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E. F. ROEBER.

TELEGRAPH AND TELEPHONE TRANSMISSION LINE.

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Fig. 1.

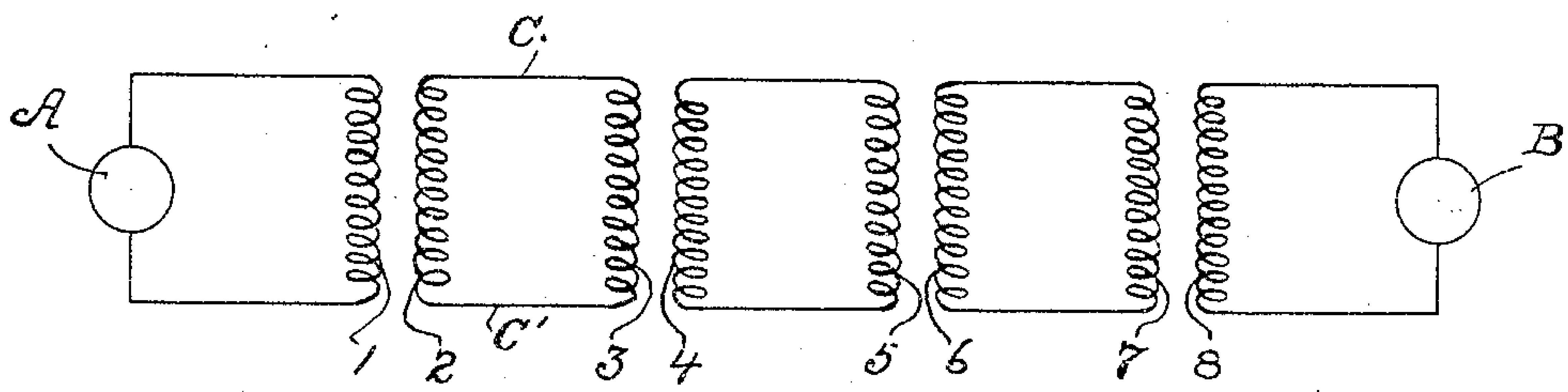
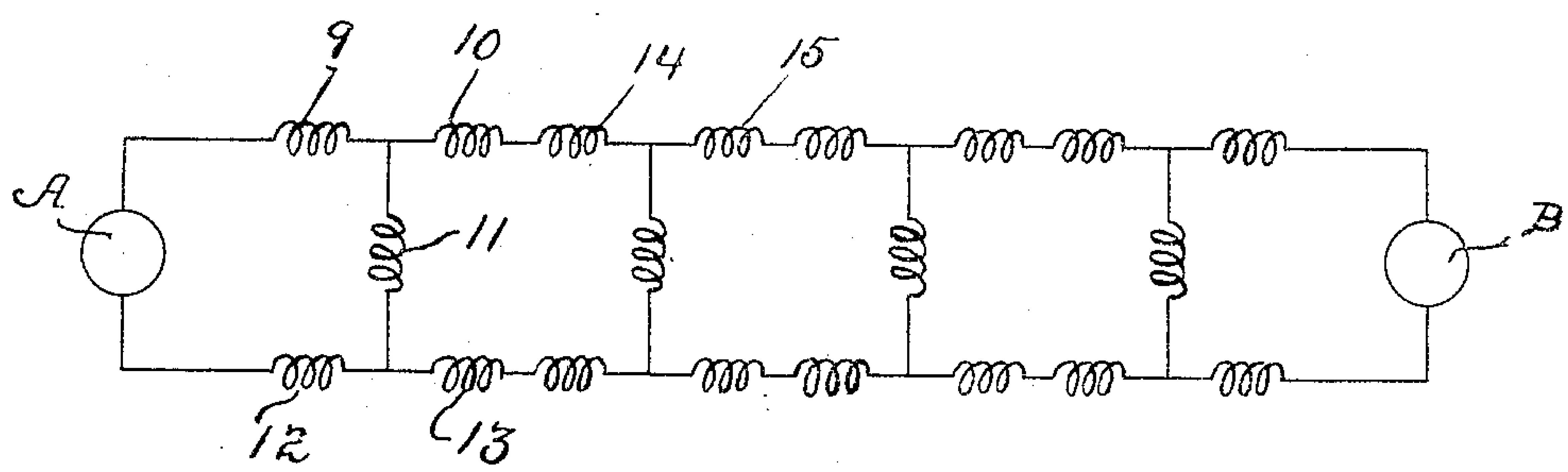


Fig. 2.



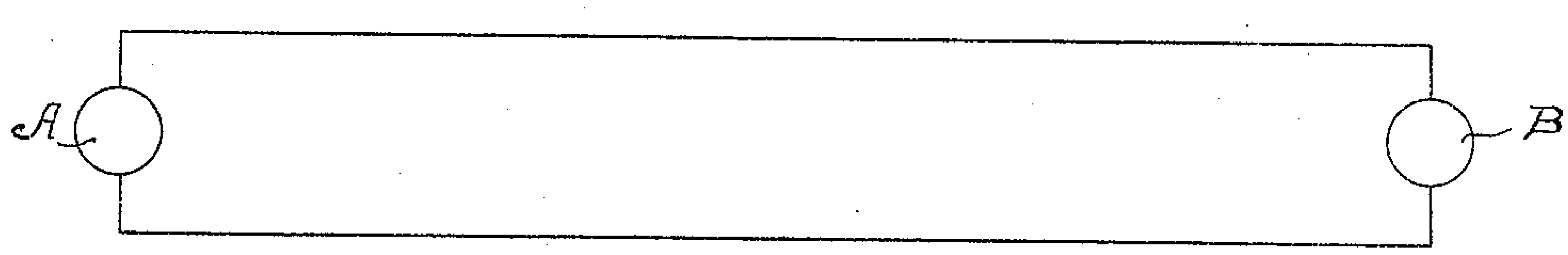


Fig. 3.

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UNITED STATES PATENT OFFICE.

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TELEGRAPH AND TELEPHONE TRANSMISSION-LINE.

SPECIFICATION forming part of Letters Patent No. 779,443, dated January 10, 1905.

Application filed March 9, 1901. Serial No. 50,433.

To all whom it may concern:

Be it known that I, EUGENE FRANZ ROEBER, a subject of the Emperor of Germany, residing at Philadelphia, in the county of Philadelphia and State of Pennsylvania, have invented a new and useful Improvement in Telegraph and Telephone Transmission-Lines, of which the following is a specification.

My invention relates to electrical-wave transmission which is utilized in telegraph or telephone service; and it has for its object to provide a transmission-line for such service in which attenuations due to resistance and regulated by capacity and inductance (but usually stated as due to resistance and capacity) are reduced to a minimum.

Another object which I accomplish in a very perfect manner in my system is to avoid distortion or to reduce the same to a minimum.

I accomplish these objects by means of the mechanism illustrated in the accompanying drawings, in which—

Figure 1 is a diagram illustrating one form of my invention. Fig. 2 is a diagram of a modified form of the same, and Fig. 3 a diagram of a transmission-line which is not provided with auxiliary apparatus.

Similar characters refer to similar parts throughout the several views.

A and B represent, respectively, a transmitting and a receiving apparatus. A may, for example, represent a Morse telegraph-sounder, and B a circuit-closing key, or A may represent a telephone-transmitter, and B a telephone-receiver. On the other hand, the system may be reversed, so as to make B the transmitting device and A the receiving device.

The apparatus shown in Fig. 1 represents a system comprising a number of transformers, in which the ratio of transformation is unity. The transmitting apparatus A is in circuit with the primary coil 1 of the first transformer. The secondary coil 2 of this transformer is electrically connected by uniform conductors C and C′ to the primary coil 3 of the second transformer. The secondary coil 4 of this transformer is similarly connected to the primary coil of the third transformer. The secondary coil 6 of the third transformer is similarly connected to the primary coil 7 of the fourth transformer. The secondary coil 8 of the fourth transformer is connected to the receiving apparatus B. Any other number of transformers may be used provided they be so distributed in accordance with the requirements which I shall hereinafter set forth as to accomplish the desired purpose.

In Fig. 2 is shown a system comprising a number of inductance-coils distributed in series in each of two conductors connecting the transmitting and receiving apparatus and a number of inductance-coils shunted or connected across between the two conductors at intervals corresponding to the position of the inductance-coils placed in series in the line. The terminals of these shunt-coils are connected to the middle points of the series coils in the manner shown in Fig. 2, so that one terminal of the first shunt-coil 11 is connected to the middle point of the first series coil 9 10 of the transmitting-line and the other terminal of the shunt-coil 11 is connected to the middle point of the corresponding or opposite series coil 12 13 of the return-wire. Similarly the remaining shunts are connected to the middle points of successive series coils in the two lines throughout the system.

The object of the introduction of the inductance-coils (shown in Fig. 2) and of the transformer-coils (shown in Fig. 1) is to increase the inductance and simultaneously reduce the resistance of the transmission-line. Both of these arrangements represent a non-uniform or "loaded" transmission-line, which is equivalent to a uniform transmission-line having a lower resistance and a higher inductance than the lines shown in Fig. 3, which has the same capacity, resistance, and inductance per unit length as the uniform lines connecting the transformer-coils in Fig. 1 and the uniform lines connecting the series coils in Fig. 2.

I am aware that the inductance on long lines has been increased by inserting inductance-coils in series, such as coils 9, 10, 14, and 15, Fig. 2; but the introduction of such series coils necessarily increases not only the inductance, but the resistance. I am also aware that the resistance of long-distance transmission-lines can be reduced by the insertion of shunt inductance-coils of proper resistance, and inductance at suitable intervals along the line; but these shunt-coils cannot be made to reduce the resistance alone, but will always necessarily reduce the inductance with the resistance.

In my improved system I accomplish the simultaneous reduction of resistance in the transmission-line and increase of inductance. In order to accomplish this purpose, the inductance-coils 9, 10, 11, 12, and 13 must have proper values of resistance and self-inductance, which can be found by mathematical calculation and which must correspond to the increase of inductance and the decrease of resistance desired on the transmission-line. The same must be true also of the characteristic constants of the transformers shown in Fig. 1. To explain these matters more clearly, I will give an outline of the mathematical theory of the subject. The first principal difficulty of wave transmission over a long line is that the wave arrives at the receiving end with attenuated amplitude. To dimish this attenuation must therefore be the first aim of any improvement in line construction. The second principal difficulty of wave transmission over a long line refers to the special case of telephony or in general to any case in which a wave is transmitted which is not simply a sine-wave of given frequency, but a superposition (a sum) of a number of sine-waves of different frequencies. The difficulty arising in such cases is generally called "distortion"—*i. e.*, the amplitudes of the different waves are attenuated in different degrees. The second aim of any improvement of line construction for such cases must therefore be to diminish distortion—or, in other words, to effect attenuation of the amplitudes of the different waves to the same degree. The degree of attenuation is determined by the "attenuation constant" h, which is defined as follows: If the amplitude of the wave at the transmitting end is unity, it is e^{-hs} at a distance s from the transmitting end, where e is the base of Naperian logarithms. It is known that for a line having a given resistance of R ohms per mile, a given inductance of L henries per mile, and a given capacity of C farads per mile the attenuation constant h is given by the formula

$$h = \sqrt{\frac{1}{2} p^{C} \left[\sqrt{p^2 L^2 + R^2} - p^{L},\right]}$$

where p equals $2\pi N$ and N the frequency. If p^{L} is large in comparison to R, this equation becomes

$$h = \frac{R}{2}\sqrt{\frac{C}{L}}$$

which shows that the attenuation can be diminished as well by an increase of the inductance as by a decrease of the resistance. This can be of course accomplished by using a larger cross-section of the conductor, and thus diminishing the resistance uniformly all along the line, and, further, by increasing the inductance uniformly all along the line with the aid of special means, such as putting iron into the cable, &c.; but with such improvements of the transmission-line, which are applied continuously and uniformly all along the line my invention has nothing to do, as my invention consists in obtaining the same results by placing either series coils, together with shunt-coils or transformers, at certain distances along the line. In other words, I construct a non-uniform line which has the same effect as a uniform line improved by the means noticed above.

I am aware that the effect of inductance-coils distributed in series along the line at certain distances has before been recognized as being equivalent under certain conditions to a uniform continuous increase of inductance all along the line. In other words, a non-uniform line with inductance-coils in series behaves, in connection with wave transmission, exactly like an "equivalent" uniform line having a higher inductance per unit length, which is an advantage, but also having a greater resistance per unit length, which is a disadvantage.

The essential point of my invention, which represents progress over the prior art, is that I have found a means of constructing a non-uniform conductor having a smaller resistance per unit length than the original uniform conductor by means of suitable coils shunted across the line at certain distances, and, further, that I determined the exact requirements for constructing a suitable conductor for wave transmission having both series and shunt coils placed at certain distances along the line of the equivalent of this arrangement, suitable transformers placed at the same distances along the line. I have published the mathematical theory by which I reached these results in an article in the *Electrical World and Engineer*, March 16, 23, 30, 1901. I have found the following results for a transmission-line having no coils inserted in series, but coils shunted across the line at certain intervals. Let 1 be the distance between the transmitting and receiving end, hence 21 the total length of conductor. This uniform original line may have per unit length the resistance R ohms per mile, the inductance L henries per mile, the capacity C farads per mile. At equal distances equal coils are shunted across the line, each having the resistance R_o ohms and the inductance L_o henries. The number of these coils may be k, so that the whole conductor is divided into $2k$ equal parts, each of the length $1/k$, which represents the distance between two consecutive coils. Then if a certain condition is fulfilled concerning this distance, which will be discussed below, this non-uniform line behaves for wave transmission exactly like a uniform line having per unit length the resistance

$$R - \frac{2k}{Cl}\;\frac{L_0 R - L R_0}{p^2 L_0^2 + R_0^2}$$

and the inductance

$$L - \frac{2k}{p^2 Cl}\;\frac{p^2 L_0 L + R_0 R}{p^2 L_0^2 + R_0^2}$$

where p equals 2π N and N the frequency. This shows that the inductance has been decreased, which is a disadvantage, but that at the same time the resistance can also be diminished, which is an advantage. For a transmission-line having both series and shunt coils inserted in the line at certain intervals I have found the following result: Let l be again the distance between the transmitting and receiving ends, and hence $2l$ the total length of the conductor. This uniform line may have again per unit length the resistance R ohms per mile, the inductance L henries per mile, the capacity C farads per mile. At equal distances $2k$ equal coils are inserted in series, each consisting of two halves, each half having the resistance R_1 ohms and inductance L_1 henries. There are, furthermore, k bridges across the line, each being a coil of the resistance R_0 ohms and inductance L_0 henries. Each of these bridges connects the middle points of two opposite series coils. This is the system diagrammatically shown in Fig. 2. It is exactly equivalent to the transformer arrangement shown in Fig. 1 if the characteristic values of the transformers have the following relations to the values R_1 L_1 R_0 L_0: R_1 is equal to one-half the internal resistance of either the primary or the secondary winding of each transformer. L_1 is equal to one-half the internal true self-inductance of either the primary or the secondary winding of each transformer. R_0 and L_0 are connected with the so-called "primary" admittance of the transformer, which is defined as the "ratio of the exciting-current to the primary counter electromotive force." If this primary admittance is $g_0 + jb_0$, (in Steinmetz's notation,) there is

$$R_0 = \frac{g_0}{g_0^2 + b_0^2}$$

$$L_0 = \frac{b_0}{2\pi N (g_0^2 + b_0^2)}$$

where N is the frequency. The complete analytical proof that under these conditions the arrangements of Fig. 1 and Fig. 2 are equivalent is given, for instance, by C. P. Steinmetz in his book *Theory and Calculation of Alternating Current Phenomena*, third edition, pages 204 to 212. A graphical proof of the equivalence of the two arrangements is to be found in Section VII of my article mentioned above. Now I have found that if a certain condition is fulfilled concerning the distance of two consecutive groups of coils or two consecutive transformers, respectively, which condition will be discussed below, then this non-uniform line (either in the form of Fig. 2 or Fig. 1) behaves for wave transmission like a uniform line having per unit length the resistance R′ and the inductance L′ given by the following equations:

$$L' = L + 2 L_1 \frac{k}{l} + \frac{F}{R_0^2 + p^2 L_0^2}$$

and

$$R' = R + 2 R_1 \frac{k}{l} - \frac{G}{R_0^2 + p^2 L_0^2}$$

where p equals 2π N and N the frequency, while F and G have the following values:

$$F = 2\left(L + L_1 \frac{k}{l}\right)(R_0 R_1 + p^2 L_0 L_1,)$$

$$+ 2\left(R + R_1 \frac{k}{l}\right)(R_0 L_1 - R_1 L_0,)$$

$$- \frac{2}{p^2 C}\frac{k}{l}\left\{ R_0\left(R + 2 R_1 \frac{k}{l}\right) + p^2 L_0 \left(L + 2 L_1 \frac{k}{l},\right) \right\}$$

$$G = 2 p^2 \left(L + L_1 \frac{k}{l}\right)(L_1 R_0 - L_0 R_1,)$$

$$-2\left(R + R_1 \frac{k}{l}\right)(R_0 R_1 + p^2 L_0 L_1,)$$

$$+ \frac{2k}{lC}\left\{ L_0\left(R + 2 R_1 \frac{k}{l}\right) - R_0\left(L + 2 L_1 \frac{k}{l}.\right) \right\}.$$

These equations form the complete solution of the problem and enable one to find by ordinary elementary algebra the characteristic values of the uniform conductor, which is equivalent to a non-uniform conductor diagrammatically shown in Fig. 1 and Fig. 2. It is evident from these equations that it is possible by properly choosing the values $\frac{l}{k}$, L_0, R_0, L_1, R_1 to accomplish that for transmission of a sine-wave of given frequency N the resistance per unit length of the line can be diminished and the inductance per unit length can be increased—in other words, that L′ can be made larger than L and R′ smaller than R; but I do not want to restrict my claims to this special case. I include in my claims the general application of the above formulas and rules for adjusting both the inductance L′ and the resistance R′ in such a way that the attenuation is diminished, as was explained above.

I will now give the condition under which a non-uniform line of the construction diagrammatically shown in Figs. 1 and 2 is equivalent to a uniform conductor having per unit length the resistance R′ and the inductance L′. The distance between the transformers in Fig. 1 or the distance between the series coils in Fig. 2 must be so small that the system becomes approximately equivalent to a uniform line. This distance depends upon the degree of approximation and the wave length of the transmitted signal on the corresponding uniform conductor, (which is equivalent to the non-uniform arrangement shown in Figs. 1 and 2.) The degree of approximation of the arrangement shown in Fig. 1 or Fig. 2 to a uniform transmission-line is the same as the degree of approximation of the sine of half the angular distance between two consecutive series coils in Fig. 2 or two consecutive transformers in Fig. 1 to half the angular distance itself. From the degree of approximation wanted and the frequency of the waves to be transmitted the angular distance can therefore be determined. The angular distance between two consecutive coils (or transformers) is defined by the term $2\pi\frac{d}{w}$, where d is the distance between two consecutive coils (or transformers) and w is the wave length on the equivalent uniform conductor, both d and w being of course measured in the same unit of length. The wave length is given by the formula

$$w = \frac{2\pi}{\sqrt{\frac{1}{2}p^{C}\left[\sqrt{p^2(L')^2+(R')^2}+p^{L'}\right]}}$$

or if $p^{L'}$ is large in comparison to R' by the simpler formula

$$w = \frac{2\pi}{p\sqrt{L'C}}$$

The foregoing rules and explanations give all the information needed for calculating a transmission-line over which a train of sine-waves of a certain given frequency is to be transmitted, as may be the case in a system of telephony. The above formulas and rules enable one to design a line for transmission of sine-waves of a given frequency, so that the attenuation of the amplitude of the wave is diminished to a certain degree. While this can be accomplished by the insertion of series coils alone on account of the resulting increase of inductance, yet this method has the disadvantage that the resistance is also increased. This disadvantage can be avoided or lessened to a certain desired degree by my system of combining shunt-coils with the series coils, (or by the equivalent system of transformers.) The introduction of the shunt-coils is made to counteract the increase of resistance due to the series coils. In consequence of this the wave length is increased, (over the value which it would have with the series coils alone without the shunt-coils,) and in consequence of this it is possible to place the coils (or transformers) farther apart, which is a very desirable result. If not simply a sine-wave of given frequency is to be transmitted, but a superposition (a sum) of several sine-waves of different frequencies, as is the case in telephony, then, as explained above, it is necessary to take care that there is no distortion. All different sine-waves are to be attenuated practically to the same degree. The above formulas and rules enable one to find whether this condition is fulfilled. It is fulfilled if the attenuation is independent of p to a degree determined by the requirements of the practice and between the limits of the maximum and minimum frequencies, which are important for the practice. One has therefore to choose the values of L_0 R_0 L_1 R_1, so that when the values of L' and R' are calculated by means of my formulas and introduced into the formula given above for the attenuation-constant h, then the value of h must be practically independent of the frequency—*i. e.*, one has first to consider what are the two extreme limits (the maximum and the minimum) of the frequency important for the special case under consideration. One has then to calculate L' and R' for these two frequencies, and therefrom the attenuation-constant h for the same two frequencies. This h must then be found to have practically the same value for both frequencies. "Practically" means that the difference between the exact values of h for both frequencies must be so small as is necessary for the special problem under consideration. If by such a calculation it would be found that this result has not been obtained, this would show that the chosen values L_0 R_0 L_1 R_1 are not the proper values. One has then to choose other values and repeat the above calculation, and one has to adjust those values until the calculation as sketched above gives the result desired.

To illustrate my method, I will now give a numerical example. A transmission-line of two hundred and seventy-five miles length is given, which has per unit length a resistance $R=5$ ohms per mile, an inductance $L=0$ henry per mile, and a capacity $C=0.3\times10^{-6}$ farad per mile. It is wanted to transmit over this line a composite wave, being the sum of various sine-waves of different frequencies. The limits of the frequencies to be transmitted may be one thousand periods per second as maximum and four hundred periods per second as minimum. The formula for the attenuation-constant h gives for the frequency $N=1{,}000$—*i. e.*, $p=6{,}300$ (roughly) $h=0.069$—and for the frequency $N=400$—*i. e.*, $p=2{,}500$ (roughly) $h=0.043$. Hence if the amplitude of the wave at the transmitting end is unity it is at the receiving end $e^{-0.069\times275}$, or about 6×10^{-9} for the frequency one thousand, and $e^{-0.043\times275}$ or about 7×10^{-6} for the frequency four hundred. There is therefore very great attenuation, together with distortion. It is proposed to diminish both the attenuation and the distortion by means of my method, so that the amplitude at the receiving end is about 0.4 times the amplitude at the transmitting end and that the amplitudes of the received waves at the receiving end are equal within ten per cent. for the limits of the frequency one thousand and four hundred. Now we have $e^{-275h}=0.4$, or $h=0.0033$, (roughly,) and if pL' is large in comparison to R'

$$\frac{R'}{2}\sqrt{\frac{C}{L'}}=0.0033.$$

Hence

$$\frac{(R')^2}{L'}=145.$$

The principal effect of the insertion of coils (or transformers) according to my method must therefore be that the ratio $\frac{R^2}{L}$ (which is infinite for the original non-inductive conductor) is reduced to one hundred and forty-five. For this we must evidently increase L, (which is originally zero.) If we would do this simply by means of inductance-coils inserted in series in the line, we would necessarily also increase R, which is evidently a disadvantage for our purpose. Moreover, even if we could make this increase of R negligibly small, this method would have the disadvantage that when we increase the inductance to the desired degree everything else is fixed, especially the distance between the coils (which becomes the smaller the more inductance we put into the line.) My method has the great practical advantage that it is more general, that it gives more liberty to the designer in the choice of the coils, and that it is possible to fulfil one other condition which may be wanted for practical reasons. For instance, in our case we may want that the coils (or transformers) shall not be nearer together than one mile. It may be further required that my non-uniform conductor shall be equivalent to the corresponding uniform conductor—say, within ten per cent. According to the above rule the sine of half the angular distance between two consecutive coils (or transformers) must be equal to half the angular distance itself within about this degree of approximation. For this it is sufficient that half the angular distance is $\frac{\pi}{4}$ —*i. e.*, that the distance between two consecutive coils (or transformers) is one-half the wave length. Hence, as that distance is to be not smaller than a mile, the wave length for the greatest frequency ($N=1{,}000$) must be not smaller than four miles. The wave length is

$$\frac{2\pi}{p\sqrt{L'C}}=4,$$

from which equation it follows that, for $N=1{,}000$, L' must be not larger than about 0.2 henry per mile. From this, together with the above equation

$$\frac{(R')^2}{L'}=145$$

it follows that $R'=5.4$, roughly. I must now choose such values of L_0 R_0 L_1 R_1 that these conditions are fulfilled. I assume L_1 equals 0.1 henry; R_1 equals 0.2 ohm; L_0 equals four henries; R_0 equals eight ohms. Further, we have $\frac{1}{k}=1$. Then my formulas give for $N=1{,}000$: $L'=0.1966$, $R'=5.450$, $h=0.00337$, $e^{-275h}=0.396$. For $N=400$ my formulas give: $L'=0.152$, $R'=4.327$, $h=0.00304$, $e^{-275h}=0.433$. It will thus be seen that the amplitude of the wave at the receiving end is about 0.4 times the amplitude at the transmitting end. 39.6 and 43.3 per cent. arrive at the receiving end for the frequencies $N=1{,}000$ and $N=400$, respectively. The difference 3.7 between 43.3 and 39.6 is less than ten per cent. of 39.6. The conditions of the problem are therefore fulfilled. I call attention to the fact that R_0 can be chosen considerably larger than eight without materially altering the result. This is of advantage for the practice, because coils which are to have a certain amount of self-inductance are easier to construct and of smaller size the higher their resistance. For the construction of coils which shall have a certain resistance and a certain inductance the ordinary well-known formulas of the text-books are to be used. (Concerning formulas for the inductance see, for instance, Grawinkel and Strecker, *Hilfsbuch der Elektrotechnik*, (1900,) page 71.)

I claim as my invention—

1. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having sources of positive reactance and of negative resistance inserted at intervals along the line, and producing a smaller attenuation of the transmitted waves than the line without these sources, substantially as set forth.

2. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having sources of positive reactance and of negative resistance inserted at substantially equal intervals along the line, and producing a smaller attenuation of the transmitted waves than the line without these sources, substantially as set forth.

3. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having inductance-coils in series and in shunt inserted at intervals along the line, the series coils raising the inductance of the line and the shunt-coils counteracting the increase of resistance due to the series coils, substantially as set forth.

4. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having inductance-coils in series and in shunt inserted at substantially equal intervals along the line, the series coils raising the inductance of the line and the shunt-coils counteracting the increase of resistance due to the series coils, substantially as set forth.

5. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having transformers inserted at intervals along the line, the true self-inductance of the transformer-coils raising the inductance of the line and the primary admittance of the transformers counteracting the increase of resistance, substantially as set forth.

6. In a system of electric-wave transmission, a wave-conductor comprising a substantially uniform line having transformers inserted at substantially equal intervals along the line, the true self-inductance of the transformer-coils raising the inductance of the line and the primary admittance of the transformers counteracting the increase of resistance, substantially as set forth.

7. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor comprising a substantially uniform line, having sources of positive reactance and of negative resistance inserted at intervals along the line, and producing a smaller attenuation and a smaller distortion of the transmitted waves than the line without these sources, substantially as set forth.

8. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor, comprising a substantially uniform line, having sources of positive reactance and of negative resistance inserted at substantially equal intervals along the line, and producing a smaller attenuation and a smaller distortion of the transmitted waves than the line without these sources, substantially as set forth.

9. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor, comprising a substantially uniform line, having inductance-coils in series and in shunt inserted at intervals along the line, the series coils raising the inductance of the line and the shunt-coils counteracting the increase of resistance due to the series coils, substantially as set forth.

10. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor, comprising a substantially uniform line having inductance-coils in series and in shunt inserted at substantially equal intervals along the line, the series coils raising the inductance of the line and the shunt-coils counteracting the increase of resistance due to the series coils, substantially as set forth.

11. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor, comprising a substantially uniform line having transformers inserted at intervals along the line, the true self-inductance of the transformer-coils raising the inductance of the line and the primary admittance of the transformers counteracting the increase of resistance, substantially as set forth.

12. In a system of telephony, the combination of a transmitting and a receiving instrument and a wave-conductor, comprising a substantially uniform line, having transformers inserted at substantially equal intervals along the line, the true self-inductance of the transformer-coils raising the inductance of the line and the primary admittance of the transformers counteracting the increase of resistance, substantially as set forth.

In testimony whereof I have signed my name to this specification in the presence of two subscribing witnesses.

EUGENE FRANZ ROEBER.

Witnesses:
J. HOWARD LONGACRE,
THOMAS B. SMITH.