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A NEW HIGH-EFFICIENCY POWER AMPLIFIER FOR MODULATED WAVES

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DESCRIPTION OF A
NEW FORM OF LINEAR POWER AMPLIFIER DESIGNED FOR
EFFICIENT OPERATION OF HIGH-POWER TRANSMITTERS

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A New High-Efficiency Power Amplifier for Modulated Waves

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Summary

This paper introduces a new form of linear power amplifier for modulated radio-frequency waves. Plate circuit efficiencies of 60 to 65 per cent independent of modulation are obtained by means of the combined action of varying load distribution among the tubes and varying circuit impedance over the modulation cycle.

The theory of operation is developed and detailed observations on the behavior of tubes in the new circuit are given in the paper. The use of stabilized feedback in connection with this circuit is discussed and significant measurements on a laboratory model of a 50-kilowatt transmitter are shown.

THE trend toward increasingly higher power levels in broadcasting in the last few years has attached new importance to the matter of more economical operation of radio transmitters. Most of the opportunity for improvement in this direction lies in increasing the efficiency of the high-power stages to reduce the cost of power, the size of high-voltage transformers and rectifier, and the water-cooling requirements. With power levels of 50 kilowatts and higher these items account for an important part of the operating expense of a broadcast station, and the development of practical methods for increasing the efficiency should provide considerable stimulus to the use of higher power.

Methods hitherto employed for reducing power consumption include the high-level Class B modulation system, such as is used at WLW,[1] and the ingenious method of "outphasing modulation"[2] invented by Chireix and employed in a number of European installations.

The development of these schemes was occasioned by the fact that the linear radio-frequency power amplifier, in the form in which it has been used for years in radio transmitters, may not be operated at an efficiency of more than about 33 per cent, for unmodulated carrier, if it is to supply the peak power output of a completely modulated wave. With this efficiency the d-c power input to a 50-kilowatt ampli-

[1] Chambers, Jones, Fyler, Williamson, Leach, and Hutcheson, "The WLW 500-Kilowatt Broadcast Transmitter," *Proc. I. R. E.*, Vol. 22, p. 1151; October, 1934.
[2] Chireix, "High Power Outphasing Modulation," *Proc. I. R. E.*, Vol. 23, p. 1370; November, 1935.

fier, for example, is 150 kilowatts, of which 100 kilowatts must be dissipated at the anodes of the water-cooled tubes.

The new form of linear power amplifier to be described in this paper removes this limitation of the conventional circuit, permitting efficiencies of 60 to 65 per cent to be realized, while retaining the advantages which account for the widespread use of linear amplifiers in broadcasting. These advantages include, notably, the elimination of high-power audio equipment, since modulation may be accomplished at a low power level; and the ease with which linear amplifiers may be added to an existing transmitter to increase its power output. Linear amplifiers, moreover, are suitable not only for the carrier-and-double-sideband signal employed in present-day broadcasting, but for any other type of transmission, such as the single-sideband system now in use in the transoceanic radio telephone circuit and frequently suggested as a remedy for the congestion in the broadcast spectrum.

A brief consideration of the mode of operation of the conventional linear power amplifier will show the reason for its low average efficiency and will afford a clew as to how, by the application of a new principle in power amplifier design, this efficiency may be approximately doubled.

Operation of Conventional Linear Power Amplifiers

The tubes are usually biased nearly to the cut-off point, so that the plate current flows in a series of pulses having approximately the shape of half sine waves, as shown in Fig. 1. The output circuit is anti-resonant to the fundamental and has a low impedance to the harmonic components of the plate current, so that the plate voltage wave is nearly sinusoidal and opposite in phase to the plate current and grid voltage.

With a peak value of plate current of i_{max} and a peak amplitude of e_{max} in the plate voltage wave, the power output of the tube is

$$P_{\text{out}} = \frac{e_{\text{max}} i_{\text{max}}}{4}. \tag{1}$$

Since the average value of the half-sine wave of plate current is $1/\pi$ times the maximum value, we have for the d-c input power to the tube

$$P_{\text{in}} = \frac{E_B i_{\text{max}}}{\pi}. \tag{2}$$

The efficiency is accordingly

$$\text{Eff.} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\pi}{4} \frac{e_{\text{max}}}{E_B}. \tag{3}$$

If one were able to utilize a value of e_{max} equal to the d-c plate voltage, the efficiency as given by (3) would be $\pi/4$, or 78.5 per cent. In practice, with a tube working close to its full output capacity, the plate swing is usually limited to a value of 0.85 to 0.9 times E_B, since the output will be decreased if the plate potential swings down to a value lower than the maximum grid voltage. Under these conditions,

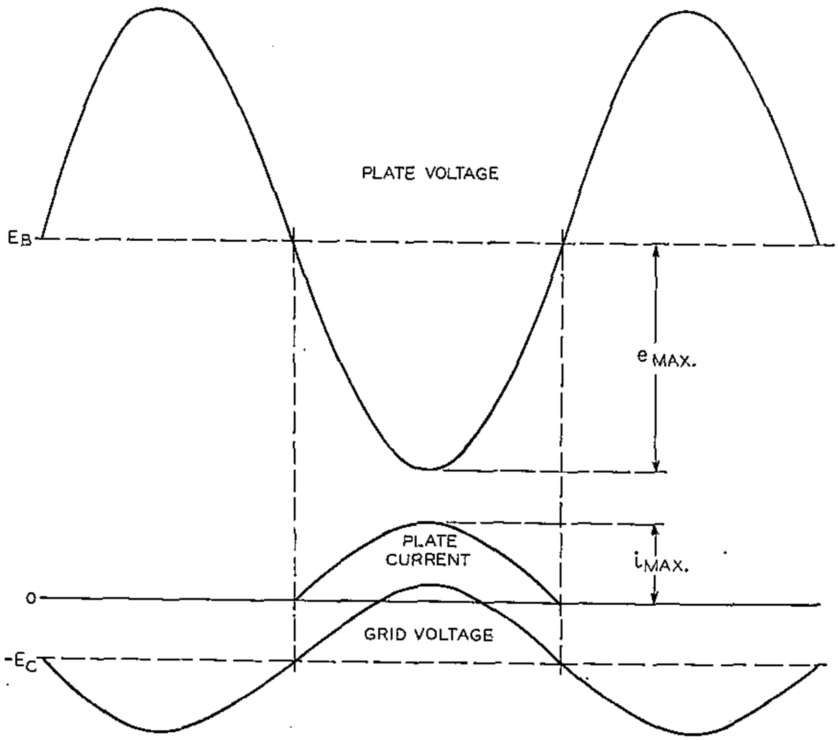

Fig. 1—Operating conditions in a linear power amplifier.

and allowing for a 5 per cent loss in the tuned output circuits of the amplifier, expression (3) will give a value of 63 to 67 per cent as the maximum overall plate circuit efficiency obtainable.

Now with a modulated wave applied to the grid this efficiency is obtained only at the maximum instantaneous output of the amplifier, and since the amplitude of the radio-frequency plate voltage wave, in a transmitter capable of 100 per cent modulation, is only half as great for the unmodulated condition as for the peaks of modulation, the efficiency with zero modulation does not exceed 33 per cent. Even during complete modulation the effective efficiency over the whole audio cycle is only 50 per cent, and for the average percentage modulation of broadcast programs the all-day efficiency is scarcely in excess of the value for unmodulated carrier.

The weakness, then, of the conventional method of amplifying a modulated wave is that the amplitude of the radio-frequency plate voltage is too small during most of the operating time, and in order to improve the situation it is necessary to devise a system in which a larger amplitude is employed.

High-Efficiency Operation

The method of attack on this problem is to consider an amplifier operating, arbitrarily, with a high plate voltage swing and consequently high efficiency at the carrier output, and then to find what must be done to permit an increase in output. We shall see that a simple and fundamental means is available for doing this.

A tube will operate at high efficiency at any desired output power, however small, provided the alternating plate voltage is high, i.e., provided the load impedance is high enough to require a large voltage output from the tube. To take a concrete example, a tube capable of delivering 100 kilowatts at high efficiency into an impedance of R ohms will deliver 50 kilowatts into $2R$ ohms at the same voltage output and consequently the same efficiency. We should find, however, upon modulating the radio-frequency grid voltage, that the tube could not respond to the upward swings of modulation because the alternating plate voltage had already reached its maximum value at the 50-kilowatt output.

Suppose now that an additional source of voltage could be inserted in series with the load, as represented by the generator of Fig. 2. If

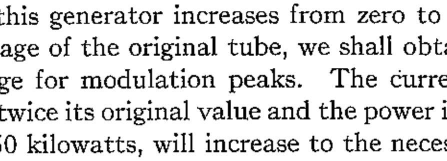

Fig. 2—Insertion of a hypothetical source of additional voltage.

the voltage of this generator increases from zero to a value equal to the output voltage of the original tube, we shall obtain the necessary increased voltage for modulation peaks. The current in the circuit will increase to twice its original value and the power in the load, which was originally 50 kilowatts, will increase to the necessary peak power of 200 kilowatts, or four times the carrier power, 100 kilowatts being furnished by the tube and the other 100 kilowatts by the generator.

The sensation experienced by the original tube as the added generator comes into play is a gradual lowering of the impedance into which it works, since its output current increases without any increase in its output voltage, and when the added generator has a voltage equal to that of the tube this impedance has effectively been reduced from $2R$ to R ohms. The increase in current occasioned by the activity of the generator of course tends to reduce the output voltage of the original tube because of the greater internal drop, but since the grid excitation on the tube is continuing to increase in accordance with the modulation the tube is able to maintain its output voltage in spite of the increase in load current.

We now have the problem of replacing this added generator with a tube. Obviously we cannot replace it directly, because while a generator would offer no impedance to the flow of current from the original tube, an inactive tube would offer an infinite impedance. The solution is to interpose, as shown in Fig. 3, a network having a certain

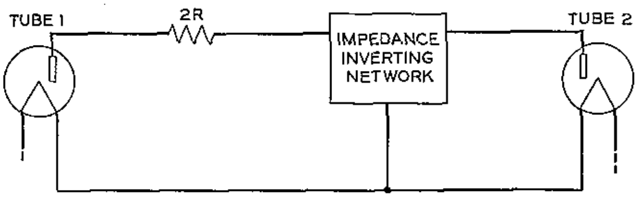

Fig. 3—Fundamental form of a high-efficiency circuit.

property, namely, that the impedance at the sending end is inversely proportional to the terminating impedance. This is a familiar property of quarter-wave transmission lines and their equivalent networks. As long as the second tube does not conduct, the network is terminated in an open circuit. Its input impedance is therefore zero and the first tube works into an impedance of $2R$ ohms. When the second tube is permitted to conduct, the terminating impedance of the network is reduced, and since the grid excitation on the tube causes the plate current to be opposite in phase to the plate potential, this terminating impedance provided by the tube is a negative shunt resistance;[3] that is, the tube delivers power to the circuit. As the contribution of the second tube increases, lowering the negative terminating resistance of the network, the input impedance of the network, which was originally zero, increases. This input impedance is a negative series resistance which reduces the impedance presented to Tube No. 1 from its original value of $2R$ ohms, and when, at the peak of modulation, Tube No. 2

[3] Crisson, "Negative Impedances and the Twin 21-Type Repeater," *Bell System Technical Journal*, Vol. X, p. 485; July, 1931.

is contributing half the total power, the load impedance to No. 1 is R ohms, and No. 1 is able to supply twice the carrier power at the same radio-frequency plate potential as at the carrier.

We may revert to the generator analogy by recalling an associated property of impedance-inverting networks, namely, that any definite current at one pair of terminals is associated with a definite coexisting voltage at the other pair, entirely without regard to the terminating impedances; the supplying of current to the circuit by Tube No. 2 at the far end of the network is, accordingly, identical in its effect to the injection of a voltage at the near end, in series with the voltage of Tube No. 1, after the fashion of our original hypothetical generator.

Considering now the dynamic characteristic of the amplifier as a whole, the operation is as follows: The grids of both tubes are excited by the modulated output of the preceding stage, but for all instantaneous outputs from zero up to the carrier level Tube No. 2 is prevented by a high grid bias, or some other means, from contributing to the output, and the power is obtained entirely from Tube No. 1, which is working into twice the impedance into which it is to work when delivering its peak output. In consequence, the radio-frequency plate voltage on this tube at the carrier is nearly as high as is permissible and the efficiency is correspondingly high. Beyond this point the dynamic characteristic of Tube No. 1, unassisted, would flatten off very quickly because the plate voltage swing could not be appreciably increased. The second tube, however, is permitted to come into play as the instantaneous excitation increases beyond the carrier point. In coming into play the second tube not only delivers power of itself, but through the action of the impedance-inverting network causes an effective lowering of the impedance into which the first tube works, so that the first tube may increase its power output without increasing its plate voltage swing, which was already a maximum at the carrier point. At the peak of a 100-per-cent modulated wave each tube is working into the impedance R most favorable to large output and delivering twice the carrier power, so that the total instantaneous output is the required value of four times the carrier power. Thus the required tube capacity is the same as in a conventional linear power amplifier.

What we have, then, is a two-tube amplifier in which the contribution of the second tube is delayed until the first tube has reached an efficient operating condition; whereupon there ensues a supplementary action between the tubes, to which the impedance-inverting network is a necessary adjunct.

The arrangement of Fig. 3 is one of the two fundamental forms of the high-efficiency circuit. The other form is shown in Fig. 4. In this case the physical load impedance used is $R/2$, which is the same as would be employed if the tubes were to be connected in parallel in the conventional type of amplifier. The impedance-inverting network is then interposed between the load and Tube No. 1, which is to deliver the carrier power. As long as Tube No. 2 is inactive the network is terminated in $R/2$ ohms, and the network is so designed that the impedance presented to Tube No. 1 under this condition is $2R$ ohms, the impedance necessary for attaining high efficiency at the carrier output. As the second tube comes into action in parallel with the load it raises the effective terminating impedance of the network, with a consequent lowering of the impedance presented to Tube No. 1;

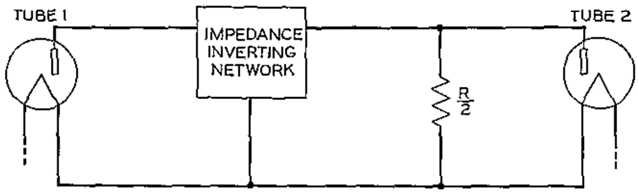

Fig. 4—Second fundamental form of high-efficiency circuit.

and again we have each tube, at the instantaneous peak of modulation, working into the desired effective load impedance of R ohms.

Fig. 4 may be said to show a shunt-connected load, as contrasted with the series-connected load of Fig. 3. The shunt connection appears to be more advantageous for most practical purposes because the load circuit is grounded, while in the series arrangement the load is neither grounded nor balanced to ground.

General Observations

Voltage and Current Relations

The voltage and current relations in the two tubes as the amplitude of the grid excitation is varied are shown by Figs. 5 (*a*) and 5 (*b*), and the corresponding shapes of the envelopes of radio-frequency plate currents and voltages during complete modulation are shown in Fig. 6.

If we denote by k the ratio of the instantaneous amplitude of the envelope to the peak amplitude reached during 100 per cent modulation, then for amplitudes between zero and the carrier point, where $k = 1/2$, the total output of the amplifier comes from Tube No. 1, and is given by the expression

$$P_{\text{total}} = P_1 = (2kE_{\max})(kI_{\max}) \\ = 2k^2E_{\max}I_{\max}, \tag{4}$$

where $E_{\max}$ and $I_{\max}$ are the root-mean-square values of radio-frequency plate voltage and plate current which are to exist when the tube is delivering its maximum power, i.e., when $k = 1$. The factor 2 above is required because the voltage on Tube No. 1 reaches the value $E_{\max}$ when $k = 1/2$.

Between $k = 1/2$ and $k = 1$ the voltage on No. 1 remains at $E_{\max}$ volts while the current in No. 1 and the voltage across No. 2 continue to rise linearly; meanwhile the current in No. 2 commences and rises

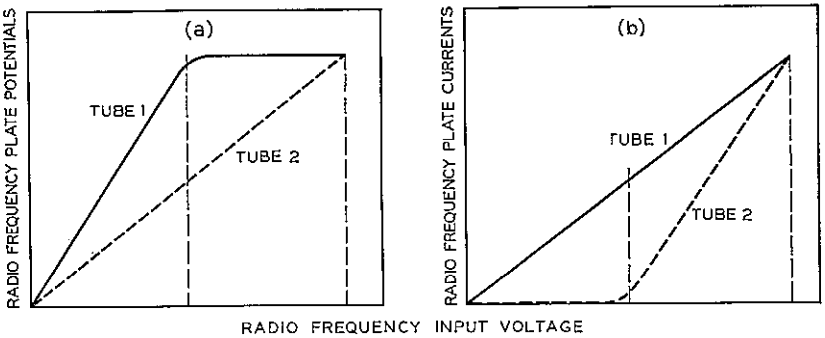

Fig. 5—Voltage and current relations in the two tubes.

twice as fast in order to reach the value $I_{\max}$ at $k = 1$. The total power between these two values of k is the sum of the outputs of the two tubes:

$$P_{\text{total}} = P_1 + P_2 \\ = E_{\max}(kI_{\max}) + (kE_{\max})(2k - 1)I_{\max} \\ = 2k^2E_{\max}I_{\max}, \tag{5}$$

which is the same as expression (4) above, showing that the current and voltage relations of Fig. 5 are consistent with continuity in the dynamic characteristic of the amplifier.

By assuming k to vary sinusoidally about its carrier value of 1/2, in accordance with the modulation, and integrating the values of P_1 and P_2 as given by (4) and (5) over the appropriate half-cycles of modulation, the average output of each tube during modulation may be determined. This integration gives for the average output of

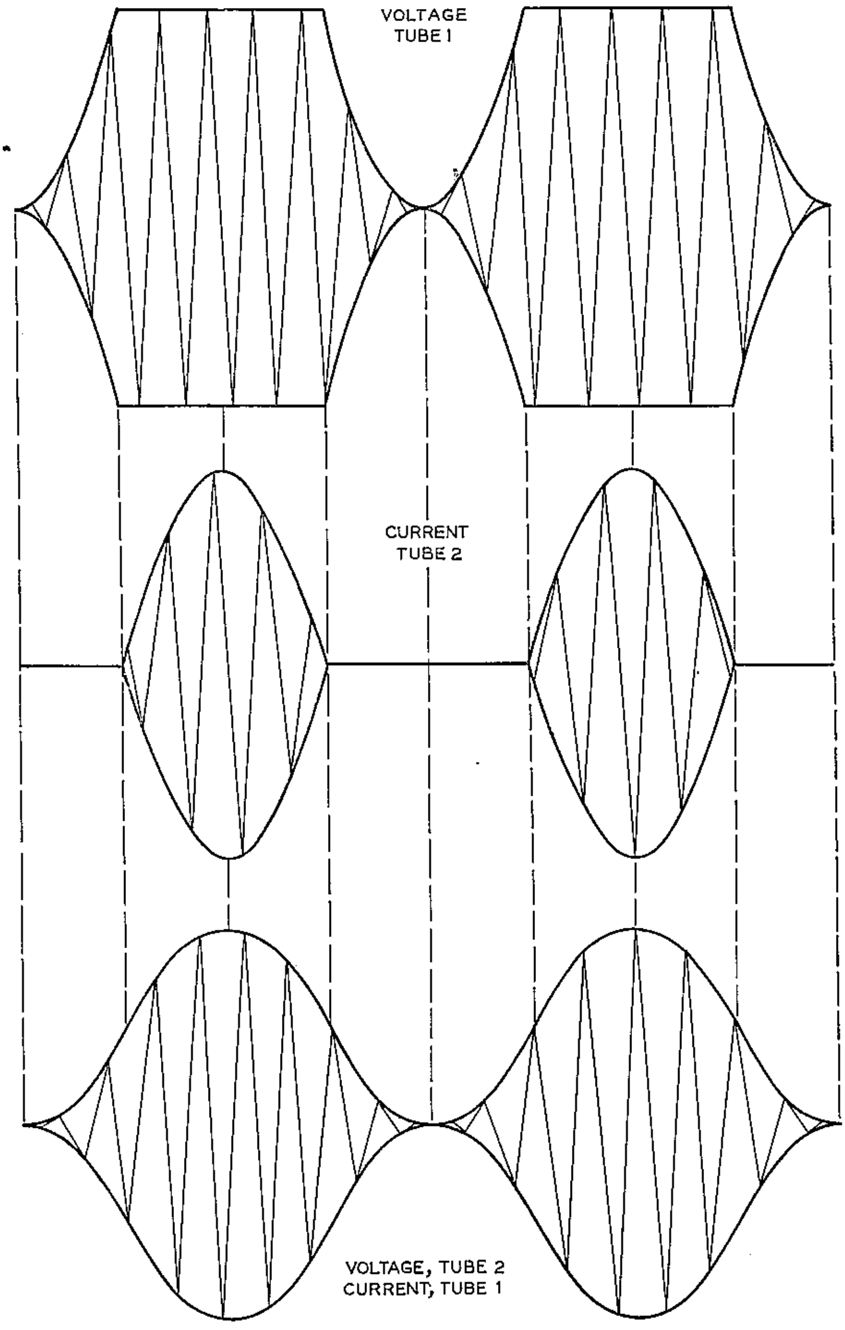

Fig. 6—Envelopes of the radio-frequency plate currents and voltages during complete modulation.

Tube No. 1 during 100 per cent modulation a value of 0.93 times the carrier output, and for Tube No. 2 a value of 0.57 times the carrier output, these two figures adding up to the factor 1.5 by which the average total output is increased when complete modulation occurs.

The sharp transitions shown at the carrier amplitude for this hypothetical case would necessitate extremely careful adjustment to insure that they were simultaneous. In practice neither transition is so abrupt, and the adjustment becomes, as will be shown, an operation requiring only reasonable care.

Since the d-c plate current of a power amplifier is closely proportional to the radio-frequency plate current, the audio-frequency component of the plate current of Tube No. 1 is very nearly sinusoidal with sinusoidal modulation, and the average or d-c plate current of this tube is unchanged from its carrier value, while the audio-frequency plate current of No. 2 is a half sine wave. The average or d-c value of a half sine wave existing during the positive half of the modulation cycle is $1/\pi$ times the peak value. This peak value is determined by the peak efficiency of Tube No. 2, and by virtue of the smaller pulse width of the radio-frequency plate current of this tube, resulting from its being biased well beyond cut-off, this peak efficiency is somewhat higher than can be obtained in Tube No. 1, whose pulse width is about a half cycle. It is easy to show, for the hypothetical conditions of Fig. 5, that if the average plate current of No. 2 at 100 per cent modulation is to be half that of No. 1, so that the overall efficiency of the amplifier may be the same as with unmodulated carrier, the peak efficiency of Tube No. 2 must be $4/\pi$ times that of No. 1, or about 80 per cent for a combined efficiency of 63 per cent.

Impedance-Inverting Networks

It will be useful at this point to note the structure and properties of the impedance-inverting networks which are employed to obtain the impedance variations necessary for high-efficiency operation.

In Fig. 7 are shown two networks having the interesting and easily verifiable property that a voltage E applied or appearing at either end of the network is associated with a coexisting current at the other end having an amplitude E/X and a phase differing by 90 degrees from the phase of E. This current is independent, in amplitude and phase, of the nature of the impedance through which it flows at the terminals of the network. When this terminating impedance is a resistance R_1 and a voltage E is applied across the other terminals, the above property leads immediately to the following relations:

(*a*) The voltage phase retardation introduced by the network is 90 degrees regardless of the value of R_1; this indicates that no phase modulation will be occasioned by the variation in terminating impedance of the network when the second tube comes into action.

(*b*) The input impedance of the network is a resistance inversely proportional to R_1; it is equal to X^2/R_1.

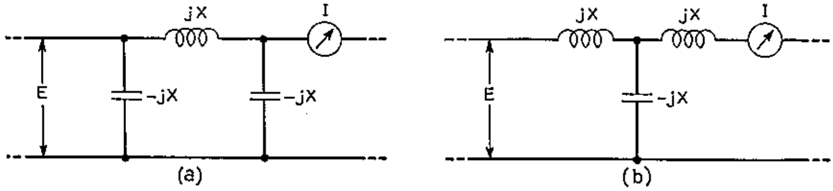

Fig. 7—Typical impedance-inverting networks.

(*c*) The voltage across R_1 due to E is proportional to R_1; it is equal to $-jE \cdot R_1/X$.

The above properties are likewise possessed by a quarter-wave transmission line whose characteristic impedance is X ohms, and by certain other network configurations.

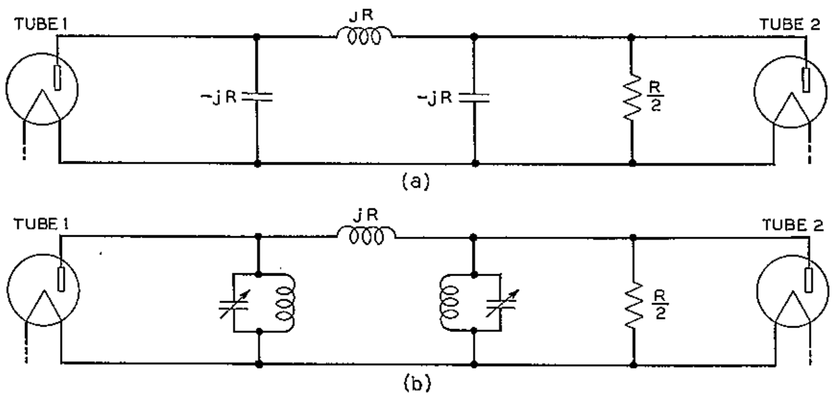

Fig. 8—Evolution of the output circuit.

If the coils in the above networks are replaced by condensers and the condensers by coils the same properties hold except that the phase is advanced 90 degrees instead of retarded.

By using the pi-network of Fig. 7 (*a*) a very simple output circuit for the amplifier may be arrived at. The fundamental relations are shown in Fig. 8 (*a*). A load circuit is designed having a shunt resistance of $R/2$ ohms, as if the two tubes were to be connected directly in parallel. R, as before, is the impedance into which each tube is to work when delivering its peak power. The 90-degree network is then interposed between Tube No. 1 and this load circuit. The constants of this network must be such that when Tube No. 2 is inactive (i.e., when the network is terminated in $R/2$ ohms) the alternating voltage across No. 2 is half the voltage across No. 1, so that if the voltage on No. 1 has reached the maximum permissible value when the carrier power is being delivered, the voltage on No. 2 will have reached only half this value and may therefore rise sufficiently to accommodate the peaks of modulation. By relation (*c*) above, this requires that the three elements of the 90-degree network should have reactances of R ohms.

Next it is desirable, as in any radio-frequency power amplifier, to connect across each tube an anti-resonant circuit to provide a path of fairly low impedance for the harmonic components of the radio-frequency plate currents. By detuning these anti-resonant circuits *sufficiently to obtain negative shunt reactances of R ohms, the shunt* condensers of the 90-degree network may be eliminated, and the complete output circuit is reduced to the simple form shown in Fig. 8 (*b*).

The effective shunt load $R/2$ would in most cases be obtained by coupling the antenna circuit to the necessary extent into the tuned circuit across Tube No. 2. The intertube coupling coil designated jR may be used to carry the d-c plate current from one tube to the other, so that only one plate choke is necessary.

The process of tuning the circuit is very simple. The proper reactance for the inter-tube coupling coil having been selected and the load having been coupled in so as to obtain the proper shunt resistance $R/2$, the condenser across Tube No. 2 is adjusted under power to give a 90-degree phase relation between the plate potentials on the two tubes, as indicated on a cathode ray oscilloscope by an elliptical pattern with axes at right angles. The condenser across Tube No. 1 is then adjusted for minimum plate current on this tube, in accordance with the usual method of tuning a power amplifier, and the plate circuit tuning is complete.

An interesting feature of this circuit is that when the carrier is unmodulated the radio-frequency harmonic output is considerably reduced because the power is coming entirely from Tube No. 1 and the harmonics generated in this tube are attenuated by the inter-tube coupling circuit.

The Input Circuit

The high-efficiency system being described is unique in being purely a method of amplification and not a modulation scheme, and therefore requiring only a modulated wave from a lower-powered transmitter for exciting the grids. In applying this modulated input to the amplifier it is necessary to have the voltages on the two grids 90 degrees apart in phase in order that each may be opposite in phase to the related plate potential, as is necessary in any power amplifier.

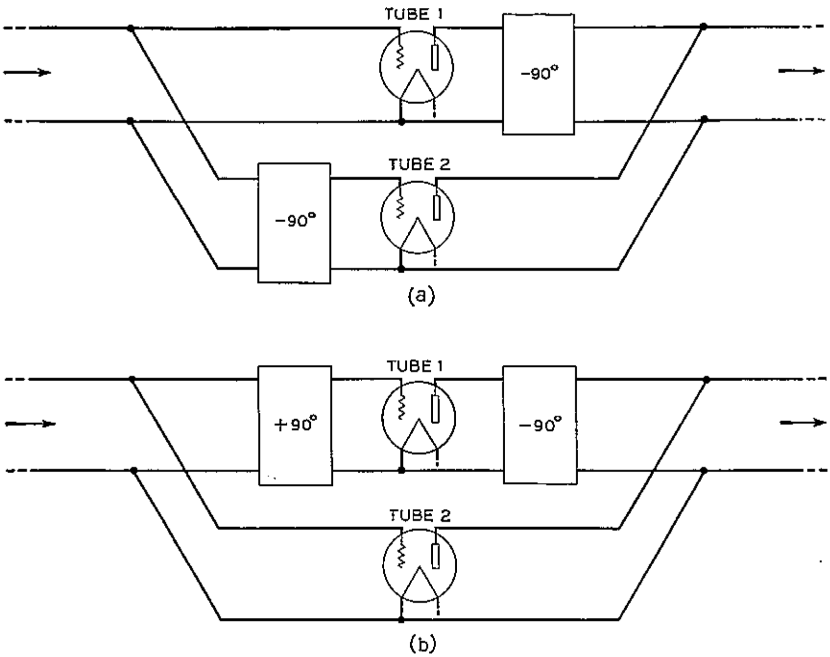

Fig. 9—Alternative arrangements of the grid phase-shifting network.

The 90-degree phase relation may be obtained by using a network of the general type shown in Fig. 7, and the adjustment is accomplished under power, using a cathode ray tube, in the same way as has been described for the plate circuit.

With the appropriate 90-degree network inserted in the grid circuit, the amplifier assumes one of the forms indicated in Fig. 9. This figure illustrates clearly the fundamental simplicity of the new system. *Obviously the operation is essentially the same as that of the conventional linear amplifier at any time that the load is equally divided between the tubes, as is the case for an instant at the peak of a completely modulated* *wave; but merely by the introduction of two phase shifts it becomes possible to make use of a variable load distribution to establish the necessary conditions for high efficiency at outputs much smaller than the peak output.*

The simplest and most obvious way of keeping the second tube inactive until the carrier point is reached is by the use of a higher grid bias on this tube, with sufficient excitation so that at the peak of modulation the required output is obtained from the tube in spite of the higher bias.

The first tube, being biased nearly to cut-off, behaves like a conventional linear amplifier from zero excitation up to the carrier point. Beyond this point, because of the changing load impedance, the excitation is not required to rise to twice its carrier value. In most of the tests it has been found that the effective excitation on the first tube is required to rise only about 40 per cent instead of 100 per cent on the positive half of the modulation cycle. A further increase in

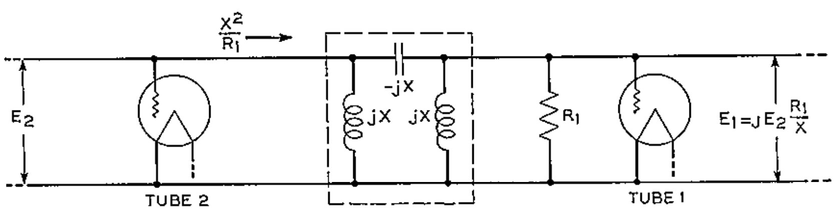

Fig. 10—Grid exciting circuit.

drive would carry the instantaneous grid potential up to a point where too many of the electrons would go to the grid instead of the plate, causing a very rapid increase in positive grid current. A number of ways immediately suggest themselves for obtaining the required limiting action; one of the simplest ways is by the use of a grid leak in the bias supply to the first tube; another useful method is to permit the grid current to limit the drive by its shunting effect on the exciting circuit. In Fig. 10 the two grids are shown connected to a phase-shifting network consisting of reactances of X ohms and a resistance R_1. When the grid of Tube No. 1 is not conducting, the voltage E_1 obtained on this grid with a voltage E_2 applied to the network is $jE_2 \cdot R_1/X$. When grid current flows in Tube No. 1, the effective reduction in R_1 causes a diminution in the ratio of E_1 to E_2. The proper value of R_1 to give the desired limiting effect is easily calculated from the approximate maximum grid current. The proper resistance is not at all critical because of the rapidity with which the grid current increases with drive at power outputs close to the maximum. This value of R_1 is considerably higher (i.e., the required driving power E_1^2/R_1 is lower) than in the case of the conventional linear amplifier, where R_1 must be made low enough so that the grid current will not cause appreciable diminution in the drive.

As R_1 is effectively lowered by the rapidly increasing grid conductance, the input impedance X^2/R_1 of the grid phase-shifting network is increased, compensating to a large extent for the shunting effect of the grid current which flows in Tube No. 2 as it approaches its peak output, so that the driving stage is assisted in maintaining the proper drive on No. 2.

On account of these effects the grid driving power required for this type of amplifier is actually less than for the conventional linear amplifier, and in the experimental work a driving stage has been used in most cases having only about half the power capacity customarily employed for exciting a conventional amplifier of the same output.

Linearity of Amplification

For high-quality transmission it is important to obtain in power amplifiers a linear relation between grid exciting voltage and output circuit voltage. In the high-efficiency circuit the high impedance used for Tube No. 1 over the lower half of the modulation envelope causes the dynamic characteristic to be quite straight in this region. To obtain linearity from the point where curvature begins on the first tube, up to the point representing the peaks of modulation, is a matter involving both the point at which the second tube comes into action, and the rate at which its contribution increases with drive. For securing a satisfactory adjustment we have available two variables, namely, the bias on the second tube and the amplitude of the excitation on this tube. A higher bias requires a higher exciting voltage to overcome it, but the rate at which it is overcome is greater. By a reasonably careful selection of these two quantities the amplifier may be made to operate with low distortion.

Careful adjustment of excitation and bias to obtain low distortion is no longer necessary when the feedback principle [4] due to Black is employed. One application of stabilized feedback to reduce distortion has been described [5] in connection with a 50-kilowatt transmitter. This application involved feeding back to the audio circuits a sample of the rectified output. With transmitters employing low-level

[4] H. S. Black, "Stabilized Feedback Amplifiers," *Electrical Engineering*, January, 1934; *Bell System Technical Journal*, January, 1934.

[5] Poppele, Cunningham, and Kishpaugh, "Design and Equipment of a 50-Kilowatt Broadcast Station for WOR," presented at I. R. E. annual convention, July, 1935.

modulation and linear radio-frequency amplifiers we have available not only this type of feedback but also the opportunity for using a radio-frequency feedback from the final power amplifier to one of the earlier stages of linear radio-frequency amplification. Such feedback may be applied independently of any audio-frequency feedback, and has an important advantage over the latter in that it corrects not only distortion and noise but carrier shift as well.

In applying feedback to a transmitter it is found that a stabilization or improvement in linearity is obtained which corresponds to the db reduction caused by the feedback in the overall gain. It is found, moreover, that each individual noise component arising in the amplifier as a result of power supply ripples is automatically reduced by an amount corresponding to the reduction in gain.

Because of the gain reduction it is necessary to increase the level ahead of the point at which the feedback is introduced. This is usually an easy matter because the power at this point is small in comparison with the output of the final stage. Moreover, the intermediate stages included in the feedback loop may be designed for smaller output than is normally required, since the distortion caused by their deficiency in output will be taken care of by the feedback itself. The use of feedback therefore requires little or no increase in the tube complement of a transmitter.

Experimental Results

The first test of the high-efficiency circuit was made with a pair of small tubes, and was intended chiefly to permit a study of the action of the tubes under these new conditions of variable load distribution and to show whether the amplifier as a whole would behave in the manner predicted. No feedback was used in this first test. Fig. 11 shows the observed variation of the radio-frequency plate potentials and d-c plate currents of the two tubes as the excitation on the amplifier was increased. The radio-frequency plate potential of Tube No. 2 is the potential across the load circuit and is required to be linear with excitation. The short dotted portion halfway up on this characteristic shows the curvature that would be obtained if the second tube were not allowed to come into action. With proper adjustment of the bias and excitation on the second tube this effect is eliminated and the characteristic continues to rise up to the desired peak amplitude.

The radio-frequency plate voltage of Tube No. 1 is seen to be twice that of No. 2 up to the point where curvature begins, and then to increase only slightly between the carrier output and peak output.

The plate current of No. 2 commences just before the carrier point is reached and rises twice as rapidly as the plate current of No. 1. The equality of plate currents and radio-frequency plate potentials on the two tubes at the peak of modulation indicates that the tubes are contributing about equally to the instantaneous output at this point.

The observed efficiency is plotted against excitation in Fig. 12. It is seen to be 63 per cent at the carrier level. It continues to rise even

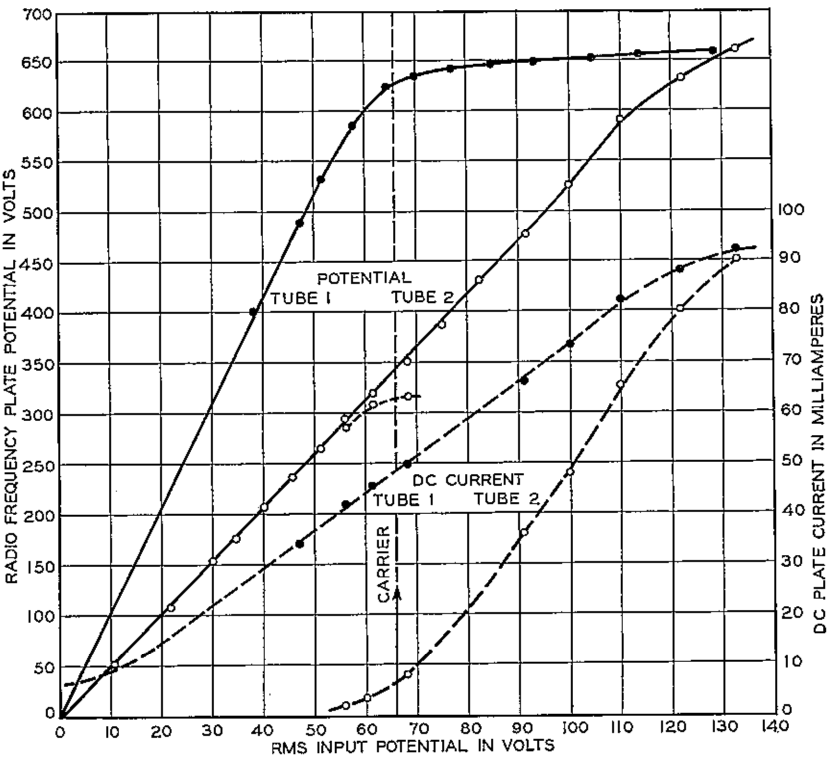

Fig. 11—Typical experimental results.

after the second tube comes in, because the plate voltage swing on the first tube is still rising slightly. The initial efficiency of Tube No. 2 is not zero, of course, but about 40 per cent, since the plate voltage swing on this tube is already half its maximum value and its plate current pulse width is very small; there is little sacrifice in efficiency, therefore, in permitting this tube to contribute a little power at the carrier point.

By integrating the d-c plate currents of Fig. 11 over a complete cycle of modulation the effective average efficiency has been calculated for various percentages of modulation. This calculation shows the efficiency to be practically independent of modulation, being 63 per cent at 100 per cent modulation as well as with unmodulated carrier, and having a minimum value of 61 per cent at about 70 per cent modulation. With this constant efficiency the d-c plate current increases 50 per cent at full modulation, as does the radio-frequency

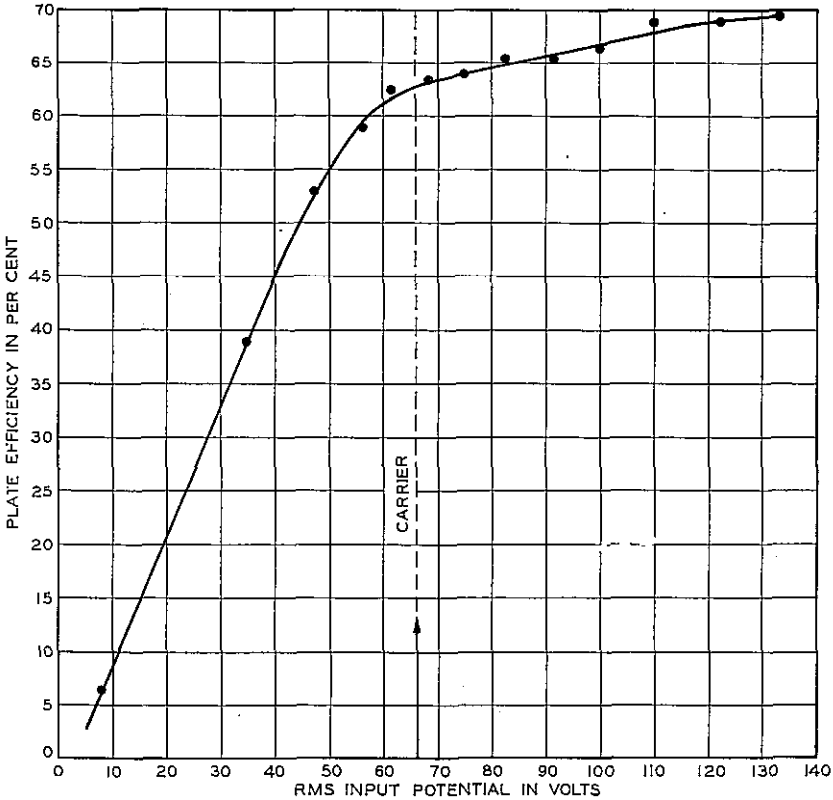

Fig. 12—Instantaneous plate efficiency for the test of Fig. 11.

output power. Chireix,[6] who obtains approximately the same efficiency as above for unmodulated carrier, gives a value of 76 per cent as the increase in d-c plate current at full modulation with his system, with a corresponding reduction in efficiency to about 54 per cent for a fully modulated output. The reduction is due to the fact that over most of the modulation cycle the tubes in the Chireix system work into loads which are not purely resistive. In the system

[6] Loc. cit.

now being described there is no such detuning effect and the load impedances are purely resistive at all times.

Fig. 13 shows typical cathode ray oscillograms of the radio-frequency plate potentials across the two tubes in a high-efficiency set-up at 100 per cent modulation. The faint horizontal lines are for the unmodulated carrier condition, the carrier potential on Tube No. 1 being twice as great as on No. 2.

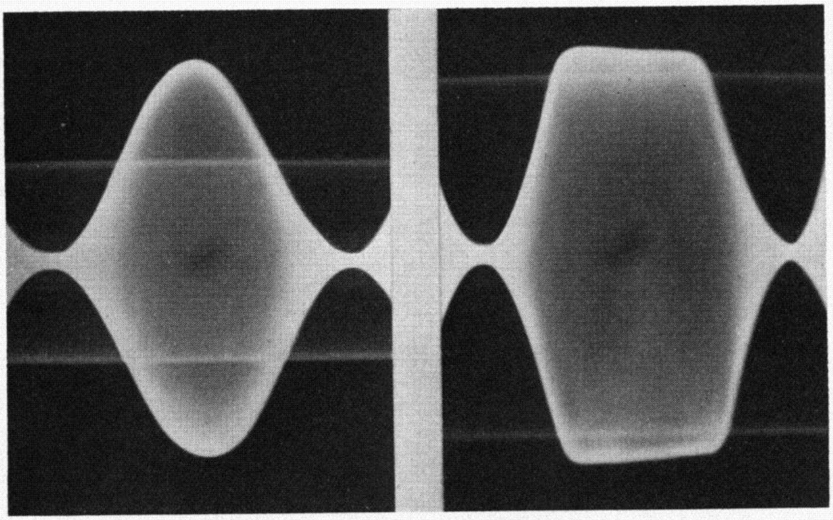

Fig. 13—Typical cathode ray oscillograms of the plate potentials of Tube No. 2 (left) and Tube No. 1 during complete modulation.

Fig. 14 gives the results of 400-cycle distortion measurements at the input and output of a two-stage amplifier having 14 db of radio-frequency feedback and with the second stage delivering a 5-kilowatt carrier at an overall plate efficiency for the tubes and output circuit of 62 per cent, the actual tube efficiency being about 68 per cent. The first stage was a 100-watt linear power amplifier of the conventional type. The distortion in the output is seen to differ only slightly from the distortion present in the source of modulated power used to excite the amplifier. This result is typical of what would be obtained in adding a high-efficiency amplifier to a transmitter already existing, and indicates that high-fidelity transmission may be achieved if the driving source has good quality.

The carrier shift measured in this test was zero. The use of feedback rendered the amplifier remarkably free from the necessity for critical adjustments of bias or relative excitations on the tubes, and the output circuit could be thrown far out of tune with no appreciable effect on the output current and no visible effect on the wave shape.

A difficulty encountered in applying feedback to radio transmitters is that introduced by cumulative phase shifts in the successive stages within the feedback loop, which not only limit the amount of feedback obtainable, but may cause the distortion at the higher modulating frequencies to be increased rather than reduced. So serious is this difficulty, particularly at the lower broadcast frequencies where the

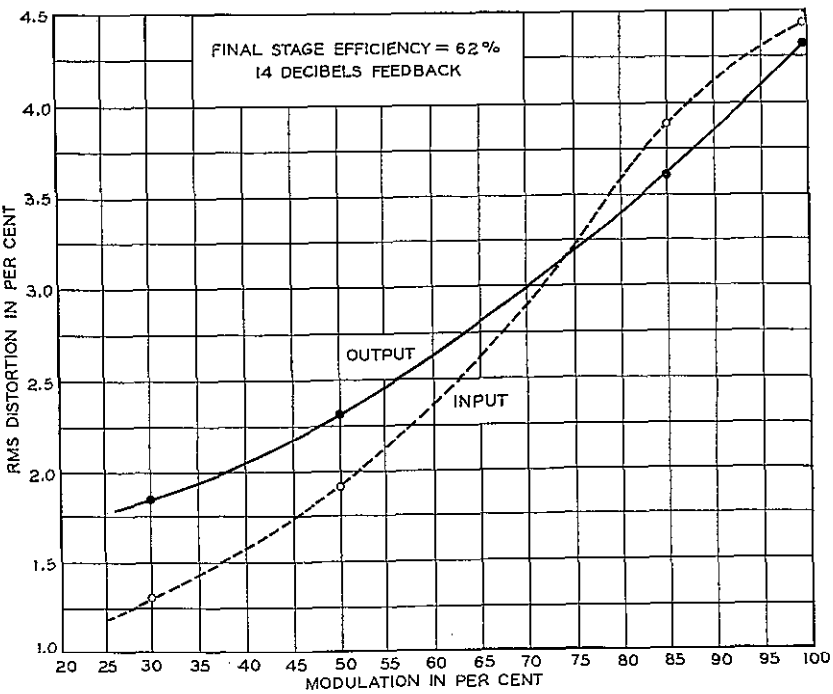

Fig. 14—Distortion measurements on a 5-kilowatt amplifier with radio-frequency feedback.

band width of the tuned circuits is least, that when an attempt is made to introduce feedback in a transmitter not designed for it, there usually results only a few db improvement in noise and in distortion at low modulation frequencies and in many cases increased distortion at modulating frequencies even as low as 1000 or 2000 cycles. Although the percentage modulation in broadcast programs is normally very small at the higher audio frequencies, it nevertheless behooves the designer to do everything possible to reduce this effect. Fig. 15, which gives the results of distortion measurements on a complete 50-kilowatt high-efficiency transmitter built in the laboratory, shows what may be accomplished by careful design of the various stages to reduce phase shifts to a minimum. This transmitter was operated at the low-frequency end of the broadcast spectrum in order that the most unfavorable conditions in the matter of band width might be encountered. Audio-frequency feedback was employed to the extent of 28 db, with a resulting distortion level less than 1 per cent at any frequency between 50 and 1000 cycles, and increasing only slowly until the high audio frequencies are reached where the modulation in an actual program of course rarely exceeds a few per cent.

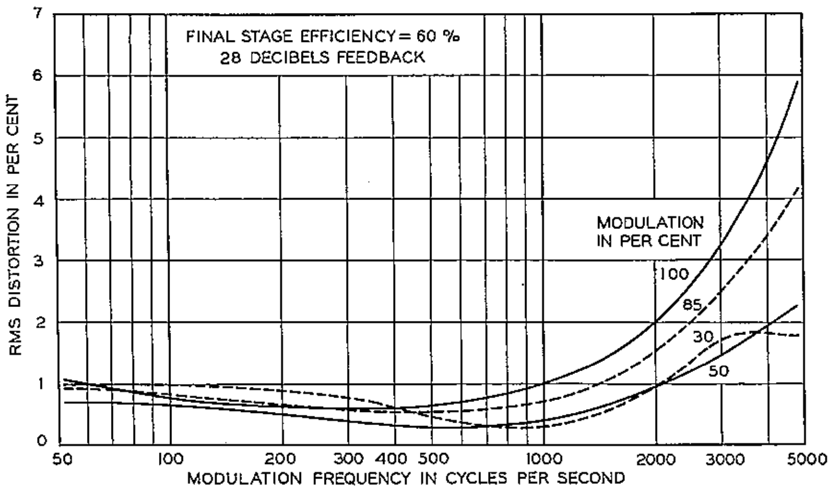

Fig. 15—Distortion measurements on a complete 50-kilowatt transmitter with audio-frequency feedback.

The frequency characteristic was flat to within 0.25 db from 30 to 15,000 cycles.

The large amount of feedback employed permitted the use of alternating-current filament supply to all of the tubes with a noise level 66 db down unweighted and 76 db down as measured on a standard program noise weighting network, with no devices employed for hum suppression except for the feedback action, which of course is entirely automatic.

The efficiency of the final stage with its output circuits was 60 per cent with the carrier unmodulated and 63 per cent at 100 per cent modulation. This high-efficiency operation of the final stage, together with the reduced grid driving power permitted by the new system, resulted in a reduction in the total power consumption of a

50-kilowatt transmitter, including all auxiliaries, from about 230 kilowatts, required by the conventional type, to approximately 135 kilowatts in the new system with normal program modulation. It is interesting to note that the total power input in this case is actually less than the power dissipated in the water-cooling system in the usual 50-kilowatt installation.

Conclusion

As compared to the conventional linear amplifier the new system affords a power saving of nearly 50 per cent in the final stage plate supply, and the plate dissipation is reduced by a factor of three or four, with a resulting economy in the cooling system and an improvement in tube life.

The absence of any such requisites as the complicated driving stages of the Chireix system or the large audio equipment involved in high-level modulation gives the new circuit an important advantage over other high-efficiency systems in cost of apparatus and simplicity of design.

To accomplish high-level modulation with the same total tube complement as required with linear radio-frequency amplifiers it is necessary to subject the smaller number of radio-frequency tubes to higher instantaneous plate voltages, with consequent likelihood of shortening of tube life and operating difficulties due to flashovers, particularly in case of overmodulation. In the proposed system, as in any low-level system, the plate voltage is held constant at a value consistent with safe operation, and overmodulation is of no particular significance as far as any harmful effect on the tubes is concerned.

The new amplifier has been found to operate in complete accord with theoretical predictions, and is believed to offer a most logical and practical solution to the problem of efficient operation of high-power transmitters.

Acknowledgment

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