THERMIONIC AMPLIFIER

Filed May 1, 1935 2 Sheets-Sheet 1

FIG. 1

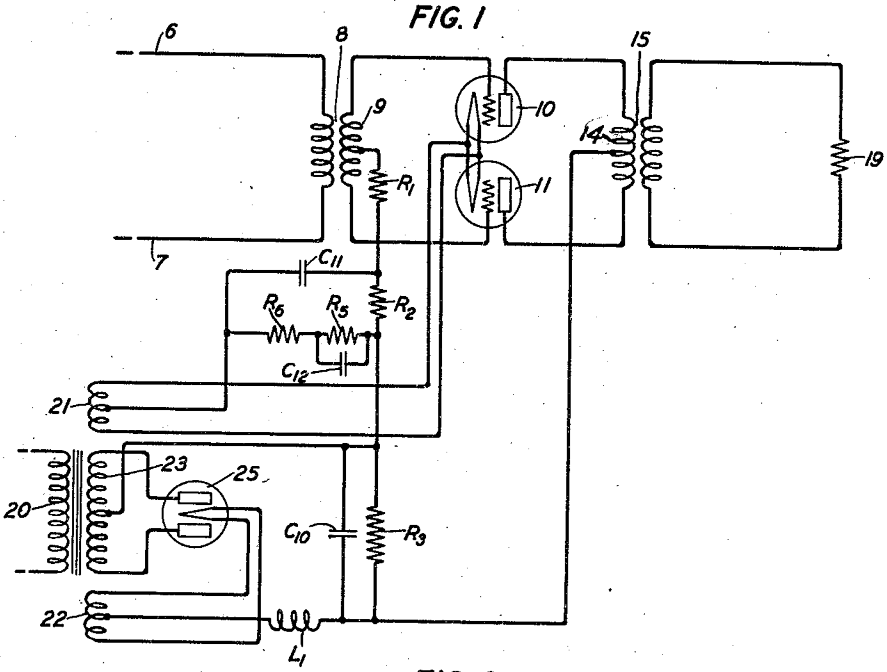


FIG. 2

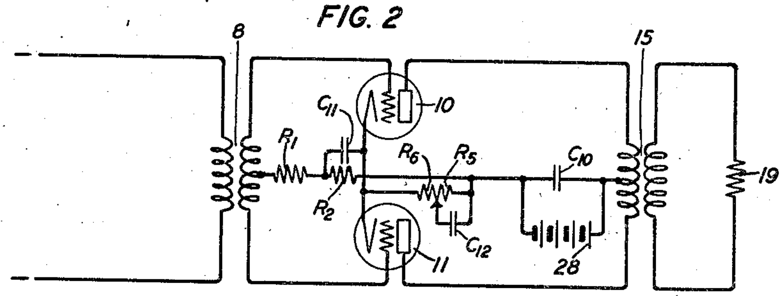
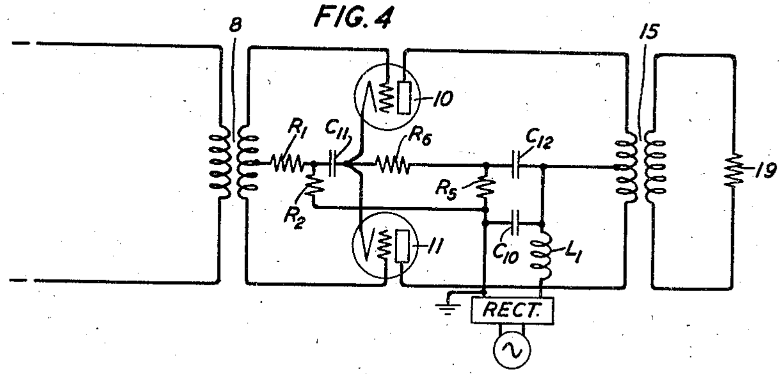


FIG. 4



INVENTOR
V. M. COUSINS
BY H. A. Burgess
ATTORNEY

Nov. 8, 1938. V. M. COUSINS 2,135,562

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FIG. 5

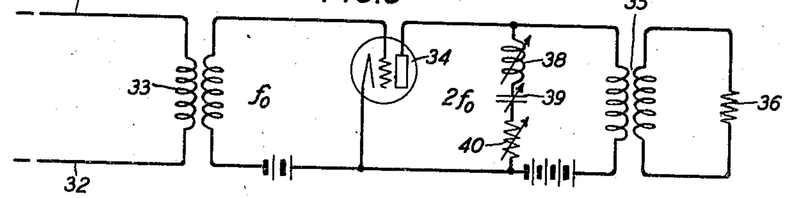


FIG. 6

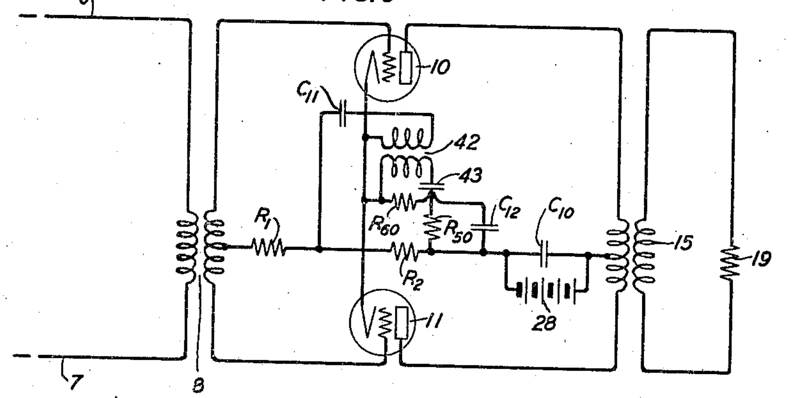
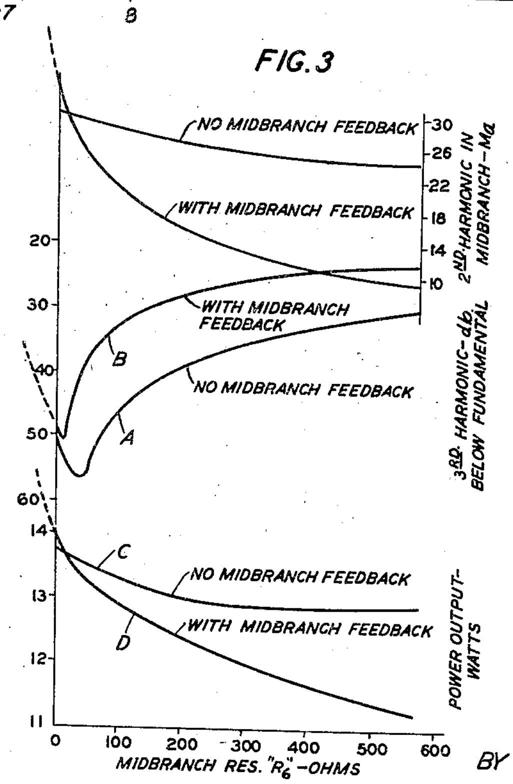


FIG. 3



INVENTOR
V. M. COUSINS

BY H. A. Burgess

ATTORNEY

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UNITED STATES PATENT OFFICE

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THERMIONIC AMPLIFIER

Van M. Cousins, Lyndhurst, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 1, 1935, Serial No. 19,150

2 Claims. (Cl. 179—171)

This invention relates to space discharge vacuum tube circuits such as are employed in signaling systems and sound reproducing systems, for example, vacuum tube amplifiers or the like. This invention has as an object the obtaining of an improved fidelity of the reproduction by an amplifier and an increased power output or efficiency. This object is attained by the control of modulation products in a manner to be disclosed, to increase the power output of fundamental frequency components while reducing undesired or objectionable harmonics in the amplifier output. A related object of the invention is to control modulation which takes place in the amplifier circuit to thereby influence the actual amount of output of the fundamental component as well as the relative amounts of fundamental and harmonic components.

A feature of the invention involves a specially designed circuit in the even order current path of an amplifier either in a push-pull stage passing one or more frequencies or in a single tube stage passing a single frequency or a narrow range as in a telegraph or carrier telegraph system.

It is well-known that the output of vacuum tube space discharge devices or the like contains distortion products. It is known that the output of an amplifier for a single frequency contains waves of the fundamental frequency and waves related to the fundamental as harmonics thereof. Some harmonic frequencies are quite objectionable, particularly the lower order harmonics since they are usually the strongest. The output of an amplifier for an impressed complex wave contains waves of frequencies equal to the sum and difference of the impressed frequencies and their harmonics. It is usually desirable for the purpose of high quality or fidelity of reproduction by an amplifier that there be a minimum of modulation products put out by the amplifier. This invention provides for utilizing the modulation products in increasing the fundamental frequency power output and in diminishing distortion, resulting in greater fidelity of reproduction. The power output in the fundamental frequency is increased without increase in energy expenditure giving an improved efficiency as well as a better reproduction of the input frequencies to be amplified.

The present invention employs in various embodiments a circuit having suitably disposed resistance and condenser elements of desired values for controlling the even order voltages in the vacuum tube plate circuit and intermodulating these voltages with the fundamental voltage. This invention makes use of the fact that odd order harmonics of the input fundamental frequencies of an amplifier may be generated or limited, or suppressed by intermodulation of the fundamental frequencies with the even order frequencies. The second order voltages when modulated with the fundamental voltages generate components consisting of new fundamental voltages and third order voltages. These new components are used to increase the output of the fundamental and decrease the output of the third harmonics, or otherwise, as will be described.

The invention will be better understood in illustrative embodiments described in the specification and shown in the accompanying drawings in which:

Figs. 1 and 2 are schematics of a single stage in an amplifier employing the present invention;

Fig. 3 shows characteristic curves for the operation using a mid-branch circuit, as shown in Figs. 1 and 2;

Fig. 4 shows a form of circuit especially applicable where a plate supply filter is used.

Fig. 5 is a schematic of a simple arrangement employed for transmitting either a single frequency or a very narrow band as in carrier telegraphy; and

Fig. 6 shows the application of a reversing transformer feed-back arrangement for giving improved operation under certain conditions.

As will be explained more fully hereinafter the invention causes the second order (e. g. double frequency) component to combine with the fundamental to produce some additional useful fundamental output. By such combination or intermodulation it is found possible also to reduce the third order distortion. Thus by reducing the third order distortion and at the same time raising the output of fundamental component, the invention achieves an increased ratio of signal to third order distortion. This is an important achievement, particularly since the reduction of the even order distortion is a comparatively simple matter, as by using the push-pull type of circuit, which is inherently balanced with respect to even order distortion.

In United States patent to Kreer 1,970,325, August 14, 1934, and in an article by Peterson and Evans entitled "Modulation in vacuum tubes used as amplifiers", published in the Bell System Technical Journal, July 1927, it is shown that the coefficient which determines the third order current components is

$$C_3=\frac{b_{03}-RC_1b_{12}+R^2C_1^2b_{21}-R^3C_1^3b_{30}-RC_2b_{11}+2R^3C_1C_2b_{20}}{1+b_{10}R}$$

where the b factors are derivatives of the tube static characteristics at the operating point:

$$b_{mn}=\frac{1}{m!n!}\frac{\delta^{m+n}i_p}{\delta^m E_p \delta^n E_g}$$

C_1 and C_2 are respectively the fundamental and second order current coefficients, and R is the load resistance in the plate circuit of the vacuum tube under consideration.

Now in a push-pull amplifier, the load resistance is not the same to all modulation components. It is well-known to those skilled in the art that in such an amplifier, second order voltages are generated in each tube, having such phase relations as to oppose each other in transmitting second order currents around the fundamental frequency path, and therefore the currents are transmitted through the output transformer out of phase, and flow back through the plate circuit mid-branch in phase. The load resistance presented to second order components of each tube is taken as twice the mid-branch circuit impedance, (neglecting the resistance of the output transformer) since the total second harmonic voltage developed across this mid-branch impedance represents the output of two tubes instead of one. It can be thought of, therefore, as the voltage developed by one of the two tubes in an impedance twice the actual impedance. In a push-pull amplifier, then, the third order coefficient C_3 for each tube may be rewritten to specify the load impedance to each current component, as follows:

$$C_3=\frac{b_{03}-R_1C_1b_{12}+R_1^2C_1^2b_{21}-R_1^3C_1^3b_{30}-R_2C_2b_{11}+2R_1R_2C_1C_2b_{20}}{1+b_{10}R_3}$$

The first four terms of the numerator of this expression involve fundamental frequency voltages and currents, and are therefore not affected by the plate circuit mid-branch impedance. The fifth term may be written as

$$-\frac{R_2C_2}{R_o^2}\frac{\delta R_o}{\delta E_g}$$

and represents a third order modulation term obtained through a second order voltage drop (R_2C_2) being applied to the plate impedance of a vacuum tube which is varying at a fundamental frequency rate under the control of the grid voltage. The sixth term represents a second order voltage (R_2C_2) and a fundamental frequency voltage (R_1C_1) applied to the non-linear plate impedance of the vacuum tube

$$\frac{\delta R_o}{\delta E_p}$$

thus producing third order modulation components. Since both the fifth and sixth terms contain R_2, which is mainly the plate circuit mid-branch impedance, it is apparent that the magnitude of these two terms, and consequently the magnitude of C_3 will be affected by the mid-branch impedance, and that C_3 can be made to vanish or be either positive or negative, depending on the value of R_2.

It is well-known that any modulation term of a given order contributes to frequencies of the same number as the order, and all lower frequency components of the same (odd or even) order. Thus, the fifth order modulation term would contribute to the fifth, third, and fundamental order components, the fourth order term to the fourth, second, and direct current order components. Similarly, the third order term C_3 contributes to the third order frequency component, and fundamental frequency component. However, the third order frequency term is totally dependent on the magnitude of C_3, while the third order contribution to the fundamental is only a part of the total fundamental energy. The magnitude of R_2 may therefore be selected such that the third order frequency term passes through a minimum at some value, as illustrated in Fig. 3, curves A and B, while the third order contribution to the fundamental frequency has a definite value. As R_2 is either increased or decreased from this optimum value for minimum third order component, the third order frequency term increases. However, the contribution to the fundamental frequency component by the third order term increases as R_2 is changed in one direction, and decreases as R_2 is changed in the opposite direction. Thus by adjustment of the mid-branch impedance, conditions may be obtained where (1) the third order frequency output and the fundamental frequency output are both large, (2) the third order frequency output is a minimum, and the fundamental frequency output has an intermediate value, (3) the third order frequency output is large and the fundamental output is a minimum. It should be pointed out that by employing a reversing transformer, and feeding back to the grid circuit through this transformer a portion of the second order voltage drop developed across the mid-branch impedance, R_2 may be given a negative sign, thus extending its effectiveness below the zero value as indicated in broken lines in Fig. 3.

The circuit of Fig. 1 has input leads **6** and **7** coming from a source of signal energy such as an earlier stage of an amplifier or a transmission line and connected to a transformer **8** the secondary winding **9** of which controls the input to tubes **10** and **11**. The push-pull output circuit of the tubes **10** and **11** includes the primary winding **14** of the transformer **15** and any suitable connection to a load **19** such as a loud-speaker or receiving apparatus. The power for operating this stage of the amplifier is obtained from the alternating current source indicated at the primary winding **20** of the transformer. The output of the secondary windings **21** and **22** of the power transformer are used for alternating current filament heating, and the secondary windings **23** furnish the B power which is rectified by the tube **25**. The B power obtained from the rectifier **25** is filtered by the inductance L_1 in series with the B supply and the condenser C_{10} and high resistance R_3 in shunt thereto. The negative side of the B supply circuit of the push-pull circuit passes to the filament through grid bias resistors R_5 and R_6 in series to the mid-point of winding 21. Resistance R_5 is shunted by condenser C_{12} of low impedance to alternating current components. The connection to the grids from the negative end of resistance R_5 extends through filtering resistances R_2 and R_1. Resistance R_2 and condenser C_{11} together form a shunt for alternating current components around the bias resistors R_5 and R_6. It is apparent that any alternating current voltage developed between the terminals across which condenser C_{11} is connected is put back on the grids. The amount of this voltage is determined by resistances R_5 and R_6 in series and by the shunting paths around these resistances comprising C_{12}, and R_2 in series with C_{11}. Therefore, by proportioning elements C_{11}, C_{12} and R_6, the voltage feed-back can be made zero or some finite value. Also by adjusting these elements the impedance of the mid-branch circuit to the alternating currents returning to the filaments can be determined, independently of the amount of feed-back, in order to control the even order modulation products as previously referred to.

The circuits of Fig. 1 were arranged, for purposes of test, as shown in Fig. 2, to variably shunt resistances R_5 and R_6 with a tap connecting to condenser C_{12}. The characteristic curves of Fig. 3 show the varying results in harmonic suppression and in power output control by the changes of values in the circuits of Fig. 2. The circuit of Fig. 2 employs a B battery source 28 in place of the rectifier filter supply circuit arrangement of Fig. 1. An optimum condition for a minimum third harmonic current is seen, in curve A of Fig. 3, to exist for a condition of about 35 ohms resistance in the mid-branch resistance R_6. At this value of mid-branch resistance the power output was nearly a maximum for a condition of no mid-branch feed-back. (Curve C.) With a mid-branch feed-back, the maximum power output is seen to be larger when the resistance R_6 is smaller. (Curve D.)

Fig. 4 shows a slight rearrangement of the elements of a push-pull output circuit to place certain elements of the mid-branch circuit in better position for a filtering of the B power. In this circuit the condensers C_{10} and C_{12} cooperate with inductance L_1 and resistance R_5 to form a filter for the plate supply circuit. They also provide a low impedance path from the mid-point of the output primary, respectively, to resistance R_2 and resistance R_6 and in shunt of resistance R_5 for the same purpose as explained in connection with Figs. 1 and 2.

The circuit of Fig. 5 adapted for transmitting a single frequency f_o has leads 31 and 32 coming from a carrier transmission line or an amplifier and through a transformer 33 controlling the grid of a single tube 34. The anode or output circuit of the tube 34 communicates through a transformer 35 to a load 36. The circuit employed for controlling even order products is tuned, as shown, to a frequency $2f_o$ the second harmonic of the input frequency f_o. This control circuit consists of an inductance 38, a condenser 39 and a resistance 40, any or all of which may be variable for purposes of control. Since there is no feed-back in this modification, the curves of Fig. 3 related to mid-branch feed-back are not applicable. However, the advantages obtained with this circuit are analogous to curves representing no feed-back in Fig. 3. The shunt for second order components enables the amount of second harmonic to be controlled and this in turn exerts a control on both the production of third order and fundamental components. By making the shunt of very low impedance to second harmonic, the production of this component is encouraged and a large amount is therefore available in the tube for intermodulation with the fundamental in the manner that has been outlined. Depending on the adjustment of this shunt in relation to tube characteristic and the impedance of the rest of the circuit the fundamental output may be increased, the third harmonic decreased, or either or both effects or their opposites can be secured. It is seen from the foregoing that this circuit is most effective in the case of a single frequency or when the frequency band transmitted is sufficiently narrow that the double frequencies or second harmonics can be effectively transmitted through the circuit 38, 39, 40.

The circuits of Fig. 6 are similar to those of Figs. 1 and 2 rearranged as to elements to permit the use of a reversing transformer 42 to provide feed-back permitting a greater power output by effectively giving a reversal of phase of voltage applied to the grids from across the resistance R_{60}, analogous to resistance R_6 of Fig. 1, making the magnitude of the resultant voltage impressed on the grids from the mid-branch circuit inversely related to the size of resistance R_{60}. A stopping condenser 43 is in series with the primary winding of this transformer 42 to prevent direct current shunting of one of the biasing resistances R_{60} corresponding to R_6 in Fig. 1. The mid-branch resistance R_{50} employed also for biasing resistance has a function similar to that of R_5 in the schematic of Fig. 1.

Advantages of this invention are shown graphically in the curves of Fig. 3 which are the results of measurements on the type of amplifier shown in Fig. 1 or Fig. 2. The measurements on which these curves are based were carried out with only a single constant frequency input at a time. The horizontal ordinates for all curves are in terms of ohms resistance of the mid-branch resistance R_6. The vertical ordinates for the power output in watts of the lower group of curves, show, for these two curves, the power output varying between 11 watts and about 14 watts for the two conditions of operation, one with feed-back and the other without feed-back. With mid-branch feed-back and a reversing transformer 42, the power output in watts is seen by the dotted extension of curve D to extend above 14 watts. The middle group of two curves is for third harmonic in terms of decibels below the power of the fundamental. These curves extend from about 22 decibels below fundamental to about 57 decibels below fundamental at the minimum point which exists for a condition of no mid-branch feed-back and a resistance of about 35 ohms value for R_6. Mid-branch feed-back with its advantages is obtained for a positive value of resistance R_6 by omission of the condenser C_{11}. Where it is desired to extend these curves in the direction of decreasing values of resistance R_6 beyond the point where that resistance is zero, this can be done by use of transformer 42, as in Fig. 6, which reverses the phase of the waves developed in resistance R_{60} before they are applied to the grids. The minimum third harmonic with mid-branch feed-back occurs theoretically when the value of the mid-branch resistance in R_6 is equal to the fraction

$$\frac{1}{1+\mu}$$

times the resistance for minimum third harmonic without feed-back. The two curves at the top of Fig. 3 are in milliamperes of second harmonic current flowing in the mid-branch circuit for varying resistance values of the resistance R_6 and are seen to vary from a value of about 8 milliamperes to about 30 milliamperes for circuits as in Fig. 1 and greater for mid-branch feed-back employing the reversing transformer **42**.

An ideal condition has been estimated to exist for a minimum presence of third harmonic current at which point there is a material improvement in the power output from the amplifier. By careful consideration of the curves, the condition most desired can be chosen. The power output is seen to be substantially flat above a condition of about 250 ohms value in the resistance R_6 for a condition of no mid-branch feed-back namely a condition employing the condenser C_{11} alone without the reversing transformer **42**. The theory to account for the existence of this flat region is somewhat in doubt. The second harmonic current flow decreases slowly as might be expected, with increase in value of resistance R_6. The diminution of power of second harmonic current in the mid-branch is seen to be much more rapid, for increases in value of resistance R_6, where feed-back is employed than where feed-back is not employed, as is seen from a comparison of the upper two curves of Fig. 3. The decrease should be greater with than without feed-back by a factor of $(1+\mu)$. R_6 should theoretically be $(1+\mu)$ times as effective with mid-branch feed-back as without mid-branch feed-back.

What is claimed is:

1. In a push-pull amplifier stage including thermionic devices having grid, anode and cathode elements, a circuit supplying anode voltage derived from an alternating current source, including a filter, a mid-branch circuit with impedance elements including resistance and condenser elements for controlling transmission to the cathodes of the second order components, said resistance being disposed in series with the anode power supply and said condenser being placed in shunt to the anode power supply to aid in filtering the anode power supply, said impedance elements being proportioned to correspond substantially to the minimum point of the curve of third harmonic distortion as a function of mid-branch resistance (R_6).

2. In a push-pull amplifier stage, a pair of thermionic amplifier tubes having cathode, grid and anode elements, an output transformer connecting the anodes of the tubes, a plate mid-branch circuit connecting the mid-point of the output transformer primary to the cathodes of the tubes, a source of anode voltage connected in the plate mid-branch circuit through an inductance in series with the positive terminal and a first resistance and a second resistance in series with each other and with the negative terminal, condensers shunted across the source of anode voltage beyond the inductance and connected to the opposite terminals of said first resistance, said second mentioned resistance being connected to the cathodes, a direct current connection extending from the grids to the negative end of said first-mentioned resistance through a filtering resistance, and a filtering condenser connected from a point in said filtering resistance to the cathodes.

VAN M. COUSINS.