

April 6, 1948.

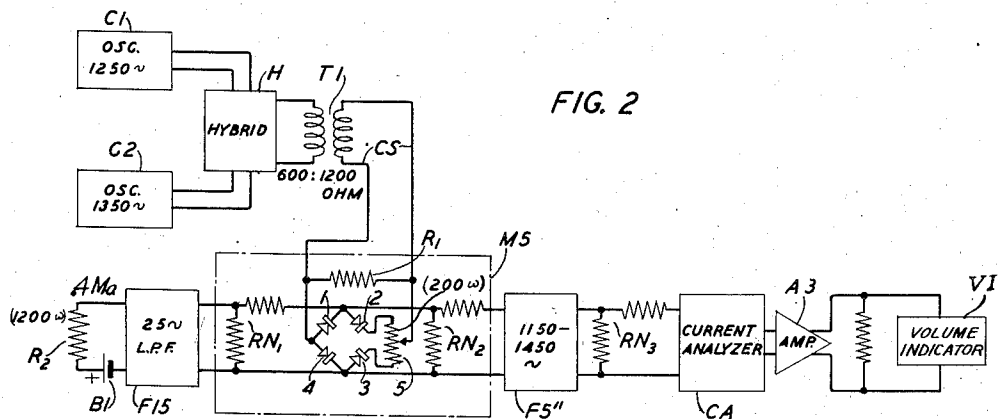
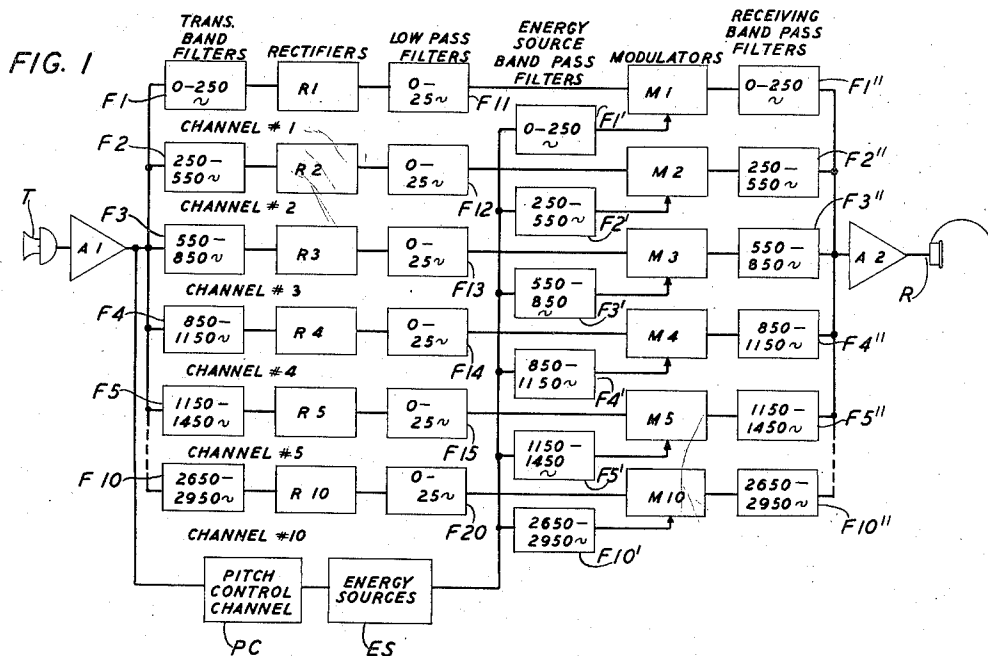
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2,438,948

MODULATING SYSTEM

Filed Jan. 21, 1944

3 Sheets-Sheet 1



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3 Sheets-Sheet 2

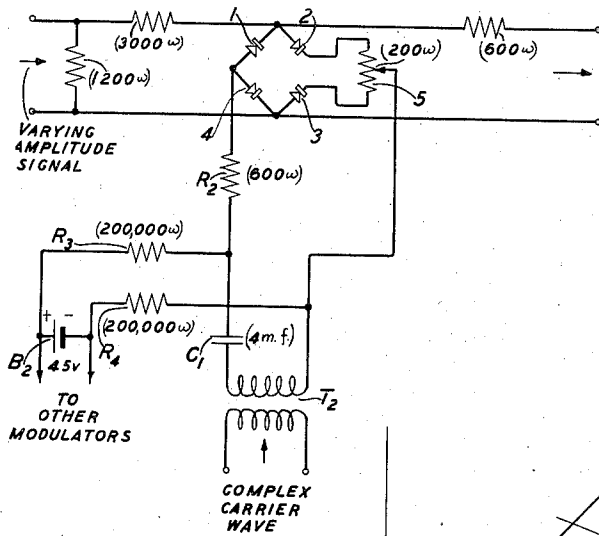


FIG. 4

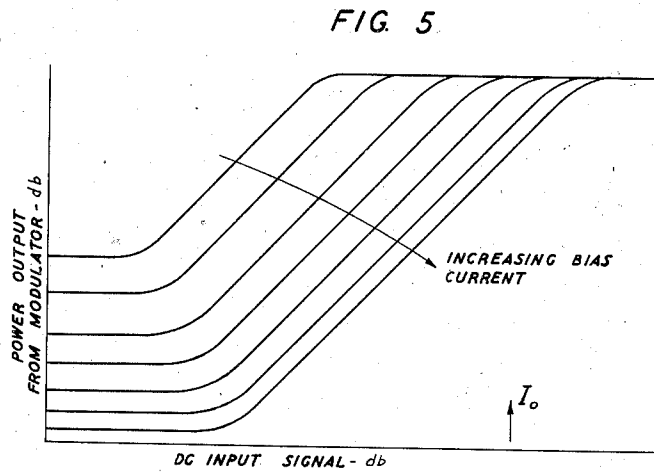


FIG. 5

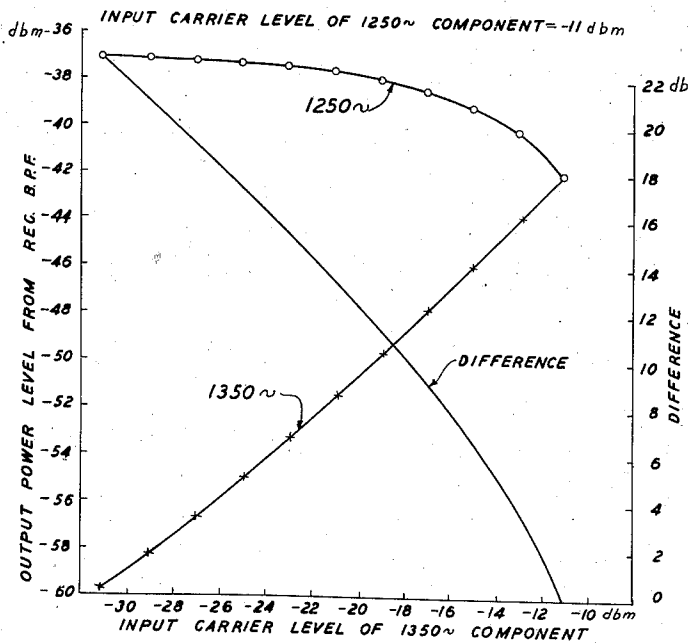


FIG. 3

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FIG. 6

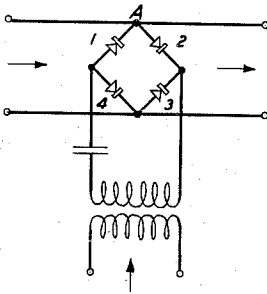


FIG. 7

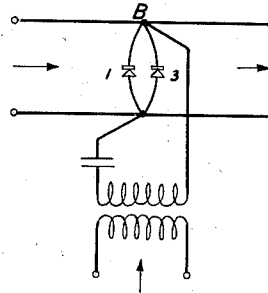


FIG. 8

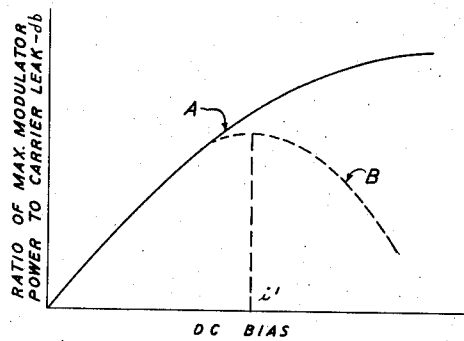
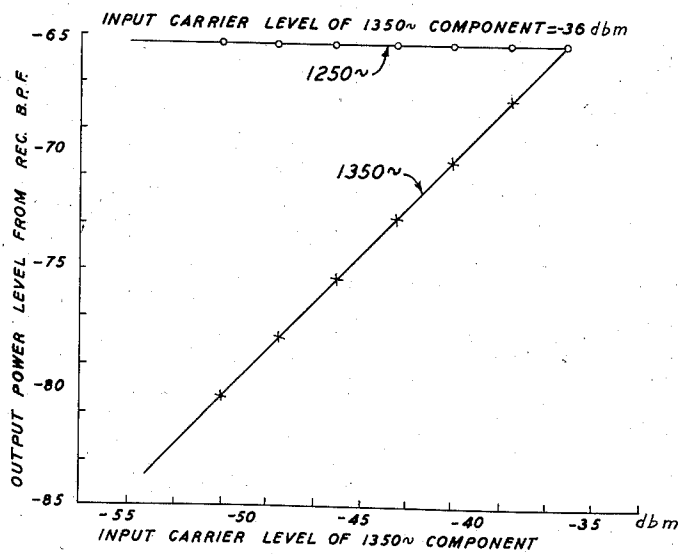


FIG. 9



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2,438,948

MODULATING SYSTEM

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Application January 21, 1944, Serial No. 519,109

3 Claims. (Cl. 179—171.5)

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The invention relates to a wave modulating system, and particularly to a wave modulating system employing a modulator comprising a plurality of physically inert elements having non-linear voltage-current characteristics, connected in a bridge arrangement.

When the usual modulator of that type is employed for combining direct current signals of varying amplitude or alternating signals of a band of frequencies and of varying amplitude with a complex carrier wave, such as one comprising a continuous band of frequencies or a series of harmonics of a given base frequency, it has been found that for a given input signal level the relative amplitudes of the wave components in the modulator output are not the same as they are in the carrier supply; and that the amount of this non-linear distortion changes as the relative amplitudes of the components in the carrier supply wave change.

An object of the invention is to reduce the distortion introduced by the modulating devices in such a modulating system.

A more specific object is to combine varying amplitude direct current or rectified alternating signals with a complex (multi-frequency) carrier wave in such manner as to provide substantially "perfect product" modulation, that is, so that the combination products are directly proportional to the product of the input signal and carrier voltages over a wide range of signal input voltages.

Other objects are to increase the linear operating range and to provide a high degree of carrier balance in a modulator of the above-described type.

These objects are attained in accordance with the invention mainly by reducing the carrier input level to the modulator bridge to a value such that the variation of impedance of its non-linear elements is small throughout the carrier cycle; and by applying a small direct current bias to the modulator bridge in the conducting direction such as to reduce the resistance of its non-linear elements to a sufficiently low value that satisfactory carrier balance can be attained by relative small adjustments of the impedances of adjacent arms of the bridge, and to provide the optimum value of bias current to give the maximum modulator operating range.

The various objects and features of the invention will be better understood from the following detailed description when read in conjunction with the accompanying drawings, in which:

Fig. 1 shows a single line, functional schematic of a multi-channel voice frequency carrier wave signaling system in which the use of channel modulators in accordance with the invention is desirable;

Fig. 2 shows an experimental test circuit which

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was employed for determining the signal distortion which would be introduced in a channel of the system of Fig. 1 by a known type of modulator;

Fig. 3 shows graphically test results obtained with the test circuit of Fig. 2;

Fig. 4 shows schematically the circuit of a modulator embodying the invention;

Figs. 5 to 8 show diagrams and curves used in connection with an explanation of the invention; and

Fig. 9 shows curves illustrating test results obtained with a test circuit similar to that shown in Fig. 2 except for the substitution of a modulator in accordance with the invention as shown in Fig. 4 for the known modulator illustrated in Fig. 2.

Fig. 1 shows in single line, functional schematic form the essential features of a system of the general type disclosed in my Patent 2,183,248, issued December 12, 1939, or in Dudley Patent 2,151,091, issued March 21, 1939, utilized for analysis and synthesis of speech or other vocal sounds, frequency range reduction and restoration or for other purposes as set forth in the patent specifications, in which the use of modulators in accordance with the invention is particularly desirable. The system as shown includes at its transmitting or analyzing end, a telephone transmitter T for transforming applied speech sounds into an electrical wave comprising a continuous band of speech frequencies, say, of the frequency range 0-3000 cycles. This frequency band is amplified in the amplifier A1 and the amplified wave impressed in common on the inputs of a plurality of wire transmission circuits or channels 1...10 extending to a receiving point. The band-pass filters F1...F10 in the inputs of the respective channels 1...10, respectively select from the impressed waves a different one of a plurality of contiguous frequency subbands, which may, for example, comprise the frequency ranges, 0-250, 250-550, 550-850, 850-1150, 1150-1450, 1450-1750, 1750-2050, 2050-2350, 2350-2650, 2650-2950 cycles per second, respectively. The selected frequency subbands are rectified by the rectifiers R1...R10 in the respective channels 1...10, and the resulting direct current components in these channels are extracted by the respective lowpass (0-25 cycles) filters F11...F20 and are transmitted to the receiving or synthesizing end of the system where they are respectively applied to the signal inputs of identical modulators M1...M10 in the individual channels, corresponding to the shaping networks SN1, SN2, ... in the individual channels of the system shown in Fig. 1 of my aforementioned patent.

The carriers supplied to the carrier inputs of the modulators M1...M10, conjugately connected with respect to the signal inputs, are the

appropriate frequency subbands filtered by the band-pass filters $F1' \dots F10'$, respectively having the same pass frequency ranges as the transmitting channel band filters $F1 \dots F10$, from the output of the electrical energy sources ES supplying a flat spectrum of either continuous or discrete frequency components which are derived by the pitch control channel PC from the original speech wave as indicated. The mechanisms of the electrical energy sources ES and the pitch control channel PC may be similar to those described in the aforementioned two patents, and need not be discussed here. The receiving band filters $F1'' \dots F10''$, having frequency pass ranges respectively corresponding to those of the transmitting band filters $F1 \dots F10$, and to the energy source band filters $F1' \dots F10'$, select the appropriate frequency subbands from the combination products appearing in the outputs of the modulators $M1 \dots M10$ in channels $1 \dots 10$, respectively. The selected frequency subbands are superposed in the input of the amplifier A2 to form a wave simulating the original speech wave applied to the input of the system, which wave, after amplification in the amplifier A2 to the desired level, is transformed into speech sounds by the telephone receiver R.

A series of experiments were made by applicant to determine the signal distortion resulting in the channels of a system such as shown in Fig. 1, by the failure to employ "perfect product" channel modulators, using a test circuit such as shown in Fig. 2. The particular set-up illustrated in Fig. 2 is similar to that used to test channel No. 5 of the system of Fig. 1 in which the channel modulator M5 was of a well-known type employing a plurality of metal oxide rectifiers connected in a balanced bridge circuit, which modulator is adapted for producing an output practically independent of variations in carrier supply level when used for combining a direct current input signal wave of a given amplitude level and a single frequency carrier wave of an amplitude level sufficiently high to vary, at the carrier frequency, the resistance of its component rectifier elements from a very high to a very low value compared with the generator and load resistance connected to the modulator. The particular modulator illustrated is of the general type disclosed in Cowan Patent No. 1,959,459, issued May 22, 1934. As shown, the modulator comprises a Wheatstone bridge network of copper-oxide rectifier elements 1 to 4, connected in shunt relation to a pair of filters. As indicated by the arrows, the rectifiers 1 and 4 in one pair of adjacent arms are conductive in a direction away from their common bridge terminal, and the rectifiers 2 and 3 in the other two adjacent arms are conductive in the direction towards their common bridge terminal. A resistance potentiometer 5, provided for adjusting the balance of the bridge to compensate for small differences in the rectifier elements, has its 200-ohm resistance element connected in series between the adjacent arms of the modulator bridge, including the rectifiers 2 and 3, and its sliding arm connected to one terminal of the carrier supply.

To simulate the multi-frequency carrier supply for the modulator employed in the system of Fig. 1, the carrier supply to the copper-oxide rectifier modulator bridge in the test circuit of Fig. 2 comprises the two sources C1 and C2 generating constant frequency waves of 1250 cycles and 1350 cycles, respectively, which are within

the pass frequency band of the energy source band-pass filter F5' for the modulator M5 of channel No. 5 in the system of Fig. 1. The outputs of the two single frequency carrier sources C1 and C2 are coupled by a hybrid circuit H, which may comprise the usual hybrid coil and associated balancing network, in conjugate relation with each other and in energy transmission relation with the carrier supply leads CS including the 600 to 1200-ohm step-up transformer T1, which impress both carrier components across the terminating resistor R_1 on the horizontal diagonal of the modulator bridge. By suitable selection of circuit constants, the power level of each carrier component from C1 and C2 was set at -11 dbm. (decibels referred to 1 milliwatt) so that with both components applied, the input carrier power level was about -8 dbm. After balancing the modulator bridge with the potentiometer 5, a direct current signal input of about 0.4 milliampere from a direct current source, represented by the battery B1 and series 1200-ohm resistor R_2 , was introduced through the 25-cycle low-pass filter F15, corresponding to the similarly designated filter of channel No. 5 of Fig. 1, and the resistance network R_{N1} , connected across the vertical diagonal of the modulator bridge, this signal input being of a value well up on the operating range of modulator M5. The products of modulation pass from the same bridge diagonal through the resistance network R_{N2} to the input of the receiving band filter F5'', corresponding to the similarly designated filter in channel No. 5 of Fig. 1, the 1250-cycle and 1350-cycle components falling within the pass-band of that filter. The wave components in the output of filter F5'' are applied through the resistance network R_{N3} to a measuring circuit including in order, the current analyzer CA, the amplifier A3 and the volume indicator VI, which may be of any of the well-known types. The output amplitudes of the 1350 and 1250-cycle components were measured in this measuring circuit as the 1250-cycle component was held constant at -11 dbm, and the carrier input level of the 1350-cycle component is reduced.

The results of these measurements are shown graphically in Fig. 3. It will be noted from the curves of that figure that as the carrier amplitude of the 1350-cycle component is reduced, the output amplitude for that component decreases by about the same number of decibels. The output amplitude of the 1250-cycle component does not stay constant but is seen to increase. When the amplitude of the 1350-cycle component has been reduced 18 decibels, the output amplitude of the 1250-cycle component has been increased 4.8 decibels. A curve of the decibel difference in output level between the 1250 and 1350-cycle components is also shown in Fig. 3. For the modulator to produce no amplitude distortion, the latter curve should be a straight line with a slope of -45 degrees, but actually it varies from the straight 45-degree line as shown. To visualize the type of distortion introduced by the modulator, assume that at some time the harmonics fall in the pass-band of one of the channels of Fig. 1. Then, due to a rising inflection of the voice, let the fundamental frequency begin to rise. The lower harmonic (1250 cycles) will remain in the pass-band of the receiving filter, but the upper harmonic (1350 cycles) will begin to move into the suppressed band of the channel and will be attenuated by the energy source band-pass filter. Due to distortion in the modulator,

the difference in level between the two harmonics at the modulator output will be greater than that produced by the attenuation of the energy source band-pass filter. The over-all effect is to decrease the relative amplitude of a component falling in the cross-over frequency region between channels compared with components falling in the pass-band. This will tend to increase the attenuation peaks which may be introduced in the transmission characteristic by the failure of the filters to satisfy the relation

$$(\alpha_1')^2 + (\alpha_2')^2 = 1 \quad (1)$$

where α_1' and α_2' are the respective ratios of the amplitude of components measured at the output of a filter to the amplitude measured at the input of that filter.

One method of eliminating this non-linear distortion is to employ in each carrier channel a substantially perfect product modulator, that is, a modulator providing output products which are directly proportional to the product of the applied signal and carrier voltages over a wide range of signal inputs. The circuit of one such modulator in accordance with the invention is shown in Fig. 4.

The modulator of Fig. 4 differs from the modulator shown in Fig. 3 essentially only in the following particulars. The complex carrier wave is applied to the horizontal diagonal of the balanced copper-oxide rectifier bridge through a circuit including the repeating coil T2 and the condenser C1 (4 microfarads) and resistor R2 (600 ohms) in series with the secondary winding of that coil, of such circuit constants as to reduce the carrier input level to the bridge to a sufficiently low value as to make the variation in impedance of copper-oxide varistors 1 to 4 in the modulator bridge small throughout the carrier cycle. When the carrier input level was reduced sufficiently to satisfy this condition, it was difficult to secure a high degree of balance in the bridge modulator without the use of an external balancing condenser, particularly in the higher frequency channels. This is due to the fact that at low voltages the phase angle of the $\frac{1}{f}$ copper-oxide rectifier discs used in each varistor was found to be about -45 degrees at 3,000 cycles. The use of an external balancing condenser with a bridge modulator is troublesome, and experience has shown that the stability of balance is not high enough to warrant its use in a commercial system.

The effect of capacity on the balance of the modulator in Fig. 4 is minimized by applying a suitable small biasing voltage to the copper-oxide rectifier bridge in the conducting direction, such as to reduce the resistance of the copper-oxide rectifier elements 1 to 4 to a sufficiently low value so that satisfactory carrier balances can be obtained by adjustment of the 200-ohm resistance potentiometer 5 and without the use of an external balancing condenser, since the capacity of each rectifier is effectively in shunt with its resistance. For the particular bridge used, this was accomplished by connecting the 45-volt battery B2 through the large (200,000 ohm) series resistors R3 and R4 and the series resistor (600 ohm) R2 across the horizontal bridge diagonal with the poling shown. The direct current input signal is applied to the other diagonal of the bridge, as shown, then in such a direction that adjacent arms of the bridge are changed oppositely to higher and lower resistance values than the normal balance values, as

the amplitude of the applied signal varies, and so unbalance the bridge by an amount proportional to the amplitude of the applied signal current.

For a balanced copper-oxide bridge modulator of the type shown in Fig. 4, there is an optimum value of bias current that will yield the greatest modulator operating range. A typical family of modulator input-output curves for various values of bias current applied to such a modulator bridge is shown in Fig. 5. For all of these curves, the carrier input level is assumed held constant. Power output levels from the modulator in the pass-band are plotted in decibels as ordinates and the direct current signal inputs to the modulator in decibels as abscissae. These curves show that there is a definite carrier leak level for low signal inputs and a common maximum saturate value of output signal power. Between these two limits lies the useful operating range of the modulator. A short portion of the upper and lower end of the characteristic, as shown in each curve, is not usable because of the departure from a straight line of a 45-degree slope.

The carrier leak level is due to capacity unbalance in the modulator rectifier discs and decreases as the bias current increases, for then the resistance of the discs decreases and the capacity unbalance has a smaller effect. To visualize why the curves all show a common saturate output level, consider the simplified balanced bridge modulator A in Fig. 6. At a sufficiently high value of signal current I_{sc} , rectifier discs 2 and 4 in opposite bridge arms will have a negligibly small resistance, and discs 1 and 3 in the other two opposite bridge arms will have the high non-conducting value of disc resistance, so that the bridge degenerates to that shown at B in Fig. 7. When this situation prevails, there will be a fixed loss between the carrier input and modulator output terminals that is independent of the initial modulator bias current. Plotting this ratio, in decibels, between the saturate output power and the output carrier leak power level as a function of modulator bias current, the curve A of Fig. 8 is obtained. However, as the system of Fig. 1 is used, there is a maximum direct current signal, I_0 , that can be furnished by each channel rectifier and low-pass filter. Plotting the ratio of the maximum output power obtained from the modulator when I_0 is the input signal, to the output carrier leak level, as a function of bias current, the curve B of Fig. 8 is obtained. The operating range is seen to have a maximum value at some bias current i' . This optimum bias current will be that bias current producing the input-output modulator curve that just gives the saturate output power for the signal direct current I_0 . For the particular system of Fig. 1 used, $I_0=0.67$ milliampere. The table below shows values of modulator operating range as a function of modulator bias current for $I_0=0.67$ milliampere into the modulator circuit of Fig. 4.

Bias Current	Ratio of Output Power for $I_0=0.67$ milliampere to Carrier Leak Power Level
Milliamperes	Decibels
0.08	59
0.11	64
0.22	57

A bias current of 0.11 milliampere was taken as the optimum value and the constants of the

circuit elements in the biasing circuit were selected to produce that value of bias current at the bridge. The receiving band-pass filters, to which the modulator outputs are connected in a system in accordance with Fig. 1, which was built, are unbalanced with one side grounded, so that the low side of each modulator is grounded. In order to leave the balance point of each modulator conveniently near the center of the 200-ohm resistance potentiometer 5 in the modulator of Fig. 4, the pair of series 200,000-ohm resistances in the bias supply circuit for each channel modulator was selected to be within ± 5 per cent of those values.

In the system of Fig. 1, the signal applied to the signal input of the modulator in each channel is not truly a direct current one, inasmuch as each of the low-pass filters F11 . . . F20 used in the channels passes all frequency components from zero to 25 cycles per second. If a modulator in accordance with the invention, as shown in Fig. 4, is used in each channel of the system of Fig. 1, and is operated as described above, it will operate as a "perfect product" modulator for a wide range of alternating signal voltages. Raising the cut-off frequency of the low-pass filter will enable the modulator to work as a "perfect product" modulator for higher alternating signal voltages. The input signal voltage must always be on the linear portion of the curves of Fig. 5 for the output to be proportional to the product of the input and carrier voltages. For the case of a single frequency carrier and a complex input signal, this is illustrated by the equation:

$$\begin{aligned}
 \text{Output} &= \text{Input} \times \text{Carrier} \\
 &= (\alpha_0 + \alpha_1 \cos \omega_1 t + \alpha_2 \cos \omega_2 t + \dots) (\alpha \cos \omega_c t) \\
 &= (\alpha \alpha_0 \cos \omega_c t + \alpha \alpha_1 \cos \omega_1 t \cos \omega_c t + \alpha \alpha_2 \cos \omega_2 t \cos \omega_c t + \dots) \\
 &= \alpha \alpha_0 \cos \omega_c t + \frac{\alpha \alpha_1}{2} \cos (\omega_c - \omega_1) t + \frac{\alpha \alpha_2}{2} \cos (\omega_c - \omega_2) t \\
 &\quad + \frac{\alpha \alpha_1}{2} \cos (\omega_c + \omega_1) t + \frac{\alpha \alpha_2}{2} \cos (\omega_c + \omega_2) t + \dots \\
 &= \alpha \alpha_0 \cos \omega_c t + \frac{\alpha}{2} [\alpha_1 \cos (\omega_c - \omega_1) t + \alpha_2 \cos (\omega_c - \omega_2) t + \dots] \\
 &\quad \text{Carrier} \qquad \qquad \qquad \text{Lower sideband} \\
 &\quad + \frac{\alpha}{2} [\alpha_1 \cos (\omega_c + \omega_1) t + \alpha_2 \cos (\omega_c + \omega_2) t + \dots] \quad (2) \\
 &\qquad \qquad \qquad \text{Upper sideband}
 \end{aligned}$$

A test circuit similar to that of Fig. 2 was set up, except that the biased "perfect product" modulator of the invention, as shown in Fig. 4, was used. The carrier input levels into that modulator of the 1250 and 1350-cycle components were each set to -36 dbm. so that the total carrier power input level to the modulator was -33 dbm. Then, the output amplitudes of the 1250 and 1350-cycle components were measured as the carrier input amplitude of the 1250-cycle component was held constant and the amplitude of the 1350-cycle component reduced. The results are shown by the curves of Fig. 9. As shown, the 1250-cycle component in the output wave remains constant in amplitude and the amplitude of the 1350-cycle component is proportional to its carrier input amplitude. Thus, in the modulator of Fig. 4 there is seen to be a negligible amount of distortion due to interaction between components in the carrier input wave as the relative amplitudes of these components vary.

In a system in accordance with Fig. 1 equipped with channel modulators such as shown in Fig. 4,

a synthesized speech-to-carrier leak ratio of about 54 decibels was measured, which was about a 12-decibel improvement over the original high-carrier-level modulators used. The reduction of carrier leak background produced a noticeable improvement in the naturalness of the synthesized speech, and a perceptible reduction of the "nasal" quality of the synthesized speech as well.

Because the "perfect product modulator" of the invention described above provides a large linear operating range and an unusual degree of carrier balance, its use is desirable in all carrier systems, of which the system of Fig. 1 is one example, where the carrier cannot be suppressed by filtering without suppressing wanted modulation products. Also in systems where the carrier is suppressed by filtering, the amount of filtering required can be reduced by the use of the described type of modulator.

Although the improved modulator circuit of the invention as described above employs copper-oxide varistors in the modulator bridge, any other type of physically inert non-linear impedance element may be used provided the direct current bias applied can bias the elements in the bridge to a resistance value low compared to the reactance of the capacity of the element used, and it is not necessary that these elements be rectifiers; for example, each non-linear element may be one which conducts equally well in both directions, such as the composition known as "Thyrite" prepared as described in the United States patent to K. B. McEachron, 1,822,742, issued September 8, 1931. Other modifications of the circuits illustrated and described above which are within the spirit and scope of the invention will occur to persons skilled in the art.

What is claimed is:

1. The method of operation of a modulator of the type consisting of a plurality of non-linear impedance elements connected in a balanced bridge arrangement across the two diagonals of which sources of signal and carrier waves to be combined are respectively connected, which consists in reducing the input level of the carrier wave applied to the bridge arrangement to a sufficiently low value so that the impedance variation of said non-linear impedance elements is low throughout the carrier cycle, and applying a direct current bias to the bridge arrangement in the conducting direction such as to minimize the effect of capacity on carrier balance and to provide the optimum amount of bias current to give the maximum modulator operating range.

2. A system for combining a carrier wave of given frequency with a multi-frequency alternating signal wave of varying amplitude so as to produce combination waves of an amplitude level proportional to the product of the signal and carrier voltages over a wide range of signal input levels, comprising a plurality of non-linear impedance elements connected in a Wheatstone bridge arrangement across the two conjugate diagonals of which the sources of signal waves and carrier waves to be combined are respectively connected, means to reduce the carrier input level to the bridge arrangement to a sufficiently low value so that the impedance variation of said non-linear impedance elements is low throughout the carrier cycle, and means to apply a direct current bias to said bridge in the conducting direction, such as to reduce the effective resistance of said non-linear impedance elements to a sufficiently low value as to enable satisfactory carrier balance to be attained by slight adjustment of

the resistance values of adjacent bridge arms, said direct current bias being of the optimum value which will provide maximum modulator operating range.

3. A system for modulating a complex carrier wave with a direct current signal wave of varying amplitude, so as to produce combination products of amplitude level proportional to the product of the signal and carrier voltages over a wide range of signal input levels, comprising a Wheatstone bridge having a non-linear impedance element in each of its four arms, a resistance potentiometer in series with two adjacent bridge arms for making small adjustments in bridge balance to reduce carrier leak, means for impressing said signal wave on one diagonal of said bridge, and said carrier wave on the other diagonal of said bridge at such a level as to make the impedance variation of the non-linear impedance elements in said bridge low throughout the carrier cycle, means to apply to said bridge

in its conducting direction a biasing direct current voltage such as to reduce the effective resistance of said non-linear impedance elements to such a low value as to enable satisfactory carrier balance to be attained by adjustment of said resistance potentiometer, and to provide the optimum amount of bridge biasing current for maximum modulator operating range, and an output circuit for taking off the combination waves.

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