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SERIES MODULATION*

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Summary—*In this paper it is pointed out that the type of modulating system used in any given case depends to some extent upon the particular type of service involved. The limitations of existing types of control are discussed, and a detailed theoretical and experimental investigation of the so-called series type of modulation is reported. Operating data, in the form of graphs, are presented for those existing tubes which because of their characteristics are adapted for use in connection with this type of control. The advantages and limitations of the series method are outlined, and the desirability of an improved tube for use as a series modulator is stressed.*

Introduction

THE rapid extension of the field of communication engineering, particularly in connection with those applications which involve the use of high-frequency alternating currents, has tended to emphasize the importance of the means whereby audio and visual generated potentials may be impressed on the carrier current. Further, the increasing diversity of high-frequency communication agencies makes it more or less apparent that a single system of carrier wave modulation is not necessarily adapted to all of the various communication processes which now obtain and which may be developed in the near future. With this situation in mind there was initiated at this laboratory several years ago a research and development program having as an objective the careful study of the then existing systems of modulation, and the design and development of possible improvements along these lines. Among the feasible systems which have received attention is the plan commonly referred to as series modulation. By series modulation is meant a procedure whereby the modulating tube is connected in series with the anode potential supply of one of the tubes constituting the high-frequency chain of circuits. A practical circuit arrangement of this nature was recently disclosed by the author.[1] Before, however, entering into a discussion of the theoretical and practical aspects of this means of modulation it will be in order to examine briefly the limitations which obtain in connection with those systems of modulation which are now in common use.

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[1] U. S. Patent No. 1,882,122, October 11, (1932).

Limitations of Older Systems

Until quite recently the "choke" or Heising system of modulation has been the one most commonly used. This method is, however, being rapidly displaced by two other systems. This change in modulation technique has been due to the inherent limitations of the choke method. Since the impedance of a choke is a function of the inductive reactance, and since the reactance is a function of the frequency, it is physically impossible to design a choke which will exhibit the same impedance for all signaling frequencies. The practice is, of course, to attempt to design a choke which shall have an impedance sufficiently high to reduce the lowest audio-current components to a negligible magnitude. The choke system is accordingly sometimes referred to as one in which "constant current" obtains, but it is a matter of common engineering experience that the current through such a choke is not constant, even in the case of a well-designed unit of 30 or more henrys. If the modulation choke is to carry even moderate current magnitudes, such as obtain in low level modulation practice, the unit is both heavy and expensive. The necessity of avoiding magnetic saturation of the iron necessitates a liberal amount of core material and thus contributes to the weight factor. While the weight is not a serious matter in fixed radio stations it does become an important factor in connection with mobile installations.

Not only is there the possibility of frequency distortion at low frequencies, but corresponding distortion may also obtain at the higher signal frequencies due to the unavoidable distributed capacitance of the choke winding.

Though still extensively used in this country the choke modulation system is, as implied above, being displaced by two other methods which to some extent avoid certain of the limitations outlined above.

One of these methods is a revival of one of the oldest plans known to the art. Reference is here made to the grid system of modulation. This general type of modulation was probably first suggested by the late Charles V. Logwood. Logwood's method consisted in impressing the signal voltage directly on the grid of the oscillator. In 1923 the author outlined a practical system of grid modulation[2] using a triode as a grid leak.

A number of years ago van der Bijl suggested a plan whereby radio-frequency carrier voltage and the signal voltage are simultaneously impressed on the grid of a class A amplifier. More recently commercial equipment has been developed which makes use of a circuit layout

[2] "An improved system of modulation in radio telephony," Proc. I.R.E., vol. 11, no. 5, pp. 479–492; October, (1923).

whereby the signal and radio-frequency voltages are simultaneously applied to the grid of a low powered radio-frequency amplifier.

In general, grid-circuit modulation schemes require only a relatively low signal level and absorb but little energy in and of themselves. They, however, have one defect in common; viz., that it is more or less difficult to adjust such circuits so that amplitude distortion is entirely avoided.

A second plan for modulating the carrier wave which is coming into favor at present is commonly referred to as class B modulation. This system is a special form of plate modulation, and makes use of the now popular class B audio amplifier organization. A good exposition of this plan of control is to be found in a recent paper[3] by C. L. Farrar. In the installation described by Professor Farrar the output of the class B audio amplifier is superimposed on the constant anode potential of the output stage of the radio-frequency train of amplifiers, thus bringing about "high level" modulation. In certain commercial broadcast equipment the class B scheme is applied to one of the intermediate radio-frequency amplifiers, rather than to the output stage, thus effecting an economy in tube capacity as well as power consumed by the modulator.

There is, however, one serious limitation to the transformer coupled class B system of modulation as it is commonly employed, and that is that it is extremely difficult to avoid frequency discrimination in the coupling transformer, as in the earlier choke system. Here again also we encounter the matter of weight, when dealing with portable transmitter units. Certain inherent defects in the class B scheme can be materially minimized by the use of a circuit recently suggested by the author,[4] and which will form the subject of a subsequent paper.

Theory of Series Modulation

In connection with all applications involving a carrier wave it is of prime importance that there be no distortion of the signaling frequency. Particularly in the fields of sound and visual broadcasting any appreciable frequency discrimination is inadmissible. Of the systems of control thus far developed series modulation is the only plan which is inherently capable of giving a strictly flat frequency response. An elementary circuit embodying the series principle of control is shown in Fig. 1(a). Tube A and its associated connections represents a radio-frequency organization, while tube M is a triode *acting as a variable "dropping" resistance.* Tube A acts as a fixed resistance. In Fig. 1(b),

[3] "Class 'B' audio power amplifiers," *Radio Eng.*, January, (1932).
[4] U. S. Patent No. 1,896,742, February 7, (1933).

R_M represents the resistance of the modulator, R_A that of the radio-frequency amplifier tube, and E_b the common anode potential. The anode current through the two tubes in series will be determined by the expression

$$I_p = f(R_A, R_M, E_b), \tag{1}$$

where R_A and R_M represent the *grid-controlled direct-current resistance* of the amplifier and modulator tube, respectively.

Because of the various types of service in which tubes function there is no common reference condition by which the grid-controlled resistance of tubes can be compared. The term *static* resistance means nothing unless the corresponding grid bias is specified; it is for this reason that we have chosen to use the term "controlled resistance." As we employ the term in this connection, controlled resistance of the tubes is taken to mean the ohmic resistance which the tubes offer when

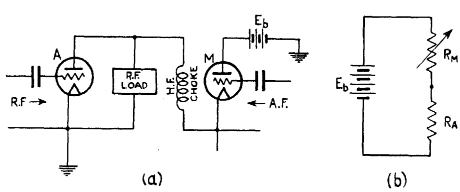


Fig. 1

biased to give the normal unmodulated carrier output. For instance, a 203A tube biased at -42 volts has a controlled resistance, as shown by measurement, of 54,000 ohms and an 830 used in the high-frequency modulated stage (class C) shows an operating effective resistance of about 18,000 ohms.

If we assume that E_b is held constant and that R_A remains substantially so, we are primarily concerned with the variations in R_M. But it is to be remembered that R_M and R_A are *in series*, and we must therefore consider what change in the *total* resistance will be brought about by any fractional change in the value of R_M, due to a given signal input level.

Suppose $R_A = R_M$, and further assume that the characteristics of the modulator tube are such that a given change in grid potential will change the tube's controlled resistance by 50 per cent. On this basis the *total change in resistance* would be 25 per cent. If, however, $R_M = 2R_A$, a 50 per cent change in R_A would bring about a change of 33 per cent in the total resistance. It is therefore evident that it is desirable, in a series system of modulation, to use as a modulator a tube whose controlled resistance is high compared with the controlled resistance of the tube being used as a radio-frequency amplifier.

A rough estimate of the comparative utility of a tube as a series modulator can be formed by computing its controlled resistance when the tube is biased to give normal anode current when operated as a class A unit. In the case of a screen-grid tube the screen-grid bias complicates the problem, but for purposes of appraisal the bias of the screen grid can be held at normal value. For instance, an 860 tube with its screen grid at +500 volts and the control grid at −30 has a controlled (static) resistance of something like 40,000 ohms, while a 203A biased at −30 shows a resistance of 50,000 ohms. It is therefore evident, on the basis of the foregoing comparison, that the 203A is more suitable for use as a series modulator than the 860. The allowable plate dissipation, however, is slightly higher in the case of the screen-grid unit. This and other considerations will be referred to later.

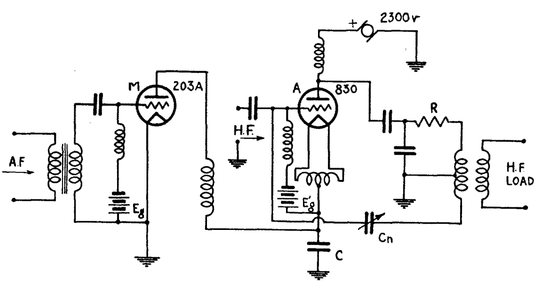


Fig. 2

Operation

A typical series modulation set-up is shown in the diagrammatic ketch appearing as Fig. 2. In the circuit illustrated it will be noted hat the filament of the modulator *M* is at earth potential while in the heoretical diagram (Fig. 1) it is the filament of the radio-frequency mplifier which is grounded. It has been found that either plan is pracicable, though with the former set-up provision for grid bias can be omewhat more conveniently arranged. The capacitance of the blocking condenser *C* must be of such a magnitude that it will not by-pass he higher audio frequencies. A capacitance of the order of 0.0002 microarad or less is desirable. The placing of the modulator tube next to he source of anode potential (Fig. 1) avoids the use of this blocking ondenser. With the combination shown in Fig. 2 very satisfactory modulation may be obtained, both as regards depth and fidelity.

Fig. 3 shows the experimentally determined characteristics of the ombination diagramed in Fig. 2. The graph gives the relation which btains between the grid potential of the modulator (203A) and the drop (E_a) across the radio-frequency amplifier tube, the anode current (I_p), and the radio-frequency tank current (I_{osc}).

An anode voltage of 750 is recommended by the manufacturers as a suitable anode potential when the 830 is operated in class C service, with a bias of -180 volts. Referring to curve *A* it will be evident that with the applied electromotive force (2300) available in the tests referred to, a grid bias of about -38 volts gave an anode potential (E_a) of 750 for the 830 and an unmodulated carrier current of approximately

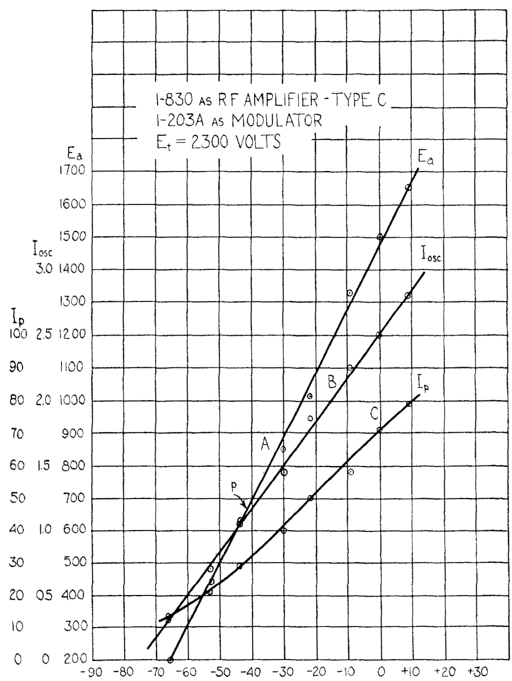


Fig. 3

1.4 amperes. (The radio-frequency tank circuit was so loaded that about 50 per cent of its energy was dissipated in the resistance *R*.) In actual operation its grid bias was set at -40, thus reducing the carrier anode potential on the 830 to 700. Under the latter operating conditions it was possible to cause the anode potential to have double its carrier value without the grid of the modulator becoming positive. The curves show, however, that it would have been possible to allow the grid to swing at least 10 volts positive without causing distortion. In order to bring about 100 per cent modulation the radio-frequency anode voltage must of course vary between zero and $2E_a$, where E_a is the voltage across the tube A when the radio-frequency amplifier is delivering normal unmodulated carrier output. It is seen that in this case a modulator grid swing of 75 volts would bring about complete modulation.

Curve C (Fig. 3) indicates that there is some departure from linearity at the lower values of E_a; the radio-frequency tank current (curve B), however, shows strict linearity throughout the observed range.

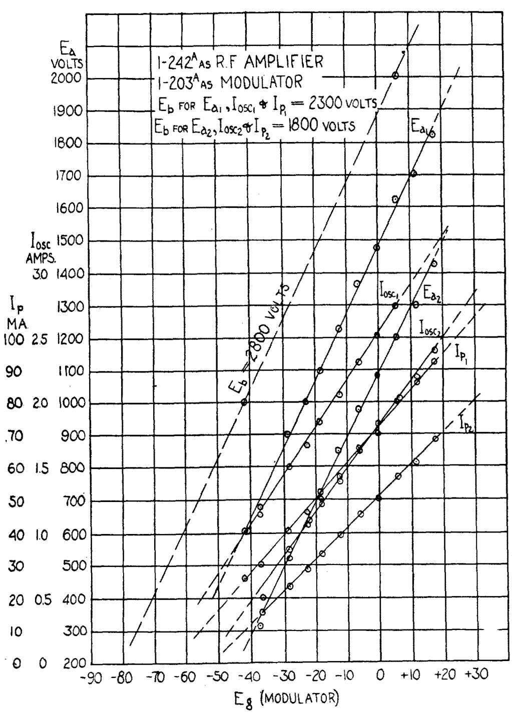


Fig. 4

In Fig. 4 is seen the interrelated variables, above mentioned, as they worked out in the case of the 242A tube used as a radio-frequency amplifier in conjunction with a 203A as a series modulator. It is to be noted that two sets of curves for this set-up are given, one for an applied voltage (E_b) of 2300 and a second where E_b is 1800. The importance of the proper applied over-all voltage for a given tube combination is strikingly shown by these graphs.

Suppose, for the purpose of discussion, that the 242A is to be operated at a normal anode potential (E_a) of 1000 volts and that the available terminal voltage is 2300. In order to modulate completely the output under the conditions named, the anode voltage on the 242A must vary between zero and 2000. Under these conditions the graph (Fig. 4) shows that the grid bias on the modulator (203A) must be -23 volts, resulting in an unmodulated tank carrier current of 1.64 amperes. The graph shows that in order to double the carrier voltage setting, it would be necessary that the modulator grid should swing 25 volts positive. The observed readings were not carried that far, but it is safe to assume that the relations would not be linear on that part of the characteristic, hence distortion would obtain. An examination of the 1800-volt curve indicates that if one were to use that over-all potential the modulator must needs be biased at -4 and that the grid would swing nearly as much positive as negative, a condition which would be worse than the situation just cited.

This undesirable condition can be obviated by applying an over-all potential of 2800 volts, as shown by the dotted graph. The 2800-volt line was drawn by interpolation. When employing an E_b of 2800 volts, a bias on the modulator of -42 would give the desired E_a of 1000 volts. Under these conditions the grid of the modulator need only swing to $+6$ in order to give 100 per cent modulation. Since the characteristics are seen to be linear in that region, the distortion would be negligible. With this particular tube combination, then, complete modulation could be secured by operating with an over-all voltage of 2800 and a modulator grid swing of approximately 90 volts.

Screen-Grid Tubes as Series Modulators

On first thought it might seem that the screen-grid type of tube might function particularly well as a control unit when employing the series form of modulation. A closer study of this type of tube, however discloses the fact that the screen-grid tube has certain inherent limitations when used as a series modulator. The operating characteristics of a combination consisting of a 242A as a radio-frequency amplifier and an 860 as a modulator are shown in Fig. 5.

On examining these graphs it will be evident that, when operated under the conditions shown, the characteristics show considerable departure from linearity even at zero grid bias of the modulator; curvature also begins at about -50. A set of curves are also shown for the condition where two 860's are operated in parallel to modulate the 242A the idea in using two tubes being to augment the total possible plate dissipation. The data as represented by the curves tend to show that a single 860 when used as modulator, would have to be operated with a grid bias between the limits of zero and -50 volts. Under these limitations the direct-current drop (E_a) over the radio-frequency tube when delivering unmodulated carrier does not exceed 725 volts, with the result that the output of the radio-frequency amplifier is somewhat less than that delivered by the system when a 203A functions as modulator. A second 860 in parallel obviously does not increase the output but does divide the modulator plate load.

The screen-grid tube does, however, possess one advantage, as a modulator, over a three-electrode unit; the working resistance of the tube can be controlled by means of the screen-grid potential, as well

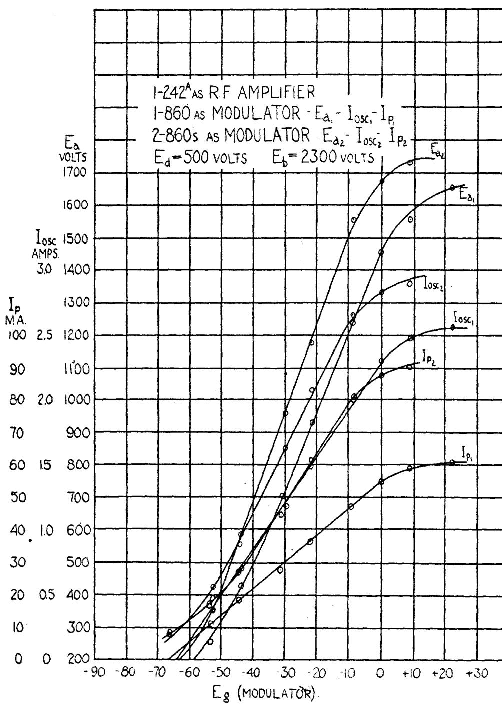


Fig. 5

as by the control grid. The curves set forth in Fig. 6 illustrate this point. It will be noted that for comparatively low and high values of E_d, the characteristic is not linear, particularly in the latter case. A 203A characteristic is shown for comparison purposes.

In the case of the triode, used as a control unit, the depth of modulation for a given signal input is determined by the nonsignaling value of E_g; increasing the negative bias tends to increase the percentage modulation and vice versa. This is due to the fact that an increase in negative bias increases the ratio of R_M to R_A. If the grid bias of the modulator is too low, the average amplitude of the modulated carrier current will be less than the nonsignaling value with the result that the modulation will be "down" rather than "up." In the case of the screen-grid modulator the percentage of modulation can accordingly be controlled by adjusting either or both E_d and E_g. It follows from the foregoing discussion that decreasing E_d will increase the degree of modulation. In practice when using a single 860 as a modulator and a 242A as the radio-frequency amplifier (with the available E_b of 2300) it was found that the optimum screen-grid potential is +450 and that

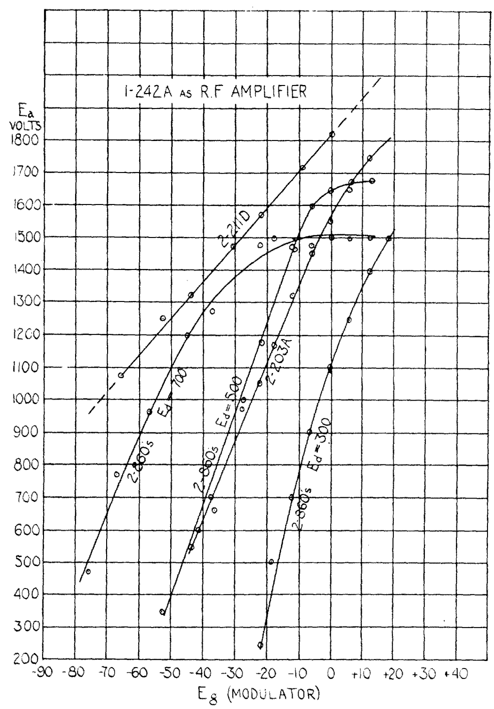


Fig. 6

the control-grid bias is −28. It is obviously important that the screen-grid potential be held absolutely constant. A higher over-all voltage (E_b) would have been more satisfactory.

The modulation characteristic for a pair of 211D tubes used with a 242A as a radio-frequency amplifier is also shown in Fig. 6. Due to the low controlled resistance of the 211D this tube is seen to be comparatively ineffective as a series modulator. An examination of the curves (Fig. 6) discloses the reason for this low modulation efficiency. The grid swing necessary to bring about 100 per cent modulation with the 211D is nearly threefold that required in the case of the 203A. Using a value of 2300 for E_b an experimental comparison of a 203A and a 211D as modulators was made. It was found that for a given signal input the percentage modulation when using the 203A as a modulator was approximately 50 per cent higher than when employing the 211D. The difference would have been even more marked had the over-all voltage been higher. This experimental evidence confirms the theoretical conclusions as to the desirability of a high resistance tube for use as a modulator, advanced in an earlier section of this discussion.

Fidelity of Reproduction

In the operating layout shown in Fig. 2 the only capacitance involved in the audio circuit is that of the blocking condenser C together with any inherent capacitance in the heating circuit. By proper attention to design both of these capacitances may be made of such a low value that their combined effect will not be appreciable below 10,000 cycles. Since this is true, and since inductance is absent, frequency discrimination is practically nil.

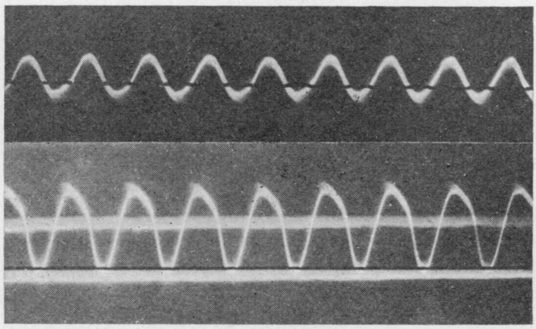
Because so far as the modulator tube is concerned we are dealing with what amounts to a pure resistance, and since throughout the comparatively straight portion of the modulating characteristic (E_g-E_a), the controlled resistance of the tube is very nearly a linear function of the grid potential, it follows that there will be comparatively little amplitude distortion. Even though the ordinary static characteristic of a tube shows some curvature, as is the case of the 203A for instance, this undesirable condition will tend to be improved when a comparatively high resistance (in this case the radio-frequency tube) is in series with the modulator. The effect of this resistance in straightening out the characteristic is well known in the art. It is thus evident that, with this system of modulation, a certain amount of possible amplitude distortion is automatically corrected for.

Exacting musical tests have been made of the radio-frequency output of the organization shown in Fig. 2 when using the several tube combinations referred to in the preceding paragraphs, with very satisfactory results. Oscillographic studies have also been made which confirm the auditory observations.

In Fig. 7(a) is to be seen the oscillogram of the output of the speech amplifier employed in securing certain experimental data connected with this study. The source of energy was a sine wave electromotive force of constant frequency and amplitude generated by a special electro-acoustic organization. In the same illustration is shown (b) a record of the same sound tone made by rectifying a portion of the output of the modulated radio-frequency stage. It is to be seen that the modulation is nearly 100 per cent and that there is only a slight amount of distortion. How much of this distortion was due to the rectifying organization and how much to the radio-frequency circuits

(a)

(b)



Modulated Carrier
Carrier
Zero

Fig. 7

was not determined. In making this oscillogram a 203A was modulating a 242A, the latter operating at less than rated output.

A series of distortion measurements were also made in the modulated radio-frequency output by means of a General Radio distortion factor meter. The data thus secured are shown graphically in Fig. 8. The

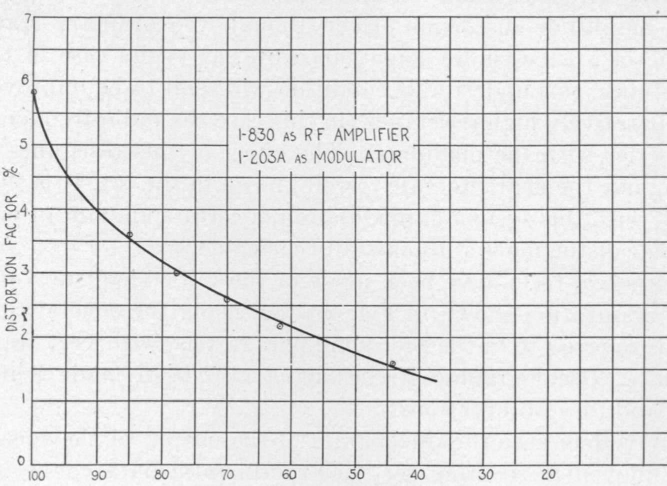


Fig. 8

distortion which may have been due to the last audio stage and to the high-frequency rectifier unit is included in the distortion thus measured. Bearing this in mind, it is evident that it is possible by proper circuit design to produce a modulated carrier which will not exceed the permissible engineering limit of distortion (5 per cent) at 100 per cent modulation.

Efficiency and Power Limitations

In the experiments referred to in the earlier part of this paper the radio-frequency power level output was of the order of 12 watts. This would, of course, be "low level" modulation. With a proper value of E_b and the necessary radio-frequency excitation, the 203A-830 or the 203A-242A combination is capable of delivering at least 25 watts of practically distortionless modulated radio-frequency power. Unfortunately there is not available at the present time a tube suitable for use as a series modulator whose plate dissipation is sufficient to permit series modulation at a higher level, unless it be the 861. What is needed is a triode whose plate dissipation is of the order of 100 watts when operating in class A service and whose grid-controlled resistance (at normal values of E_g and E_p) is of the order of 10,000 ohms. It is to be hoped that such a unit will be available in the near future.

English engineers[5] evidently have developed tubes suitable for series modulators which are capable of handling considerable power, thus making it possible to modulate at a higher level, and thereby reducing the inherent distortion due to succeeding radio-frequency stages. The Marconi engineers have developed the series method of modulation to the point where it is possible to secure a radio-frequency output of some 30 kilowatts modulated to 90 per cent with a distortion factor below 4 per cent.

The over-all efficiency of the series modulator and the radio-frequency amplifier can be readily computed by the relation

$$\text{efficiency} = \frac{I_p^2 R_A/2}{I_p^2 R_A + I_p^2 R_M} = \frac{R_A}{2(R_A + R_M)}.$$

The introduction of the constant 2 is based on the assumption that the radio-frequency amplifier operates at an efficiency of at least 50 per cent. In our tests no particular effort was made to secure high efficiency. When delivering normal carrier output (see Fig. 3) the 830 showed a controlled ohmic resistance of 18,000 and the 203A, 54,000 ohms. Substitution in the above equation, therefore, gives an over-all efficiency of approximately 12.5 per cent. This is, of course, a low efficiency, but since only a few watts are involved, the matter of

[5] A brief account by W. T. Ditcham of the British engineering practice in connection with series modulation is to be found in the March-April, (1933), number of the *Marconi Review*.

efficiency is relatively unimportant. However, by proper attention to the adjustments of the radio-frequency amplifier circuit the efficiency could probably be raised to something like 25 per cent.

Conclusion

Our calculations and experiments lead us to the following conclusions:

(1) Of the tubes now available on the American market, the type 203A is probably the most suitable for use as a modulator at low power levels.

(2) A 203A as a series control unit used in conjunction with one or more 830's makes it possible to modulate completely a carrier at the 25-watt level without frequency discrimination and with a negligible amplitude distortion.

(3) With the tube combination above suggested, the over-all voltage need not exceed 2500. This relatively high supply voltage may, in certain cases, impose a limitation on the use of this type of modulation in portable transmitters, but does not serve to restrict its use in connection with fixed installations.

(4) There is little if any tendency for the transient peak voltages to cause flashovers either within or without the modulator tube.

(5) In arranging operating conditions the modulator grid bias and the over-all voltage should be so adjusted that the normal radio-frequency carrier output occurs when the fixed modulator grid bias falls at the median point of the straight portion of the static characteristic of the modulator tube. It is advisable to adjust E_g and E_b so that the E_a equals twice its unmodulated carrier value when the least negative grid swing reaches zero.

(6) In selecting a tube for use as a series modulator the controlled resistance of the tube, measured when the fixed grid bias has the value above indicated, may be taken as a criterion of suitability. This controlled resistance should be high compared with the corresponding resistance of the tube combination which serves in the radio-frequency system. Since the modulator tube functions as a class A unit, plate dissipation should be provided in adequate amount.

(7) In order to secure 100 per cent modulation at normal signal input the ratio E_b/E_a should be of the order of three to one.

(8) In a triode modulator the percentage modulation is controlled by the value of the fixed grid bias. The greater the negative bias the deeper the modulation. In the case of the screen-grid tube the depth of modulation can, within limits, also be controlled by means of the screen-grid potential.

(9) The weight of the modulating radio-frequency stage is materially less when using series modulation than when the choke or transformer plan is employed.

(10) There is need of a tube specially designed for use as a series modulator.

In conclusion it may be said that work is in progress on the design of two commercial models embodying series modulation; one a compact portable unit and the other a 100-watt layout which will serve as the basic unit in a larger broadcast transmitter.