May 16, 1939. M. BOWMAN-MANIFOLD ET AL 2,158,978

ELECTRIC SIGNAL TRANSMISSION SYSTEM

Filed Feb. 26, 1937

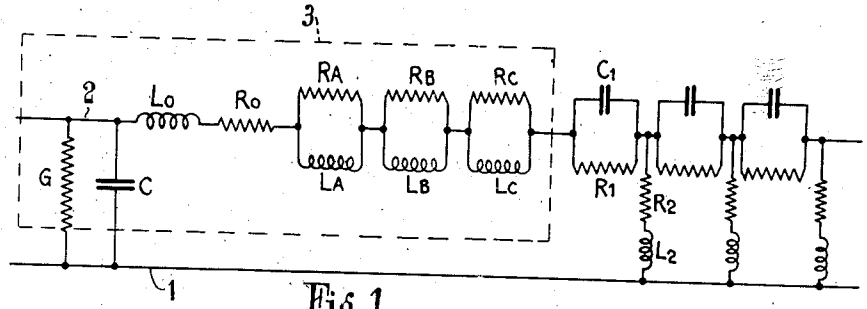

Fig. 1.

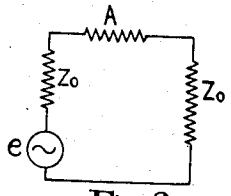

Fig. 2.

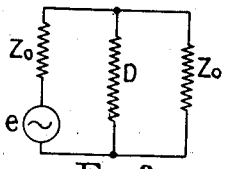

Fig. 3.

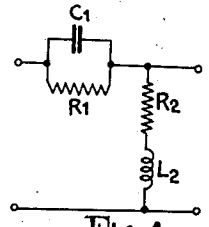

Fig. 4.

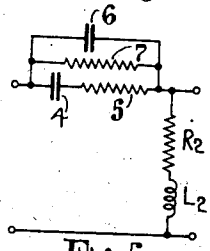

Fig. 5.

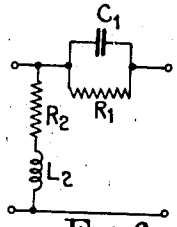

Fig. 6.

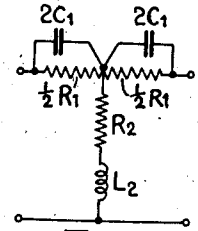

Fig. 7.

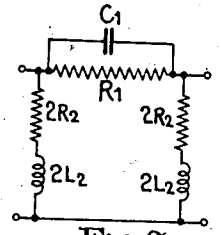

Fig. 8.

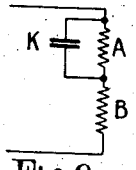

Fig. 9.

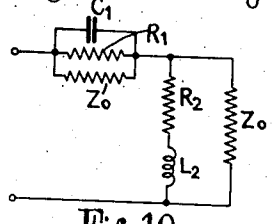

Fig. 10.

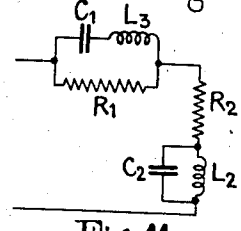

Fig. 11.

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ELECTRIC SIGNAL TRANSMISSION SYSTEM

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Application February 26, 1937, Serial No. 127,924
In Great Britain March 3, 1936

19 Claims. (Cl. 178—44)

This invention relates to electric signal transmission systems and more particularly to transmission systems which are required to handle signals covering a wide band of frequencies.

It is known that if a transmission line has an attenuation constant which is independent of frequency and a phase constant which is directly proportional to frequency, then the line is distortionless. It is also known that in general these conditions are not satisfied so that a transmission line is not distortionless.

In what follows it is stated that the attenuation and phase of a line are equalised; what is meant is, that the attenuation constant has been made substantially independent of frequency while the phase constant has been made substantially directly proportional to frequency.

Arrangements have been proposed for independently neutralising or equalising the variations with frequency of the phase and attenuation of a cable by inserting equaliser sections or networks in series with the cable.

It is an object of the present invention to provide an improved arrangement including an artificial line composed of a plurality of equaliser sections whereby, over a substantial range of frequencies, the variations with frequency of the phase and attenuation of a line are simultaneously eliminated or substantially reduced.

It is known that equaliser sections somewhat similar to the sections that are contemplated in the present invention have been used for equalising submarine cables over a very narrow frequency band. However, the errors which arise in submarine cables are totally different from the errors which are encountered in cables which are required to handle frequencies extending over a wide band of frequency, such as a cable which is required to handle television signals.

In order to facilitate differentiation of the two types of cable and equaliser, the fundamental theories underlying the two types will be briefly discussed.

The general expressions for the propagation constant P and the characteristic impedance Z_0 of a transmission line are:

$$P=\alpha+j\beta=\sqrt{(R+j\omega L)(G+j\omega C)} \quad \text{(1)}$$

$$Z_0=\sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad \text{(2)}$$

where α represents the attenuation constant, β the phase constant R, L, G and C are, respectively, the resistance, inductance, leakance and capacitance of the transmission line per unit length, and ω represents the angular frequency of the signal being transmitted and is equal to $2\pi f$ where f is the frequency in cycles per second.

In the case of a submarine telegraph cable, or any other form of telegraph cable where only frequencies up to 20 or 30 cycles per second are encountered, the term ωL is very small compared with R, and G is small compared with ωC. The expressions for the propagation constant and the characteristic impedance, therefore, become:

$$P=\sqrt{Rj\omega C}$$

$$=\sqrt{\omega RC}\,\underline{/45^\circ}$$

$$\alpha=\beta=\sqrt{\frac{\omega RC}{2}} \quad \text{(3)}$$

and

$$Z_0=\sqrt{\frac{R}{j\omega C}}$$

$$=\sqrt{\frac{R}{\omega C}}\,\underline{/45^\circ} \quad \text{(4)}$$

Over this small frequency range the values R and C can be considered as constant. It will be seen therefore that the variations in attenuation and phase constants are due to the

$$\sqrt{\omega}$$

term and not to any variation with frequency of the primary constants. Furthermore, it will be observed that the characteristic impedance of the cable is essentially variable with frequency. It will be apparent from what follows that the conditions for the equaliser in accordance with the invention, and which are necessary for its correct operation, are the exact inverse of the conditions discussed above for the telegraph cable.

It has been suggested in connection with equalisers for submarine cables, to make the constant impedance of an equaliser equal to that of the cable to be equalised; but since the impedance of the submarine cable is essentially variable with frequency, the making of the impedance of the equaliser equal to that of the cable is an impossible condition to satisfy.

Now the cable or transmission line which is contemplated in the present specification, is one capable of transmitting a very wide frequency range extending at least up to a hundred kilocycles per second. More particularly, the present invention is concerned with a cable capable of transmitting frequencies from substantially zero frequency to about two or three megacycles per second, such frequencies being ordinarily

encountered in the transmission of television signals. In these cases, except at the very lowest frequencies, ωL is large compared with R and ωC is large compared with G, so that the characteristic impedance is approximately

$$\sqrt{\frac{L}{C}}$$

At very low frequencies the cable impedance, assuming that the output end is terminated by an impedance

$$\sqrt{\frac{L}{C}}$$

approximates to the value

$$Rl+\sqrt{\frac{L}{C}}$$

where Rl is the total series resistance of the cable. In practical cases this value is not appreciably different from

$$\sqrt{\frac{L}{C}}$$

It can also be shown that if ωL is fairly large compared with R and ωC is fairly large compared with G, then,

$$P=\frac{R}{2}\sqrt{\frac{C}{L}}+\frac{G}{2}\sqrt{\frac{L}{C}}+j\omega\sqrt{LC} \quad \text{------} \quad (5)$$

This expression applies except at the very low frequencies where ωL is no longer large compared with R, but at the lower frequencies it is possible to employ other means in order substantially to correct the errors at these low frequencies due to cable distortion.

Now, if it is assumed that R, L, G and C are all constant with frequency, then the above Equation 5 indicates that the attenuation constant is independent of frequency, while the phase constant is directly proportional to frequency. The time delay of the cable is, however, proportional to

$$\frac{d\beta}{d\omega}$$

so that the time delay is also independent of frequency. Hence, any signals transmitted over the line for which the above-mentioned assumptions hold, will arrive at the output end with all the components in correct amplitude relationship and all delayed by the same amount. In other words, the cable is substantially distortionless.

In an actual high frequency cable, however, owing to the skin effect in the conductors, the resistance increases with frequency and the inductance falls. Further, owing to the fact that the capacity of the cable acts not like an ideal condenser but like a somewhat complicated network of condensers and resistances the capacity tends to decrease slightly and the leakance to rise as the frequency rises. It will be apparent, therefore, that since in an actual cable all four primary constants vary with frequency, the attenuation constant will vary with frequency and the phase constant will not be proportional to frequency. Distortion of the signals sent over the cable will therefore occur. Since both the inductance and capacity fall with rise in frequency, their ratio, and consequently the characteristic impedance of the cable, is approximately constant. It will be appreciated, therefore, that the conditions which exist with a cable required to handle a wide frequency band are exactly the reverse of the conditions existing in the submarine telegraph cable abovementioned. The characteristic impedance of a cable handling a wide frequency band is practically constant over the whole frequency range and the variations in attenuation and phase constant are not due to any

$$\sqrt{\omega}$$

term but due to actual variations with frequency of the primary constants of the cable.

According to the invention, an electric signal transmission system is provided comprising a transmission line or cable for transmitting a wide frequency band extending at least up to a hundred kilocycles, and an artificial line in series therewith comprising a plurality of equaliser sections, some or all of which consist of, or are electrically equivalent to, series elements consisting of resistances shunted by condensers and shunt elements consisting of inductances in series with resistances, the time constants and the magnitude of the components of said sections being so chosen as substantially to equalise simultaneously the greater part of the variation of attenuation and phase delay due to variation with frequency of the effective resistance, inductance, capacity and leakance of said line or cable.

The sections of the artificial line or equaliser may be sufficiently divided that the resultant line approximates to one having uniformly or infinitely distributed constants.

In another embodiment of the invention the various sections of the equaliser need not be so finely divided so as to approximate to a line having infinitely distributed constants and, in this case, it is preferred that the various equaliser sections be spaced or centred at frequencies corresponding substantially to equal loss increments on the attenuation curve of the transmission line or cable to be equalised. In the last mentioned embodiment of the invention, it is found that the characteristic impedance of such a form of equaliser is not constant over the frequency range, and in accordance with a further feature of the invention an improved form of termination impedance is provided for terminating the artificial line. Alternatively, the sections of the equaliser are modified and the equaliser terminated as hereinafter more particularly referred to.

It is also possible in accordance with another feature of the invention, to reduce the number of sections employed by an improved form of section which replaces the sections operative at the highest frequencies of the band.

Another feature of the invention consists in the use of a plurality of equalisers which are designed to equalise various lengths of the transmission line or cable whereby such equalisers can be readily selected for equalising certain lengths of the cable in cases where, for example, it is necessary to transmit signals at different tapping points along the transmission line or cable.

In order that the said invention may be clearly understood and readily carried into effect, the same will now be more fully described with reference to the accompanying drawing in which:

Fig. 1 illustrates diagrammatically a transmission line or cable with an equaliser constructed in accordance with the invention,

Figs. 2 and 3 are explanatory diagrams,

Fig. 4 is a diagram illustrating the type of equaliser section employed in the invention,

Figs. 5, 6, 7, and 8 illustrate further forms of equaliser sections electrically equivalent to that shown in Fig. 4,

Fig. 9 illustrates a form of terminating im-

pedance for an equaliser in which the sections do not approximate to an infinite distribution of constants,

Fig. 10 illustrates a further form of equaliser section for use in the invention, and,

Fig. 11 illustrates a modified form of section for use at the highest frequencies of the band.

Referring first to Fig. 1 of the accompanying drawing, a short length of a transmission line which may be arranged as a balanced or unbalanced line is shown comprising two conductors 1 and 2. The series resistance of the line and the series inductance are denoted by R_0 and L_0 in series with a number of units each comprising an inductance and a resistance. In Fig. 1 three such units, R_A, L_A, R_B, L_B, R_C, L_C, are shown. For convenience, series impedances in the line are shown in one conductor only. In practice, series impedances are distributed between the two conductors, but if R_0 and L_0 in series with the units R_A L_A etc., denote the total resistance and inductance for the short length, the distribution between the two conductors does not affect the calculations. The shunt capacity of the line is denoted by C and the shunt leakage by G.

The components so far described representing the cable constants are enclosed in a dotted rectangle 3, in order to distinguish them from components which are added in accordance with the invention and which will be hereinafter more fully described.

At low frequencies the impedances ωL_A and ωL_B are very small compared with their appropriate resistances so that the resultant circuit may be considered as consisting of R_0 and L_0 in series with L_A, L_B, and L_C, so that the effective low frequency inductance is $L_0+L_A+L_B+L_C$ and the corresponding resistance is R_0. At high frequencies the ωL terms become large compared with the resistances so that the resultant circuit now approximates to the inductance L_0 in series with a resistance $R_0+R_A+R_B+R_C$. The inductance has therefore fallen from $L_0+L_A+L_B+L_C$ to L_0 and the resistance has risen from

$$R_0 \text{ to } R_0+R_A+R_B+R_C.$$

By arranging the time constants of the different resistance-inductance units correctly and by employing a sufficient number of units, it is possible to cause the changes in inductance and resistance of the network described to correspond to those of the length of cable to any desired degree of accuracy.

These changes of resistance and inductance of the cable produce distortion and it is, therefore, necessary to provide a form of equaliser to substantially overcome this distortion. The resistance R_0 and inductance L_0 can be neglected since they are constant and produce no distortion and it is, therefore, only necessary to consider the resistance-inductance units R_A L_A, etc. Since a short length of cable is being considered the inductance-resistance units are small and since their effects are additive we can deal with a single unit at a time. The short length of cable being considered forms a part of a longer length of cable and if, as is the case in practice, the cable is terminated by its characteristic impedance, we can consider the short length of line as terminated each end by the characteristic impedance Z_0 of the cable. Furthermore, if the single inductance-resistance unit is represented by an impedance A the circuit shown in Fig. 2 results. In this figure e represents conventionally the applied E. M. F. With the circuit represented as shown in Fig. 2,

$$A=\frac{R\omega^2L^2+jR^2\omega L}{R^2+\omega^2L^2} \qquad \text{----------(6)}$$

If A is zero, the current produced in the terminating resistance will be

$$\frac{e}{2Z_0}$$

and when A is not zero, the current will be

$$\frac{e}{A+2Z_0}$$

so that the effect of the impedance A is to reduce the current in the ratio of $2Z_0/A+2Z_0$. It is found more convenient to work with the reciprocal of this ratio in which case k, representing the current ratio, is equal to

$$1+\frac{A}{2Z_0}$$

If now an equaliser section is constructed similar to that shown in Fig. 2 with a resistance B in place of the resistance A, and assume that the characteristic impedance is equal to that of the cable, i. e., Z_0, then it is necessary to determine the value of B so that the cable section shown in Fig. 2 and the equaliser section together will give a constant attenuation and time delay at all frequencies within the required predetermined range. With an equaliser section constructed in this manner, the current ratio

$$k'=1+\frac{B}{2Z_0}$$

Hence for proper equalisation, the product of k and k' must equal a constant

or

$$\left(1+\frac{A}{2Z_0}\right)\left(1+\frac{B}{2Z_0}\right)=\text{a constant}$$

or

$$1+\frac{A}{2Z_0}+\frac{B}{2Z_0}+\frac{AB}{4Z_0^2}=\text{a constant}$$

It has been assumed in the above considerations that a short length of cable is contemplated so that A and B are small quantities and hence the product of A and B is very small and can be neglected. Thus the conditions are that,

$$\frac{A}{2Z_0}+\frac{B}{2Z_0}=\text{a constant}$$

or $A+B$=constant.

Now the impedance of A is given by Equation 6 and if B is composed of a condenser C_1 shunted by a resistance R_1, its impedance will be

$$\frac{R_1(1-j\omega C_1R_1)}{1+\omega^2C_1^2R_1^2}$$

If $R_1=R$ and

$$C_1=\frac{L}{R^2}$$

the impedance of B is

$$\frac{R^3-jR^2\omega L}{R^2+\omega^2L^2}$$

Adding the impedance of B to the impedance of A a combined impedance equal to R is obtained. Hence $A+B$ is a constant and the requirement for correct equalisation is obtained.

Instead of employing an equaliser section of the form equivalent to that shown in Fig. 2 in which the resistance B is a small series quantity, let it be assumed that an equaliser of the form shown in Fig. 3 is employed which differs from the equaliser equivalent to Fig. 2, in that the resistance B is replaced by a resistance D, which

is a large shunt quantity. The current ratio for this type of section is

$$\frac{2D}{Z_0+2D}$$

or by taking the reciprocal as before

$$k''=1+\frac{Z_0}{2D}$$

If this section is to produce the same effect as the equaliser equivalent to Fig. 2, then $k'=k''$ or

$$1+\frac{B}{2Z_0}=1+\frac{Z_0}{2D}$$

Hence $BD=Z_0^2$.

The impedance of B is

$$\frac{R_1(1-j\omega C_1R_1)}{1+\omega^2C_1^2R_1^2}$$

and if D consists of a resistance R_2 in series with an inductance L_2, its impedance will be $R_2+j\omega L_2$. The product of these two impedances must be equal to Z_0^2, and the following conditions are therefore obtained:

$$\frac{L_2}{C_1}=R_1R_2 \text{ and } R_1R_2=Z_0^2$$

From the above it will be appreciated that it is possible to obtain the correct equalisation either by using a series impedance B or a shunt impedance D, and hence it is evident that the series impedance and the shunt impedance can be combined, as shown in Fig. 4, the series element comprising a condenser C_1 shunted by a resistance R_1 and the shunt element comprising a resistance R_2 in series with an inductance L_2.

In order that B and D shall give the required equalisation, it is necessary (*a*) that B should be small and D large, and (*b*) that they should work between impedances equal to Z_0. Let it be assumed that B is made infinitely small and D infinitely large, then the equaliser becomes, in effect a line with uniformly distributed constants. Its characteristic impedance will, therefore, be

$$\sqrt{BD}$$

But since $BD=Z_0^2$ the characteristic impedance of the uniformly distributed equaliser is equal to that of the cable and hence the requirement that the small elemental values of B and D should work between impedances Z_0 is satisfied.

The equaliser section so obtained will equalise the effect of one of the single inductance-resistance units described above so that one equaliser section of this type will be required for each of the inductance-resistance units. In Figure 1, for example, three such units are illustrated so that in this case three corresponding equaliser sections are required. The constants of the three equaliser sections will be different, but if they are designed in accordance with the above principles, they will each have the same characteristic impedance and can, therefore, all be connected in series without producing reflection effects. The composite equaliser formed, in this example, by joining together the three equaliser sections, would form an equaliser suitable for equalising a short length of the cable. Since the cable will have appreciable length, a number of these composite equalisers would be placed in series to build up a total equaliser having a length equivalent to that of the cable to be equalised.

In what has been said above in developing the conditions to be satisfied by the equaliser, the current ratios referred to were the complex ratios, and therefore, include both the attenuation and phase effects. It follows, therefore, that an equaliser designed in accordance with the above principles will equalise simultaneously both the attenuation and the phase of the cable. One of the assumptions made, however, was that the equaliser should consist of a large number of sections each equalising a very small length of cable so that the equaliser does, in effect, approximate to the case of an actual line in which the sections are infinitely finely distributed. Provided, therefore, that this condition of approximation to the infinitely finely divided sections is met the equaliser will equalise simultaneously both the attenuation and the phase of the cable.

Referring again to Fig. 1 of the drawing, it will be observed that three equaliser sections similar to that shown in Fig. 4 are associated with the conductors 1 and 2, these three sections corresponding in the example shown with the three units R_A, L_A, etc.; the number of equaliser sections actually employed depending on the degree of approximation required.

The artificial line comprises, as will be seen from Figs. 1 and 4, a plurality of series elements each comprising a condenser C_1 arranged in series with the line and shunted by a resistance R_1. Corresponding to each series element there is provided a shunt element comprising a resistance R_2 in series with an inductance L_2 the impedance of the shunt element with respect to the impedance Z_0 of the artificial line is the inverse of the series element to which it corresponds. The product of the impedances of the series element and the corresponding shunt element is then equal to Z_0^2 at all frequencies.

In constructing an artificial line for equalising a transmission line, the first step is to measure the attenuation and phase constants of the transmission line over the desired range of frequencies. The introduction of an artificial line will produce an attenuation equal to

$$\frac{R}{Z}\frac{1}{1+\omega^2T^2}$$

where R is the total resistance of the artificial line, Z is the impedance of the artificial line (the impedance about which the series elements are inverted to obtain the shunt elements) ω is the frequency in radians per second and T is the time constant of the condenser and resistance of the particular loading considered.

It is possible by trial and error to find a number of values of R and associated values of T which will give a total increase of attentuation at each frequency sufficient to bring the total attenuation of the artificial line and the transmission line to a desired degree of constancy over the required frequency range. The number of different elements (different values of C_1 R_1 etc.) required depends on the accuracy to which the attenuation is to be equalised.

The determination of values of R and T is most easily done by plotting a typical attenuation-frequency curve for the artificial line using logarithmic scales for attenuation and frequency. This typical curve is obtained by giving R/Z and T any desired value, for instance, unity. Since the curve is plotted to logarithmic scales a change in the value of R/Z only results in moving the curve bodily up or down and does not change its shape. Similarly, changing the value of T does not alter the shape of the curve but merely moves it sideways.

A curve is then plotted for the transmission

line with the same scales as before, the values of this curve being the attenuation at the top frequency, for which equalisation is required minus the attenuation at the individual frequencies. The curve for the artificial line is then superimposed on that of the transmission line and if transparent paper is used it is easy to see when the two curves coincide. In general, it will be found that good agreement can only be secured over part of the frequency range with one artificial line. The best fit is then obtained over the lower part of the frequency range. The amount by which the curves had to be moved vertically in order to secure agreement gives the value of R/Z for the desired artificial line while the amount they had to be moved horizontally gives the value of T. The attenuation for this first artificial line is then added to the curve for the transmission line giving a resultant curve which is flat over the lower frequency range where the artificial line curve was fitted to the transmission line curve, and which rises as before at the higher frequencies. The typical curve for the artificial line is now superimposed on this new curve and is made to fit over a range of frequencies next above the range fitted by the first artificial line. In this way a second artificial line is obtained which, when its attenuation is added to that of the previous artificial line and the curve used for the transmission line, gives a resultant curve which is flat still further up the frequency scale. By proceeding in this way a series of artificial lines is obtained which, when put in series with the transmission line, gives a substantially flat attenuation-frequency characteristic throughout the desired range. The various elements of each artificial line are then divided into sufficiently small portions to approximate to an infinitely distributed line. In one example it is found that the series resistances should not exceed

$$\frac{Z}{10}$$

A test which may be applied in order to ascertain whether the approximation to infinite distribution is sufficiently close is as follows:

One of the series elements is replaced by two elements which are similar to one another and, when connected in series with one another, are together electrically equivalent to the element which they replace. The original shunt element is also replaced by two shunt elements, one corresponding to each of the two series elements. The two series and two shunt elements are then connected to form two sections of a ladder network. The new attenuation of the line is then measured and compared with the attenuation before the sub-division. If no appreciable change is found, then the previous degree of approximation is sufficiently accurate and sub-division of the elements is unnecessary. When the artificial line approximates to infinite distribution the propagation constant is proportional to the sum of the impedances of the series elements.

It has been found that if the attenuation of a system is equalised by the above method, then the phase is simultaneously equalised. Alternatively, if the correcting artificial line is designed to produce an equalisation of phase, then the system will also have substantially constant attenuation.

If a line is being equalised for phase, it has been found most convenient to plot the total time of transmission of the cable and to design networks to reduce the transmission time down to the transmission time of the highest frequency to be considered. Correcting networks of the type described have apparent negative transmission times.

The equaliser section described with reference to Fig. 4 may be replaced by a section which is electrically equivalent thereto. Thus, it is possible that two adjacent series elements of the equaliser, comprising two resistances in series each shunted by a condenser, can, by a suitable choice of values be replaced, as shown in Fig. 5, by a condenser **4** in series with a resistance **5** and shunted by a condenser **6** and resistance **7** in parallel.

The resistance R_2 and inductance L_2 of Fig. 4 may, of course, be disposed at the left-hand side of the series element, as shown in Fig. 6 without affecting the characteristics. In addition, the sections can be converted to sections of the T-type as shown in Fig. 7, or of the π type, as shown in Fig. 8. The arrangement of the components of the sections in these last two mentioned figures will be clearly appreciated without further description whilst the values of the components compared with the values of the components of the section shown in Fig. 4 being indicated by the numerical prefixes. It will also be understood that by employing one of these types of section in conjunction with another type for an adjacent section, it is possible to combine some of the elements of the sections so as to obtain a different type of section.

It will be evident from the description of the above embodiment of the invention that the equaliser undergoes two forms of subdivision. Initially, the equaliser is divided into small sections so that the errors in fitting the attenuation curve are not of practical importance, such subdivision being a comparatively coarse one. The sections are subsequently divided more finely in order that the equaliser may approximate to the infinitely distributed case, in which event the phase and attenuation of the cable are simultaneously equalised.

It has been found, however, that for certain cases it is possible to obtain simultaneous equalisation of phase and attenuation of a cable with much larger sections of equaliser than those required to approximate to the case having infinitely distributed constants. These cases are when the cable attenuation varies either as a direct function of the frequency or as a direct function of the square root of the frequency, the phase of the cable following the appropriate corresponding law. In these cases, the extent to which the equaliser sections have to be sub-divided depends merely on the practical consideration of obtaining a good fit of the equaliser sections to the attenuation curve of the cable. If this fit is obtained to the required degree of accuracy, then for the two cable loss laws quoted above the phase of the cable will also be satisfactorily equalised.

It has been shown above that if the equaliser is so sub-divided that it approximates closely to the infinitely distributed case, then the impedance will be independent of frequency and will be equal to Z_0. If, however, the sections do not approximate to the infinite distribution, as is contemplated in accordance with a further embodiment of the invention, that is to say, when the attenuation varies either as a direct function of the frequency or as a direct function of the square root of the frequency, it has been found that the characteristic impedance of the equaliser

varies with frequency and is only equal to Z_0 at very high frequencies. If, therefore, the equaliser is terminated with a constant impedance Z_0, this termination will not be found correct over most of the frequency range resulting in reflection, and the attenuation and phase curves of the equaliser will differ from the theoretical curves calculated on the assumption of a correct termination and will thus give rise to difficulties in the design of the equaliser.

It is, therefore, a further feature of the invention to provide an improved form of termination for this further embodiment of the invention so that the attenuation and phase curves actually obtained for the equaliser are substantially the same as those theoretically calculated for it. It has been found that the characteristic impedance of the type of equaliser above referred to can be represented to a close degree of accuracy over the whole frequency range by the network shown in Fig. 9 which is employed to terminate the equaliser consisting of a shunt element composed of resistances A and B in series, the resistance A being shunted by a condenser K where,

$$B=Z_0$$

$$A=\frac{k-1}{2\sqrt{k}}Z_0$$

$$kA=R_1C_1=\frac{L_2}{R_2}$$

and k represents the current ratio at zero frequency of the equaliser sections.

According to another feature of the invention, instead of employing the "artificial line" type of equaliser described above use is made of a constant resistance type of equalizer section. These sections are identical with the sections shown in Fig. 4, with the exception that in order to obtain a constant resistance an additional resistance equal to Z_0 (i. e. a resistance substantially equal to the characteristic impedance of the cable) is inserted in parallel with the resistance R_1 as shown in Fig. 10. If, in this case, the equaliser is terminated by a constant impedance equal to Z_0, it will be found that the input impedance is substantially constant and equal to Z_0 at all frequencies within a predetermined range. It will of course be appreciated that other forms of constant resistance section can be employed.

It has been found that in order to obtain the optimum fit of the equaliser curves to the cable attenuation curve, in the case contemplated according to the further embodiment of the invention, that is to say, where the cable attenuation varies directly with the frequency or directly with the square root of the frequency, the equaliser sections in accordance with another feature of the invention, are centred at successive frequencies which correspond to equal increments of loss on the cable attenuation-frequency curve. It will be appreciated that the attenuation of a single equaliser section has a maximum value at zero frequency and gradually falls to zero as the frequency rises. At some frequency the attenuation will have fallen to half its maximum value and this frequency is conveniently referred to as "the centre frequency". Thus, in accordance with this last mentioned feature of the invention, an equalised section is centred at a predetermined frequency by adjusting the time constant of the section so that at the predetermined frequency the loss of the section has fallen to half its maximum value.

To take an example, suppose that a certain section is centred at a frequency f_1 and that the corresponding cable loss at that frequency is L_c db; then the next higher section will be centred at a frequency f_2 which corresponds to a cable loss of L_c plus x db. The next higher section will be centred at a frequency f_3 corresponding to a cable loss of L_c plus $2x$, and so on. The value of x has been calculated for the constant resistance type of equaliser section referred to above and it is found that the ideal value of x is

$$x=\frac{\pi}{2}\frac{k-1}{k}$$

for a cable loss varying directly with frequency and

$$x=\frac{\pi}{\sqrt{2}}\frac{\sqrt{k}-1}{\sqrt{k}}$$

for a cable loss varying directly as the square root of the frequency. In these expressions k is the current ratio corresponding to the zero frequency attenuation of the equaliser section.

It is found that the attenuation curve of a cable can, over the greater part of the frequency range, be represented as the sum of two terms, one proportional to frequency and the other proportional to the square root of frequency. It is, therefore, possible to design two equalisers using the spacing factors x given above one equaliser equalising the attenuation which varies with frequency and the other attenuation which varies with the square root frequency. By combining these two equalisers it is possible to obtain a single equaliser which will simultaneously equalise the attenuation and phase of the cable while not requiring to be so finely divided that it approximates to the infinitely distributed case. It will be appreciated that the centering of the section of the composite equaliser so formed, will at any part of the frequency range depend on the proportion of the two terms mentioned above, and the spacing will, therefore, vary. Over the lower portion of the frequency range the attenuation varies as the root of frequency whilst at the higher frequncies a term directly proportional to frequency becomes progressively prominent. At the low frequencies, therefore, the spacing of the section is substantially constant as stated above, but at the higher frequencies the spacing of the sections progressively increase.

Whilst it is necessary that the sections of the equaliser should over the greater part of the frequency range, be of the type described in Fig. 4, or their electrical equivalents, it is, nevertheless, possible, in accordance with another feature of the invention to obtain a reduction in the total number of sections required in the equaliser by employing for these sections operating at the highest part of the frequency range, a different type of section. A section of this type is shown in Fig. 11 in which the series element consists of a resistance R_1 in parallel with a condenser C_1 and an inductance L_3 in series whilst the shunt element consists of an inductance L_2 and a resistance R_2, the inductance L_2 being shunted by a condenser C_2. This type of section differs from the artificial line type above described in that the inductance L_3 is provided in series with the condenser C_1 and the condenser C_2 is also added in shunt with the inductance L_2. The values of C_2 and L_3 are chosen so that at a predetermined frequency C_2 resonates with L_2 and L_3 with C_1. The effect of these added components is to cause the attenuation curve of the equaliser section to fall off more

rapidly over a part of the frequency range up to the resonant frequency so that the same rate of change of attenuation can be obtained with one section of this type that could be obtained with a large number of the normal type. This increase in slope is only effective over about one octave of the frequency range below the resonant frequency and the effect of the additional inductance and condenser above the resonant frequency is to make the equaliser curve rise again instead of falling, and hence this type of section can only be used for the highest frequencies, it being arranged that the resonant frequency coincides with or is above the maximum frequency at which equalisation is required so that the rise in the equaliser curve above-mentioned occurs beyond the frequency range for which equalisation is to be effected.

In some cases it may be necessary to transmit signals, such as television signals, along a cable from a number of alternative tapping points, and in this event the equaliser at the end of the cable must be capable of adjustment to suit the different lengths of the cable due to the different tapping points. For example, it may be required to have an equaliser which can be adjusted to equalise any length of cable from a quarter to seven-and-three-quarter miles in quarter-mile steps. In this case, it is possible to design equalisers for a quarter, half, one, two and four miles, and by employing one or more of these sections together, the necessary number of equalisers can be obtained. Since no equaliser is quite perfect, there will inevitably be small humps in the equaliser curves and when a number of these equalisers are employed in conjunction with one another, the random addition of the humps may give rise to inconveniently large humps in the overall curve. The fact, however, that it is advantageous to space the equaliser sections at frequencies corresponding to equal increments on the cable loss curves, enables this difficulty, due to connecting the different equalisers in series, to be substantially overcome. Assume that an equaliser is designed for an eight mile length of cable and the sections have to be centred at frequencies f_0, f_1, f_2, f_3, f_4, f_5, etc., these frequencies corresponding to equal increments of x db. on the attenuation curve for a cable eight miles long. If, now, a cable four miles long is contemplated it will be apparent that at each frequency the loss is exactly half that of the eight mile section. The sections of the equaliser must, however, still be centred at frequencies corresponding to equal increments of x db. on the cable attenuation curve and it follows, therefore, that there will only be half as many equaliser sections as before. In fact, it is possible to obtain the correct equaliser for a four-mile section by omitting every other section of the equaliser which is necessary for the eight-mile section. In the same way the correct equaliser for a two-mile section can be obtained by omitting every other section from a four-mile equaliser, and so on. By spacing the equaliser sections at frequencies corresponding to equal increments of loss on the cable loss on the cable loss curve, it is possible to obtain a range of equalisers for different lengths of cable such that they can be connected together to equalise still further lengths without causing the addition of errors in the individual equalisers which would otherwise occur.

The above-described method of correction does not remove the reduction of velocity at low frequencies due to the Heaviside condition not being satisfied. This low frequency effect can be eliminated by inserting series capacity loading as described in the specification of British Patent No. 455,492. Since the characteristic impedance of a series capacity loaded cable is that of a condenser in series with a resistance, it is not possible to insert the artificial lines, the characteristic impedance of which is a pure resistance, at intermediate points in the line. The artificial line may be connected to the transmission line through a condenser equal to the series capacity of the transmission line, the characteristic impedance of the artificial line being equal to the resistive term of the characteristic impedance of the transmission line. The line is thus correctly terminated. Alternatively, the artificial line may be connected in a repeater between two sections of the transmission line.

So far it has been assumed that the capacity of the transmission line was constant and its leakance negligible. In actual practice it is found that the capacity of the line tends to fall as the frequency rises while the leakance rises with frequency and at the higher frequencies cannot be neglected. The reason for these changes is that the dielectric of the transmission line is not perfect so that the capacity of the line, instead of being a pure capacity, behaves as though it were a complicated network of condensers and resistances in series-parallel arrangement. Now it is a feature of the artificial line of this invention that, in addition to equalising the variations in attenuation and phase due to the changes in resistance and inductance of the transmission line, it is capable of equalising the variations brought about by the changes in capacity and leakance. In fact if the procedure outlined above for designing the artificial lines is followed all variations whether due to resistance and inductance or capacity and leakance will be equalised and, provided the type of artificial line described above is used, variations in both attenuation and phase will be simultaneously equalised.

Partial equalisation at high frequencies may also be obtained in the manner described in the aforesaid specification, final equalisation according to the present invention then being applied.

In practice it may be found convenient where the transmission line or cable feeds into a repeater or amplifier to connect the equaliser sections either on the input or output side of the amplifier. For example, the cable may feed directly into one amplifier stage between which and a further amplifier stage an equaliser section is provided additional equaliser sections being provided between additional amplifier stages.

We claim:

1. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, and a plurality of equaliser sections all connected in series with said line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, said elements being substantially different for different sections as to time constant and magnitude of the components and being so chosen as to substantially and simultaneously compensate for the greater part of said variations.

2. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, means for introducing said signals into said transmission line, and a plurality of equaliser sections all connected in series with said line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, said resistance of said series element being small compared with said resistance of said shunt element, the time constant and the magnitude of the components of said elements being substantially different for different sections and being so chosen as to substantially and simultaneously compensate for the greater part of said variations.

3. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, and a plurality of equaliser sections all connected in series with said line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, said resistance of said series element being small compared with said resistance of said shunt element, said elements being substantially different for different sections as to time constant and magnitude of the components and being so chosen as to substantially and simultaneously compensate for the greater part of said variations within a selected portion of said line.

4. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, and a plurality of equaliser sections all connected in series with said line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, said elements being substantially different for different sections as to time constant and magnitude of the components and being so chosen as to substantially and simultaneously compensate for the greater part of said variations, the number of said sections being chosen so as to approximate substantially an infinitely fine distribution of said sections.

5. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, up to and including television range, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, and an artificial line connected to said transmission line and comprising a plurality of equaliser sections all in series with said transmission line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, the time constant and the magnitude of the components of said elements being substantially different for different sections and being so chosen that the total of the variations of attenuation and phase delay, causing distortion of said artificial line and of said transmission line together are zero to a desired substantial degree.

6. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, up to and including television range, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay resulting in distortion of said signals, means for introducing said signals into said transmission line, and an artificial line connected to said transmission line comprising a plurality of equaliser sections all in series with said line, said sections comprising a series element and a shunt element, said series element composed of resistance shunted by capacity, said shunt element composed of inductance in series with resistance, said elements being substantially different for different sections as to time constant and magnitude of the components and being so chosen that said sections form constant resistance sections and the total of the variations of attenuation and phase delay, causing distortion of said artificial line and of said transmission line together are zero to a desired substantial degree.

7. A system for transmitting electric signals of frequencies within a given substantial range, comprising a transmission line, of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby producing variations of attenuation and phase delay resulting in distortion of said signals, said variations of attenuation comprising the sum of a pair of terms, one of said terms varying substantially as the square root of said frequency, the other varying substantially directly as said frequency, and two equalizers composed of equaliser section groups connected all in series with said line, the components in one of said groups being substantially different for different sections and being so chosen that the greater part of the variation corresponding to said term varying as the square root of frequency is compensated, the components in the other of said groups being substantially different for different sections and being so chosen that the variation corresponding to said other term is substantially compensated, and that the variations of phase delay causing distortion are substantially compensated simultaneously.

8. A system for transmitting electric signals of frequencies within a given range, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby producing variations of attenuation and phase delay resulting in distortion of said signals, said variations of attenuation comprising a term varying substantially as the square root of said frequency, and a group of equalizer sections connected in series with said line, the components of said group being so chosen that the attenuations of said sections fall to half at predetermined frequencies within said range, said latter frequencies being arranged at substantially equal

increments of attenuation on the curve representing said term varying as the square root of said frequency.

9. A system for transmitting electric signals of frequencies within a given range, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby producing variations of attenuation and phase delay resulting in distortion of said signals, said variations of attenuation comprising a term varying substantially directly as said frequency, and a group of equaliser sections connected in series with said line, the components of said group being so chosen that the attenuations of said sections fall to half at predetermined frequencies within said range, said latter frequencies being arranged at substantially equal increments of attenuation on the curve representing said term varying directly as said frequency.

10. A system for transmitting electric signals of frequencies within a given range, comprising a transmission line, of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby producing variations of attenuation and phase delay resulting in distortion of said signals, said variations of attenuation comprising the sum of a pair of terms, one of said terms varying substantially as the square root of said frequency, the other varying substantially directly as said frequency, and two groups of equaliser sections connected all in series with said line, said equaliser sections comprising series and shunt elements, said series elements composed substantially of resistance shunted by capacity, said shunt elements composed substantially of inductance in series with resistance, the components in one of said groups being substantially different for different sections and being so chosen that the greater part of the variation corresponding to said term varying as the square root of said frequency is substantially compensated, the components in the other of said groups being substantially different for different sections and being so chosen that the variation corresponding to said other term is substantially compensated, and that the variations of phase delay causing distortion are substantially compensated simultaneously.

11. A system for transmitting electric signals comprising a transmission line of the type as exemplified by a cable, the attenuation of which can be represented by the sum of two terms, one proportional to frequency and the other proportional to the square root of frequency, and a plurality of equalizer sections, said equalisers being of the constant resistance type, the spacing of said sections correspond to x increment of loss on the attenuation curve of said line the value of x for that part of the attenuation which varies directly with frequency being substantially equal to,

$$\frac{\pi}{\sqrt{2}}\frac{k-1}{k}$$

and for that part of the attenuation which varies as the square root of frequency the value of x is substantially equal to,

$$\frac{\pi}{\sqrt{2}}\frac{\sqrt{k-1}}{\sqrt{k}}$$

where k is a current ratio

$$1+\frac{A}{2Z_0}$$

and A represents the total series-impedance of the respective equalizer section and Z_0 the characteristic impedance of said line.

12. A system for transmitting electric signals of a range including lower and higher frequencies, comprising a transmission line of the type as exemplified by a cable, the attenuation of which varies substantially as the square root of the frequency range within said lower frequency range and more rapidly within said higher frequency range, and a plurality of equalizer sections, said sections equivalent to, and including, series elements and shunt elements, said series elements substantially composed of resistance shunted by capacity, said shunt elements substantially composed of inductance in series with resistance, part of said sections arranged for compensating said transmission line as far as its attenuation varies substantially as the square root of the frequency and the other part of said sections arranged for compensation of higher frequencies, the impedance and time constant of said first part of sections being adjusted so that their attenuations fall to about half of their maximum value at frequencies corresponding substantially to equal loss increments on the attenuation-frequency curve of said transmission line within said lower frequency range, the impedance and time constant of said other part of sections being adjusted so that their attenuations fall to about half of their maximum values at frequencies corresponding to progressively increasing loss increments on the attenuation-frequency curve of said transmission line within said higher frequency range.

13. A system for transmitting electric signals comprising a transmission line of the type as exemplified by a cable, the variation of attenuation of which with frequency causing distortion of said signals can be represented by the sum of two terms, one proportional to frequency and the other to the square root of frequency, and two groups of equalizers, each composed of sections centered at frequencies corresponding substantially to equal loss increments of attenuation with respect to one of said turns, one of said groups adjusted so as to substantially equalize the attenuation of said line which varies directly with frequency, the other of said groups adjusted so as to substantially equalize the attenuation which varies as the square root of frequency.

14. A system as described in claim 10, wherein the components of a group of equalizer sections are so chosen that the attenuations of said sections fall to half at predetermined frequencies within said range, said latter frequencies being arranged at substantially equal increments of attenuation on the curve representing the term to be compensated by the group.

15. A system for transmitting electric signals of frequencies within a given range, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby producing variations of attenuation and phase delay resulting in distortion of said signals, said variations of attenuation in the lower frequency portion of said range approximating to a variation as the square root of frequency, and a plurality of equalizer sections connected in series with said line, said equalizer sections comprising series and shunt elements, said series elements composed substantially of resistance shunted by capacity, said shunt elements composed substantially of inductance in series with resistance, the components of said sections being so chosen that the

attenuations of said sections fall to half at predetermined frequencies, said latter frequencies being arranged on the curve representing the variation of attenuation at substantially equal increments of attenuation within said lower portion of said range, and at progressively increasing increments of attenuation in the higher frequency portion of said range, so as to substantially and simultaneously compensate said variations of attenuation and phase delay.

16. In a system as described in claim 1, in which the equalizer sections possess an image impedance which varies with frequency, an impedance arranged for terminating said sections, said impedance consisting of a resistance in series with a further resistance, said latter resistance shunted by a condenser.

17. A system for transmitting electric signals of frequencies within a range covering at least about 100 kilocycles, comprising a transmission line of the type as exemplified by a cable, having its primary constants varying with frequency within said range, thereby causing variations of attenuation and phase delay so as to cause distortion of said signals, means for introducing said signals at a number, including one, of points along said line spaced from its ends, and a plurality of equalizers, each equalizer possessing a plurality of equaliser sections, the elements of the sections being substantially different for different sections and being so chosen that each equaliser equalises an associated substantial length of line so that the distortions of said signals injected at said point, due respectively to said variations of attenuation and phase delay, are substantially and simultaneously equalised.

18. A system for transmitting electric signals, comprising a transmission line of the type as exemplified by a cable, the variation of attenuation of which with frequency causing distortion of said signals can be represented by the sum of two terms, the first of said terms proportional to frequency of said signals and the second of said terms proportional to the square root of said frequency, and two groups of equaliser sections, the components of one of said groups being substantially different for different sections and adjusted so as to substantially equalise the attenuation represented by said first term, the components of the other of said groups being substantially different for different sections and adjusted so as to substantially equalise the attenuation represented by said second term.

19. A system for transmitting electric signals, comprising a transmission line of the type as exemplified by a cable, the variation of attenuation of which with frequency causing distortion of said signals can be represented by the sum of two terms, the first of said terms proportional to frequency of said signals and the second of said terms proportional to the square root of said frequency, and two groups of equaliser sections, the components of one of said groups being substantially different for different sections and adjusted so as to substantially equalise the attenuation represented by said first term, the components of the other of said groups being substantially different for different sections and adjusted so as to substantially equalise the attenuation represented by said second term, all of said sections being of the constant resistance type, and those in said group equalising the attenuation represented bys aid first term being centred at frequencies corresponding to increments in said first term substantially equal to

$$\frac{\pi}{2}\cdot\frac{k-1}{k}$$

while those in said group equalising the attenuation represented by said second term are centred at frequencies corresponding to increments in said second term substantially equal to

$$\frac{\pi}{\sqrt{2}}\cdot\frac{\sqrt{k}-1}{\sqrt{k}}$$

wherein k is a current ratio

$$1+\frac{A}{2Z_0}$$

and A represents the total series-impedance of the respective equaliser section and Z_0 the characteristic impedance of said line.

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