Nov. 8, 1960 E. HANNEWALD ET AL 2,959,749

DISTORTION CORRECTION IN MODULATORS

Filed June 9, 1955 6 Sheets-Sheet 1

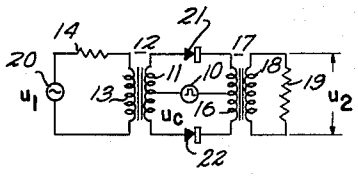


FIG. 1a.

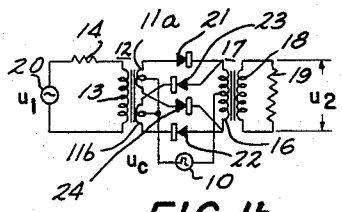


FIG. 1b.

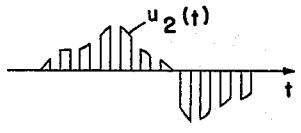


FIG. 1c.

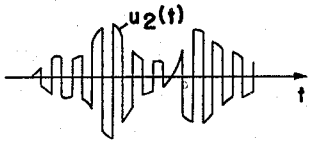


FIG. 1d.

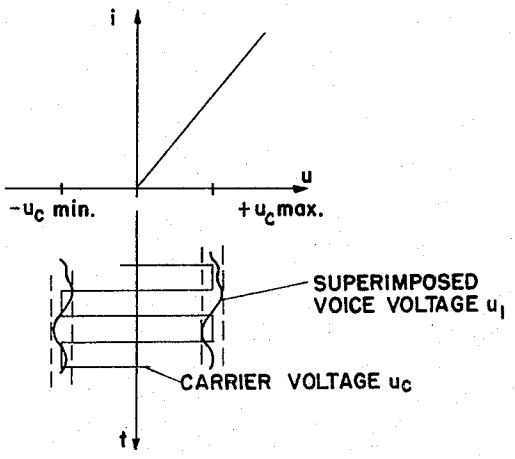


FIG. 2.

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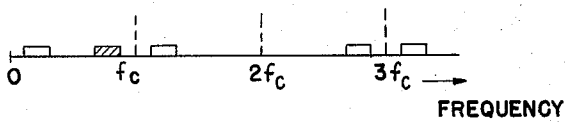


FIG. 3.

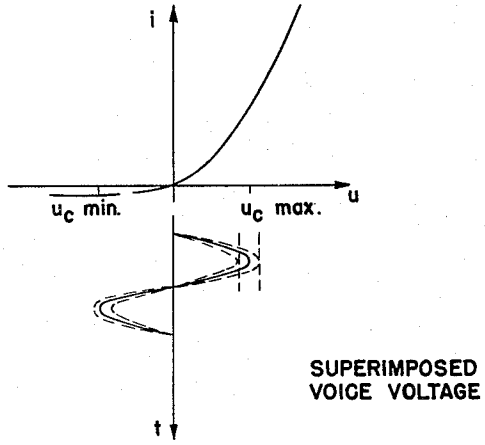


FIG. 4.

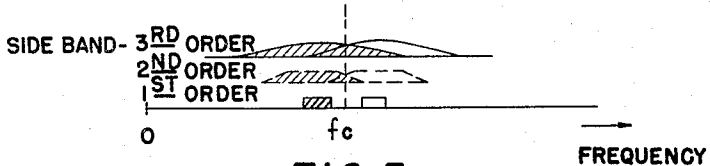


FIG. 5.

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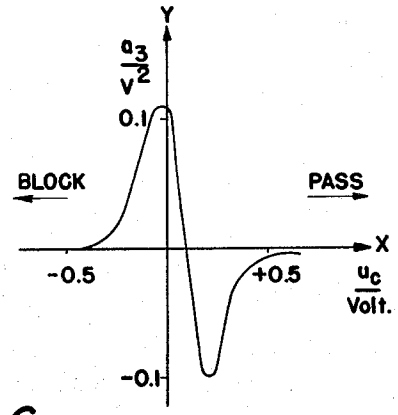


FIG. 6.

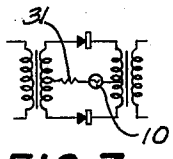


FIG. 7a.

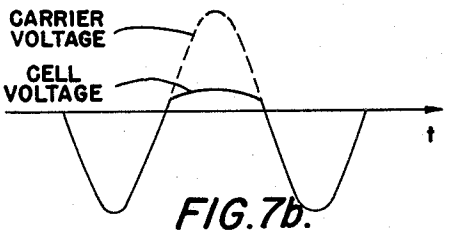


FIG. 7b.

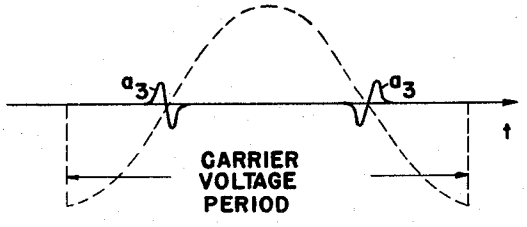


FIG. 8.

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FIG. 9a.

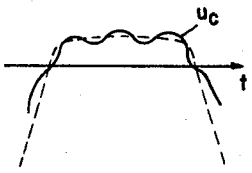
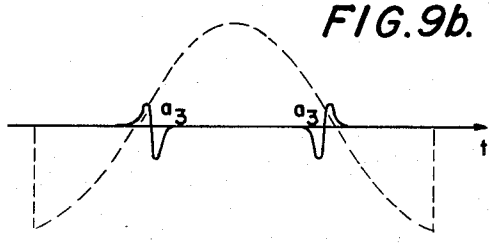
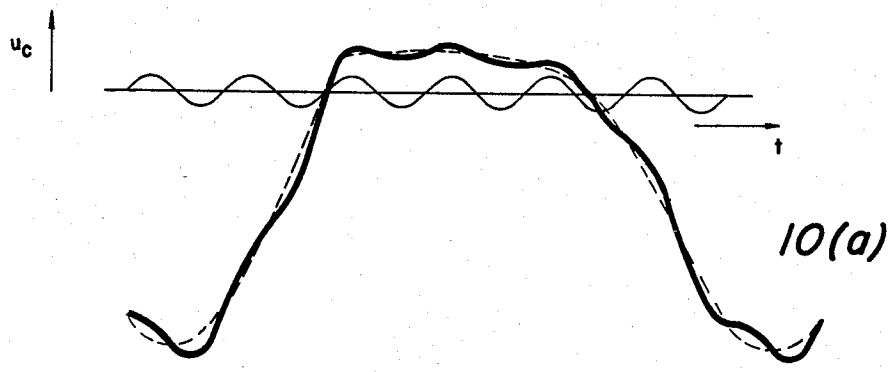
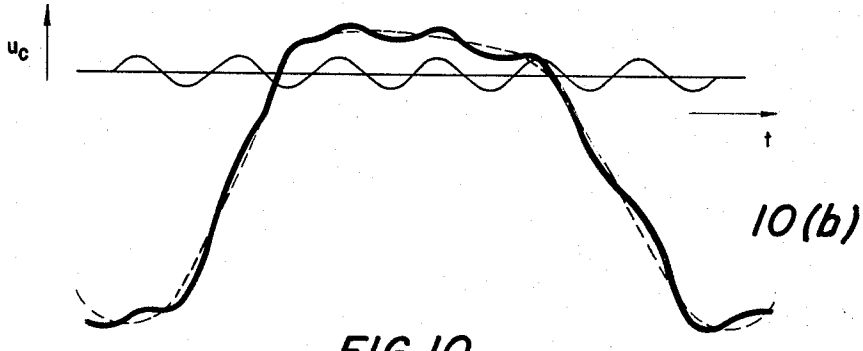


FIG. 9b.





10(a)

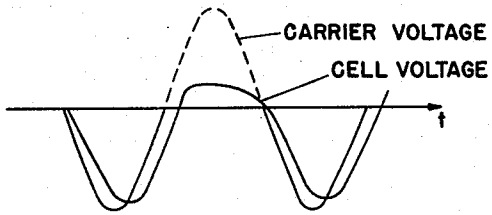


10(b)

FIG. 10

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FIG. 11.



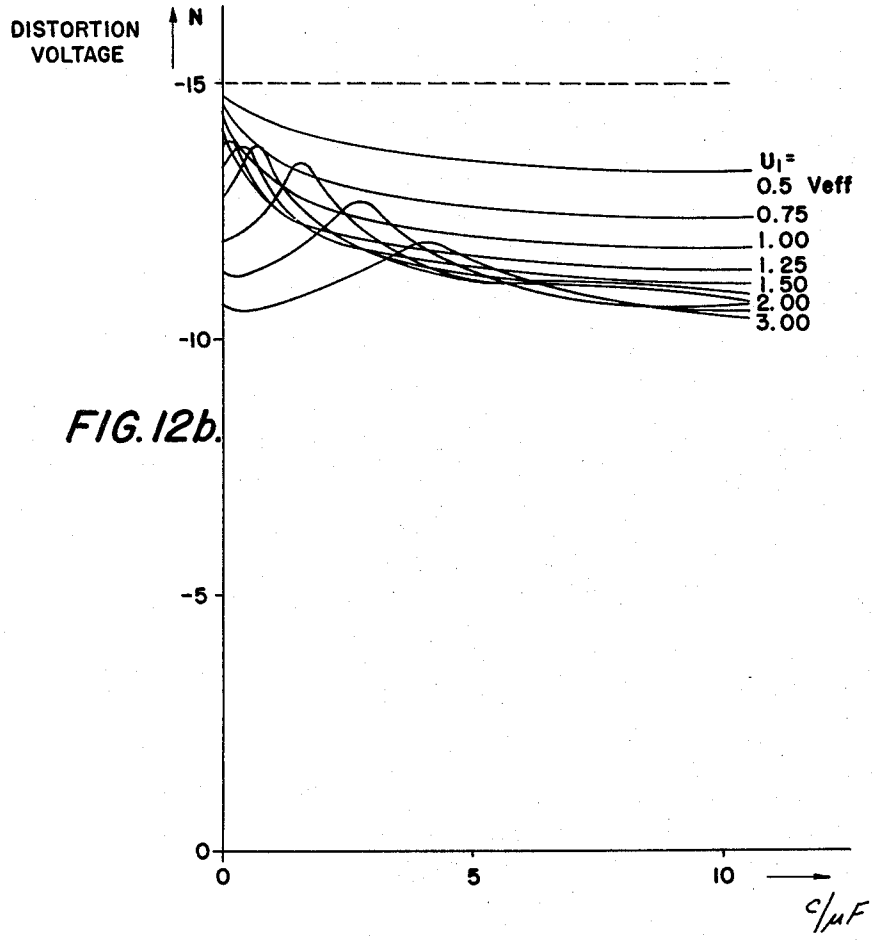


FIG. 12b.

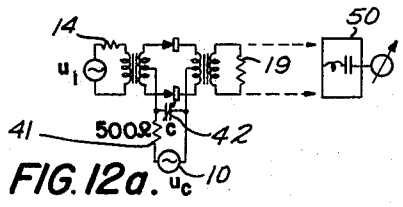


FIG. 12a.

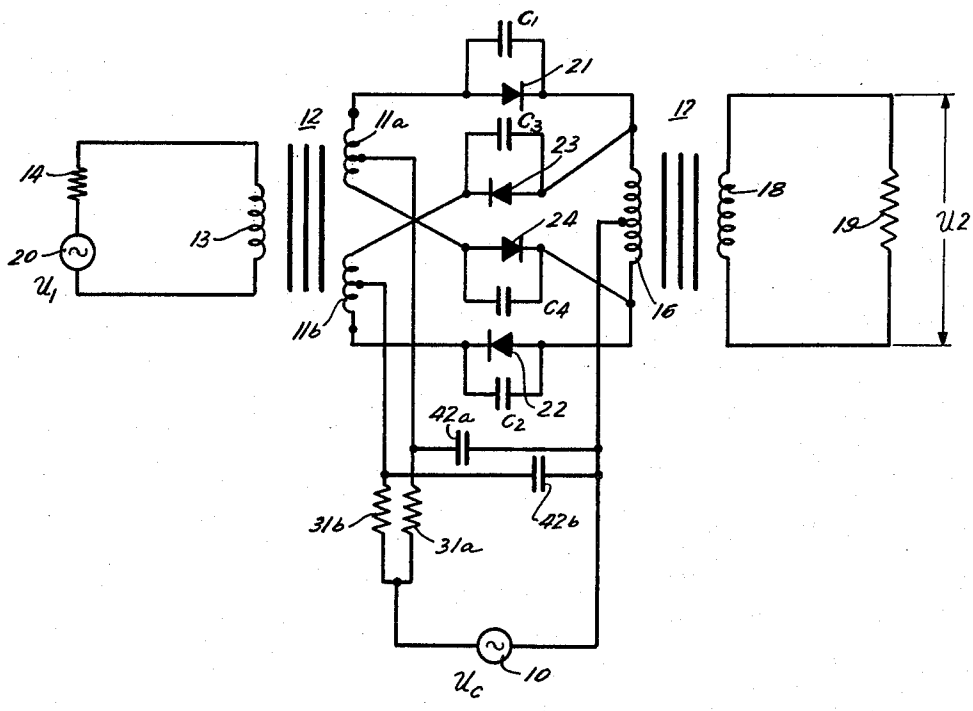
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DISTORTION CORRECTION IN MODULATORS

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FIG. 13



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United States Patent Office 2,959,749 Patented Nov. 8, 1960

2,959,749

DISTORTION CORRECTION IN MODULATORS

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Filed June 9, 1955, Ser. No. 514,216

4 Claims. (Cl. 332—9)

The present invention relates to modulator and demodulator circuits. More particularly, the present invention relates to a method and apparatus for reducing the non-linear distortion present in modulating and demodulating circuits.

Modulators are used in transmitting circuits to transmit voice frequencies by transposing the voice frequencies to a more suitable frequency range for transmission. In the receiving circuits, the demodulators perform the reverse function and return the voice frequencies back to their normal frequency range for reproduction. The modulator and demodulator circuits generally include direction-dependent elements such as rectifiers which in the ideal case have broken straight line characteristics with respect to the current produced by the voltage applied thereto.

Actually, however, the direction-dependent elements do not operate along their ideal characteristics but they operate with an actual characteristic which is quite different from the ideal characteristic in that it is not linear. Accordingly, a signal distortion is introduced during the modulation operation which distortion is carried through the transmitting circuits and reproduced in the receiver circuits.

Accordingly, it is an object of the present invention to reduce non-linear distortion in modulators and demolulators.

It is another object of the present invention to provide a new and improved method and apparatus for correcting non-linear distortion introduced in modulating and demodulating circuits by rectifier elements.

A further object of the present invention is to provide a new and improved method and apparatus for reducing distortion in modulating and demodulating circuits by varying the wave shape of the carrier voltage used with the modulating and demodulating circuits.

With the above objects in view, the present invention mainly consists of modulating apparatus including at least two direction-dependent, non-linear elements having input and output terminals; input means connected to the input terminals of the elements, output means connected to the output terminals of the elements, a first voltage source producing a modulating voltage and connected to said input means, a second voltage source producing a carrier voltage adapted to be modulated by the modulating voltage and connected between the input and the output means, and a resistor connected in series with the second voltage source for limiting the amplitude thereof.

The novel features which are considered as characteristic for the invention are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of specific embodiments when read in connection with the accompanying drawings, in which:

Fig. 1*a* is an electrical schematic diagram of a push-pull modulator;

Fig. 1*b* is an electrical schematic diagram of a double push-pull modulator;

Fig. 1*c* is a graphical representation of the output voltage obtained from the modulator of Fig. 1*a*;

Fig. 1*d* is a graphical representation of the voltage appearing at the output of the modulator of Fig. 1*b*;

Fig. 2 is a graphical representation of the ideal characteristics of rectifier elements and a carrier voltage used with a modulator;

Fig. 3 is a graphical representation showing the side bands in the frequency spectrum of the output voltage of an ideal modulator;

Fig. 4 is a graphical representation of an actual rectifier characteristic and carrier voltage;

Fig. 5 is a graphical representation of a frequency spectrum showing the side bands contained in the output of an actual modulator;

Fig. 6 is a graphical representation showing the distortion appearing in the third harmonic of the signal voltage with respect to the carrier voltage;

Fig. 7*a* is an electrical schematic diagram of a push-pull modulator constructed in accordance with the present invention;

Fig. 7*b* is a graphical representation showing the limiting of the carrier voltage due to the improved operation of the apparatus constructed in accordance with the present invention;

Fig. 8 is a graphical representation of the distortion voltage in one period of the carrier frequency;

Fig. 9*a* is a graphical representation of the distorted carrier voltage;

Fig. 9*b* is a graphical representation showing the variation of the distortion voltage with time;

Fig. 10*a* is a graphical representation showing distortion of an actual carrier voltage containing the sixth harmonic;

Fig. 10*b* is a graphical representation showing the distortion of an actual carrier voltage containing the sixth harmonic which is shifted in phase with respect to Fig. 10*a*;

Fig. 11 is a graphical representation of the carrier voltage and the voltage appearing on the rectifier cell when the modulator is constructed in accordance with the principles of the present invention;

Fig. 12*a* is an electrical schematic diagram of a modulator constructed in accordance with the present invention in conjunction with a harmonic analyzer;

Fig. 12*b* is a graphical representation of the various output produced by the apparatus of Fig. 12*a*; and

Fig. 13 is an electrical schematic diagram of a modified double push-pull modulator.

Referring now to the drawings and more particularly to Fig. 1*a*, the sine-wave carrier voltage u_c is generated from an alternating current source **10** having one terminal connected to the center tap of a secondary winding **11** of a transformer **12**. Connected across the primary winding **13** of the transformer **12** is an input resistor **14** and a source **20** of the modulating voltage u_1.

The other terminal of the source **10** is connected to the center tap of the primary winding **16** of a transformer **17**, the secondary winding **18** of which has a terminating output resistor **19** connected thereacross. Connected between one end of the secondary winding **11** of the transformer **12** and one end of the primary winding **16** of the transformer **17** is a rectifier **21**. Connected between the other end of the secondary winding **11** and the other end of the primary winding **16** is a secondary rectifier **22**. It should be noted that the rectifiers **21** and **22** are connected in the same sense.

In operation, the modulating voltage u_1 generally has a substantially lower frequency than the carrier voltage u_c emitted by the source **10**. Since the rectifiers **21** and

22 are connected in the same sense, they act as half-wave rectifiers so that they permit passage of the signal when the carrier frequency waveshape is positive and they prevent passage of the voice frequency signal when the carrier frequency waveshape is negative. Therefore, the output voltage u_2 of the push-pull modulator illustrated in Fig. 1*a* and taken across the output resistor **19** is modulated in rhythm with the carrier frequency and appears as shown in Fig. 1*c*.

Referring now to Fig. 1*b*, a push-pull modulator is shown using two circuits, everyone with a pair of rectifier elements. The parts of Fig. 1*b* that correspond to the parts of Fig. 1*a* have the same numerals. However, in this figure, the secondary winding **11** of the transformer **12** is separated into two separate widings **11**[a] and **11**[b], respectively. The rectifiers **21** and **22** are connected in the same sense between one end of the secondary winding **11**[a] of the transformer **12** and one end of the primary winding **16** of transformer **17** and between the other end of the secondary winding **11**[a] and the other end of the primary winding **16**, respectively. The rectifiers **23** and **24** are connected in the same manner, but inverted poled, between the secondary winding **11**[b] of the transformer **12** and the primary winding **16**, of the transformer **17**.

Accordingly, the output voltage appearing across the output resistor **19** has the characteristics shown in Fig. 1*d*. In this latter figure, it can be seen that the output voltage is again modulated in accordance with the carrier frequency but in this case the wave is continuous and the polarity thereof is merely reversed rather than being interrupted when the carrier frequency voltage u_c is negative. This results from the operation of the four rectifiers **21**—**24** arranged in the push-pull modulator.

The voice frequency is contained within the envelope of the output voltage of the modulators. Also contained in the output voltage are high and low side bands.

By the use of the push-pull modulation, assuming ideal symmetry, the carrier voltage and its harmonics are retained. However, the associated side bands are separated. If the carrier frequency is chosen to be at least double the highest voice frequency, then the principal frequency side band containing the desired information is sufficiently separated from the remaining side bands and it is possible by means of a filter to separate the desired frequency side band from the remainder of the frequency spectrum.

In Fig. 3, for example, the principal frequency side band which is to be utilized is shown cross hatched. It can be seen that this principal frequency side band occurs near the carrier voltage frequency f_c. It can also be seen that the remaining side bands are sufficiently separated from the principal side band in frequency so that they may easily be filtered and removed from the modulated signal without affecting the information contained in the principal side band.

The information discussed above with respect to the various frequency side bands only apply in the case of ideal modulators using ideal rectifier elements. However, in Fig. 4 an actual modulator characteristic is shown wherein the carrier frequency is a sine wave. It can be seen from this figure that the variation of current of the rectifier element with the applied voltage is no longer a straight line. Accordingly, the current passing through the rectifier elements due to the applied voice frequency signal is distorted, which in turn distorts the output voltage of the modulator.

Accordingly, the resulting frequency spectrum contained in the output from the modulator not only contains side bands of the first order as shown in Fig. 3, but also contains side bands of higher orders. This is graphically shown in Fig. 5. In this figure it can be seen that the side bands of even order, such as the second order illustrated, are eliminated. This is due to the symmetry of the even order side bands, which causes them to compensate for each other and accordingly to be cancelled from the output voltage of the push-pull or double push-pull modulator.

Accordingly, the only side bands remaining in the output of the modulator are the odd order side bands. From Fig. 5 it can be seen that the third order side band overlaps the first order side band so that it is not possible to subsequently separate these side bands from one another. That is, both the first order side band, which is the desired side band and contains the desired information, and the third order side band, which is an undesired side band, both contain the same frequencies so that no frequency separation between the two is possible.

In accordance with the principles of the present invention, the distortion introduced in the output of the modulator is reduced by changing the characteristic of the modulator. That is, the effect of the third order side band is decreased by the present invention.

The output voltage u_2 from the modulator can be represented as a potential series as follows:

$$(1) \quad u_2=a_1(u_c)u_1+a_3(u_c)u_1^3+a_5(u_c)u_1^5+ \ldots$$

from which it can be seen that only the uneven harmonics of the input voltage u_1 are effective due to the above described symmetry of the even harmonics. The coefficients depend on the modulator circuit elements, such as the resistors **14** and **19** of Figs. 1 and 2, and also on the carrier voltage u_c.

The distortion in the output of the modulator can best be seen when the input voltage u_1 is set equal to $u_1 \cos \omega t$ and the third harmonic of the output voltage is measured or calculated. The amplitude of the third harmonic of the output voltage, in the first approximation, is proportional to the coefficient a_3.

In Fig. 6, a graph is shown which plots the variation of the coefficient a_3 with respect to the carrier voltage for a particular terminating resistance **19**. The portion to the right of the Y-axis is for the positive half of the carrier voltage and accordingly corresponds to voltage that is passed by the rectifier elements. The portion to the left of the Y-axis is for the negative half of the carrier voltage and accordingly corresponds to voltage that is blocked by the rectifier elements.

From Fig. 6 it can be seen that the distortion voltage is very small for large values of the carrier voltage u_c. Accordingly, the length of time during which the amplitude of the carrier voltage remains very small essentially determines the amount of distortion that is present in the output of the modulator. This is particularly true in the region where the amplitude of the carrier voltage passes through zero.

Accordingly, the present invention decreases the distortion appearing in the output of the modulator by decreasing the amount of time during which the amplitude of the carrier voltage passes through zero and remains in the zero region. This amount of time can be decreased by increasing the amplitude of the carrier voltage when a sine wave is used. However, if the amplitude of the carrier voltage is increased the current passing through the rectifier cell sharply increases, thereby unnecessarily loading the cell and requiring an inordinately large carrier voltage supply.

In accordance with the present invention, a resistor device of suitable magnitude is placed in series with the source of carrier voltage. This is shown, for example, in Figs. 7*a* and 13 where the resistor device (**31***a*, **31***b* respectively) is shown in series with the source of carrier voltage **10**. This limits the current induced by the carrier voltage in the pass band of the modulator without affecting the slope of the carrier voltage curve in the zero region.

This is shown in Fig. 7*b* where the voltage applied to the cell in the pass region (positive u_c) is limited to the amplitude indicated by the solid black line above the time axis. The dotted line above the time axis indicates the actual amplitude of the carrier voltage applied which has

been limited to the lower amplitude by the use of the series resistor **31** of Fig. 7*a*. It can be seen that the carrier voltage in the blocking region (below the time axis) is not affected.

Referring to Equation 1 hereinabove it can be seen that the distortion might also be reduced by reduction of the modulation voltage u_1. However, it is apparent that some minimum output voltage is necessary at the output of the modulator in order to have a usable apparatus.

Since Fig. 6 indicates the variation of the distortion coefficient a_3 with respect to carrier voltage, and Fig. 7*b* indicates the variation of carrier voltage with respect to time, by combining these two curves, it is possible to construct the variation of a_3 with respect to time. This result is shown in Fig. 8, from which it is possible to perceive the modulation curves of the third harmonic of the signal voltage. The amplitude of the distortion side band for the curve shown in Fig. 8 may be finally determined by means of harmonic analysis wherein the amplitude of the first harmonic can be determined. From Fig. 8 it can be seen that the shape of the a_3-curve can be affected by changing the slope of the carrier voltage in the region of its zero amplitude.

In Fig. 9*a* the slope of the carrier voltage has been changed to produce an a_3-curve as shown in Fig. 9*b*. A comparison between Figs. 8 and 9*b* indicates that the third harmonic portion has become smaller since both the positive and negative portions of the slope of the a_3-curve are under the positive half of the sine wave.

Figs. 10*a* and 10*b* are indicative of two experimentally obtained carrier voltage curves produced by modulating apparatus. These curves have been determined by the superposition of a ground wave and its sixth harmonic and the curves differ only in the phase of the sixth harmonic. The distortion voltages present in the output of the modulator measured in both cases were in a ratio of 1 to 10.

The present invention can preferably be carried out by connecting capacitors in parallel with the rectifier elements or with the carrier voltage input in addition to having the limiting resistor means in series with the source **10** as shown in Fig. 7*a*. An embodiment of this kind is illustrated by Fig. 13 which generally corresponds to Fig. 1*b* except for the addition of capacitors C_1, C_2, C_3 and C_4 in parallel with rectifiers **21**, **22**, **23**, **24**, respectively, and the inclusion of resistors **31***a*, **31***b* in the connections between source **10** and primary windings **11***a*, **11***b*, respectively. There are also capacitors **42***a*, **42***b* connected in parallel with the series combination of the source **10** and the resistor means **31***a*, **31***b*. In Fig. 11, the wave shape of the carrier voltage and the voltage appearing on the cell is shown when the carrier voltage input is bridged by a capacitor. If this curve is compared to the curve of Fig. 7*b*, it can be seen that the passing region of the modulator has been decreased. Also, the side flanks of the voltage on the cell have been moved closer together as was done in Fig. 9*a*. Accordingly, the useful voltage is somewhat decreased because of its effect. However, this actually affects the useful voltage in only a minor way since the sides of the almost rectangularly formed passing impulse contributes very little to the amplitude of the first harmonic. However, small displacements of both small apexes of the a_3-curve produce a relatively large effect since these alone contribute to the shape of the first harmonic.

The connecting of capacitors (as shown in Fig. 13) in parallel with rectifier elements, such as germanium cells which have very little capacitance, does not adversely affect any of the other modulating properties, such as damping or residual carrier voltage effects. Accordingly, by the use of such capacitor and resistor connections, it is possible to provide a substantial saving in the carrier voltage supply.

In order to obtain an adequate correction of the non-linear distortion, merely by raising the carrier voltage, it is necessary to provide a carrier voltage supply in the order of 200 or 300 milliwatts. On the other hand, by means of the present invention, it is possible to obtain a substantial improvement in the correction of non-linear distortion with a carrier voltage supply of only 60 milliwatts.

A further advantage of the present invention results in the fact that the correction of non-linear distortion in accordance with the present invention is substantially less frequency-dependent than other methods of correction. Therefore, the apparatus of the present invention may be used throughout a wide frequency range.

In Fig. 12*a* is shown the push-pull modulator of Fig. 1*a* with the addition of a resistor **41** placed in series with the carrier voltage source **10** and a variable capacitor **42** placed in parallel with the carrier voltage input. In addition, an output resistor **19** of 600 ohms is used and an input resistor **14** of 80 ohms.

In Fig. 12*b* is shown several different measuring results of the distortion voltage for different settings of the variable capacitor and different modulation voltage levels. For this graph a harmonic analyzer **50** was used. The following values were set up. The carrier voltage u_c equalled 4 volts (effective); the carrier frequency u_c equalled 48 kilocycles per second; and the modulation frequency u_1 equalled 5.33 kilocycles.

On the Y-axis of Fig. 12*b* is plotted the distortion voltage in Nepers and on the X-axis is plotted the capacitance setting of the variable capacitance **42**. The several curves represent different effective carrier voltage outputs ranging from 0.5 volt to 3.5 volts.

Accordingly, it can be seen that by use of the present invention it is possible to change the characteristic curve of the carrier voltage to correct the non-linear distortion of the modulator and particularly accomplish this without raising the carrier voltage or reducing the modulation voltage output.

It will be understood that each of the elements described above, or two or more together, may also find a useful application in other types of modulation circuits differing from the types described above.

While the invention has been illustrated and described as embodied in push-pull and bridge circuit modulators, it is not intended to be limited to the details shown, since various modifications and structural changes may be made without departing in any way from the spirit of the present invention.

Without further analysis, the foregoing will so fully reveal the gist of the present invention that others can by applying current knowledge readily adapt it for various applications without omitting features that, from the standpoint of prior art, fairly constitute essenial characteristics of the generic or specific aspects of this invention and, therefore, such adaptations should and are intended to be comprehended within the meaning and range of equivalence of the following claims:

What is claimed as new and desired to be secured by Letters Patent is:

1. Modulating apparatus comprising, in combination, at least two direction-dependent, non-linear elements having input and output terminals; input means connected to the input terminals of said elements; output means connected to the output terminals of said elements; a first voltage source producing a modulating voltage and connected to said input means; a second voltage source producing a carrier voltage adapted to be modulated by said modulating voltage and connected between said input and said output means; a resistor connected in series with said second voltage source for limiting the amplitude thereof; and a capacitor connected in parallel with said series connection of the second voltage source and said resistor.

2. Modulating apparatus comprising, in combination, at least two direction-dependent, non-linear elements

having input and output terminals; input means connected to the input terminals of said elements; output means connected to the output terminals of said elements; a first voltage source producing a modulating voltage and connected to said input means; a second voltage source producing a carrier voltage adapted to be modulated by said modulating voltage and connected between said input and said output means; capacitors, respectively in parallel with each of said direction-dependent, non-linear elements; and at least one resistor connected in series with said second voltage source.

3. Modulating apparatus comprising, in combination, at least four direction-dependent, non-linear elements connected in a double push-pull arrangement having input and output terminals; input means connected to said input terminals; output means connected to said output terminals; a first voltage source producing a modulating voltage and connected to said input means; a second voltage source producing a carrier voltage adapted to be modulated by said modulating voltage and connected between said input and said output means; a capacitor, respectively, in parallel with each of said direction-dependent, non-linear elements; and resistor means connected in series with said second voltage source for limiting the amplitude thereof.

4. Modulating apparatus comprising, in combination,

at least four direction-dependent, non-linear elements connected in a double push-pull arrangement having input and output terminals; input means connected to said input terminals; output means connected to said output terminals; a first voltage source producing a modulating voltage and connected to said input means; a second voltage source producing a carrier voltage adapted to be modulated by said modulating voltage and connected between said input and said output means; resistor means connected in series with said second voltage source for limiting the amplitude thereof; and capacitor means connected in parallel with said series connection of the second voltage source and said resistor means.

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