Dec. 20, 1938. H. S. BLACK 2,140,492

DISTORTION CORRECTION IN WAVE TRANSMISSION

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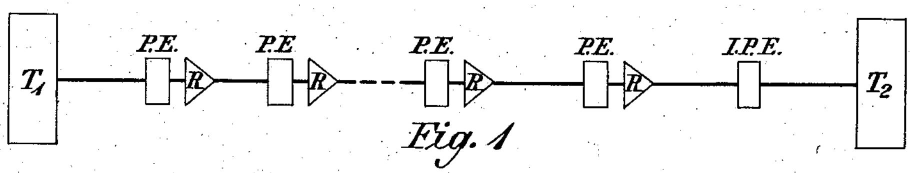

Fig. 1

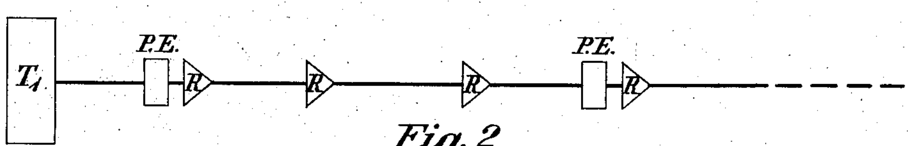

Fig. 2

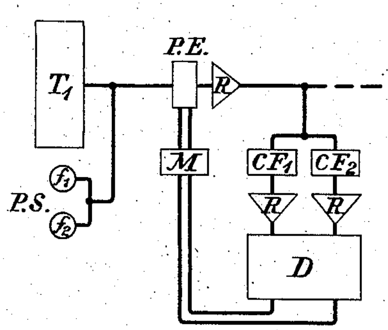

Fig. 3

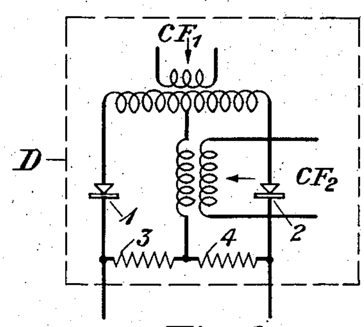

Fig. 4

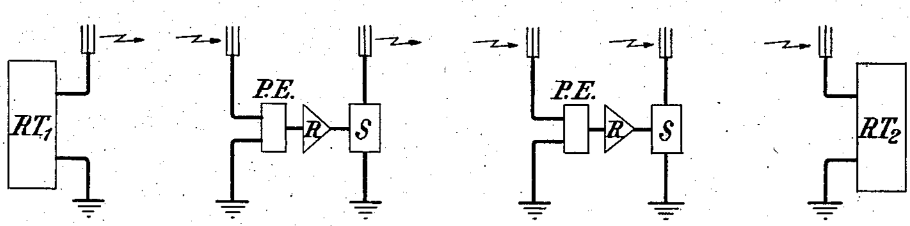

Fig. 5

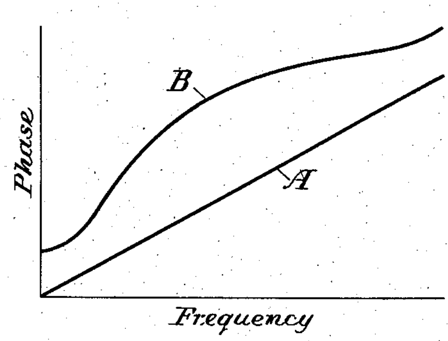

Fig. 6

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DISTORTION CORRECTION IN WAVE TRANSMISSION

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10 Claims. (Cl. 178—44)

This invention relates to a system of electrical communication and more especially to a system of the multiplex type generally known as a carrier system, in which a number of channels, each occupying a band of frequencies of a definite width, are transmitted over a single conducting medium between the transmitting and receiving stations. At the receiving station the various bands or channels are eventually selected out and translated either into audible or visual signals by apparatus at the receiving station. In systems of this kind it is common practice to use amplifiers between the transmitting and receiving stations which are common to several or all of the channels and which both repeat and amplify the signals in the several or all channels. In amplifiers or repeaters of this type operating upon a number of different channels which may be carrying different signals of different frequencies, there is ordinarily a reaction of the signals in one channel on signals in the other, which is frequently referred to as inter-channel modulation or sometimes as cross-talk in the case of telephone systems. There is also present intramodulation, i. e., reactions of frequencies within a channel, giving new frequencies within that channel. Such modulation results from a lack of strict linearity in the amplifiers.

In a transmission system with repeaters it is the usual practice to make the amplification at each repeater sufficient to just offset the loss due to attenuation in one repeater section of the cable. Thus, after passing through n repeater sections, the signal strength has been unchanged. The modulation products, however, being introduced additionally at each repeater station tend to increase as the number of repeaters in the line increases. Considerations which will be gone into further show that the total modulation product may be held down to a value where it is proportional to the

$$\sqrt{n}$$

Experiment indicates that it may increase faster than this. Thus, in one case measured there was a telegraph cable with 12 telegraph channels. There were 70 repeaters in tandem separated by 25 miles of cable and the modulation voltage at the output was found to be substantially 70 times the modulation voltage of one repeater. The purpose of my invention is to provide method and means for keeping this modulation voltage as low as

$$\sqrt{n}$$

times the modulation product for a single repeater.

While the above example related to a telegraph system, substantially the same results would hold for telephone systems. Thus in a recently developed multiplex system, using a special cable, known as the coaxial cable, it is possible to transmit simultaneously a very large number of channels which may easily extend to the number of 500 to 1,000 telephone channels. In such a system the repeaters may have a spacing of 5 miles or less and on a 4,000-mile circuit there would then be involved at least 800 repeaters. If the intermodulation product follows the law indicated by the experiment referred to above, it will either become excessive in amount or will require extraordinarily careful design of repeaters to keep down the modulation generated in any one repeater. A more general purpose of this invention, then, is to provide means for reducing the interchannel modulation which would otherwise be present in this type of system. As will be pointed out later, the results are accomplished by bringing in certain phase frequency relationships in each repeater section by which the modulation voltage product will increase less rapidly than the number of repeaters.

The invention will be better understood by reference to the following specification and the accompanying drawing, in which:

Fig. 1 is a schematic representation of a transmission line with a large number of repeaters in tandem and which at the same time incorporates the features of my invention;

Fig. 2 is a modification of the circuit of Fig. 1;

Fig. 3 is a detailed circuit of one of the repeater stations providing automatic compensation for temperature or other variations in the repeater sections;

Fig. 4 is a detail relating to Fig. 3;

Fig. 5 is a further modification of Fig. 1; and

Fig. 6 is a phase frequency curve used to illustrate my invention.

For a better understanding of the invention one may consider first a single amplifier. For an ideal amplifier (which is a physical impossibility), it is assumed that the output is a faithful copy or replica of the input voltage except as enlarged and except as it may be delayed. Due to unavoidable non-linearity, harmonics and other undesired products of modulation are present and will be represented as voltage variations in the output not present in the input but in the signal frequency band. From the standpoint of how these products of modulation combine as a function of the number of repeaters, it will be necessary to distinguish and consider separately the even and the odd order products of modulation. For the purpose of this discussion, it will be sufficient to consider only the second order products and the third order products of modulation.

Consider a resistance line of loss L followed by a flat gain amplifier, and consider a group of such identical units in tandem. Let X be the input at the transmitting end of the line which attenuates to x in passing through the first section of line so that the input at the first repeater is represented by x. The output of the amplifier may be represented by

$$X+k_2x^2+k_3x^3+\ldots \quad (1)$$

It will be observed that poling or reversing the input of the repeater does not change k_2x^2 but does reverse the other two terms given above.

Passing to the second amplifier, its input is

$$x+(k_2x^2+k_3x^3+\ldots)\epsilon^{-L} \quad (2)$$

where L is in Napiers. The output of the second amplifier is the amplified output due to the term x, namely, $X+k_2x^2+k_3x^3+\ldots$, plus the distortion introduced by the second amplifier which is $(k_2x^2+k_3x^3+\ldots)$. It will now be observed that by poling the input to the second amplifier the second order terms cancel each other in the output of the amplifier but the third order terms do not, so that the output of the second amplifier is $-X-2k_3x^3-\ldots$ Thus, in the absence of phase shift in either line or amplifier, which implies flat loss and flat gain with frequency, if every other amplifier is poled, then with an even number of amplifiers the even order modulation products are theoretically zero and the odd order modulation voltage products are equal in amplitude to those of a single amplifier multiplied by the number of amplifiers. Thus, the modulation voltage products for these terms add up arithmetically and the modulation power output is proportional to n^2E^2 where E is the modulation voltage set up by one repeater.

If the resistance line in the previous example is replaced by a telephone cable for which the velocity of transmission of a wave is the same for all frequencies, then there will be a time delay as one passes over a repeater cable section but the wave shape at the input of one repeater is identically the same as the wave shape at the output of the previous repeater. Such a condition is quite closely approximated over a wide frequency band in the so-called coaxial cable and it will be apparent from what has been said heretofore that by suitable poling at the successive repeaters it is possible to balance out even order terms but the odd order modulation voltage terms are those of a single amplifier multiplied by the number of amplifiers. For such an ideal transmission medium, the actual phase shift, expressed in radians, as one passes over a repeater section is proportional to the frequency and would be represented by a phase frequency characteristic which is a straight line passing through zero, as indicated by curve A of Fig. 6.

If the straight line phase relationship stipulated above is not satisfied then the rule previously cited is no longer valid. Assume, for example, that by additional phase retardation at certain points on the transmission line, such as at the input of each repeater, the phase frequency characteristic departs from the previous straight line relationship as indicated by curve B of Fig. 6. Assume, also, that X is a sine wave. The output of the first amplifier of the string is not affected by these changes, neither is the signal input to the second amplifier to the extent that the harmonics generated in the second amplifier depend only upon the fundamental applied. They are unchanged. Added to them, however, are the amplified harmonics from the first amplifier which by comparison to the original condition are retarded in phase by the input equalizer of the second amplifier. Assuming even numbered amplifiers are poled, if the amplified second harmonic as produced in the first amplifier originally opposed or canceled the second harmonics produced in the second amplifier, then with the added phase retardation to the frequency $2f$ but not f in the input equalizer this opposing action or balance is impaired to an extent depending upon the amount of phase increment introduced. In a similar way, when considering a third order product such as one of frequency $3f$, if without the extra phase shift in the input equalizer to $3f$ the effect of the $3f$ from the first amplifier were to add precisely in phase with the $3f$ produced by the second amplifier, then with the extra phase shift the vector sum of the two is less. Similar effects take place at succeeding amplifiers. Analysis shows that if E represents the modulation voltage of one amplifier at a specific frequency and n the total number of repeaters, the resultant vector addition at the end of the system is given by

$$M=E\sqrt{n+2\sum_{1}^{n-1}r(n-r)\cos r\Theta} \quad (3)$$

valid for either even or odd order products. Θ may be defined by the following illustration: Suppose f_1 and f_2 combine to set up a modulation frequency f_3 due to third order modulation, such as $f_3=2f_2-f_1$. If Φ_1, Φ_2 and Φ_3 are the combined shift of line plus repeater at these frequencies, $\Theta=\Phi_3-(2\Phi_2-\Phi_1)$. Again if $f_3=f_1+f_2$ (a second order frequency) then $\Theta=\Phi_3-(\Phi_1+\Phi_2)$ or if $f_3=3f_1$ then $\Theta=\Phi_3-3\Phi_1$, all in a manner which can be readily demonstrated. Θ then represents the phase difference between any modulation frequency generated in a given repeater as compared to the phase of that same modulation frequency arriving at the input of the amplifier from the previous amplifier.

A favorable condition so far as modulation products are concerned would be obtained if in the relationship given above the summation of the cosine terms is equal to zero, in which case the modulation voltage will be given by

$$M\sqrt{n}$$

If $(n-1)\Theta$ is large compared to 2π then the values of $\cos r\Theta$ will be nearly uniformly distributed between ±1 and the desired condition is approximately reached. In other words, the vectors representing the modulation voltage generated in the successive repeaters will have phase angles with respect to the first of these vectors distributed over all values from 0 to 2π and will approach a random angular distribution, in which case the summation term approaches zero. To attain this condition, then, I propose to introduce at the input of each amplifier, or of certain specified amplifiers, or at certain specified points on the line, a phase shifting network or equalizer the characteristic of which departs from linearity in some such manner as indicated by curve B of Fig. 6.

Referring now to Fig. 1, there is shown a transmitting station T_1 and a receiving station T_2, joined by a transmission line equipped with a plurality of repeaters R in tandem. In front of each repeater is shown a phase equalizer PE which has a phase frequency characteristic preferably of a non-linear form, such as indicated in curve B of Fig. 6. While this equalizer is indicated as a separate unit from the repeater, it is to be understood that it may be built into the repeater as an integral part thereof. The particular form of the phase frequency characteristic for a repeater section of cable plus the equalizer may take on a large variety of forms, any departure from the simple relationship of curve A of Fig. 6 tending to bring about the desired effect. Since the summation in expression (3) is rendered small through an averaging process it is obvious that a large number of terms will be required to bring about a high degree of precision; nevertheless even with a relatively small number of repeaters such averaging as is obtained would, in general, represent a reduction in the modulation output over that obtained without this shift. A certain amount of phase shift or distortion is ordinarily present in any cable section but frequently, and especially in the case of the coaxial cable, this will not be sufficient to assure the extent of phase shift which is brought about by additional phase distortion.

The presence of the phase equalizers will of course have a cumulative phase distorting effect upon the signal itself, quite aside from the effect it has on the modulation products. Such phase distortion of the signal, if it becomes appreciable, can be compensated for completely at one point or another in the transmission line, such, for example, as at the receiving end where there is shown an inverse phase equalizer IPE.

While in Fig. 1 I have shown a phase equalizer in front of each repeater, it is apparent that this may not be necessary in some cases, but that, as shown in Fig. 2, there may be a phase equalizer for groups of two, or three, or more repeaters. In that case the group of repeaters plus their cables associated with one phase equalizer may be considered as the equivalent of one of the repeaters plus its cable in Fig. 1. The line may even be divided into but two sections at any desired point and still yield substantial improvement with proper choice of phase shift. In general, however, it is desirable but not necessary that the number of points at which the phase equalizers are introduced should be sufficiently large so that statistical conditions tend to hold.

In some cases the phase shift for one section may vary either because of temperature or humidity variations as they affect the cable, or because of aging of the repeaters, or for other reasons. For a short line such variations may not be significant but in the case of a line involving, for example, several hundred or several thousand repeaters in tandem the accumulated effect may be very substantial and in this case it may be desirable to make the phase equalizer at the input of a repeater variable in such a manner as to compensate for the variations arising otherwise in the repeater section. A large variety of circuit arrangements may be used for this purpose and one such arrangement is shown in Fig. 3, this being for illustrative purposes only. In Fig. 3 there is shown at the beginning of one repeater section a pilot signal source which may consist of a generator of two frequencies f_1 and f_2, these being chosen as typical frequencies for which compensation should be made. Obviously more pilot frequencies could be used if required. Signals of these frequencies are impressed on the repeater section and are shown as being taken off at the output of the repeater R by sharply selective filters, such as crystal filters CF_1 and CF_2. These two frequencies may now be amplified and passed through a suitable detecting device D which will have an output the phase and amplitude of which are dependent on the phase relationship between f_1 and f_2, and they may be used to control some device such as a motor M to change the phase equalizer by an amount sufficient to compensate for the variation which has taken place in the repeater section. The motor, for example, may be used to control a variable air condenser.

While the detecting device D may take on a large variety of forms, one such form is shown in Fig. 4 for illustrative purposes. Here the output of the filter CF_1 is impressed by means of a transformer on a circuit comprising two rectifiers **1** and **2**, such as copper-oxide rectifiers. The circuit also includes an impedance such as the resistances **3** and **4**. Bridged across this particular network is a transformer the primary of which is supplied from the output of the filter CF_2. The direction of flow of the rectified current in the resistances will be in the one direction or the other depending upon whether there has been a shift in phase in one direction or the other of one of the pilot signals with respect to the other.

I have here described compensation to be made for variations in the repeater section such as may be due to temperature changes. There will at times, however, be other variations, such as humidity or such as aging of tubes, which may be quite independent of the temperature variation. Compensation for any such variations may be made in a similar manner, or if necessary by similar additional pilot frequencies which, through a detecting device analogous to D, would bring about such other adjustment in the repeater circuit as to compensate for the particular variation being considered and such variations may relate either to amplitude changes as a function of frequency or phase changes as a function of frequency. The interest in the case of this invention is, of course, primarily related to changes in the phase frequency relationship.

Corrections such as described may be added at and for each repeater or each phase equalizer or in groups of repeaters in any desired arrangement, dependent on the nature and magnitude of the variations.

While the invention has thus far been described in terms of a physical structure such as a coaxial cable, it is to be understood that it may be used in other instances also, such, for example, as ultra-short wave radio beam systems using repeaters. Such a system is shown in Fig. 5, in which a radio beam sent out from RT_1 is picked up by and relayed from successive stations which may be fairly close together. At each of these relay stations, ordinarily involving a change of carrier frequency, there will be repeaters, thus bringing in problems fundamentally of identically the same character as those discussed above in connection with Fig. 1. The fact that there is no metallic circuit between the stations does not alter the situation. Under ideal conditions the velocity of transmission of the wave from one station to the next is independent of frequency although in any actual case changes in the medium between the two stations or other reasons may cause a departure from this. In order then to keep the modulation products to a reasonably low value, I propose to introduce a phase equalizing device at each station or at specified stations for the same purpose and functioning in the same manner as has already been described. Such signal channels would also be subject to variations of the kind analogous to those described in connection with Fig. 3, and if these become large enough to be troublesome then compensating means analogous to that shown in connection with Fig. 3 would be added to the circuits.

What is claimed is:

1. In a signal transmission system comprising a transmission line with a plurality of repeaters in tandem, the method of reducing the ratio of modulation products to signal intensity which consists in introducing phase frequency distortion throughout the entire transmitted band at a plurality of intermediate points on the transmission system to introduce phase displacement between the even and odd order modulation products at one point in the line and the corresponding modulation products generated at subsequent points on the line.

2. In a signal transmission system comprising a transmission line with a plurality of repeaters in tandem, the method of reducing the ratio of modulation products to signal intensity which consists in introducing phase frequency distortion at a plurality of intermediate points on the transmission system to introduce phase displacement between the modulation products at one point in the line and the modulation products generated at subsequent points on the line, such phase frequency distortion incidentally producing cumulative phase distortion in the desired signal, and introducing at a point in the line a correcting network for the phase distortion given to the desired signal.

3. In a signal transmission system comprising a transmission line with a plurality of repeaters in tandem, the method of reducing the ratio of modulation products to signal intensity which consists in introducing phase frequency distortion at a plurality of intermediate points on the transmission system to introduce phase displacement between the even and odd order modulation products at one point in the line and the corresponding modulation products generated at subsequent points on the line and introducing near the end of the transmission line a correcting network for the phase distortion given to the desired signal at the plurality of intermediate points.

4. The combination of claim 1 characterized by the fact that the phase frequency distortion is introduced at regular intervals along the transmission circuit.

5. The combination of claim 1 characterized by the fact that the phase frequency distortion is introduced at each repeater point.

6. The combination of claim 1 characterized by the fact that the phase frequency distortion is introduced at each repeater point in front of each repeater.

7. In a signal transmission system comprising a transmission line with a plurality of repeaters in tandem, the method of reducing the ratio of modulation products to signal intensity which consists in introducing phase frequency distortion at a plurality of intermediate points on the transmission system to introduce phase displacement of the various modulation products in such manner that the modulation vectors at the plurality of intermediate points have phase angles randomly distributed with respect to each other.

8. In a signal transmission system comprising a transmission line with a plurality of repeaters in tandem, the method of reducing the ratio of modulation products to signal intensity which consists in introducing phase distortion at a plurality of points of such number and of such magnitude that the net result of the modulation products increases approximately in accordance with the square root of the number of repeaters.

9. In a broad band signal transmission system comprising a transmission line with a multiplicity of spaced repeaters in tandem relation in the line with intermediate sections of line between the said repeaters, phase distorting networks associated with the individual repeaters, each of said networks together with the corresponding section having a resultant phase frequency characteristic which is non-linear over the transmitted band.

10. In a broad band wave transmission system including a multiplicity of spaced repeaters in tandem relation, phase distorters at distributed points along the system producing phase frequency distortion throughout the entire transmitted band for so introducing phase displacement between modulation products of even and odd order generated in the successive repeaters as to cause said products generated in the various repeaters to add to a total resultant modulation for the system less than the total resultant modulation that would be obtained in the absence of the aforesaid phase distorters.

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