Fig. 7.

Fig. 8.

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

In a transmission line having distributed resistance, inductance and capacity the propagation constant \( P \) is given by

\[
P = \sqrt{(R + j\omega L)j\omega C}
\]

where \( R, L \) and \( C \) are the resistance, inductance and capacity per unit length of the line respectively and \( \omega \) 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.

When \( \omega \) has a high value so that \( \omega L \) is much greater than \( R \) the propagation constant \( P \) is given by

\[
P = j\omega \sqrt{LC} + \frac{R}{2}\sqrt{\frac{C}{L}} \text{ approximately}
\]

In this equation

\[
\omega \sqrt{LC}
\]

represents the wave length constant and is denoted by \( \beta \) and since the wave velocity \( W \) is given by

\[
W = \frac{\omega}{\beta}
\]

in this case we have

\[
W = \frac{1}{\sqrt{LC}}
\]

The wave velocity \( W \) is therefore independent of frequency. Further, the second term in the expression for \( P \) in Equation 1 denotes the attenuation constant which is also independent of frequency. The line is therefore distortionless, when \( \omega \) is large.

Equation 1 however, can only be applied when \( \omega \) has a high value. If \( \omega \) is small it is found that both the wave velocity and the attenuation constant are functions of \( \omega \) and the line is, therefore, not distortionless. The variation of wave velocity and attenuation constant with \( \omega \) at low frequencies will be termed the low frequency effect.

Even when \( \omega L \) is large compared with \( R \), there is another effect which may introduce distortion. This is the change of the so-called cable constants \( L \) and \( R \) at high frequencies due to the skin effect. A change of these constants with frequency introduces changes in the propagation constant with frequency and distortion results. This will be called the high frequency effect.

It is an object of the present invention to provide a new or improved electric transmission system for transmitting electric currents extending over a wide band of frequencies, said system comprising a transmission line wherein, distributed along the length of the line, there are provided impedance elements of such nature and magnitude and so connected and arranged as to increase the attenuation of said transmission line over a substantial part of said band of frequencies and to render the attenuation and wave velocity of said transmission line substantially constant over said band of frequencies.

The invention will now be described by way of example with reference to the accompanying diagrammatic drawings in which

Fig. 1 shows a transmission system according to the invention.

Figs. 2 to 5 show details of various arrangements according to the invention for equalizing a cable.

Fig. 6 shows an alternative arrangement according to the invention of the cable termination shown in Fig. 1, and

Figs. 7 and 8 are explanatory figures showing graphs which will be referred to in the course of the following description.

Reference is first directed to Fig. 2 of the drawings, in which a transmission line is shown as having two conductors 1 and 2. The series resistance of the line is denoted by \( R \) and the series inductance by \( L \). For convenience, series impedances in the line are shown in one conductor only. In practice the series impedances are distributed between the two conductors but if \( R \) and \( L \) denote the total resistance and inductance per unit length the distribution between the conductors does not affect the calculations. The shunt capacity of the line is denoted by \( C \) and the shunt leakance by \( G \). It will first be assumed that \( G \) is so small that it can be neglected.

The components \( L, R, G, C \), representing the cable constants are enclosed in a dotted rectangle 3 in order to distinguish them from added loading impedances.

The low frequency effect may then be sub...
stantially eliminated by inserting series capacity denoted by $C'$ in each unit length of the line. The effective series impedance term for the line then becomes

$$R + j\omega L + \frac{1}{j\omega C'}$$

If $C'$ is made equal to

$$\frac{4L}{R^2}$$

then the series impedance becomes

$$R + j\omega L + \frac{R^2}{4j\omega L}$$

which equals

$$j\omega L \left(1 + \frac{R}{2j\omega L}\right)^2$$

The propagation constant $P$ is now given by

$$P = \sqrt{j\omega L \left(1 + \frac{R}{2j\omega L}\right)^2}$$

There is a term equal to

$$\frac{j\omega\sqrt{LC} \left(1 + \frac{R}{2j\omega L}\right)}{2\sqrt{L}}$$

The wave velocity and attenuation are then constant for all frequencies even when $\omega$ is small as well as large provided $L$, $C$, $C'$ and $R$ are independent of frequency.

The characteristic impedance of the line then becomes

$$\sqrt{\frac{L}{C} \left(1 + \frac{R}{2j\omega L}\right)} = \sqrt{\frac{L}{C} + \frac{R}{2\sqrt{LC}}}$$

which is an expression for the impedance of a condenser and resistance in series.

In practice it is usually necessary to arrange the series condensers at intervals, which intervals are preferably short compared to the wavelength, at the frequency for which $\omega L = R$. For example a required loading of 1 microfarad kilo-ohm may be made up by introducing condensers every half kilometre. For a concentric line the condensers can be introduced in series with the central conductor, the above loading requiring 2 microfarads every half kilometre. For a balanced line the condensers are preferably put in each conductor, e.g., 4 microfarads in each conductor every half kilometre. For lines without added inductance loading, spacings between the condensers greater than a kilometre may be satisfactory.

If $G$ is not so small as to be negligible, then it is necessary to shunt the capacity $C'$ by a leakance $G'$. It can be shown that the ideal values of $C'$ and $G'$ are as follows

$$C' = \frac{R}{2\sqrt{LC}}$$

$$G' = \frac{G}{2\sqrt{LC}}$$

It may then be shown that the propagation constant is given by

$$P = j\omega\sqrt{LC} + \frac{R}{2\sqrt{L} + \frac{G}{2\sqrt{C}}}$$

and the characteristic impedance $Z$ of the line is given by

$$Z = \sqrt{\frac{L}{C} + \frac{R}{2\sqrt{L} + \frac{G}{2\sqrt{C}}}$$
condensers being shunted by resistances $R_1, R_2, R_3$ respectively. The values of the condensers $C_1, C_2, C_3$ are given by the equations $C_1=\frac{R_1}{C_2}$, $C_2=\frac{R_2}{C_3}$, $C_3=\frac{R_3}{C_1}$. A capacity-resistance circuit is included to correspond to each of the inductance-resistance circuits into which the circuit constants have been analysed.

The inclusion of the condenser-resistance circuits renders the resistance of the line invariant with frequency and equal to $R_1+R_2+R_3$ and the inductance term is also invariant with frequency and equal to $L$. This represents the frequency range within which the circuits enclosed in the dotted rectangle accurately represent the effective resistance and reactance of the line. The effect of this capacity-resistance lodgment is to produce a line with substantially constant inductance, resistance and capacity at all frequencies within the range over which the circuits considered represent the constants of the cable.

Since the attenuation of a line equalized in the manner described above may be considerable, it is necessary to provide amplifiers at intervals along the length of a long line. In practice it is sometimes found desirable to introduce attenuation and velocity equalization up to a frequency which is somewhat lower than the highest frequency which the line is required to handle. Correction is then provided in the amplifiers for the increasing attenuation and falling velocity between the frequency up to which the line has been corrected and the highest frequency to be handled.

For example, if the cable constants can be represented to a desired degree of accuracy up to a frequency $f$ by considering only two resistance-inductance circuits $R_1, L_1$ and $R_2, L_2$ and if it would be necessary to consider a third circuit $R_3, L_3$ in order to represent the constants up to the highest frequency $f_0$, to which it is desired to operate the line, then the line may be equalized up to frequency $f$ by including two capacity-resistance circuits $C_1, R_1$ and $C_2, R_2$. The resistance of the line for frequencies up to $f$ is then $R_1+R_2+R_3$ and above frequency $f$ the resistance rises from this value to $R_1+R_2+R_3+R_4$ at frequency $f_0$. Similarly the inductance has a value $L_1+L_2$ at frequencies up to $f$ and a value $L_3$ at frequency $f_0$.

By not equalizing to the top frequencies, the noise in the middle frequency range (due to Johnson noise and valve noise in amplifiers) is reduced and also loading at very short distances is avoided. On the other hand, the complexity of the amplifiers is increased. It may be found in practice that it is more economical to load the cable to substantially constant attenuation and velocity over the entire range and to reduce the repeater distances slightly to allow for the increased noise. It must be realized that the three resistance-inductance circuits shown representing the variable cable constants, are given by way of example, and the cable covering a very wide range may require many more circuits to represent it to a particular desired degree of accuracy.

Similarly, the type of capacity-resistance loading shown need not necessarily be adhered to. When two different types of loading are inserted at any point, the equivalent electrical network to two condensers in series each shunted by a resistance may be used. For example, one condenser shunted by a resistance, the whole being shunted by resistance and condenser in series, can by the proper choice of values, be made identically equal to two of the circuits shown in Fig. 3. There are many other possible equivalent circuits which provide the same impedance with a physically different arrangement of inductance and condensers. Such equivalent circuits are well known in the art and an example of four such equivalent circuits are shown on page 278 of "Transmission Circuits for Telephonic Communication" by K. S. Johnson, second printing, published by the D. van Nostrand Company, Inc.

It may in many cases be found more convenient not to calculate the values of $R_1, L_1$ etc., at all, but to proceed directly to the determination of the values for $R_1, C_1$ etc. This may most conveniently be done by measuring in well known manner the primary constants of the cable over the required frequency range.

Referring to Fig. 7, curve a represents a series resistance of a smooth line, measured experimentally, and plotted with respect to frequency, over the frequency range zero to $f_0$. Then in order to equalize the attenuation the design line over this frequency range, it is required to provide loading means the resistance of which varies with respect to frequency as shown by curve b. The resistance of the loaded line over the frequency range zero to $f_0$ will then be $R_0$.

The required loading when determined experimentally is determined as follows: By plotting to the same scale as that of curves a and b the variation with frequency of the resistance of a circuit comprising a resistance and condenser being determined experimentally, the curve $c$ can be obtained.

Assuming that this circuit is connected in series in the line; then the resistance-frequency characteristic of the loading which is still required is shown by curve $d$, which is obtained by subtracting curve $c$ from curve $b$.

From curve $d$, it is clear that the introduction of the resistance-capacity circuit whose frequency characteristic is represented by the curve $c$ has had the effect of rendering the attenuation of the line substantially uniform up to the frequency $f_1$, this frequency being lower than $f_0$.

Referring now to Fig. 8, a further resistance-capacity circuit is designed having a frequency characteristic shown by curve $e$. This circuit is also connected in series in the line, and the frequency characteristic of the loading still required is given by curve $g$, which is obtained by subtracting curve $e$ from curve $d$ of Fig. 7. The introduction of this second resistance-capacity circuit results in an approximate equalization of attenuation up to the frequency $f_3$ lying between the frequencies $f_1$ and $f_0$.

Similarly, a third resistance-capacity circuit is designed and connected in series in the line, this third circuit being designed to have a frequency characteristic shown by curve $h$, which is obtained by subtracting curve $c$ from curve $b$ of Fig. 7. The addition of this third resistance-capacity circuit results in an approximate equalization of attenuation up to the frequency $f_4$.

If it be required to equalize the attenuation of the line up to a frequency greater than $f_4$, one or more further series circuits, designed in the manner set out above, are connected in series in the line.

The addition of condensers and resistances such as $C_1, R_1, C_2, R_2$ and $C_3, R_3$ increases the inductance of the cable at low frequencies, and increases the magnitude of the low frequency effect. It therefore becomes important, if satisfactory working at low frequencies is required.
to correct for this low frequency effect. In Fig. 2 the series condenser $C'$ which is used as already described for correcting for the low frequency effect must have a value

$$C' = \frac{4L}{(R + R_i + R_i)^2}$$

If the values used in this equation are the values per kilometre, value of capacity shown is that of the condenser which must be used if the loading is introduced once every kilometre. For shorter distances of loading, a larger condenser is necessary. The unit for the introduction of capacity in series is really of the form

$$\frac{1}{\text{farad}}$$

per unit length. Thus if the cable is to be loaded at $n$ points per kilometre, the condensers must have capacities $n$ times the value of $C'$ as given by the last equation above. Similarly, if $C_i$, $R_i$ circuits are inserted at $n$ points per kilometre, the condensers and resistances must have magnitude

$$mC_i \text{ and } \frac{R_i}{m}$$

respectively. If in the original loading unit $C_i$, $R_i$ was not included, then $R_i$ must be omitted from the equation above, giving $C'$. If there is any leakage at low frequencies in parallel with the capacity of the cable, this can be allowed for by modifying the value of $C'$ and shunting it with a suitable leakage $G'$ as already described. It will be noted that when

$$\frac{R}{L} = \frac{C}{G},$$

the added series capacity becomes infinite, i.e., no added capacity is required. It should also be noted that an added condenser shunted by a resistance will correct for a cable where the leakage loss exceeds the series resistance loss. The characteristic impedance in this case, however, is inductive at the low frequencies.

It must be borne in mind that high frequency correction can be applied without low frequency correction and that low frequency correction can be applied without high frequency correction. The magnitude of the low frequency correction however depends on whether any high frequency correction has been introduced, since high frequency correction alters the low frequency resistance of the cable.

In cables for operating up to very high frequencies (several megacycles per second for example) there may be a certain amount of conductance or dielectric loss, which increases the attenuation of the cable at high frequencies. The dielectric loss may be allowed for by considering it as an increase of effective series resistance, producing the same attenuation, and designing the capacity-resistance loading circuits accordingly. An increase of effective conductance, the two effects producing a change of attenuation and velocity analogous to that produced by the change of resistance due to skin effect. The introduction of suitable loading of the type used to neutralise resistance inductance change is also effectively in equalising the effect of capacity conductance change.

The distances between the loadings depend on the frequency range corrected by the elements considered. The capacity-resistance circuits with a long time constant can be separated at wider distances along the cable than capacity-resistance circuits with a short time constant, and similarly the $C'$ condenser can be put at yet longer spacings. This type of loading is well worth considering when there is a short cut-off frequency, since the value of the loading impedance falls with increase of frequency instead of rising as with series inductive loading. In general, the loadings should be spaced so that for a given type of loading the added impedance of the loading is small compared with the characteristic impedance of the circuit at frequencies where the distance between loadings represents a quarter wavelength. For example, the impedance of the loading should certainly not exceed say 10% of the characteristic impedance of the cable for a frequency at which a quarter wavelength occupies the distance between two such loadings.

The optimum loading distances depend upon the smoothness of an attenuation-frequency characteristic required, and can be determined by trial and error. For this purpose it is possible to calculate an equivalent T network representing the unloaded cable between two loads. To each of the two cross branches of the T the impedance of half a load is added. The propagation constant of the T with the additional half loadings can then be calculated, and this compared with the propagation constant deduced for a smoothly distributed loading. Such calculations can be repeated at a number of frequencies and will indicate the departure of the attenuation from that predicted for smooth loading. Any irregularities in attenuation and velocity will be apparent and if these are not within the required limits the distances between loadings must be reduced.

It will be found convenient to make the loading distances for the lower frequency corrections a multiple of the loading distances for the highest frequency correction, since this will mean the minimum number of breaks in the cable. Incidentally, if a single capacity-resistance circuit does not adequately correct the cable in a given part of the frequency range, two slightly dissimilar circuits can be used and put in at alternate loading points. Other similar modifications are possible.

The extra capacity of the condensers and resistances to earth at the loading point may be corrected for by adding small series inductances on each side of them, or in the case of a balanced circuit the added mutual capacity of the loadings of the two wires may be corrected similarly. The value of the total inductance added will be given by $cZ$, where $c$ is the added capacity and $Z$ the impedance of the cable. The added stray capacity however, must be kept so small that the added capacity with correcting inductances forms a filter with a cut-off well above the working frequency.

For aerial cables, or cables subject to large variations of temperature, the attenuation-frequency characteristic of the cable will alter with temperature unless the loading components are altered suitably with the temperature of the cable.

Assuming the cable conductors to have a temperature coefficient $\alpha$, then added resistances $R_i$, $R_i$, etc. are also given a temperature coefficient of $\alpha$, and if the loading capacities are given a temperature coefficient of $-2\alpha$, the shape of the equalised attenuation frequency characteristic will remain equalised, but the absolute attenuation will have a temperature coefficient equal to...
The required temperature coefficient of the resistances may be obtained by choosing a suitable metal. The temperature coefficient of the condensers may be obtained by using a suitable dielectric such as one of the alcohols, or by arranging a loosely stacked condenser which is compressed owing to a reduction of temperature by some contraction control. It may be found convenient to make the inner conductor of a concentric cable in the form of a thin metal tube, so as to reduce as far as possible its change of resistance and inductance with frequency. This will reduce the amount of loading correction required to obtain a uniform response in the middle and high frequencies, but will increase the amount of low frequency correction required in the same manner as adding capacity-resistance high frequency correctors increases the low frequency correction required.

Series capacitative loading may be introduced for example either by lumped condensers or by forming the cable conductor or conductors of twisted wires thinly insulated from one another (e.g., by an oxide film) which wires are broken at intervals (the breaks in various wires being out of step) so that the current flows from wire to wire through the thin insulation. Fig. 4 shows a circuit alternative to that of Fig. 3 whereby correction may be applied for the high frequency effect. The cable constants are as in Fig. 3 but, instead of the series circuits Rs, Cs, Rs, Cs and Rs, Cs there are provided shunt circuits each comprising an inductance in series with a resistance. The resistances are denoted by A1, A2, A3 and the inductances by B1, B2, B3. The variations of the cable constants may then be greatly reduced by arranging that

\[ A_1 = \frac{L}{CR_1}, \quad B_1 = \frac{L}{2CR_1}, \quad A_2 = \frac{L}{CR_2}, \quad B_2 = \frac{L}{2CR_2} \]

etc. These expressions for the values of A1, B1, A2, B2, etc., are obtained from binomial expansions which can only be made on certain assumptions which may not always be justified. The values must therefore be taken as approximations and correct practical values may be found by experiment.

The result of connecting resistance-inductance circuits A1, B1, A2, B2 and A3, B3 in shunt across the line is to produce a cable with constant wave velocity and attenuation at the higher frequencies but, at low frequencies, the series inductance remains \( L_1 + L_2 + L_3 \). The shunt capacitance is however decreased by the effective negative capacitance introduced by A1, B1, etc. The shunt inductance \( G \) is increased by

\[ \frac{1}{A_1} + \frac{1}{A_2} + \frac{1}{A_3} \]

As in the case of resistance-capacity loading, the number of different loading circuits used for resistance-inductance loading depends on the frequency range and the degree of approximation required. As before, it may be desirable to correct the cable by loading only up to a frequency short of the highest frequency to be handled and to provide correction at the highest frequencies in the amplifiers which are necessary at intervals along the line.

Assuming that A1 and B1 are at the same temperature as the cable, it is preferably arranged that A1 has a temperature coefficient equal in magnitude but opposite in sign to the temperature coefficient of the series resistance of the cable, and that B1 has a temperature coefficient of magnitude double that of the series resistance of the cable and of opposite sign.

Resistivity-inductance loading may also be employed for correcting for the low frequency effect. If the low frequency constants are \( R, C, L, G \) as shown in Fig. 5 (these constants must be the effective values and must therefore allow for the effect of any high frequency correction which has been applied and may therefore be different from the corresponding values in Fig. 3 or 4) the low frequency correction may be applied by connecting a resistance \( A_1 \) and inductance \( B_1 \) in series with one another and in shunt with the line. The values of \( A_1 \) and \( B_1 \) are given by

\[ A_1 = \frac{R}{G} \left( \frac{1}{L} + \frac{1}{2C} \right) \]

\[ B_1 = \frac{L}{G} \left( \frac{1}{L} + \frac{1}{2C} \right) \]

The propagation constant of a cable treated in this way is then equal to

\[ j\omega/\sqrt{L} \cdot c + \frac{R}{G} \left( \frac{1}{L} + \frac{1}{2C} \right) \]

for all frequencies. The first term shows the wave velocity to be independent of frequency and the other terms show that the attenuation is also independent of frequency.

Either the high or the low frequency correction may be applied separately to modify the characteristics of the cable over a part or the whole of the frequency bands over which these corrections are effective. The two corrections may also be applied simultaneously.

The high-frequency correction by resistance-inductance loading may be applied in conjunction with low frequency correction as described with reference to Fig. 2.

The low frequency correction by resistance-inductance loading may be applied in conjunction with high frequency correction as described with reference to Fig. 3.

High-frequency correction can also be effected in part by resistance-inductance loading and in part by resistance-condenser loading. If this correction is effected half by the one arrangement and half by the other method it is found that a closer approximation to continuous loading is obtained and it is therefore possible to space the loading points further apart from one another than when all the correction is applied by one only of these arrangements. By suitably distributing the correction between the two arrangements it may be possible to arrange that, at low frequencies, \( GL = 1/C \) in which case the cable is uniform for all frequencies and no low frequency correction is necessary.

Similarly the low frequency correction may be applied when necessary in part by resistance-inductance loading and in part by resistance-capacity loading, whether or not high frequency correction by resistance-capacity or resistance-inductance loading has been applied.

The theory of cables is worked out for continuous loading but in practice lumped loading is generally applied at loading points suitably spaced along the cable. For the method of loading by resistance-inductance elements it is found that if a frequency \( \omega \) is involved such that \( A = m/B \), A being a loading resistance and B the inductance associated therewith, then the distance between consecutive loading points must
be quite small compared with the wavelength corresponding to frequency \( \omega \). The actual distance employed depends on the accuracy of correction of the cable which is required. The maximum distance which will satisfy any given requirements is best found by trial and error. The cable constants are measured and the cable is transformed to its equivalent \( \pi \) network. This network is then terminated at each end by a load equal to one half the load of the cable. The new propagation constant is then determined. It is found that a hump or hollow in the transmission curve of the cable is most likely to occur at a frequency corresponding to a wavelength one quarter or one half of which is equal to the loading distance. If the curve is substantially flat in the neighborhood of both these frequencies, then it is likely to be flat over the frequency range for which the cable has been corrected.

It is to be understood that the calculated values of \( A \) and \( B \) are expressed in ohms and henries for a unit length. Since these loading elements are connected in shunt with the cable the units should be the reciprocals of these quantities. It follows that, if the loading impedance be halved, the values of the loading elements (\( A \) and \( B \), etc.) must be doubled.

Referring now to Fig. 1 the cable comprising conductors 1, 2 has constants denoted by \( L_c, C, R \), \( L_r, R_r \). The high frequency effect is corrected by including resistance-capacity circuits \( C_r, R_r \). The low frequency effect is corrected by series capacity \( C' \). As in Figs. 2, 3 and 4 the components within the dotted rectangle 3 represent the constants of the cable itself.

It is to be understood that the cable constants are distributed along the line and that the loading impedance elements must, in practice, also be distributed along the line. Dotted lines \( X \) \( X \) denote the ends of the cable, the feeding and output coupling units being shown outside these lines.

The cable is fed from a valve 4 (shown as a pentode) provided with an anode resistance 5.

A coupling condenser 6 is connected between the anode 7 of valve 4 and one end of conductor 1. The corresponding end of conductor 2 is earthed. The cable loaded in the manner shown appears like a resistance 6 in series with a condenser 7.

In such cases the components actually exist the resistance 8 and condenser 9 are shown dotted.

It will be seen that at frequencies at which resistance 5 in parallel with the output impedance of valve 4 is large compared with the impedance of condensers 6 and 8 in series with one another, constant current will be fed to the cable. By this means that when a constant voltage is applied to the grid 16 at different frequencies, the input current to the cable is constant. At very low frequencies the impedance of condensers 6 and 8 becomes high and a constant voltage feed to the cable results (with constant voltage on the grid 16).

The termination shown in Fig. 1 comprises two condensers 11 and 12 which, in series with one another, have a capacity equal to the capacity 9. Resistance 10 is made equal to resistance 6, i.e., the high frequency surge impedance of the cable. At frequencies at which the valve 4 is feeding constant current into the cable, it is arranged that the impedance of condenser 12 is small compared with resistance 10 so that, since the cable is loaded to have uniform attenuation, a constant current output is obtained from the cable and this produces a constant voltage on the grid 14 of valve 15. At very low frequencies the valve 4 is feeding a constant voltage to the cable and it is arranged that at these frequencies the capacity of condenser 12 is such that its impedance is large compared with resistance 10 and a constant voltage is therefore applied to the cable. By suitably proportioning condensers 11 and 12 and resistance 10 with reference to the constants of the cable and the elements of the feeding unit, it is possible to obtain a substantially flat overall response for the equalised range of the cable from the grid 16 of valve 4 to the grid 14 of valve 15.

If the cable has leakage, the condenser \( C' \) must be shunted by a resistance as described with reference to Fig. 2 and shunt resistances must also be connected across condensers 11 and 12, there being in effect an imaginary shunt resistance across condenser 5.

Fig. 6 shows an alternative termination which may be used in place of that shown in Fig. 1. Condensers 11 and 12 and resistance 13 are provided as before but an autotransformer 17 is connected as shown. When the impedance of the lower portion of the autotransformer 17 is comparable with the impedance of condenser 12, an effective voltage step-up is obtained between the cable and the grid 14 of valve 15. The inductance of the lower part of autotransformer 17 is such that this step-up realised only over the upper part of the frequency band being handled and voltage noise is thereby kept low.

A condenser 18 is advantageously shunted across resistance 13, its capacity being made equal to \( L/Z \)

where \( Z \) is equal to resistance 13 (which is also equal to the surge impedance of the cable) and \( L \) is the inductance of the lower part of the autotransformer 17. The arrangement of Fig. 6 is of particular use in cases where the cable is not equalised up to the highest frequency which it is desired to handle.

If desired an arrangement similar to that of Fig. 6 can be substituted for the feeding unit shown in Fig. 1. The autotransformer at the feeding end would preferably have its upper end connected to the right hand terminal of condenser 6, its intermediate tapping point connected to conductor 1 of the cable and its lower end connected through a resistance and condenser corresponding to 13, 12 of Fig. 6 to conductor 2 of the cable. In this way the autotransformer gives a voltage step-down, at high frequencies, from the feeding unit to the cable.

Where the cable is of the so-called concentric type (one conductor insulated from and surrounding the other conductor) the loading is preferably all applied to the inner conductor. The invention may also be applied to other cables such, for example, as one comprising a paper insulated pair of conductors in which series inductance loading is not provided. The introduction of series condensers into such a cable in order to correct for the low frequency effect makes the attenuation over the low frequency range more uniform and it also raises the velocity so that such pairs form very high quality circuits for audio frequencies.

We claim:

1. An electrical signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a working frequency range extending to limit-
ing frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leakage of said line, said loading means comprising resistance and reactance elements, said elements being equivalent electrically to a condenser in series with said line and shunted by a resistance and having magnitudes such as to compensate for said finite resistance and leakance values, thereby preventing the attenuation and wave velocity to depart substantially from uniformity in the neighbourhood of said limiting frequencies.

2. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a working frequency range extending to limiting frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leakage of said line, said loading means comprising resistance and reactance elements, said elements being equivalent electrically to a condenser in series with said line and shunted by a resistance and having magnitudes such that the characteristic impedance (Z) of the loaded line is given by the expression

\[ Z = \sqrt{\frac{L}{C}} \frac{j\omega L C + R + G R}{2V L + 2V C} \]

C, L, R and G being respectively the capacity, inductance, resistance and leakance of said line per unit length, thereby rendering the attenuation and wave velocity of the line substantially uniform in the neighbourhood of the lower limiting frequency of said range.

3. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a working frequency range extending to limiting frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leakage of said line, said loading means comprising resistance and reactance elements, said elements being equivalent electrically to a condenser in series with said line and shunted by a resistance and having magnitudes such that, in the neighbourhood of the upper limiting frequency of said range, the series inductance and resistance of said line, together with the loading means, simulate a substantially pure constant resistance and a substantially constant inductance in series, thereby rendering the attenuation and wave velocity of said line substantially uniform in the neighbourhood of said upper limiting frequency.

4. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a pre-determined working range of frequency, said loading means comprising a number, including one, of series circuits, each said circuit comprising a condenser shunted by a resistance connected in series in said transmission line, said circuits when their number exceeds one being spaced from one another at intervals along said line so that the magnitudes \( C' \) and \( G' \) of the effective series capacity and resistance, respectively, in a unit length of said line due to said loading means satisfy the relationships

\[ C' = \frac{\frac{R}{C} - \frac{G}{L^2} - \frac{L}{C}}{3} \]

and

\[ G' = \frac{\frac{R}{C} - \frac{G}{L^2} - \frac{L}{C}}{3} \]

wherein C, L, R and G are respectively the capacity, inductance, resistance and leakance of said transmission line per unit length.

5. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a pre-determined working range of frequency, said loading means comprising a number, including one, of shunt circuits, each said circuit comprising an inductance in series with a resistance connected in shunt across said transmission line, said shunt circuits when their number exceeds one being spaced from one another at intervals along said line so that the magnitudes (A) and (B) of the effective shunt resistance and inductance, respectively, in a unit length of said line due to said loading means satisfy the relationships

\[ A = \frac{\frac{R}{C} - \frac{G}{L^2}}{3V C} \]

and

\[ B = \frac{\frac{R}{C} - \frac{G}{L^2}}{3V L} \]

wherein C, L, R and G are respectively the capacity, inductance, resistance and leakance of said transmission line per unit length.

6. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a pre-determined working range of frequency, extending to limiting frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leakage of said line, said loading means comprising a number, including one, of series circuits, each said circuit comprising a condenser shunted by a resistance connected in series in said transmission line, said series circuits when their number exceeds one being spaced from one another at intervals along said line so that the magnitudes of the effective series capacity and resistance due to said loading means are such that the rise of resistance and fall of inductance of said line with increasing frequency are reduced, thereby preventing the attenuation and wave velocity to depart substantially from uniformity in the neighbourhood of said limiting frequencies.

7. An electric signal transmission system comprising a transmission line and loading means, said line simulating a smooth line over a pre-determined working range of frequency extending to limiting frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leakage of said line, said loading means comprising a number, including one, of shunt circuits, each said circuit comprising an inductance in series with a resistance connected in shunt across said transmission line, said shunt circuits when their number exceeds one being spaced from one another at intervals along said line.
line so that the magnitudes of the effective shunt inductance and resistance due to said loading means are such that the rise of resistance and fall of inductance of said line with increasing frequency are reduced, thereby preventing the attenuation and wave velocity to depart substantially from uniformity in the neighbourhood of said limiting frequencies.

8. An electric signal transmission system comprising a transmission line and two types of loading means, said line simulating a smooth line over a predetermined working range of frequency extending to limiting frequencies at which the attenuation and wave velocity depart from uniformity due to the finite values of the series resistance and shunt leaktance of said line, said first type loading means comprising a number, including one, of series circuits, each said circuit comprising a condenser shunted by a resistance connected in series in said transmission line, said series circuits when their number exceeds one being spaced from one another at intervals along said line, said second type loading means comprising a number, including one, of shunt circuits, each said shunt circuit comprising an inductance in series with a resistance connected in shunt across said transmission line, said shunt circuits when their number exceeds one being spaced from one another at intervals along said line, each said shunt circuit corresponding to one of said series circuits of which it is the inverse with respect to the characteristic impedance of the line.

ALAN DOWER BLUMLEIN.
JOHN HARDWICK.
CERTIFICATE OF CORRECTION.


ALAN DOWER BLUMLEIN, ET AL.

It is hereby certified that the name of the assignee in the above numbered patent was erroneously described and specified as "Electrical & Musical Industries Limited" whereas said name should have been described and specified as Electric & Musical Industries Limited, of Hayes, Middlesex, England, a company of Great Britain, as shown by the record of assignments in this office; and that the said Letters Patent should be read with this correction therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 29th day of August, A. D. 1939.

Leslie Frazer,
(Seal)
Acting Commissioner of Patents.