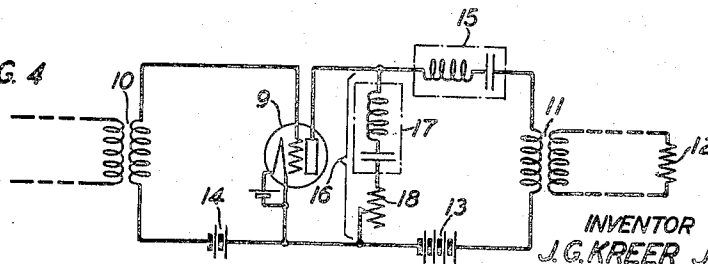


FIG. 4



INVENTOR

J. G. KREER JR.

BY

H. A. Burgess

ATTORNEY

UNITED STATES PATENT OFFICE

1,970,325

REDUCTION OF DISTORTION IN VACUUM
TUBE CIRCUITSJohn G. Kreer, Jr., Bloomfield, N. J., assignor
to Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application February 27, 1932, Serial No. 595,502

9 Claims. (Cl. 179—171)

This invention relates to electric space discharge tube circuits such as are employed in signaling systems, for example, vacuum tube amplifiers, modulators and the like, and particularly to the control of modulation in such circuits.

It is an object of this invention to suppress effectively modulation products and particularly third order modulation products, in signaling systems employing electric space discharge devices.

It is well known that the electric space discharge tubes employed in signaling systems because of inherent distortion characteristics, produce in their outputs certain modulation products in addition to the waves of frequencies which are impressed on their inputs. Thus, when a wave of a single frequency is impressed on the input circuit of a space discharge tube, the output circuit will contain a wave of the fundamental frequency and other waves of frequencies harmonically related to the fundamental. If a complex wave, that is, one composed of a plurality of frequencies, is impressed on the input of the device, the output circuit will contain certain waves of frequencies harmonically related to the frequencies of the impressed waves, waves having frequencies equal to the sum and difference of the respective fundamental impressed frequencies, and various higher order components.

When a space discharge device is utilized in a signaling system for producing certain transformations in waves transmitted thereover, for example, amplification, it is desirable from the standpoint of quality that the effects of all modulation products produced by the device, be minimized. As the effects of the modulation products in amplification systems on quality of transmission of orders higher than the third are usually negligible compared to the effects of the second and third order modulation products, if the second and third order products present are eliminated or reduced to a negligible value by suitable means, the system for practical purposes is made distortionless. With some other tubes or other systems such as modulators some higher order product such as the fourth may predominate.

Heretofore, it has been found that the amplitude of third order modulation products produced by space discharge devices of certain types in such a system may be reduced to a negligible value if the space discharge devices are operated with certain critical load impedances. The reduction in third order modulation by this method has the disadvantage with certain types of space discharge devices that the critical load impedances so selected may not be at the optimum

value from the standpoint of other considerations, such as maximum power output, minimum reflection losses, etc.

In accordance with the present invention, it has been found that the amplitude of third or higher order modulation products produced by electric space discharge devices of any type in a system may be reduced to zero or to an unobjectionable amount by means not dependent on a critical value of load impedance. This is accomplished by inserting in the external circuits of the space discharge tubes (not the load circuit) means to provide such modulation voltages, of lower order, as substantially to suppress unwanted higher order modulation products.

In one embodiment of the invention applicable to a balanced vacuum tube amplifier circuit, third order modulation products are made to vanish or are reduced to an unobjectionable amount by the insertion of a resistance of appropriate value in the common portion of the plate circuits of the two tubes.

The invention will be better understood from the following detailed description thereof when read in connection with the accompanying drawing in which:

Fig. 1 shows diagrammatically a push-pull vacuum tube amplifier circuit in which the suppression of the third order modulation products is obtained by an impedance of suitable value inserted in the common portion of the plate circuit of the two tubes;

Fig. 2 shows a series of curves used to illustrate the invention;

Fig. 3 shows diagrammatically a modification of the invention applicable to a push-pull vacuum tube amplifier circuit; and

Fig. 4 shows diagrammatically an embodiment of the invention applicable to a single tube amplifier circuit.

If the output current of a vacuum tube is expressed as a power series of the variable component of the grid voltage, it can be shown that the third order coefficient is a function of the derivatives of the static characteristic at the operating point, the impedance to the fundamental current, the impedance to the second order currents and the impedance to the third order currents. This may be expressed mathematically as follows:

$$C_3 = \left[\frac{b_{03} - R_1 C_1 b_{12} + R_1^2 C_1^2 b_{21} - R_1^3 C_1^3 b_{30}}{1 + b_{10} R_3} \right] - C_2 R_2 \left[\frac{b_{11} - 2 R_1 C_1 b_{20}}{1 + b_{10} R_3} \right]. \quad (1)$$

The expression (1) has been derived from a corresponding one designated as (6) in a paper "Modulation in vacuum tubes used as amplifiers" by E. Peterson and H. P. Evans, published in the Bell System Technical Journal for July, 1927, by adding the proper subscripts to the impedances to indicate the order of the modulation product involved.

In expression (1) C_1 , C_2 , C_3 are, respectively, the fundamental, second and third order modulation coefficients. Thus, the plate current of a vacuum tube is given by:

$$J_p = C_1 e + C_2 e^2 + C_3 e^3 \dots;$$

the fundamental component being $J_1 = C_1 e$, the second order components are $J_2 = C_2 e^2$, and the third order components are $J_3 = C_3 e^3$, where e is the applied input voltage to the tube; b_{01} , b_{10} , b_{02} , b_{11} , b_{20} etc. are coefficients in the power series expansion of the tube characteristic.

It can be shown mathematically that if the tube characteristic satisfies certain conditions as to continuity, then

$$b_{01} = \frac{\partial J_p}{\partial E_c},$$

that is, the partial derivative of the plate current with respect to grid voltage evaluated at the operating point;

$$b_{10} = \frac{\partial J_p}{\partial E_p},$$

that is, the partial derivative of the plate current with respect to the plate voltage evaluated at the operating point; and the higher order b coefficients are higher order partial derivatives, e. g., b_{mn} is the $(m+n)$ th partial derivative of the plate current with respect to plate voltage m times and with respect to grid voltage n times.

R_1 , R_2 , R_3 are the impedances of the external vacuum tube circuit to fundamental, second order, and third order modulation components, respectively.

Examination of expression (1) shows that the third order coefficient is made up of two portions, one, indicated by the first term, which is independent of second order currents, and the other, indicated by the second term, which is dependent on the flow of second order currents. It is obvious that if the two terms of expression (1) have the same sign and are of the same magnitude, the third order coefficient, C_3 , will vanish and there will be no third order modulation products.

Now, since the denominators of the two terms involved in C_3 are identical, only the numerators need be considered. Then,

$$C_3 = \frac{\alpha}{1 + b_{10} R_3} = \frac{\beta}{1 + b_{10} R_3} \quad (2)$$

where

$$\alpha = b_{03} - R_1 C_1 b_{12} + R_1^2 C_1^2 b_{21} - R_1^3 C_1^3 b_{30} \quad (3)$$

and

$$\beta = [b_{11} - 2R_1 C_1 b_{20}] R_2 C_2. \quad (4)$$

Now β can be put in the form:

$$\beta = \frac{R_2}{2R_0(R_2 + R_0)} \left[\frac{\partial \mu}{\partial E_p} - \frac{\mu}{R_0 + R_1} \frac{\partial R_0}{\partial E_p} \right] \left[\frac{\partial \mu}{\partial E_c} + \frac{\mu(R_0 - R_1)}{R_0 + R_1} \frac{\partial \mu}{\partial E_p} \frac{R_0^2}{(R_0 + R_1)^2} \frac{\mu^2}{R_0} \frac{\partial R_0}{\partial E_p} \right] \quad (5)$$

obtained directly from the above definition of the b_{mn} 's, where R_0 equals the internal impedance and μ the amplification factor of the vacuum tube.

It has been found from inspection of available

experimental data on a number of commonly used types of three element vacuum tubes that for most tubes,

$$\frac{\partial \mu}{\partial E_p} \text{ and } \frac{\partial \mu}{\partial E_c}, \quad 80$$

are positive with the latter much larger; also that

$$\frac{\partial R_0}{\partial E_p} \text{ and } \frac{\partial R_0}{\partial E_c} \quad 85$$

are negative. Under these conditions β will usually be positive. No such general conclusions can be drawn concerning α , but such values as have been computed are positive also. Therefore, if R_2 is adjusted until α is equal in magnitude to β , then C_3 may be made to vanish.

It so happens that if the impedance to the second harmonic R_2 , can be varied independently of the impedance to the fundamental, R_1 , the third order coefficient for most types of tubes can be made zero while the fundamental impedance remains at some value desired for other circuit reasons. The balanced vacuum tube amplifier illustrated diagrammatically in Fig. 1 presents just such a means for varying the impedance to the even order currents independently of the impedance to the odd order currents.

In the circuit of Fig. 1, the modulated waves to be amplified are impressed upon the input circuits of the space discharge devices 1 and 2 by means of input transformer 3. The devices 1 and 2 are connected in opposing or push-pull relationship in the usual manner well known in the art. The currents in the output circuits of these devices are impressed by means of output transformer 4 upon a suitable load or line which is represented by the resistance 5.

Assuming a balanced amplifier with an ideal output transformer and identical tubes, as is well known the second order currents of the tubes balance out in the output transformer and it acts as a low impedance. However, the second order currents are in phase in the common portion 6 of the plate-filament circuits of the tubes 1 and 2 and the second order voltages of the two tubes are thus effectively connected in parallel so that the impedance to each is twice the common branch impedance. If the impedance of the common branch 6 is R' as indicated in Fig. 1, then

$$R_2 = 2R'. \quad (6) \quad 125$$

The odd order voltages operate in the output circuits of the tubes 1 and 2 in series aiding, so if the load impedance as reflected through the output transformer 4 is R , then the impedance to the fundamental currents will be

$$R_1 = \frac{R}{2} \quad (7)$$

In the latter case the common branch has been neglected because with identical odd order voltages it connects points of the same potential.

From the above mathematical exposition, it will be apparent to persons skilled in the art that modulation products of orders higher than the second may be made to vanish or may be reduced to negligible values by proper choice of external circuit impedances independent of the load impedance. The mathematics to show this would be quite complex and will not, therefore, be given here.

As shown mathematically above, it would be expected that the third order modulation products could be reduced substantially to zero merely by obtaining the proper value for the impedance R'

of the common branch of the output circuits of the two push-pull tubes 1 and 2 by making the resistance element 7 in that branch of suitable value, and experiments which have been carried out under direction of the applicant indicate that with standard types of three element tubes commonly used in such amplifier circuits, the third order modulation products may be made negligible by this method.

Fig. 2 shows curves illustrating the variation of third harmonic outputs with different values of resistance used in the mid-branch of a balanced amplifier using Western Electric Company 104-D vacuum tubes. These tubes were operated with a plate potential of 120 volts and a 22.5 volt grid bias, and a specially designed low leakage output transformer was used. In Fig. 2 each curve represents the result obtained with a different input voltage. The experiments indicated that the best results from the standpoint of third harmonic reduction in the case of balanced amplifiers using 104-D tubes were obtained at most operating points if the tubes were made to work into an output impedance equal to their internal plate impedance, although the optimum mid-branch resistance varied somewhat when the operating point was changed. The operating points tried out varied from a plate potential of 90 to 130 volts and a grid bias of 20 to 40 volts with the 104-D tube. When ordinary output transformers were used in place of the special low leakage output transformers, it was found necessary to insert a reactive network of suitable value in the mid-branch to annul the leakage reactance to insure suitable reduction of the third order modulation products for impressed waves over a wide frequency band.

Experiments were also made with balanced amplifiers using Western Electric Company 101-D vacuum tubes. In the case of these tubes, it was found necessary to increase the output impedance to twice the internal plate impedance before a maximum reduction of the third harmonic could be obtained with a resistance in the common branch. In the case of the 101-D tube, it was found that the external resistance in the mid-branch giving maximum suppression of third order modulation products, was much lower than that required in the case where Western Electric Company 104-D tubes were used. As in the case of the 104-D tubes it was found that the optimum mid-branch resistance varied for different sets of tubes and different operating points.

The experimental results indicated that by proper selection of the operating point, both in the case of the balanced amplifiers employing Western Electric Company 101-D or 104-D vacuum tubes, on the average a ten to twenty decibels reduction of the third harmonic output could easily be obtained by properly adjusting the resistance in the common portion of the plate circuits of the balanced tubes. The exact resistance, required is not critical within 10 per cent for any particular pair of tubes, but does vary with the operating point of the tubes between zero and one thousand ohms depending also upon the output at which the maximum suppression is desired. Placing greater suppression at higher inputs usually will not give as great suppression at the lower inputs.

In some cases it may be desirable to reduce the third order products generated in the grid circuits of balanced amplifiers when grid current is permitted to flow, that is, when the amplifier

is overloaded. For that case, it would be necessary in order to obtain maximum reduction of the third order modulation products, to insert a resistance of proper value in both the common portion of the input circuit and the common portion of the output circuit of the balanced tubes.

Furthermore, it is not necessary in either the grid or plate circuit to obtain the necessary second order voltages by means of IR drops as shown in Fig. 1. They may be obtained in any way desirable in the particular circuit under consideration as long as the proper phase and amplitude relations are maintained. For example, as illustrated in Fig. 3, a second order modulator 8 with its input paralleled with the amplifier input and its output in series with the mid-branch of the amplifier output might be used to provide the proper second order voltages in the plate circuits of the tubes.

Fig. 4 shows a modification of the invention embodied in an amplifier comprising a single space discharge tube. The waves to be amplified are impressed upon the input circuit of the space discharge tube 9 by means of input transformer 10 and the amplified waves in the output circuit of the tube 9 are impressed by means of output transformer 11 upon any type of load circuit or line represented in the figure by the resistance 12. Space current for the tube 9 is supplied by plate battery 13 and a suitable biasing potential is supplied to the grid of the tube 9 by means of battery 14. A suitable selective network 15 such as a resonant circuit tuned to reject the second order products while transmitting the fundamental components of the waves impressed on the input of the tube 9, is connected in the output circuit of the tube 9 between the plate and filament thereof. Connected directly across the plate and filament of the tube 9 is a circuit 16 comprising selective network 17, such as a resonant circuit, and a variable resistance 18 in series. The selective network 17 should be of such a nature as to have a free transmission range including the second order modulation products generated in tube 9, and also as to present a high impedance to other modulation products and the fundamental.

By suitable adjustment of the resistance 16, the impedance of the circuit 14 to the second harmonic or second order modulation products may be made of the critical value at which the third harmonic or the third order modulation products generated by the tube 7 are suppressed or reduced to low amplitudes, so that substantially, only the fundamental waves will be impressed by the output transformer 9 upon the load circuit 10.

Although this invention has been illustrated and described as applied to a particular system, it is not to be limited thereto, but only in accordance with the scope of the following claims.

What is claimed is:

1. In combination in a wave transmission system, an electric space discharge device having an input and an output circuit, for transmitting in modified form electric waves from an incoming to an outgoing transmission circuit, and means for effectively suppressing from said outgoing circuit third or higher order modulation products of the waves impressed on the input circuit of said device, said means comprising means which introduces into said output circuit such modulation voltages of a lower order as to reduce to a negligible amount the unwanted modulation products transmitted to said outgoing transmission circuit.

2. In combination in a wave transmission sys-

- tem, a pair of space discharge devices having input and output circuits and connected in push-pull relation with respect to an incoming and outgoing wave transmission circuit, and means common to the output circuits of said devices and independent of the impedance of the outgoing circuit, reducing in said outgoing circuit third or higher order modulation of the waves received over said incoming circuit.
3. In combination in a wave transmission system, a pair of space discharge devices connected between an incoming and an outgoing circuit, and having a portion of their input and their output circuits in common, and means for reducing in said outgoing circuit the amplitudes of third order modulation products of waves impressed on the input circuits of said space discharge devices from said incoming circuit, said means comprising means proportioning the impedance of the common portion of the output circuits of said devices to second order modulation products of the impressed waves to the critical value at which the amount of third order modulation current transmitted to said outgoing circuit is a minimum.
4. In a wave transmission system, an incoming circuit and an outgoing circuit, a pair of space discharge devices having their input and output circuits connected in push-pull relation with said incoming circuit and said outgoing circuit, respectively, said devices being balanced so as to suppress effectively in said outgoing circuit second order modulation products of the waves from the incoming circuit and means common to the output circuits of said devices and independent of the impedance of said outgoing circuit substantially preventing transmission to said outgoing circuit of third order modulation products of the waves from said incoming circuit.
5. The system of claim 4 and in which said means substantially preventing transmission of third order modulation products to said outgoing circuit comprises means making the impedance of the common portion of the output circuits of said devices to second order modulation products of the critical value at which third order modulation currents are substantially suppressed from said outgoing circuit.
6. An amplifier comprising a pair of space discharge devices having portions of their input and output circuits in common so that said devices are connected in push-pull relation with respect to an incoming and outgoing wave transmission circuit, said devices being balanced so as to suppress effectively from the outgoing circuit the second order modulation products of waves from the incoming circuit, and resistance means in the common portion of the output circuits of said devices proportioning the impedance of said common portion to the second order modulation products therein to the critical value at which the third order modulation products of said waves in the respective output circuits of said devices substantially neutralize each other.
7. In combination in a wave transmission system, a pair of three-electrode space discharge devices, said devices having a portion of their cathode-grid circuits and a portion of their anode-cathode circuits in common, so as to be connected in push-pull relation with respect to a source of waves to be repeated and an outgoing circuit, said devices having substantially similar characteristics with respect to second order modulation products appearing in the individual portions of their anode-cathode circuits whereby transmission of said second order products to said outgoing circuit is substantially prevented, and a resistance element in the common portion of the output circuits of said devices, and of such value as to make the impedance of said common portion to second order modulation products appearing therein of the critical value which will reduce the amplitudes of the third order modulation products transmitted to said outgoing circuit to a minimum.
8. In combination in a wave transmission system, a three-electrode electric space discharge device having a space path, a cathode-control electrode circuit and a cathode-anode circuit, means for impressing waves to be repeated on said cathode-control electrode circuit, a load circuit coupled to said cathode-anode circuit so as to receive the repeated waves, a circuit connected effectively in shunt with the space path of said device and comprising a resonant circuit tuned to second order modulation products of said waves, and means for reducing the effects of third order modulation products of said waves in said load circuit, said means comprising means for proportioning the impedance of said shunt circuit with respect to the second order modulation products of said waves to the critical value at which the amplitudes of the third order modulation products transmitted to said load circuit are a minimum.
9. In combination in a wave transmission system, a three-electrode electric space discharge device comprising a space path, input and output circuits, means for impressing on said input circuit of said device waves to be repeated, a load circuit, means for impressing the repeated products of said waves in said load circuit, and means for reducing the effects of modulation products of said waves in said load circuit, comprising a selective network in said output circuit of such nature as to suppress second order modulation components of said waves, a circuit in parallel with said output circuit and directly in shunt with said space path, a selective network in said parallel circuit of such a nature as to pass the second order modulation components of said waves, and means for proportioning the impedance of said parallel circuit with respect to second order components of said waves to the critical value at which the amplitudes of third order modulation components of said waves transmitted to said load circuit are a minimum.

JOHN G. KREER, JR.

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CERTIFICATE OF CORRECTION.

Patent No. 1,970,325.

August 14, 1934.

JOHN G. KREER, JR.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 4, claim 9, strike out line 122 and insert instead the words and comma waves in said output circuit on said load circuit,; and that the said Letters Patent should be read with this correction therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 17th day of December, A. D. 1935.

(Seal)

Leslie Frazer
Acting Commissioner of Patents.