No. 767,818. PATENTED AUG. 16, 1904.

W. W. JACQUES.

TELEPHONE CIRCUIT.

APPLICATION FILED APR. 18, 1904.

NO MODEL. 4 SHEETS—SHEET 1.

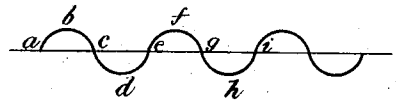


Fig. 1.

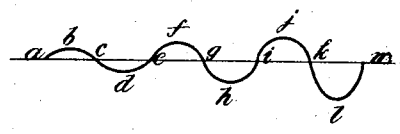


Fig. 2.

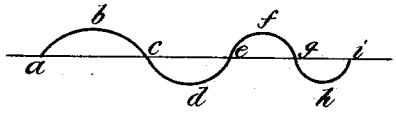


Fig. 3.

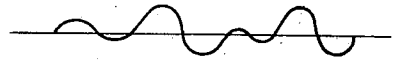


Fig. 4.

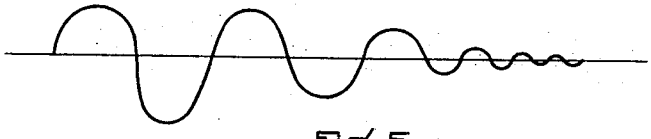


Fig. 5.

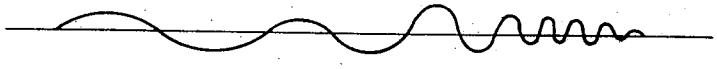


Fig. 6.

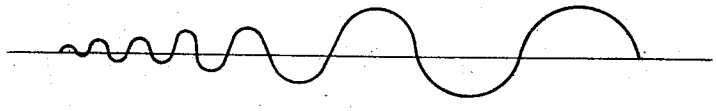


Fig. 7.

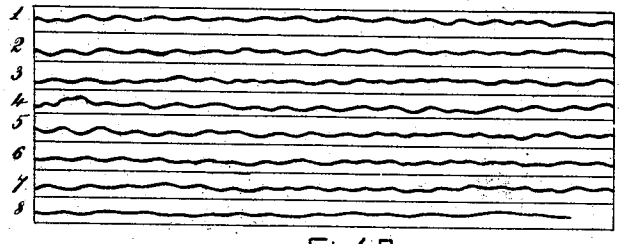


Fig. 8.

WITNESSES:

William W. Swan

Ida E. Sanders.

INVENTOR:

William W. Jacques

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NO MODEL. 4 SHEETS—SHEET 2.

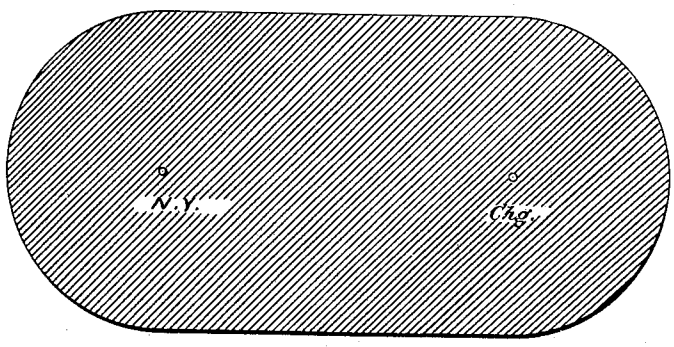


Fig. 9.

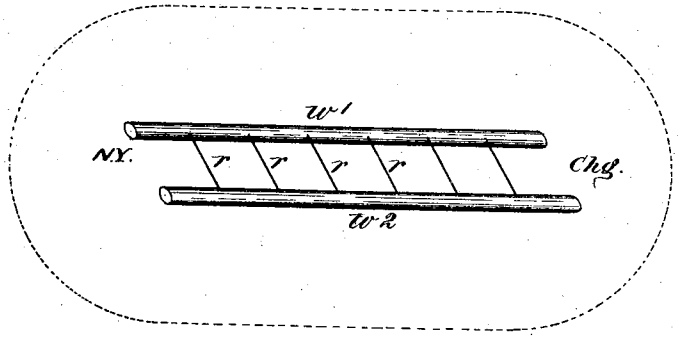


Fig. 10.

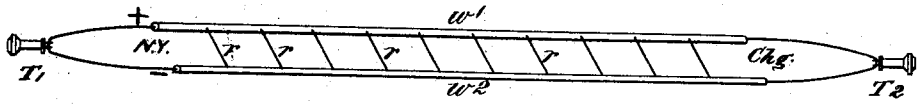


Fig. 11.

WITNESSES:

William W. Swan.

Ida B. Handren.

INVENTOR:

William W. Jacques

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NO MODEL. 4 SHEETS—SHEET 3.

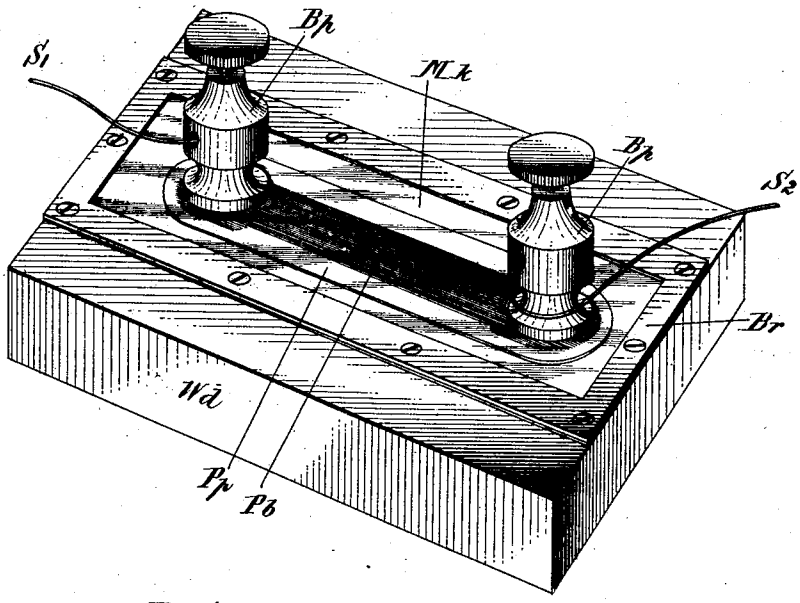


Fig. 12.

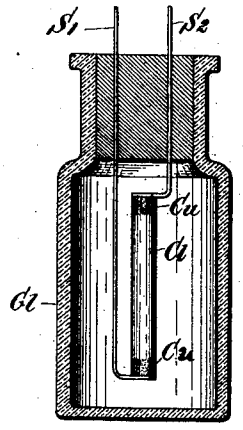


Fig. 13.

WITNESSES:

William W. Swan

Ida E. Landreth

INVENTOR:

William W. Jacques

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W. W. JACQUES.

TELEPHONE CIRCUIT.

APPLICATION FILED APR. 18, 1904.

NO MODEL. 4 SHEETS—SHEET 4.

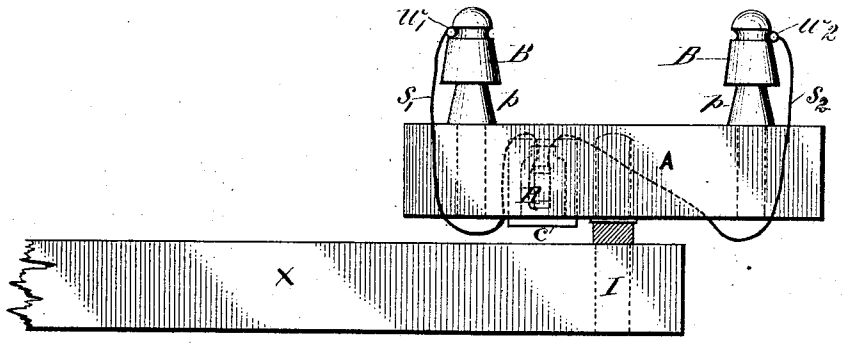


Fig. 14.

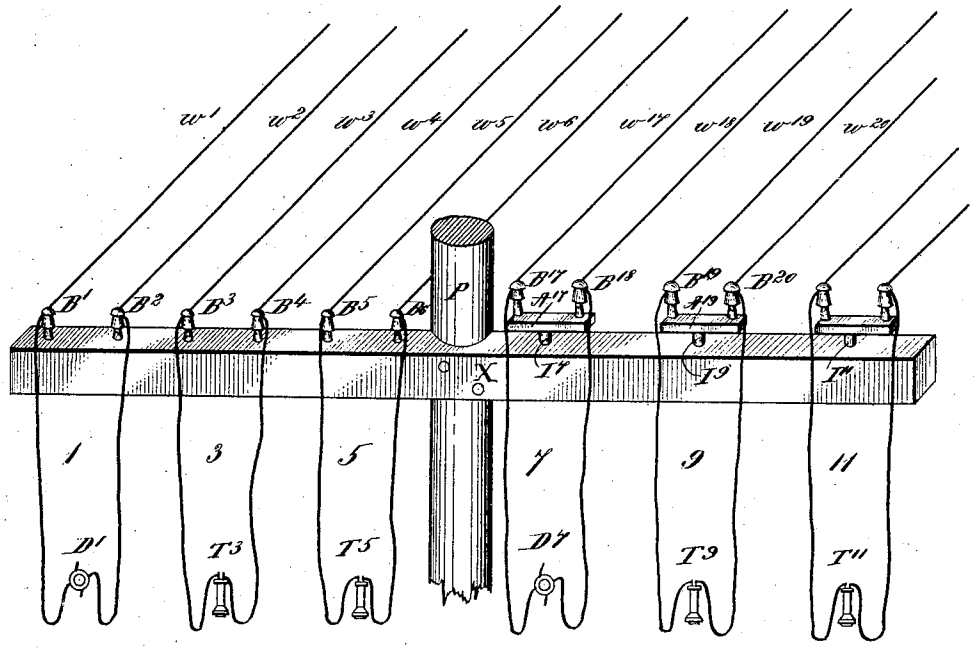


Fig. 15.

WITNESSES:

William W. Swan

Ida E. Handrow.

INVENTOR:

William W. Jacques

No. 767,818. Patented August 16, 1904.

UNITED STATES PATENT OFFICE.

WILLIAM W. JACQUES, OF BOSTON, MASSACHUSETTS.

TELEPHONE-CIRCUIT.

SPECIFICATION forming part of Letters Patent No. 767,818, dated August 16, 1904.

Application filed April 18, 1904. Serial No. 203,705. (No model.)

To all whom it may concern:

Be it known that I, WILLIAM W. JACQUES, of Boston, in the State of Massachusetts, have invented a new and useful Improvement in Telephone-Circuits, of which the following is a specification.

The object of my invention is to provide a telephone-circuit over which conversation may be carried on without distortion of the speech and with comparatively little attenuation even for very long distances, and, further, a circuit which is protected from the disturbing influences of neighboring electric circuits and which does not disturb neighboring circuits. A marked advantage of my new telephone-circuit is that the cost of construction for long distances is much smaller than has heretofore been found necessary.

The act of transmitting speech telephonically consists in converting the waves of sound that issue from a speaker's lips by means of the transmitting-telephone into electric waves similar in form to the sound-waves, which electrical waves travel with great velocity along the telephone-wires to a distant station, where by means of the receiving-telephone they are reconverted into similarly-shaped sound-waves which fall upon the listener's ear.

In speech it is the shape of the sound-wave that passes from the speaker's lips to the listener's ear that determines one intelligible syllable from another, and similarly in telephony it is the shape of the electrical wave that travels along the wire that determines the intelligibility of speech. It is very important that these electrical telephone-waves be transmitted along the wires without considerable "distortion" in their shape, for in so far as their normal shape is distorted just so far will the transmitted speech become indistinct and unintelligible.

Some years ago I devised an apparatus by means of which I was enabled to record the shapes of sound-waves as they passed from the speaker's lips to the transmitting-telephone and the shapes of the corresponding electrical waves at any part of a circuit over which they were transmitted and the shapes of the reconverted sound-waves as they issued from the receiving-telephone.

It will help to a clearer understanding of my invention if I first show briefly the shapes of telephone-waves for a few simple syllables and point out what it is in the shape of the wave that determines one word or syllable from another and also what changes or distortions in the shapes of the waves take place when they pass over very long circuits of the kind heretofore generally used. Having thus seen clearly the exact nature of the distortion of telephone-waves, the manner in which I prevent this distortion will be more clearly understood.

If we utter the sound "O" into a telephone-transmitter, taking care to keep the voice of uniform pitch and loudness throughout, we get on a distortionless circuit the curve shown in Figure 1, in which the undulation *a b c d e* is in every respect like the undulation *e f g h i*. If we maintain the voice at the same pitch, but increasing in loudness, we get the curve shown in Fig. 2, in which the distances *a c*, *c e*, *e g*, &c., are equal; but the curve has an increasing amplitude. If we maintain a uniform loudness and increase the pitch, we get the curve shown in Fig. 3, in which the amplitude remains constant, but the distances *a c*, *c e*, *e g*, *g i* become continually shorter. If we vary both loudness and pitch, we get the curve shown in Fig. 4, in which both the amplitude and length of the successive undulations vary.

Now the curves of articulate speech are of the kind shown in Fig. 4, though each syllable may have perhaps fifty or a hundred or more vibrations, where I have shown only a few. From a study of many such records I find that it is the characteristic manner in which the pitch and loudness change during the utterance of each syllable that determines one intelligible syllable from another. Thus if we utter a syllable beginning with a low pitch and loud vowel and ending with a high pitch and feeble consonant we get a curve like Fig. 5. If we utter another syllable beginning with a low pitch and not very loud vowel and ending with a high pitch and intense consonant, we get a curve like Fig. 6. If the syllable begin with a high-pitch consonant of feeble intensity and end with a low-

pitch vowel of considerable loudness, we get Fig. 7. Now these three syllables uttered by the speaker's voice and heard by the listener's ear convey three radically-different ideas from mind to mind. The shapes of the three sound-waves as they travel through the air or their electrical facsimiles as they travel along the wire in the direction shown by the arrows are radically different. Each changes its pitch and loudness in its own characteristic manner from its beginning on the left to its end on the right. The above curves are somewhat idealized in order to more clearly bring out the distinctions between different syllables; but in Fig. 8 I have reproduced the complete actual record of the word "Hello" as it passes along a distortionless telephone-circuit. It does not, of course, follow that if we again speak the word "Hello" the second record could be superimposed upon the first and found to coincide with it at all points, for the word may be spoken quickly or prolonged, may be spoken loudly or faintly, may be spoken in a high or low tone, and may be spoken with a rising or falling inflection. Nevertheless the characteristic manner in which the long low undulations change into shorter and higher ones and again fade out into long and low ones is found by experiment to be the same. A written word may be formed by different writers in many shapes, and yet the word will possess characteristics that give it always the same significance. The study of these records not only shows us the manner in which the length and amplitude of the undulations—that is, their pitch and loudness—change during the utterance of a word or syllable, but they also show us the actual wave length or pitch of any component undulation, so that we are enabled to say what pitches of the voice it is necessary to transmit in order to secure good, clear, intelligible conversation. Thus I find that when all undulations less than Ut_5—that is, ten hundred and twenty-four vibrations per second—which is two octaves above the usual average pitch of a man's voice, are transmitted the conversation is excellent, and I shall refer to these undulations as the telephone-waves essential to conversation or as the telephone-waves, neglecting those feeble and high-pitch hissing or sibilant sounds that often accompany vocal utterance, but are quite unnecessary to telephonic conversation.

Coming now to the cause of the distortion of the shapes of telephone-waves as they travel along a circuit, I find that in long-distance circuits as usually constructed the little high-pitch undulations and the larger low-pitch undulations, that together make up the wave shape of a syllable, do not travel along the circuit with the same velocity. The reason why they do not travel with the same velocity is because the electrical properties of the circuit are usually such as to accelerate the high-pitch undulations more than the low-pitch undulations. The effect of this unequal velocity is to distort the normal shape of the syllable-wave. The effect of distorting the shape of the telephone-wave is of course to distort the syllable-sound issuing from the receiving-telephone, so that it is indistinct and sometimes quite unintelligible. Further, the same properties of the circuit that accelerate the little high-pitch undulations also enfeeble them more than they do the larger low-pitch undulations and often extinguish them entirely, so that the wave shape of the syllable is further distorted and the vocal sound itself as it issues from the receiving-telephone is indistinct and perhaps meaningless. Conversation uttered into the transmitting-telephone in a clear and distinct tone is thus so distorted by its passage over the circuit that when it issues from the receiving-telephone it is muffled and indistinct, as if the speaker mouthed his words in a barrel. In extreme cases it becomes simply an inarticulate "boom," "boom," "boom." On the other hand, circuits may have electrical properties that enfeeble the low-pitch undulations more than the high-pitch undulations. These telephone-waves, too, are distorted; but the distortion is now of the opposite kind, and the vocal sounds that issue from the receiving-telephone are shrill and squeaky, like "Punch and Judy." This form of distortion is not usual on commercial lines.

Of course in a circuit absolutely free of distortion there will be a gradual loss in loudness or an attenuation of the sound with distance; but this attenuation of the wave is normal and uniform for all undulations and results merely in decreased loudness of the vocal sounds issuing from the receiving-telephone. I have found by experiment that in a quiet room and by careful attention I have been able to converse over a distortionless telephone-line in which the attenuation was so great that the words issuing from the receiving-telephone were only one thirty-thousandths as loud as when spoken into the transmitting-telephone.

The human ear has a wonderful adaptability and will readily understand vocal sounds that are enormously attenuated in loudness, provided they are not distorted.

I have discovered that provided we can give a circuit such electrical dimensions that all telephone-waves travel along it with the same velocity, there will be no distortion, the attenuation will be uniform, and the amount of attenuation will be reduced to a minimum. Such a circuit, I find, may be very conveniently and economically realized in practice. I have done this and abundantly proved by experience the truth of the above proposition.

In order to make my invention perfectly clear in its full breadth, I will first describe

the physical and mathematical theory of my new circuit and will then describe specific methods of construction that I have found by experience are conveniently and economically adapted to put my invention into practical use.

I shall first show how a telephone-circuit may be entirely freed from distortion and with so little attenuation as to make the conversation at the receiving-telephone plenty loud enough for all practical purposes.

Let us suppose that we wish to transmit telephone-waves undistorted between any two points—say New York and Chicago. We will first, in imagination, fill all the space between and around these two points with a huge mass of metal, so that New York and Chicago occupy the two foci of a great egg-shaped metallic mass, something as is shown in Fig. 9. We will suppose this metallic mass to have for telephone-waves a certain electric conductivity c, a certain magnetic conductivity m, a certain dielectric inductivity k, and a certain magnetic permeability μ, these quantities being expressed in absolute units of the centimeter, gram, second, system. It may be shown mathematically that telephone-waves of any size or shape will all pass through this metallic mass with the same velocity, and therefore without distortion, provided we give these various quantities such specific values that

$$m\,k = c\,\mu \quad (1;)$$

that is, when the product of the magnetic conductivity and the dielectric inductivity is equal to the product of the electric conductivity and the magnetic permeability. It is true that the attenuation of the waves in this mass would be very great; but this is immaterial at the present stage of our investigation, as we are now dealing with an imaginary structure created purely for mathematical purposes and which it is hardly expected will be realized by the actual inclosure of New York and Chicago in such a metallic mass.

Let us next, still in imagination, carve away the greater bulk of our huge mass of metal in such a way as to leave only a ladder-shaped structure of this metal extending from New York to Chicago, as shown in Fig. 10. It is still true of the ladder-shaped structure, as of the egg-shaped mass, that telephonic waves may be transmitted by means of it from New York to Chicago without distortion provided the relationship $m\,k = c\,\mu$ be still maintained.

Let us now suppose the uprights of our ladder to become simply two wires of our conducting and magnetic metal extending from New York to Chicago and the rungs to become fine wires of the same metal bridged across at frequent intervals. Suppose also at the New York end we connect the terminals of a telephone T_1 to the wires w_1 and w_2 and that we similarly connect a telephone T_2 at the Chicago end, all as shown in Fig. 11. We have a metallic ladder which forms a telephone-circuit between a telephone T_1 at New York and a similar telephone T_2 at Chicago.

In order to determine the necessary mechanical, electrical, and magnetic dimensions to be given to our ladder-circuit that it may transmit telephone-waves without distortion, I shall next express the above equation 1 in more concrete and available terms. For convenience I shall first suppose the rungs or cross-wires to become exceedingly small and to be placed close together, so that they form a mere conducting-film connecting together the wires w_1 and w_2. We shall see later that it is immaterial in practice whether these rungs be fine and close together or coarse and far apart, provided their distance apart is not greater than a certain limit then to be determined and which does not concern us at this stage.

Let us now consider the electric and magnetic relations between the different parts of our ladder-circuit per unit of length of the ladder. Let C be the telephonic electric conductance along the two main wires, M be the telephonic magnetic conductance between the two main wires, K be the telephonic electrostatic capacity between the two main wires, L be the telephonic magnetic inductance along the two main wires, all of course expressed in absolute units of the centimeter, gram, second, system.

The modifying term "telephonic" is here prefixed to each of the above quantities and the symbols of the quantities are written in italics, because in general these quantities are not at all numerically equal to "ordinary" conductance, capacity, and inductance as ordinarily measured by the Wheatstone bridge and tabulated in books. They are the conductance, capacity, and inductance that the circuit possesses for telephonic waves—that is, for waves of such frequency and intensity as are essential to telephone conversation—and which may of course be measured by suitable methods, if we desire. I shall, however, presently give the relationships that exist between these telephonic quantities and their corresponding ordinary quantities as usually dealt with in practice, so that we may be able to measure and calculate by familiar methods and with available data in ohms, mhos, farads, and henries.

Now instead of the electric conductivity c of equation 1 we may write the telephonic electric conductance C, instead of the magnetic conductivity m we may write the telephonic magnetic conductance M, instead of the dielectric inductivity k we may write the telephonic electrostatic capacity K, and instead of the magnetic permeability μ we may write the telephonic magnetic inductance L, giving as the relationship

$$M\,K = C\,L \quad (2.)$$

Further, instead of the telephonic electric conductance C we may write its equivalent $\frac{1}{R}$ and instead of the telephonic magnetic conductance M we may write its equivalent $\frac{1}{S}$ where R is the telephonic electric resistance of the main wires per unit of length of the ladder and S is the shunting electric conductance or shuntage of the film between the wires per unit of length of the ladder. The equation now becomes

$$R\,K = S\,L \quad (3.)$$

So that in a ladder-circuit when the product of the telephonic resistance of the main wires by their telephonic electrostatic capacity is equal to the product of the telephonic inductance of the main wires by their telephonic shuntage, telephone-waves of all sizes and shapes will be transmitted along the circuit with the same velocity, telephonic transmission will be absolutely without distortion, and attenuation will be reduced to a minimum. It should be remembered that R is the resistance of both main wires—that is, twice the resistance of one wire—and similarly that L is the inductance of both main wires, (twice the inductance of one wire:)

I shall next state the relationships that exist between the telephonic resistance, capacity, inductance, and shuntage R, K, L, and S and ordinary resistance, capacity, inductance, and shuntage as ordinarily measured and tabulated in books. I will designate these ordinary quantities, respectively, R, K, L, and S, these quantities being of course expressed in absolute units of the c. g. s. system. Let μ equal permeability of the wire; n equal pitch or number of vibrations of telephone-wave; p equal $2\,\pi\,n$; a equal radius of wire; b equal distance between centers of two wires of the circuit. Then

$$R = \mathrm{R}\left[1 + \frac{1}{12}\frac{\mu^2 p^2}{\mathrm{R}^2} - \frac{1}{180}\frac{\mu^4 p^4}{\mathrm{R}^4} + \&\mathrm{c}\ldots\ldots\right] \quad (5.)$$

$$L = 4\log_e \frac{b}{a} + \mu\left(\frac{1}{2} - \frac{1}{48}\frac{\mu^2 p^2}{\mathrm{R}^2} + \frac{13}{8640}\frac{\mu^4 p^4}{\mathrm{R}^4} - \&\mathrm{c}\ldots\ldots\right) \quad (6.)$$

These equations are sufficiently expanded for all ordinary usage, and, indeed, it will usually be found that the last term of each becomes insignificant in ordinary use. Should it be desired to expand them to a greater number of terms in order to obtain the desired accuracy for any particular case, we may proceed as follows: Add terms $\frac{\mu^6 p^6}{\mathrm{R}^6}\frac{\mu^8 p^8}{\mathrm{R}^8}$, &c.—*i. e.*, even powers of $\frac{\mu p}{\mathrm{R}}$—until the equations are sufficiently expanded to secure the desired degree of accuracy. Determine the numerical values of the coefficients of these terms by actual algebraic division of $f(x)$ by $f'(x)$, where

$$f(x) = 1 + \frac{x}{1^2} + \frac{x^2}{1^2\,2^2} + \frac{x^3}{1^2\,2^2\,3^2} + \frac{x^4}{1^2\,2^2\,3^2\,4^2} + \&\mathrm{c.} = \sum_{n=o}^{n=\infty} \frac{x^n}{(\mathrm{L}^n)^2},$$

$$f'(x) = o + 1 + \frac{2\,x}{1^2\,2^2} + \frac{3\,x^2}{1^2\,2^2\,3^2} + \frac{4\,x^3}{1^2\,2^2\,3^2\,4^2} + \&\mathrm{c.} = \frac{d}{dx}[f(x)],$$

noting that alternate numerical coefficients continued in the order shown in 5 and 6 apply to R and L and that the coefficients of $\frac{\mu p}{\mathrm{R}}$ having powers of two, six, ten, &c., (but not four, eight, twelve, &c.,) must change their signs. For those who prefer the use of higher mathematics and may desire to inquire into the relationships between R and R and L and L in unusual cases these relationships, although fully expressed by the above equations 5 and 6 when sufficiently expanded, may be more conveniently considered by means of Bessel's Functions, which are defined by infinite series of the form closely related to $f(x)$ and $f'(x)$, as above defined. Without going into the demonstration in detail it may be shown that

$$R = \mathrm{R}\frac{x}{2}\frac{\mathrm{ber}\,x\,\mathrm{bei}'\,x - \mathrm{ber}'\,x\,\mathrm{bei}\,x}{(\mathrm{ber}'\,x)^2 + (\mathrm{bei}'\,x)^2} \quad (5\text{ A.})$$

$$L = 4\log_e \frac{b}{a} + \frac{x}{2\,\chi\,p}\frac{\mathrm{ber}'\,x\,\mathrm{ber}\,x + \mathrm{bei}\,x\,\mathrm{bei}'\,x}{(\mathrm{ber}'\,x)^2 + (\mathrm{bei}'\,x)^2} \quad (6\text{ A.})$$

In the above x equals $2\sqrt{\frac{\mu p}{\mathrm{R}}}$, χ equals conductivity, "ber" indicates the real part of the Bessel Function, "bei" indicates the coefficient of $\sqrt{-1}$ in the imaginary part of the Bessel Function, and "ber′" and "bei′" indicate that these terms are to be differentiated.

From tables of Bessel's Functions we may determine the values of R and L for any given case. We may, if desired, obtain analogous

expressions for inductive shuntage directly from equations 5 and 6 or 5A and 6A; but as we soon find that in practice non-inductive shunts are used, we may write

$$S = \mathrm{S} \quad (7.)$$

The telephonic electrostatic capacity is equal to the ordinary electrostatic capacity measured for exceedingly small time charge, so that possible errors due to electric absorption are eliminated. In other words, it is equal to the true electrostatic capacity. We may therefore write

$$K = \mathrm{K} \quad (8.)$$

Equation 3 is generally applicable to circuits of iron, steel, aluminium, copper, alloys, or, indeed, any conducting material, and to pole-lines or to cables in which any kind of insulating material is used. Together with equations 5 to 8 we are enabled to calculate the necessary dimensions of any circuit in ordinary ohms, mhos, farads, and henries.

The relationships revealed by equations 5 and 6 when embodied in the construction of circuits in the manner directed by equation 3 are of the very essence of my invention. The equations 5 and 6 are full of information, and they may be utilized in many ways. I shall presently fully illustrate two fundamental uses of these equations, in connection with equation 3, by applying them to the construction of distortionless circuits. I shall first show how by means of the relationships shown in 5 and 6 we may choose wires of such materials and give these wires such dimensions that when incorporated into a distortionless circuit the telephonic resistance and inductance become practically equal to the ordinary resistance and inductance. Secondly, I shall make use of these equations to show how, desiring to construct a distortionless circuit out of wires whose telephonic resistance and inductance are widely different from their ordinary resistance and inductance, we may by means of the relationships shown in the equations give to these wires such dimensions in ordinary inches, ohms, henries, and farads that when incorporated into the circuit in the manner directed by equation 3 we shall obtain a circuit free of distortion and with minimum attenuation.

Besides the above two specific uses of equations 5 and 6 we shall find as we get on in this specification that we are continually looking to them for information and continually making application of this information. Thus these equations show us that materials and dimensions of wires that might be quite impossible to use for the transmission of a series of similar sinusoidal undulations of very high periodicity may be excellently adapted to the transmission of telephone-waves in which the frequencies of the vibrations transmitted and the resultant frequencies that determine the characteristic changes in pitch and loudness that constitute the intelligibility of speech are of comparatively low periodicity. These equations show us the advantages of using metallic wires of very low magnetic permeability over wires of very high permeability, and that therein, far more than in difference of ordinary resistance, lies the superiority of copper to iron in circuits as heretofore constructed; but they also show the very great advantage of using wires having a medium permeability so chosen that we may materially increase the telephonic inductance of the circuit without materially increasing its telephonic resistance. This I shall fully illustrate by a concrete example. When read together with equation 3, these equations show the great advantage of using a wire of large and constant telephonic inductance combined with small and constant telephonic resistance, and they enable us to determine quantitatively to what extent these desiderata may be attained with specific constructions. I shall presently show how by sheathing a non-magnetic wire of proper size with a coating of properly chosen and prepared magnetic metal we may materially increase the uniformly-distributed telephonic inductance of the wire without materially increasing its telephonic resistance, and I shall further show how we may approximate the same result and construct an approximately distortionless circuit of high inductance by inserting inductance-coils into a copper wire at properly-determined intervals, together with shuntage in such amount that the requirements of equation 3 shall be substantially fulfilled.

Coming now to the use of specific materials as line-wires in the construction of a distortionless ladder-circuit, we see, by introducing the known values into the second members of equations 5 and 6, that a copper wire, whose value of μ is unity and, say, of No. 12 gage, so that $\mathrm{R} = 5.7 \cdot 10^4$, has, for telephonic waves of such frequency as we have found to be essential for good telephonic conversation, a telephonic resistance and inductance substantially equal to its ordinary resistance and inductance, so that for this case, though it may not be at all true of other materials or even for widely-different sizes of copper, we may write $R = \mathrm{R}$ and $L = \mathrm{L}$. Copper wire of this size has excellent conductance for telephone-waves and has already been very largely used in long-distance telephony, but its inductance is very small. I have discovered that by nickel-plating the copper wire and, still better, by annealing the nickel-plated wire down to freezing temperature we may give the wire a greatly-increased and constant inductance toward telephone-waves, while still maintaining substantially the same low and constant resistance. The nickel-plating may be very thin,

few or many thousandths of an inch, according to the inductance desired, and excellent results may be had by plating the wire first with pure iron and then with nickel or with an alloy of about five per cent. of nickel and the rest of pure iron. The increased inductance arises from the fact that the nickel, or iron and nickel, affords, at all points along the path of the telephone-wave that travels along the copper wire, an annular path of high and constant magnetic permeability and low and constant magnetic resistance for magnetic waves of telephonic frequency and intensity. Equation 5 tells us that the electrical resistance of the wire is not substantially changed toward telephone-waves, because the area of cross-section of the nickel is small compared with that of the copper and because the nickel, although it has a considerable magnetic permeability, has also a large electrical resistance. The above-stated facts have also been amply confirmed by experiment. Indeed, these nickel-copper wires are when used in my ladder-circuit for long distances superior to much larger wires of plain copper, while their cost is much less than the larger copper wires. We shall presently see that the application of the various features of the ladder-circuit to a general system of telephony throughout the length and breadth of the country would result not only in clear and distortionless telephony, but in a saving in investment of large sums of money over what would be necessary if present methods of long-distance construction be adhered to.

Provided we use nickel-copper wire or plain copper wire or, indeed, any wire of low resistance and low permeability (though it may have high inductance) in our ladder-circuit, I find that the telephonic resistance and inductance are for practical purposes the same as the ordinary resistance and inductance, so that we may write $R = \mathrm{R}$ and $L = \mathrm{L}$. Provided we make the shunts of non-magnetic material, we may also write $S = \mathrm{S}$. Thus I have found that in practice each bridge may conveniently consist of plumbago rubbed upon the surface of paper in sufficient amount to afford the desired conductance, the paper being then coated with varnish or covered with mica to protect it from moisture, and the whole being bridged in between the line-wires and properly boxed in upon the cross-arm to afford protection from the weather. We have already seen that we may write $K = \mathrm{K}$. Our formula therefore for the above-described construction becomes

$$\mathrm{R\,K = L\,S} \quad (4.)$$

This formula must, however, always be used with discretion, always looking back for safety to equations 5 to 8 if any new element is introduced.

I will now make an application of my invention as thus far disclosed to a particular case. I will show the concrete numerical dimensions that may be given to a ladder-circuit to insure its transmitting undistorted conversation between New York and Chicago. Since the relationship $\mathrm{R\,K = L\,S}$ is an equation in which each term is the product of two factors, it is clear that we may give a wide variety of values to each term and still have distortionless telephony, so long as the proper relationship between them is maintained. Thus if K and L were fixed, as they practically have been hitherto in telephone construction, we might build a distortionless circuit by making R small and S small—*i. e.*, by using very large copper line-wires and very small shuntage, or we might equally well attain distortionless telephony by using much smaller line-wires, provided we introduce proper conductance at the bridge-wires; but the difference in cost between large line-wires and small line-wires is enormous, while the cost of the shunts is trifling, so that minimum cost becomes a very important factor in determining what values of R, K, L, and S had best be used.

We must of course always so choose our values that the attenuation shall not be a serious matter; but I shall presently show that this becomes in practice a comparatively simple matter. We will call the distance between New York and Chicago one thousand miles. We will use No. 12 copper wire, nickel-plated with an alloy presently to be described to a thickness of about one one-hundredth of an inch. We will suspend the wires twenty inches apart on poles, and at intervals of ten miles we will cross-connect the two line-wires by means of a plumbago resistance of thirty-six thousand three hundred ohms. Such a circuit will be distortionless and will have so small an attenuation that conversation may be carried on over it with the greatest ease. Following are the data more in detail: resistance of line-wire 4.59 ohms per mile equal 2.85 ohms per kilometer, or, since there are two wires in the circuit, 5.7 ohms per kilometer of the ladder equal $5.7 \cdot 10^{5}$ centimeter gram second units. Inductance of both wires .0248 henries per mile equal .0155 henries per kilometer equal one hundred and fifty-five centimeter gram second units. Capacity of line .0075 microfarads per mile equal .0047 microfarads per kilometer equal $47 \cdot 10^{-24}$ centimeter gram second units. Shunt conductance .00000276 mhos per mile equal .00000173 mhos per kilometer equal $1.73 \cdot 10^{-20}$ centimeter gram second units. Inserting these values in equation 4 for a distortionless line we have

$$\mathrm{R\,K = L\,S} \quad (4)$$

or

$$5.7 \cdot 10^{5} \cdot 47 \cdot 10^{-24} = 155 \cdot 1.73 \cdot 10^{-20}$$

or

$$268 \cdot 10^{-20} = 268 \cdot 10^{-20}$$

The two products being equal, the line is dis-

tortionless. The attenuation on the line is represented by

$$e^{-\alpha l} \quad (9,)$$

in which e is the base of the naperian system of logarithms equal 2.718; l is the length of the line in centimeter gram second units, and α is calculated from the equation

$$\alpha = \frac{R}{L}\sqrt{L\,K} \quad (10.)$$

Substituting the above-given values of R, L, and K in equation 10, we find $\alpha = 3.14 \cdot 10^{-8}$, and substituting this value and the value of $l (= 1.6 \cdot 10^{8}$ centimeter gram second) in equation 9 we find that the attenuation is one one-hundred-and-fifty-second—that is, the waves arriving at the receiving end are still one one-hundred-and-fifty-second as strong as those at the transmitting end, which is ample to allow of excellent commercial conversation.

I will now show dimensions that may be given to a cable in accordance with my invention.

Let the cable be one hundred miles in length. We will use wires of approximately No. 20 gage, having a resistance of 45.9 ohms to the mile, and sheath them with nickel-iron alloy to an inductance of .248 henries per mile. We will twist the two wires of the cable about each other and space them so that the mutual capacity is .075 microfarads per mile. At intervals of a mile we will cross-connect the two wires through a plumbago resistance of thirty-six thousand three hundred ohms. Following are the data more in detail: resistance of one wire equal 45.9 ohms per mile equal 28.5 ohms per kilometer, or for both wires equal 57 ohms per kilometer equal $57 \cdot 10^{4}$ c. g. s. Inductance equal .248 henries per mile equal .155 henries per kilometer equal fifteen hundred and fifty c. g. s. Capacity of line equal .075 microfarads per mile equal .047 microfarads per kilometer equal $470 \cdot 10^{-21}$ c. g. s. Shunt conductance of line equal .0000276 mhos per mile equal .0000173 mhos per kilometer equal $17.3 \cdot 10^{-20}$ c. g. s. units. Inserting these values in equation 4 for a distortionless line we have

$$R\,K = L\,S$$

or

$$57 \cdot 10^{4} \cdot 470 \cdot 10^{-24} = 1550 \cdot 17.3 \cdot 10^{-20}$$

or

$$268 \cdot 10^{-18} = 268 \cdot 10^{-18}$$

The two products being equal, the line is distortionless. Calculating the attenuation, we have in this case

$$\alpha = 3.14 \cdot 10^{-7}, l = 1.6 \cdot 10^{7}, \text{and } e^{-\alpha l} = 1/152,$$

which allows excellent conversation. It may be noted here that had plain copper or iron wires been used in this cable instead of nickel-copper wires and had the leakage-bridges been omitted the distortion on this cable would alone have rendered the conversation absolutely unintelligible and the attenuation would have been many times as great. Telephony would have been impossible, as, indeed, experience has amply shown.

Suppose now we wish to arrange a circuit between New York and Chicago to be made up in part of pole-line and in part of cable. Suppose, for example, we enter New York by ten miles of cable, Chicago by another ten miles of cable, and that we have numerous river-crossings and underground lines through various cities along the route, aggregating, say, another five miles of cable, all of this twenty-five miles of cable to be added to, say, one thousand miles of pole-line to complete the circuit from New York to Chicago. Note now that the resistance, capacity, inductance, and shuntage per unit of length—say per mile of the above cable—are each the same multiple (in this case ten times) the corresponding quantities of the pole-line, so that one mile of cable has all of the electrical dimensions of ten miles of pole-line. It is exactly as if we had telescoped ten miles of pole-line into one mile of cable, or, in the case of the New York and Chicago line, two hundred and fifty miles of pole-line into twenty-five miles of cable. In this case, and generally when the cable constants and pole-line constants bear a definite ratio, there will be no reflection at any junction of cable and pole-line. There will be no distortion on the circuit. The telephone-waves arriving at the receiving end of the circuit will still be one five-hundred-and-thirtieth as strong as they were at the transmitting end, which is ample. Over such a line we shall have good, clear, loud telephonic communication.

The reflection of telephone-waves in circuits as ordinarily heretofore constructed every time they pass into or out from each of the many little cables distributed along a line not only result in loss of energy, but by their repeated surgings to and fro largely distort and obliterate the normal telephone-waves.

Instead of sheathing a copper wire with nickle or iron to increase its inductance we may give a circuit of copper wire increased and approximately uniformly distributed telephonic inductance by inserting inductance-coils in series with the conducting-wires at sufficiently-frequent intervals along the line, provided the shuntage, resistance, and capacity be such as to approximately fulfil the relationship $R\,K = L\,S$ for the completed circuit.

The directions already given are quite sufficient to enable us to calculate the amount of inductance that may be profitably used, and

I shall now give the method of determining the intervals along the line at which the coils should be placed.

The problem of the most efficient distribution of inductance-coils in a telephone-circuit has seemed to others one that having merely data as to the resistance, inductance, and capacity of the line could be easily solved by purely mathematical processes, and rules have been published, following which it is said we may determine the proper distribution in all cases. I have not found these rules applicable to all cases or, indeed, to such actual cases of long-distance pole-lines, as it is most desirable that coils be used, and, indeed, in some very practical cases I find that, following the rules, the inductance-coils sometimes do more harm than good.

If the electrical waves transmitted be a continuous series of similar sinusoidal undulations of known frequency—as, for instance, may be the case in the electrical transmission of power to great distances by rapidly-alternating currents—then it is easy to attain a high efficiency by calculating the wave length and distributing the coils in a determined ratio to this wave length; but we have seen that telephone-waves are not a continuous series of similar sinusoidal undulations of known frequency. On the contrary, we have seen that it is upon the characteristic manner in which the frequency and amplitude of the undulations change during a syllable that the intelligibility of the syllable depends, and we have seen that the product of the telephonic resistance and capacity of the circuit must be equal to the product of its telephonic inductance and shuntage in order that these waves shall not be distorted.

I have had in my laboratory for many years artificial telephone-lines so constructed that their resistance, capacity, inductance, and shuntage can each be varied as much as we please, so that with this apparatus it becomes easy to exactly reproduce the electrical dimensions of any existing telephone-line or to actualize any ideal telephone-line. Results obtained with these artificial circuits have been so many times and in such widely-different ways found to agree with results obtained on actual lines extending between widely-different cities as to make it quite certain that the artificial lines are, so far as all electrical properties are concerned, equivalents of actual lines. By means of these artificial lines I have been able to make an extended study of the effects of introducing coils of various inductances distributed at various intervals throughout circuits the product of whose telephonic resistance and capacity was made equal to the product of their telephonic inductance and shuntage as well as the effect of such coils in circuits where this balance was not maintained. I may say here that I find that at least the approximate attainment of this balance is of very great importance in high-inductance circuits; but my purpose at the present moment is to disclose the empirical rule for the proper distribution of inductance-coils in distortionless circuits that has resulted from these experimental investigations. Let D equal distance apart of the coils in centimeters; L equal inductance of the circuit in c. g. s. units, including the normal inductance of the line and the added inductance due to the coils; K equal capacity of the circuit in c. g. s. units; A equal a numerical constant equal seven thousand five hundred. Then

$$D = \frac{1}{A\sqrt{LK}} \quad (11)$$

will be the formula for determining the distance apart the coils are to be placed.

Knowing the total inductance that it is desired that the circuit shall possess when the coils are added and the distance apart of the coils, it is of course simple arithmetic to determine the inductance to be given to each coil. It is of course desirable that the inductance of the coil should be large relative to its resistance and that there should be a minimum loss due to Foucault currents and to hysteresis; but all of this is a matter of common engineering practice. Of course, too, the R of the coils should be added to the normal R of the circuit in using the formula

$$RK = LS \quad (3.)$$

The equation 11, introducing a value of A equals seven thousand five hundred, is a good practical rule for spacing coils and is applicable to either pole-lines or cables of widely-varying dimensions; but the empirical constant A does not have a rigidly-fixed value for any particular case. If A is made much smaller, so that the interval between the coils becomes much larger, we shall introduce very serious distortions; but A may be increased indefinitely—that is, the space between the coils may be indefinitely reduced, of course simultaneously reducing the inductance of each coil, with the result that the already slight distortion grows continually less, although in a continually less degree. In fact, we thus approach the condition of uniformly-distributed inductance. The objection to such multiplication of coils lies in the increased expense and the greater liability to faults due to so great complication, while the increased benefit is practically very small.

The same empirical rule that has been given for coils is applicable to the determination of the intervals at which the shunts should be placed, although I find that on pole-lines, where there is a variable weather leakage, the shunts may be profitably inserted more frequently than the coils, and since the expense of these shunts is exceedingly small this practice is to be recommended. This rule being

purely empirical may not be found to be applicable to extreme cases—such, for instance, as trans-Atlantic telephony; but I find that it is applicable to cables and pole-lines of such dimensions as are now in use or as commercial considerations are likely to cause to come into use. In order to illustrate the use of this empirical rule, I will apply it to a mixed cable and pole-line having the dimensions above given to the New York and Chicago circuit, but supposing the increased inductance now to be attained by introducing coils into a No. 12 copper wire instead of sheathing the wire with iron and nickel. The desired inductance L for this circuit we found to be for the pole-line one hundred and fifty-five centimeter gram seconds and for the cable fifteen hundred and fifty centimeter gram seconds. The capacity of the pole-line we found to be $47 \cdot 10^{-21}$ and of the cable $470 \cdot 10^{-21}$. Introducing these values and the value A equal seven thousand five hundred into equation 11 we find for the pole-line

$$D = \frac{1}{7500\sqrt{155 \cdot 47 \cdot 10^{-21}}} = 15.7 \cdot 10^{5} \text{ cm.} = 10 \text{ miles (approximately)}$$

and for the cable

$$D = \frac{1}{7500\sqrt{1550 \cdot 470 \cdot 10^{-21}}} = 1.57 \cdot 10^{5} \text{ cm.} = 1 \text{ mile (approximately)}$$

so that we should obtain an approximately distortionless circuit by inserting inductance-coils of .248 henries at intervals of ten miles along the pole-line and of one mile along the cable and then so adjusting the conductance of similarly-distributed plumbago shunts that $R K = L S$.

The rule for the distribution of coils and shunts, now that we have found it by experiment, may be expressed in less empirical terms. The length of any telephone-wave in a distortionless circuit, but not in other circuits, is expressed by the formula

$$\lambda = \frac{1}{n\sqrt{L K}} \quad (12,)$$

in which n is the number of vibrations per second or pitch of the sound transmitted, and L and K have the same meaning as above.

Now the second members of equations 11 and 12 are alike, excepting that 11 has the coefficient A equals seven thousand five hundred and 12 has the coefficient n equals number of vibrations per second equals pitch of sound transmitted. By assigning a value to n therefore we may express D directly in terms of λ. Further, I have found from experiments on the reflection of sound-waves propagated in speaking-tubes a case closely analogous to the propagation of electrical waves in a wire; that whereas points of discontinuity at intervals $= \lambda$ gave rise to resonance, at intervals of $\frac{\lambda}{2}$ to interference, and at intervals of $\frac{\lambda}{4}$ to serious distortion, the distortion disappears very rapidly at fractional intervals of $\frac{\lambda}{4}$. Now we have already seen that the highest pitch of the telephone-waves essential to telephony is 1024. Substituting this value of n in equation 12 and expressing D in terms of $\frac{\lambda}{4}$ we have $D = \frac{1}{2} \cdot \frac{\lambda}{4}$ (approximately,) and from the allowable variability of A, found by our experiments on telephone-circuits, it follows that D may have any smaller value we see fit to pay for.

Our rule may now be expressed as follows: In a telephone-circuit, the product of whose telephonic resistance and capacity is equal to the product of its telephonic inductance and shuntage, the intervals between successive inductance-coils should be a fractional part of the quarter-wave length of the highest-pitched wave essential to good telephonic conversation. The same rule is applicable to the distribution of shunts. The numerical value of the quarter-wave length may be determined either by measurement or by calculation from equation 12. It should also be noted that in the ladder-circuit any slight distortion that may be introduced into the line because of the use of non-distributed instead of distributed inductance may be compensated by a corresponding adjustment of the shunt-conductance.

The present long-distance circuits of plain copper may very easily be converted into ladder-circuits and cleared of all distortion by the introduction of proper shuntage. Thus the present circuits of No. 12 copper wire in use by the American Telephone & Telegraph Company have a wire resistance of 5.28 ohms per mile. The mutual capacity between the two wires is about .0075 microfarads per mile. The inductance of both wires is about .0038 henries per mile. From equation 4 we find that the shuntage should be about .0000198 mhos per mile—that is, there should be introduced a shunt of about five hundred and five thousand ohms every ten miles. The line thus modified will be distortionless and we shall be able to talk far more clearly and to a much greater distance.

In new construction it would be much bet-

ter to use the nickel-copper wire, because while it retains all of the advantages of clearness the attenuation is so much less that we shall be able to talk much farther than with the plain copper wire; but we may by the proper introduction into the present plain copper-wire circuits of both shunts and inductance-coils maintain an approximately distortionless circuit and greatly extend the distance over which we may converse. The above equations furnish ample directions for so improving existing lines.

Aluminium wires may be conveniently and economically used in my ladder-circuit, either plated or sheathed with iron or nickel, to give them an increased and uniformly-distributed inductance or with inductance-coils inserted at intervals, as directed by equation 11.

Iron and steel wires are very largely used in telephony, particularly for limited distances and for terminal circuits, and the use of these materials is very desirable for mechanical and economic reasons. In fact, it is very rarely that a telephone connection is made up between two subscribers that some portion of the circuit is not composed of these metals. I will therefore show briefly how ordinary iron and steel wires may be advantageously used by practicing my invention, and will also show how by a slight and inexpensive alloying iron and steel wires may be given properties that especially adapt them to be used as a part of the invention.

The equation now to be used in calculating the dimensions for a distortionless circuit is not the limited equation 4 that we found applicable in the case of the nickel-plated copper wires; but the more general equation

$$R\,K = L\,S \quad (3,)$$

since in ordinary iron and steel wires the telephonic quantities are not in general equal to the ordinary quantities as measured for non-magnetic wire.

The telephonic resistance and inductance of the iron and steel wires differ from the ordinary resistance and inductance that we have found sufficient to use in calculating copper wires, chiefly because of the greatly-increased permeability of iron and steel, which telephonic permeability—that is, permeability toward waves of telephonic shape and magnitude—although varying with the particular specimen of the metal used may for practical purposes here be taken to have a value of one hundred. The telephonic capacity and shuntage are of course, as above, equal to the ordinary capacity and shuntage.

Applying equations 5 and 6 to a large iron wire—say No. 2—which has an ordinary resistance substantially equal to the ordinary resistance of the smaller No. 12 copper wire that we have found suitable for use in long-distance telephony, we find that R is some four times R and very variable with slight changes of period and permeability, while L is not substantially increased over L of a non-magnetic wire. If we apply the equation to a still larger wire, the ratio of R to L and its variability with period and permeability becomes even greater, so that we see right away that large wires of ordinary iron are not suitable for long-distance telephony. If, however, we apply our equations 5 and 6 to a much smaller wire—say a No. 16—we find that R is larger than R by less than one per cent. and is only slightly variable with telephonic periods and permeability, while L is about three times as large as L of a non-magnetic wire. Since the wire is small, K, too, is small. It is of course easy, by means of the equation 3, to adjust S. It thus appears that by using very small iron wires we may readily construct a distortionless circuit, and, moreover, a circuit which for the size of wire used is very efficient—indeed, fully half as efficient as a copper circuit of the same size of wire. Of course the attenuation in a No. 16 wire, whether of copper or iron, quite unfits it for use in very long distance circuits; but for stretches of fifty miles the attenuation is very small, and the circuit may be made beautifully clear of distortion.

I have confirmed the above dictates of equations 5 and 6 by making an experimental comparison between a circuit of very large iron wire—about No. 4—and a circuit of very small iron wire—about No. 16—both extending between two cities about fifty miles apart. It was found that the ordinary commercial conversation between subscribers in the two cities was carried on with greater ease and less frequent repetition over the smaller wires.

The above-chosen sizes of wire are of course extreme cases. I will show the application of the invention to the construction of a distortionless circuit built of No. 12 iron wires strung twenty inches apart on poles. The permeability of the wire is taken at one hundred and the frequency is taken at five hundred, which is an octave above the usual average frequency of a man's conversational voice. The ordinary measured resistance of this wire is thirty ohms per mile, or 18.6 ohms per kilometer, so that for both wires $R = 3.6 \cdot 10^5$ centimeter gram second.

From equation 5 we calculate the telephonic resistance $R = 3.82 \cdot 10^5$, which is 1.06 times R. From equation 6 we calculate the telephonic inductance $L = 69$, which is nearly three and a half times the ordinary inductance of a non-magnetic wire. We have seen that

$$K = \mathrm{K} = 47 \cdot 10^{-24}.$$

From equation 3 we calculate

$$S = \frac{R\,K}{L} = 26 \cdot 10^{-20}$$ centimeter gram second or .000042 mhos per mile. The value of α in this circuit is $= \frac{R}{L}\sqrt{L\,K} = 10^{-7}$. The atten-

uation for one hundred miles is only to one one-hundred-and-fiftieth, which is very small, so that, provided we build our wire into a distortionless ladder-circuit, we shall get first-rate telephony for distances not exceeding one hundred miles. Of course we should have to use iron or steel, in which the permeability does not vary greatly from one hundred; but such wire is commonly in use and is easily selected.

It appears from the foregoing that the value of μ is a very important factor in the use of iron and steel in telephone-circuits.

It is well known that different kinds of iron and steel wires possess normally quite different values of μ, some having a much higher value than one hundred and some a lower value.

Now we may give an iron or steel wire any (decreased) fixed value of μ we please by alloying with it a small percentage of manganese or any of the numerous metals that are well known to render iron and steel less magnetic without seriously affecting their conductivity. Such alloys have most superior mechanical properties and are not expensive to produce. By thus decreasing μ to a lower value than the unalloyed wire possesses we may retain the advantage of such telephonic inductance as the new value of μ allows and at the same time increase the size of the wire without unduly increasing or affecting the stability of the telephonic resistance, and what we have already seen is of great importance. We obtain a wire not only of increased inductance, but of uniformly-distributed inductance, so that the difficulties introduced by inserting inductance-coils into copper wire do not now arise.

The method of applying the above equations to the calculation of the most advantageous electrical and mechanical dimensions to be given to a distortionless circuit built of materials whose telephonic properties are different from their ordinarily-measured electrical properties has already been sufficiently illustrated. Much valuable information may be had by inserting different values of μ into equations 5 and 6 and using the values of R and L thus obtained to calculate the dimensions of distortionless circuits and the attenuation of such circuits, particularly if we keep in mind the always important question of pecuniary cost of telephone construction. As a concrete illustration, attention is called to the fact that these equations show us that by adding to iron only the small percentage of manganese necessary to reduce its permeability to ten, thereby increasing its steady resistance only by about ten per cent., we produce a manganese steel of great tensile strength and durability, from which we may easily construct a telephone-circuit five hundred miles in length, over which, together with the necessary cables, we may carry on practically undistorted conversation and with very little attenuation.

In plating or sheathing copper or aluminium wires it is of course desirable to use a metal having both high and constant magnetic permeability for currents of telephonic intensity. I have made a considerable study of the magnetic permeability of various metals and alloys when magnetized by currents of the order of magnitude of those used in telephony and also when subjected to actual telephone-currents. I find that pure nickel and pure iron, particularly when electrochemically deposited and then annealed down to 0° centigrade, possess a very high and constant permeability for telephonic currents. I find that an alloy of the two consisting of a small percentage (say five per cent. or less) of nickel and a large percentage of iron is excellently adapted to my purpose. I also find that a sheath of high and constant permeability is obtained by electrically depositing upon the conducting-wire a coating, first of iron and then of nickel, in the above-described proportions and then annealed, as described.

In Figs. 12 and 13 I have shown two forms of apparatus that I have found by experience are suited to use as shunts in my ladder-circuit. They are non-inductive and their conductivity does not change considerably with weather or with time.

Fig. 12 consists, essentially, of a plumbago film P*b* (more or less wide and thick according to the conductance desired) spread upon a sheet of dry paper P*p*, which is in turn spread upon the face of the wooden block W*d*. B*p* B*p* are binding-posts having platinum faces where they make contact with the two ends of the plumbago film. The film is protected from the weather by a mica cover M*k*, held tightly in place by the brass frame B*r*. This apparatus is shunted into the main-line wires of the circuit by the connecting-wires S_1 S_2, as shown in Fig. 14.

An alternate form of shunt is shown in Fig. 13. This consists, essentially, of a conducting-rod C*l*, made by baking a mixture of clay and sugar water, (the proportions being varied according to the conductance desired.) The two ends of the rod are plated with copper C*u* C*u*, so that the terminal wires S_1 S_2, by means of which the rod is shunted into the circuit, make good electrical contact with the rod. The whole is sealed into a glass bottle G*l* to protect it from the weather. The apparatus is hunted into the circuit, as shown in Fig. 14.

In cable-circuits the conductivity of the insulating material between the wires may often be used as shuntage. I find by experiment that the so-called "insulating" material or dielectric used in ordinary telephone-cables often possesses and may always readily be given a conductivity such as to allow of its use as shuntage, which, together with the in-

ductance, particularly when the inductance has been increased by the above-described methods, is sufficient to balance the resistance and capacity to such an extent that the distortion is practically eliminated and the attenuation reduced to a minimum.

Before leaving the subjects treated in the foregoing part of this specification I wish to point out that while the relationship

$$R K = L S \quad (4)$$

or the more general relationship

$$R K = L S \quad (3)$$

expresses with mathematical accuracy the ideal condition toward which we should strive if we desire to construct a telephone-circuit absolutely free of distortion and with minimum attenuation the purpose of the invention is often attained with a sufficient absence of distortion and attenuation for practical purposes even when the numerical equality of the two products is considerably departed from. Considerations of expense and convenience sometimes make it desirable to construct circuits in accordance with the general direction of this rule rather than to apply it with mathematical accuracy.

In order that the telephone engineer to whom this specification is addressed may be able to determine in any particular case how far the equality between the four electrical quantities may be departed from by varying any one or more of them to meet some demand—say of convenience or expense—without introducing serious distortion or attenuation, I here give the necessary equations together with directions for using them. The symbols are all such as have been defined above, excepting that v_g and $e_g^{-\alpha l}$ here represents the velocity and attenuation of a telephone-wave in any kind of a telephone-circuit, while v_d and $e_d^{-\alpha l}$ represent the velocity and attenuation of a telephone-wave in a distortionless telephone-circuit only. Equation 17 is the simplification of equation 15, and equation 18 is the simplification of equation 16 for the particular case of a distortionless circuit.

$$v_g = \frac{2\pi}{n\sqrt{\frac{1}{2}\left[(R^2+p^2L^2)^{\frac{1}{2}}(S^2+p^2K^2)^{\frac{1}{2}}-(RS-LKp^2)\right]}} \quad (15.)$$

$$e_g^{-\alpha l} = e^{-l\sqrt{\frac{1}{2}\left[(R^2+p^2L^2)^{\frac{1}{2}}(S^2+p^2K^2)^{\frac{1}{2}}+(RS-LKp^2)\right]}} \quad (16.)$$

$$v_d = \frac{1}{\sqrt{LK}} \quad (17.)$$

$$e_d^{-\alpha l} = e^{-l\frac{R}{L}\sqrt{LK}} \quad (18.)$$

Having decided on the values of R, K, L, and S necessary for a completely-distortionless circuit, we first determine from 17 and 18 the velocity of propagation and the attenuation of the telephone-waves, which are, as we have already seen, in a distortionless circuit the same for the little high-pitch undulations and the larger low-pitch undulations.

We may now by increasing or diminishing one or more of the four quantities R, K, L, and S to such extent as motives of convenience or expense may seem to make desirable insert these new values into equations 15 and 16 and by solving these equations for telephone undulations of different frequencies determine whether or not such new values have introduced any considerable distortion or increased attenuation, or, more generally, by giving to the four quantities R, K, L, and S each in its turn successively-larger increments or decrements and solving equations 15 and 16 we obtain data which when plotted, say, with frequencies of vibration as abscissas and velocities or attenuations as ordinates enable us to see at a glance in what directions and to what extent equations 3 and 4 may be departed from without introducing serious distortion or attenuation. I have plotted such curves and have also confirmed the more important lessons they teach by experiments both upon artificial and actual circuits. These curves show very markedly the importance of the distortionless circuit in general; but they also show that in particular cases the rule may be considerably departed from. For instance, in cable-circuits in which the inductance has been considerably increased by any of the above-described methods the shuntage required for a distortionless circuit is small and it may be decreased to a fractional part of the amount necessary to rigidly satisfy the equations 3 or 4 without introducing serious distortion or seriously affecting the attenuation; but it cannot be correspondingly increased—that is, it cannot be multiplied several times—without seriously affecting the distortion and attenuation. In pole-lines the shunting action of the weather leakage is large and its great variability with wet and dry weather quite unfits it for use as shuntage to obtain a distortionless circuit, as we shall presently more fully see.

I shall next describe a method of suspending my ladder-like circuit upon poles, that I

find helpful in maintaining a distortionless circuit and also peculiarly adapted to prevent the telephone-waves from leaking into neighboring circuits and to prevent telephone-waves or electrical disturbances from extraneous sources from leaking into it.

It is well known that the insulation of wires carried on poles is far from perfect. In wet weather, particularly, the cross-arms and the surfaces of the insulators all become high-resistance conductors over which more or less current may pass from wire to wire or wire to earth. This conductance is technically called "weather leakage." It should be distinguished from the systematic conductance of the shunts of my ladder-circuit, which I have called "shunt conductance" or "shuntage." The shunt conductance, as we have already seen, is determined and fixed for any given circuit and exists only between the two conducting-wires of each circuit. The weather leakage varies enormously with the weather and extends everywhere. This weather leakage is harmful in circuits as ordinarily suspended upon the poles, because it allows currents to leak from each circuit to all of the others upon the same structure, so that conversation normally taking place upon any one telephone-circuit may be more or less overheard upon other telephone-circuits, and, further, currents from telegraph, lighting, and power circuits sometimes, even when carried on neighboring structures, may leak into the various telephone-circuits and cause disturbing noises in the telephones. This leakage is also harmful because it affords an uncontrolled and greatly-variable conductance between the two wires of each telephone-circuit, whose effect, as the above consideration of the phenomenon of conductance would predict and as experience has amply shown, is to greatly disturb the efficiency of certain circuits with changes in the weather. I have found by experience that these various evils are greatly reduced and that an excellent method of constructing my ladder-circuit is afforded by adopting the construction shown in Fig. 14 and Fig. 15. This construction is an adaptation to my ladder-circuit of a somewhat similar construction intended for ordinary metallic circuits disclosed in a patent issued to Alfred C. Cousens October 3, 1893, and numbered 506,002. I do not, therefore, claim this construction broadly, but only as it is improved and adapted to my ladder-circuit.

Referring to Fig. 14, B B are two ordinary glass or porcelain insulators to which the two conducting-wires w_1 w_2 of my ladder-circuit are attached. These insulators are supported by wooden pins p p from the short cross-arm A. The cross-arm A is in turn supported from the main cross-arm X by a third wooden pin I. R is a receptacle within the cross-arm A and protected from the weather by the cover c for containing the shunt apparatus, and S_1 S_2 are wires connecting the shunt with the line-wires w_1 w_2.

In Fig. 15, P is a portion of a pole to which is attached a cross-arm X. Upon this arm to the left of the pole are three metallic circuits 1, 3, and 5, supported by insulators upon pins in the cross-arm in the usual way. Circuit 1, we will assume, is a dynamo-circuit, and 3 and 5 telephone-circuits. Upon the arm X to the right of the pole are three other metallic circuits, 7, 9, and 11, which, we will assume, are respectively duplicates of the circuits upon the left, excepting that they are carried upon the improved supports instead of the old form. Practical demonstration has shown that this improved construction so far neutralizes or equalizes leakage that its disturbing effect is reduced to a minimum. The manner in which the leakage causes disturbances between neighboring circuits when the wires are carried upon the old construction of insulators and the way in which such disturbances are prevented by the use of the improved supports may be accounted for as follows: With the old construction illustrated in circuits 1, 3, and 5 a leakage from wire w^2 of the dynamo-circuit 1 finds its way over the surface of insulator B^2 to the cross-arm X and thence into the nearest neighboring wires w^3 w^4, and since the path w^2 B^2 X B^3 w^3 is shorter than the path w^2 B^2 X B^4 w^4 more of the leakage current from w^2 will pass into w^3 than into w^4. Consequently a part of the leakage-current will flow through the telephone T^3 and cause a disturbance therein. In the same manner there will be leakage from one to the other of the telephone-circuits 3 and 5. Consequently conversation uttered into telephone T^5 will be heard in telephone T^3, and vice versa.

In the improved construction shown at the right of the pole the leakages from wires w^{17} and w^{18} over insulators B^{17} and B^{18} will meet at pin I^7 and largely neutralize each other. Any remaining slight leakage that may then succeed in passing pin I^7 may pass along the cross-arm X to pin 1^9, where it will be equally distributed to insulators B^{19} and B^{20}, and if it succeeds in passing these will leak equally onto wires w^{19} and w^{20}, where since these two wires are connected with opposite poles of the telephone T^9 the leakages will neutralize and produce no disturbance in the telephone. In the same way leakage from one to the other of the telephone-circuits 9 and 11 will be neutralized and its disturbing effect eliminated. Now—and this feature is important in the prevention of interference between circuits—the presence of the plumbago shunts greatly diminishes the tendency to leakage out from any telephone-circuit and also tends to equalize any leakage that may find its way into any telephone-circuit.

I have found by experience that much of

the so-called "induction" disturbance that we find on telephone-lines is in reality due to leakage and that with the adoption of this new construction the disturbance largely disappears. As an illustration of the superiority of the new construction I will cite an experiment in which I carried circuits arranged as in Fig. 15 along a series of one hundred and fifty poles and wet all of the cross-arms thoroughly with salt water in order to give a leakage equivalent to that of a far longer line. Between circuits 3 and 5 conversation was easily overheard and understood, while between the improved circuits 9 and 11 there was absolutely no cross-talk, and, again, the operation of dynamo D′ on circuit 1 produced such disturbances in telephone-circuits 3 and 5 that conversation was quite impossible, while the operation of the same dynamo D′ on the improved circuit 7 in no way interfered with telephonic conversations being carried on over the improved telephone-circuits 9 and 11.

It has heretofore been the aim of telephone engineers to secure a more perfect form of pole-line insulator, and thus to maintain a higher and less variable insulation not only between neighboring circuits but between the two wires of each circuit. Many years of experimenting have not resulted in any considerable increase in the permanent insulating power of insulators. Extended tests that I have made with a large number of forms of insulator show that in this respect no marked advance has been made since the introduction of telephony.

By means of the above-described method of neutralizing weather leakage interference between neighboring circuits is readily prevented while using the old and economical and well-tried form of glass insulator, and, further, the ladder-circuit possesses this marked advantage in the matter of insulation that since a large shuntage is purposely introduced between the two wires of each circuit the addition of a comparatively small weather leakage does no considerable harm, and it is immaterial how much this leakage varies with wet and dry weather so long as it is small compared with the normal shuntage.

The correct quantitative value of the weather leakage on long lines in wet weather is seldom determined even approximately, because methods customarily in use for measuring the insulation for short lines in dry weather are not at all applicable to long lines in wet weather. I have given much attention to this matter and find, both from the theory of the subject and from an extended series of measurements made in all sorts of weather between wires of different sizes and lengths up to one thousand miles, that the steady current arriving at the receiving end is attenuated by weather leakage proportionately to the hyperbolic secant of the length of the line multiplied by the square root of the product of its resistance and leakage per unit of length—that is,

$$\frac{\text{Current at sending end}}{\text{Current at receiving end}} = \frac{1}{\text{Sech } l\sqrt{RW}} \quad (13.)$$

in which l equals length of line in centimeters; R equals resistance of the two wires in centimeter gram seconds; W equals leakage between the two wires in centimeter gram seconds; Sech equals symbol for hyperbolic secant.

By measuring at both ends of a circuit a steady current introduced at one end and using the above formula we may determine the leakage in any kind of weather.

The purposely-introduced shuntage on my above-described ladder-circuit of nickel-copper wire is .00000276 mhos per mile. The average weather leakage is only about one per cent. of this, and even in the worst weather it is not large. In the other example, where I have assumed the use of ordinary copper wire with shunts, the percentage of weather leakage is even less.

So long as the weather leakage is not large compared with the systematic shuntage it can do no harm to a ladder-circuit. On the other hand, weather leakage may be a very serious matter, particularly on very high inductance-circuits not of the ladder type.

I claim—

1. A telephone-circuit in which the product of the telephonic resistance and capacity is so balanced by the product of the telephonic inductance and shuntage as to be substantially free of distortion.

2. A telephone-circuit in which the product of the telephonic resistance and capacity is so balanced by the product of the telephonic inductance and shuntage that all telephone-waves are transmitted with substantially the same velocity.

3. A telephone-circuit constructed of such materials and dimensions that its telephonic resistance, capacity, inductance and shuntage are substantially equal to its ordinary resistance, capacity, inductance and shuntage, and having the product of its resistance and capacity so balanced by the product of its inductance and shuntage as to be substantially free of distortion.

4. A ladder-shaped telephone-circuit consisting of two line-wires with shunts placed at fractional intervals of the quarter-wave length of the essential telephone-waves transmitted by the circuit.

5. A nickel-plated copper telephone-wire.

6. A ladder-shaped telephone-circuit consisting of two line-wires of non-magnetic metal sheathed with metal of large and constant magnetic permeability for telephone-waves, with non-magnetic shunts placed at in-

tervals of fractional parts of the quarter-wave length of the essential telephone-waves, and having the product of the resistance and capacity of the circuit so balanced by the product of its inductance and shuntage as to be free of telephonic distortion.

7. A telephone-circuit, consisting in part of cable and in part of pole-line, in which the telephonic resistance, capacity, inductance and shuntage of the cable each bear substantially the same ratio to the corresponding quantities of the pole-line.

8. A ladder-shaped telephone-circuit consisting of two line-wires with inductance-coils inserted in series and non-inductive resistances shunted across, both at fractional intervals of the quarter-wave length of the essential telephone-waves, and having the product of the telephonic resistance and capacity of the circuit so balanced by the product of its telephonic inductance and shuntage that distortion of the telephone-waves is eliminated.

9. A telephone cable-circuit having two line-wires with inductance-coils inserted in series at fractional intervals of the quarter-wave length of the telephone-waves essential to conversation, the conducting-wires being separated by a semiconducting dielectric, and having the product of the telephonic resistance and capacity of the circuit so balanced by the product of its telephonic inductance and shuntage that distortion of the telephone-waves is eliminated.

10. A ladder-shaped telephone-circuit consisting of two iron or steel conductors, with shunts placed at intervals of a fractional part of the quarter-wave length of the telephone-waves essential to conversation, and having the product of the telephonic resistance and capacity of the circuit so balanced by the product of its telephonic inductance and shuntage as to eliminate distortion of the telephone-waves.

11. A telephone-wire of iron alloyed to a decreased magnetic permeability toward telephone-waves.

12. A telephone-wire of iron alloyed with manganese to a decreased magnetic permeability toward telephone-waves.

13. A ladder-shaped telephone-circuit consisting of two iron or steel conductors alloyed to a decreased magnetic permeability, with shunts placed at intervals of a fractional part of the quarter-wave length of the telephone-waves essential to conversation, and having the product of the telephonic resistance and capacity of the circuit so balanced by the product of its telephonic inductance and shuntage as to eliminate distortion of the telephone-waves.

14. A distortionless telephone cable-circuit consisting of two high-inductance conductors separated by a semiconducting dielectric, and having the product of the telephonic resistance and capacity of the circuit so balanced by the product of its telephonic inductance and shuntage as to eliminate distortion of the telephone-waves.

15. A ladder-shaped telephone pole-circuit consisting of two conducting-wires bridged, at intervals of a fractional part of the quarter-wave length of the telephone-waves, by non-inductive shunts of such conductance that the shuntage of the circuit is greater than its weather leakage.

16. A ladder-shaped telephone pole-circuit consisting of two conducting-wires supported upon insulators placed at opposite ends of a centrally-supported cross-arm, and bridged, at intervals of a fractional part of the quarter-wave length of the essential telephone-waves, by non-inductive shunts of such conductance that the shuntage of the circuit is greater than its weather leakage.

WILLIAM W. JACQUES.

Witnesses:
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IDA E. HANDREN.