No. 815,322.

PATENTED MAR. 13, 1906.

D. M. THERRELL.

ART OF TELEPHONY.

APPLICATION FILED AUG. 2, 1905.

6 SHEETS—SHEET 1.

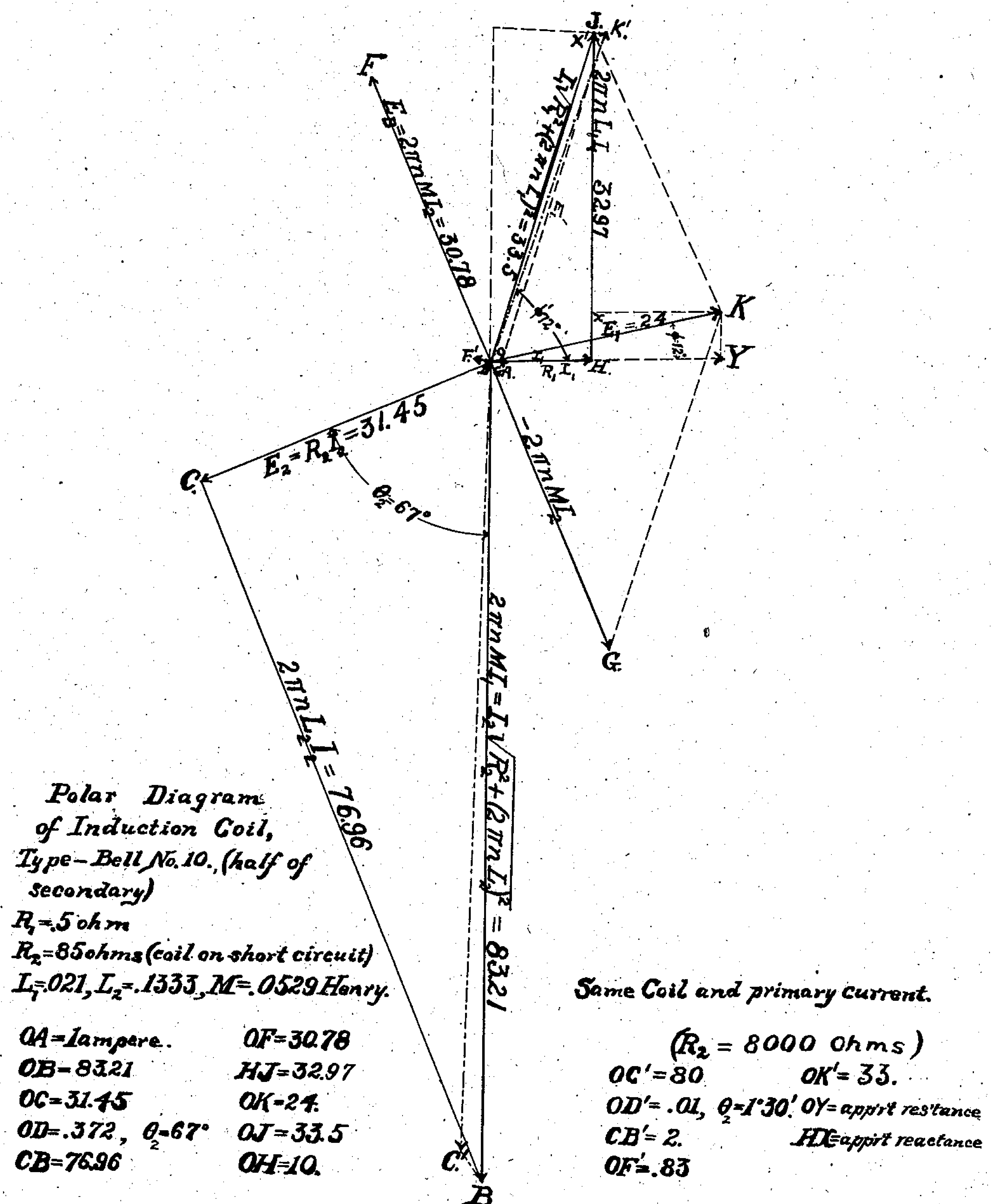

Fig. 1.

WITNESSES:

R. E. Robinson
T. M. Harvey

INVENTOR.

J. McLaughlin Therrell

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6 SHEETS—SHEET 2.

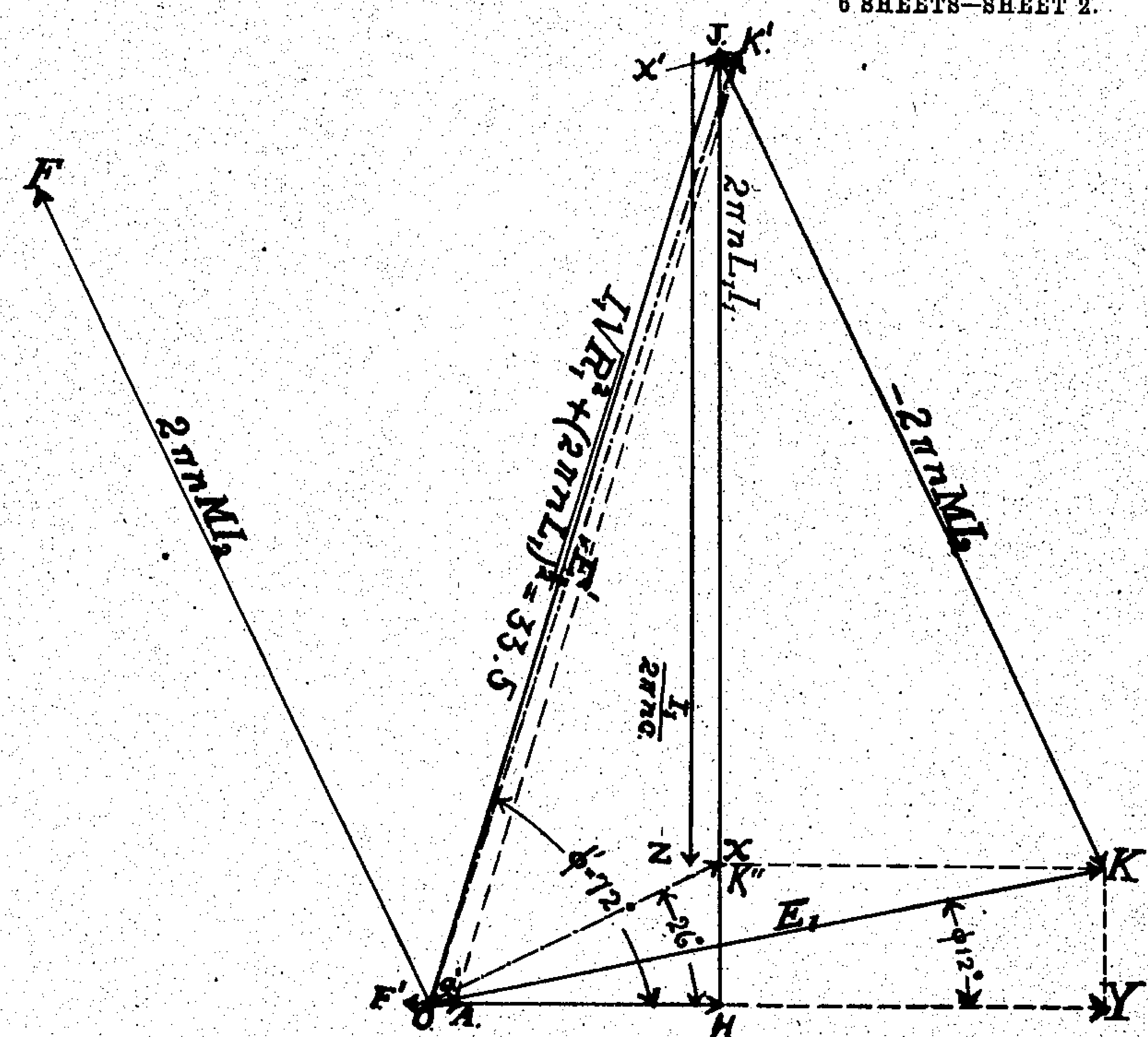

Fig. 2.

Enlarged portion of Fig 1, showing method of neutralizing the effects of self induction in the primary, by a capacity = J Z.

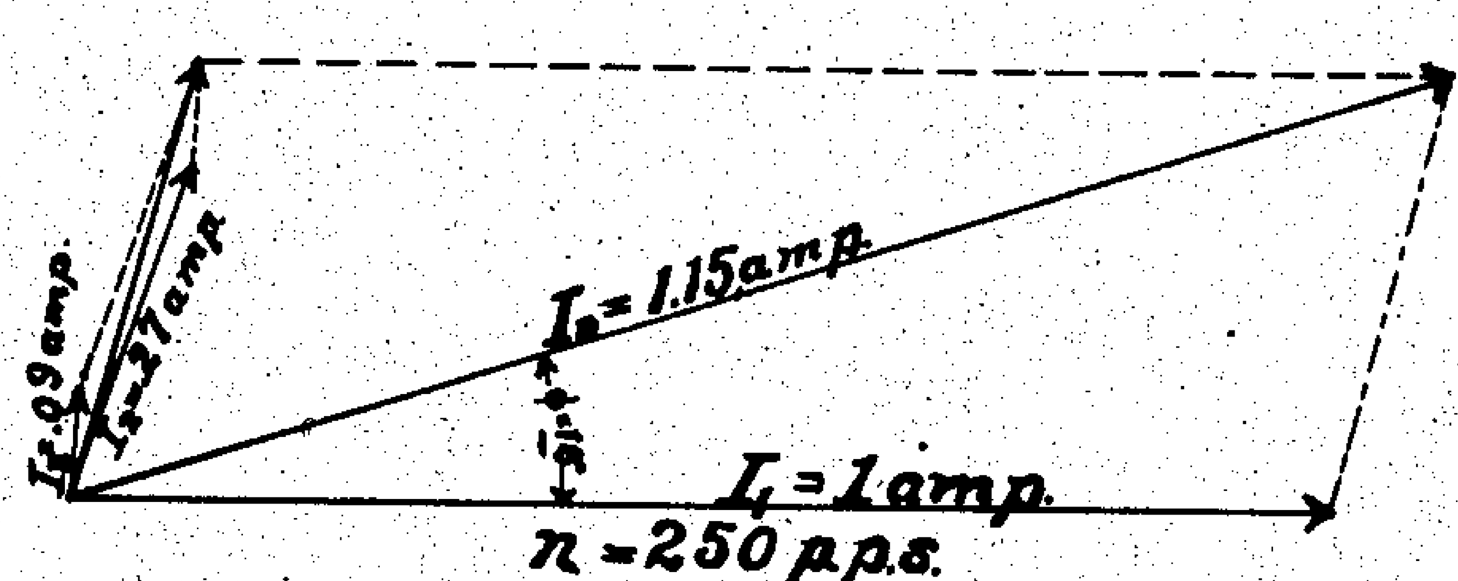

Fig. 5.

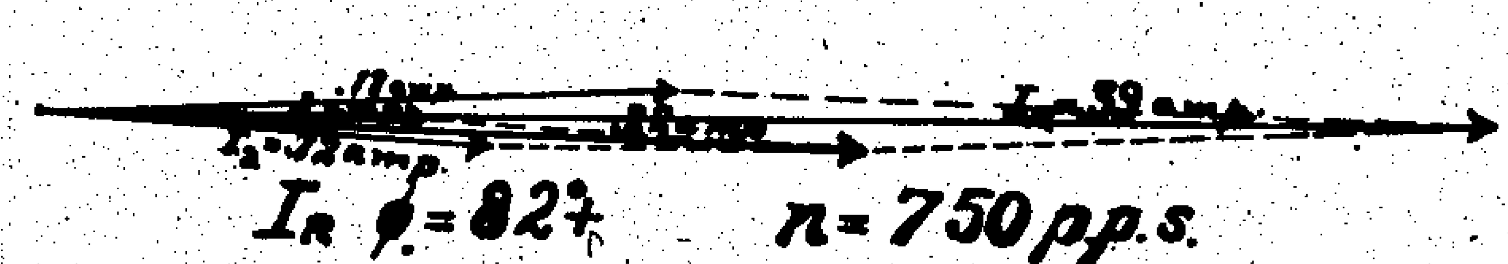

Fig. 6.

WITNESSES.

R. C. Robinson

T. M. Harvey

INVENTOR.

D. MacLauchlin Therrell

No. 815,322.

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D. M. THERRELL.

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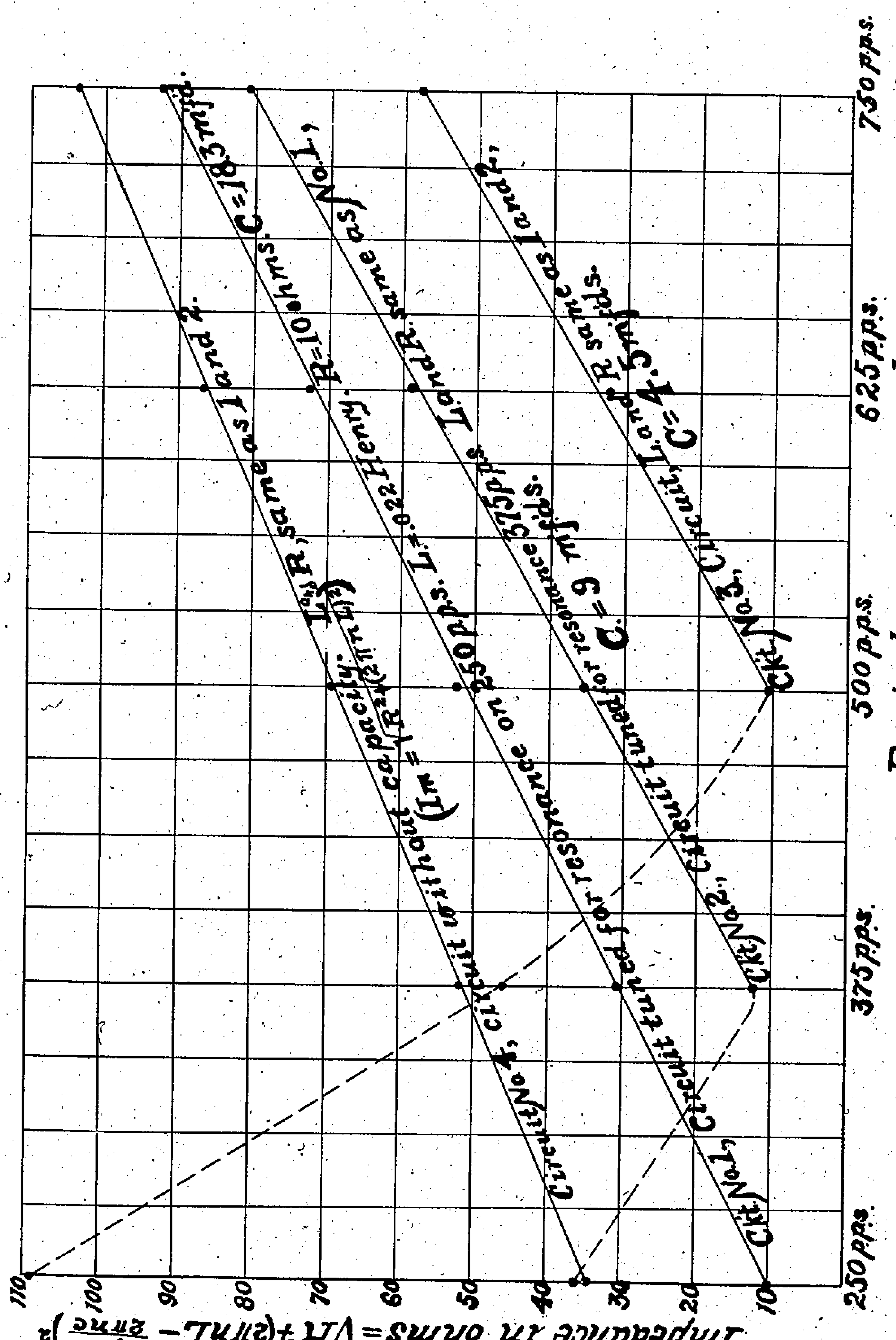
6 SHEETS—SHEET 3.



n = Periods per second.

Fig. 3.

Curves showing impedance of primary for different pps., and values of capacity; also for same coil without capacity. R. and L. the same in each circuit.

WITNESSES:

O. E. Robinson

Geo. T. Carey

INVENTOR

D. Maclauchlin Therrell

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D. M. THERRELL.

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6 SHEETS—SHEET 4.

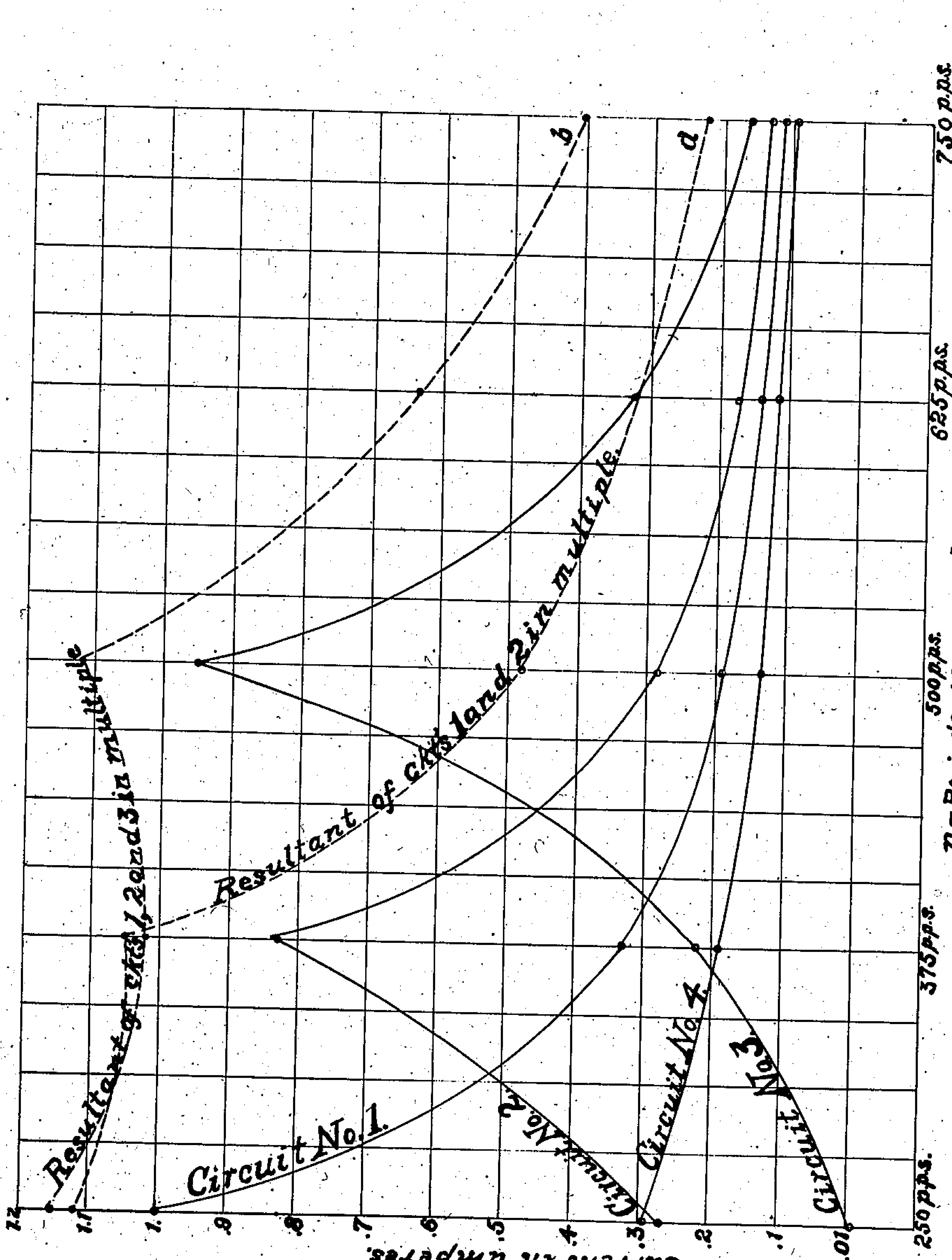

Fig. 4.

Curves showing value of currents for circuits 1, 2 and 3, and 4, and in broken lines, also, resultant of secondary current, with P and S. of Nos 1, 2 and 3 connected in multiple. $E_1 = 10$ volts primary. Transformation ratio 1:1. Secondary on short circuit.

WITNESSES:

R. E. Robinson

Geo. T. Carey

INVENTOR.

A. Maclauchlin Morrell

No. 815,322. PATENTED MAR. 13, 1906.

D. M. THERRELL.

ART OF TELEPHONY.

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6 SHEETS—SHEET 5.

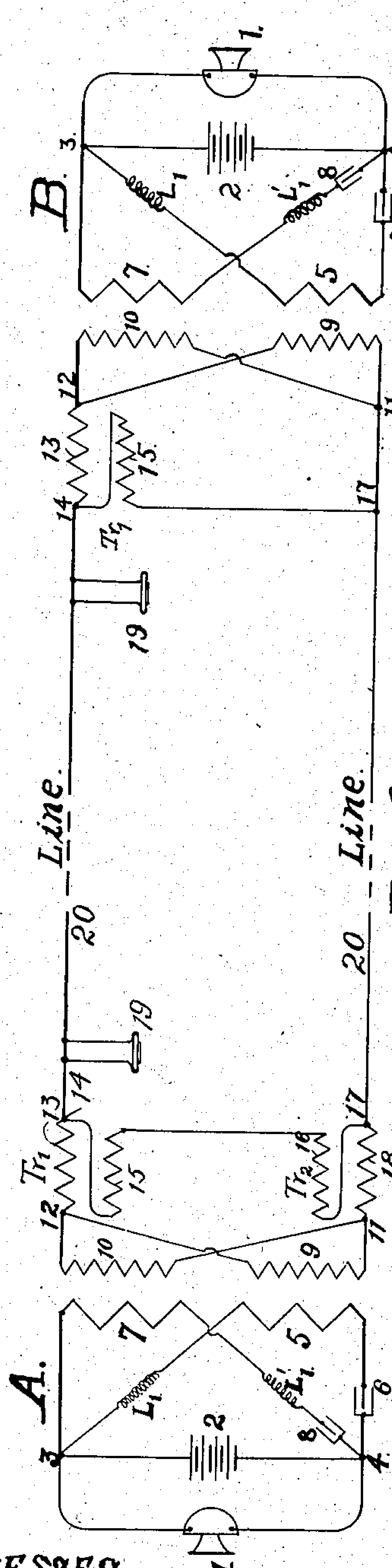

Fig 9

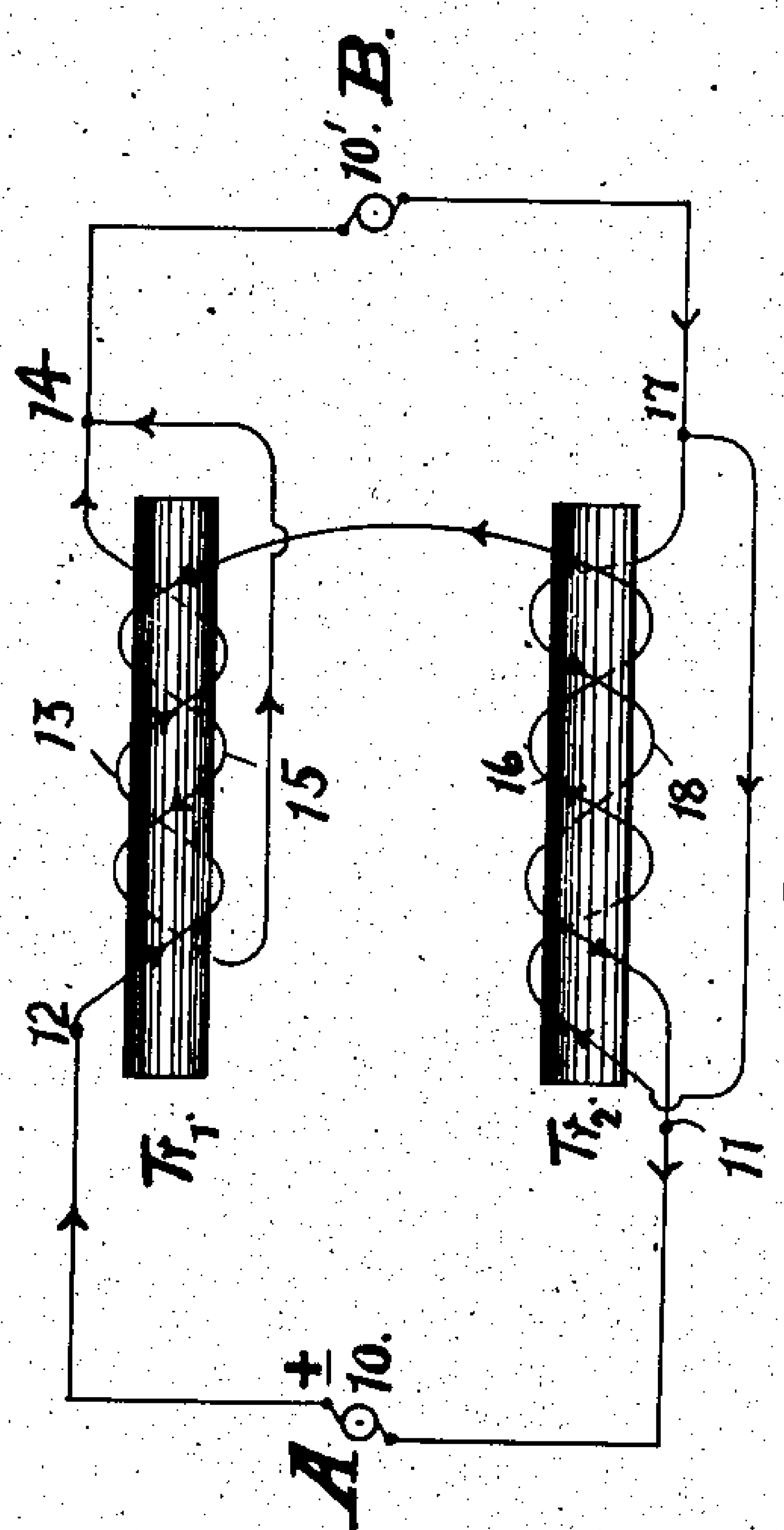

Fig 8.

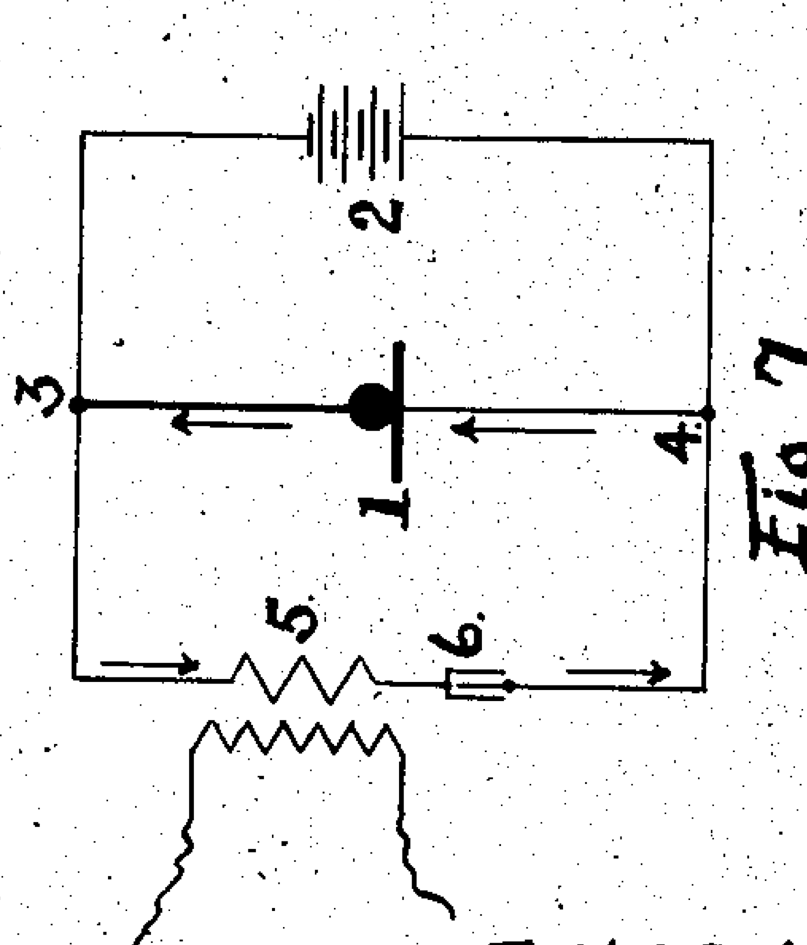

Fig 7

WITNESSES.

H. E. Robinson

Geo. J. Carey

INVENTOR.

D. Maclauchlin Therrell

No. 815,322. PATENTED MAR. 13, 1906.

D. M. THERRELL.

ART OF TELEPHONY.

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6 SHEETS—SHEET 6.

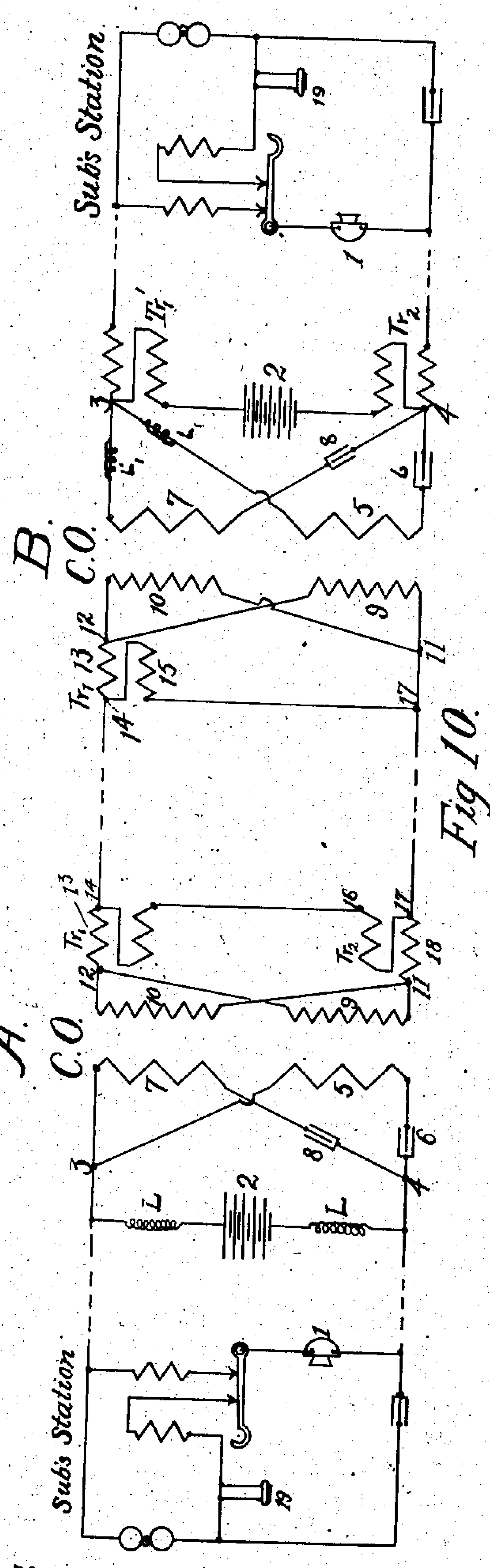

Fig 10.

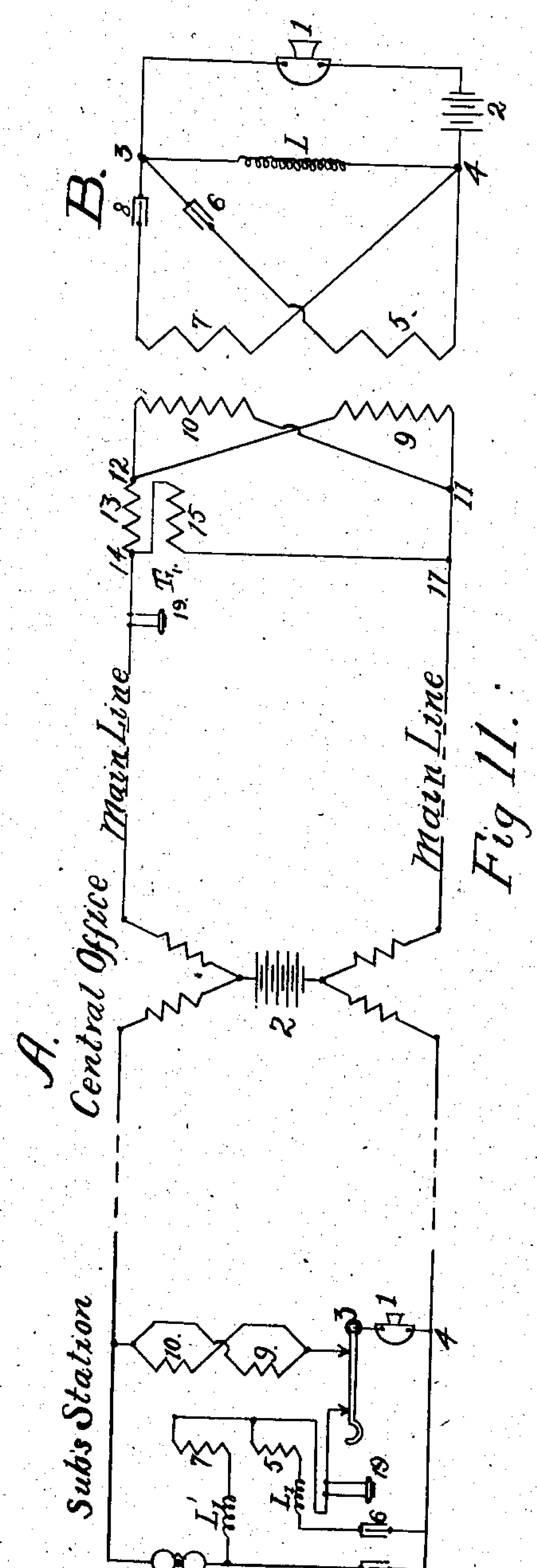

Fig 11.

WITNESSES:
R. E. Robinson
Geo. T. Cady

INVENTOR.
D. Maclauchlin Therrell

UNITED STATES PATENT OFFICE.

DANIEL MACLAUCHLIN THERRELL, OF CHARLESTON, SOUTH CAROLINA.

ART OF TELEPHONY.

No. 815,322. Specification of Letters Patent. Patented March 13, 1906.

Original application filed July 23, 1904, Serial No. 217,846. Divided and this application filed August 2, 1905. Serial No. 272,375.

To all whom it may concern:

Be it known that I, Daniel Maclauchlin Therrell, a citizen of the United States, residing at Charleston, in the county of Charleston and State of South Carolina, have invented new and useful Improvements in the Art of Telephony, of which the following is a specification.

My invention consists in an improved method or system for the transmission of electrical energy by means of electrical waves, and particularly such waves as are employed in the electrical transmission of articulate speech or sonorous sounds, and comprises various improvements to be hereinafter more particularly described and claimed.

In the transmission of a simple electrical wave over an electrical conductor of great length characterized by high resistance, electrostatic and conductive leakages, the energy lost or dissipated is proportional to and expressible in simple terms of the reactive constants of the system, and there is no distortion of the wave form. Such, however, is not the case for a complex electrical wave composed of a plurality of coexisting waves, such as the waves involved in the telephonic transmission of the human voice or other sonorous sounds composed of a prime or fundamental and an ascending series of partials corresponding to the overtones or characteristics of articulation and quality. In the latter case each constituent wave of the series is differently and independently affected, and hence the resultant wave form at the distant end or terminus of transmission is no longer identical with the initial wave form impressed upon the conductor. This is due to the physical fact that each wave is oppositely as well as differently affected by the electromagnetic and electrostatic constants of the system, though both conspire to discriminate in favor of the lower while retarding or attenuating the upper harmonics directly as the frequency, resulting in the loss of articulation and the natural characteristics of speech which are dependent upon the transmission of the upper harmonics or overtones, and while conceding that great losses are properly chargeable to the dissipation of the main-line conductors, owing to their electrical characteristics as outlined above, my researches of the subject, mathematical and experimental, have confirmed me in the opinion that, in so far as long aerial lines are concerned, operating under actual conditions, which might be called existing "meteorological" conditions, little, if anything of average and permanent value is to be obtained by a tuning or readjustment of the line constants, but that much may be gained by improving the methods and apparatus in use for the electrical transformation and transmission of the primary energy equivalents of the voice—that is, by reducing the impedance of the primary coil and obtaining thereby larger primary currents, by maintaining a higher mutual inductance and obtaining thereby a higher efficiency of transformation, and by so adjusting the secondary system as to generate a larger line current at a higher effective line potential a higher efficiency of transmission may be effected.

In the art of telephony a primary circuit consists of a circuit including a variable resistance in relation to a diaphragm, a source of electrical energy, and the primary winding of an induction-coil or transformer. The vibrations of the voice acting upon the diaphragm in operative relation to the variable resistance causes this resistance to vary in consonance therewith, thereby setting up in the primary circuit a current which follows the variations of the said resistance, and therefore the vibrations of the voice. This current being of the variable or pulsating type is capable of transformation by means of an induction-coil or transformer the primary of which is included in circuit with the ordinary variable resistance and source of energy, while the secondary is connected into the main line. By this means it is possible, even with the small current to which we are restricted by the transmitter, to so step up the voltage impressed upon the main line as to reach over relatively vast distances; but in saying this it must be admitted that such results speak far more for the sensitiveness of the receiver than for the efficiency of transformation or transmission, for though ordinarily we may have flowing in the primary circuit something like .3 of an ampere the maximum value of the current impressed upon the main line is not more than .0001 of an ampere for the lowest frequency, with a far greater loss in transformation for the higher frequencies.

In order to successfully effect the long-distance transmission of speech, the prime requisite must be an increased power or watt efficiency of the system for each and every frequency involved, and particularly for such frequencies as correspond to the overtones of speech characteristics if the speech so transmitted is to be satisfactorily intelligible. The power factor of the system is, first of all, dependent upon the amount of energy available in the primary circuit. Unfortunately we are here restricted to a very small amperage on account of the I^2R loss in the variable-resistance portion of the transmitter, which causes the transmitter-electrodes to heat, and thus directly affect the transmission to such an extent as to place the available current limit considerably below one ampere, as mentioned above. This is not the only difficulty. Long-distance transmission makes it necessary to raise the line potential by transformation. Anything like efficient transformation presupposes a maximum mutual induction. This in turn calls for a high magnetic inductance, which is only possible by the use of iron in the magnetic circuit. Now there are two paramount reasons why neither of these requisites are admissible in telephony. If we endeavor to increase the magnetic intensity of the coil by the use of an increased amount of iron in the core, we are met with a loss due to an oversaturation of the core. This results from the direct current used in the primary circuit, which saturates the core and leaves no margin for the variation of the lines of force due to the variations in the primary current following the vibrations of the voice, and hence a loss in the secondary instead of a gain. In addition there are hysteresis losses due to high frequencies and magnetic density. Again, just in proportion to the amount by which we increase the mutual induction of the coil by an increased efficiency of the magnetic field we also increase the self-induction of the primary, and therefore its effective impedance, which means a proportional reduction of primary current unless the voltage be raised. Even if this be done the primary current is only increased at the expense of the power factor, for the wattless component of the primary will be so great that the point is soon reached where the heating of the transmitter-electrodes makes a larger current impracticable without having improved the efficiency of the system. This calls for a compromise and also throws light upon what has been to many for years the paradox of the art. I refer to the constants and proportions of the standard long-distance induction-coil as used by the American Telephone and Telegraph Company. In this coil a minimum of iron is used and the coefficients of self and mutual induction are amazingly low. This of course means low efficiency; but experience has shown, as stated above, that to attempt a further increase in the efficiency of transformation but invites other losses which outweigh any apparent gains. Hence the standard "cigar-coil" and the attempt to force the problem by attacking the capacity losses upon the main line.

I have discovered a method of maintaining a high efficiency of transformation without entailing upon the system either the losses due to oversaturation, hysteresis, primary or secondary impedance. These discoveries, which are the result of years of laborious researches, experimental and mathematical, form the basis of my invention, which will be better understood by reference to the accompanying drawings, which form a part of this specification.

Figure 1 is a polar diagram of a standard telephonic transformer or induction-coil having the maximum amount of core-iron, mutual and self-induction, allowable in practice, with secondary on short circuit. Fig. 2 is an enlarged portion of Fig. 1 with eight thousand ohms in secondary circuit, showing the method of neutralizing the primary self-induction by a capacity reactance. Fig. 3 is a set of curves, drawn to rectangular coördinates, showing the impedance of a primary circuit of given constants for different p. p. s., also the values of the impedance for the same circuit wherein the self-inductance is neutralized by capacities corresponding to the given p. p. s. Fig. 4 is a set of curves showing the values of current for the same circuit and p. p. s. as shown in Fig. 3, together with the values of the current after a neutralization of the self-inductance by capacities corresponding to the given p. p. s., also curves showing the resultant secondary-current values when two or three such circuits tuned to different p. p. s. are connected in multiple, primary, and secondary. Figs. 5 and 6 are vector diagrams showing the method of graphically determining the resultant values of secondary current and phase relation under the multiple conditions noted in reference to Fig. 4. Fig. 7 is a diagram illustrating the method of placing a capacity in series with the primary coil and transmitter for the purpose of tuning. Fig. 8 is a diagram illustrating the principle and method of using compensating-transformers in the main line for the purpose of reducing secondary effective impedance and increasing the effective line potential. Fig. 9 is a conventional diagram of my system in theory as applied to local-battery systems. Figs. 10 and 11 are conventional diagrams of the same adapted to common-battery or central-energy systems.

Inasmuch as the principles underlying my invention involve a considerable departure from the standard practices of the art, it will be necessary here to briefly discuss the laws governing the actions and reactions of the general transformer, their effects upon transformation, and the principles of resonance in relation thereto in order that the claims of this application may be placed in their true light and the specification rendered more intelligible. Let us consider a current flowing in a single turn of wire. A magnetic field is set up consisting of a definite amount of magnetic flux or lines of force forming closed curves around the given conductor. This flux increases and decreases with increase and decrease of current. If the permeability of the medium is constant, the magnetic flux is directly proportional to the current. If there are *s* turns of wire instead of one, the flux N passes through each turn, and consequently there are *s*N lines threading or linked with the circuit. The quantity *s*N may be termed the "flux turns" or "inductance" of the circuit. If the magnetic induction through any circuit be changed due to any cause whatsoever, an electromotive force is developed in the circuit proportional to the rate of change of the magnetic induction, as first shown experimentally by Faraday. The change in the induction to which this induced electromotive force is due may be produced by a change in the current flowing in the circuit itself, in which case the electromotive force so induced is dependent upon the rate of change of the current and is known as the "electromotive force of self-induction." Let us now consider two coils in juxtaposition, which we will designate as "primary" and "secondary," each with a given number of turns or convolutions. Let there be a current of given intensity flowing in the primary coil. This current in the primary if caused to vary produces a magnetic induction which varies in consonance therewith. Now this induction not only induces an electromotive force of self-induction in the primary itself, but also induces an electromotive force in the secondary, due to the changing lines of force of the primary and the relative position of the two coils, which is proportional to the rate of change of the induction in the primary. This is mutual induction. This mutual induction may be defined as the "ratio" of electromotive force induced in one circuit to the time-rate of change of the current in the other producing it. It may also be expressed in terms of the induction threading the secondary, due to the current in the primary being equal to the rate of change of the number of lines of force linked with the secondary. The effect is greatly increased by the use of iron in the magnetic circuit. Upon these principles is based the operation of the devices used for changing an alternating or varying current from one potential to another of higher or lower pressure, known as "induction-coils" or "transformers." In order to determine the action between the primary and secondary circuits of a transformer through the medium of their common magnetic field, we must ascertain the amount of induction due to the current flowing through the turns of the primary and embracing a magnetic circuit of known permeability. This may be readily calculated from the laws of the magnetic circuit. The total magnetic flux or induction N is equal to the magnetomotive force divided by the reluctance. The secondary electromotive force induced by the primary current is proportional to the rate at which the primary current is changing and is equal to this time-rate of change multiplied by the coefficient of mutual induction.

Conventions used in this specification:

n = frequency or periods per second.
C = capacity.
I_1 = primary current.
I_2 = secondary current.
E_1 = primary electromotive force.
E_2 = secondary electromotive force.
L_1 = primary inductance.
L_2 = secondary inductance.
M = mutual inductance.
N = total flux of magnetic field.
R = ohmic resistance.
Im = impedance.
ϕ = primary phase angle.
Θ_2 = secondary phase angle.
p. p. s. = periods per second.
γ = transformation ratio.

Subscripts 1 and 2 refer to primary and secondary circuits, respectively, throughout this specification.

Having briefly outlined the underlying principles of the transformer, we may proceed, by way of further exposition, to construct the diagram of a telephonic high-potential transformer or induction-coil such as is in standard use by the American Telephone and Telegraph Company. Fig. 1 is a polar diagram of such a coil. The solid lines indicate secondary on short circuit, the broken lines the same coil with eight thousand ohms in secondary circuit.

The constants of the coil are taken as follows:

R_1 = .5 ohm.
R_2 = 85. ohms.
L_1 = .021 henry.
L_2 = .1333 henry.
M = .0529 henry.
n = 250 p. p. s.

Each vector is assumed to represent maximum values. Let us consider the secondary on short circuit, the primary current as one ampere, flowing through an average resistance, including the transmitter of, say, ten ohms, represented by O A and O H, respectively. It is desired to know what will be the electromotive force and the current in the secondary, how this secondary current affects the primary, what is the primary impedance, and the electromotive force necessary to maintain the given current in the primary. Attacking the problem geometrically, we draw a line O A to represent the value of the harmonic primary current flowing through a circuit of resistance O H and inductance H J. Ninety degrees behind O A we draw the line O B, equal to

$$2 \pi n M I_1 = I_2 \sqrt{R_2^2 + (2 \pi n L_2)^2}.$$

This line represents the electromotive force induced in the secondary circuit by the primary current. When the secondary circuit is closed, a current flows which acts inductively both upon the primary and secondary circuits. This secondary current lags behind the impressed electromotive force O B in the secondary, due to self-induction, by an angle Θ^2, such that

$$\tan. \theta_2 = \frac{2 \pi n L_2}{R_2}.$$

We may represent the secondary effective electromotive force and current by the vector O C and O D, respectively, wherein

$$E_2 = R_2 I_2 \text{ and } I_2 = \frac{2 \pi n M I_1}{\sqrt{R_2^2 + (2 \pi n L_2)^2}}.$$

By the graphical construction for simple circuits we know that the right triangle O C B upon B as a hypotenuse represents the secondary electromotive forces, O C representing that necessary to overcome resistance $= R_2 I_2$, C B that necessary to overcome the self-induction $2 \pi n L_2 I_2$. The relation between the primary and secondary circuits is entirely a mutual one. A current flowing in the secondary induces an electromotive force in the primary, just the same as a current flowing in the primary induces an electromotive force in the secondary. The electromotive force set up by the secondary current in the primary is termed the "back" electromotive force and is ninety degrees behind the secondary current and equal to

$$2 \pi n M I_2.$$

Therefore in Fig. 1 we may represent the back electromotive force by the line O F ninety degrees behind the secondary current O D. Having assumed a primary current, we have, as based thereupon, determined the secondary electromotive force, the secondary current O D, and the back electromotive force O F. It now remains to find what impressed primary electromotive force is required to cause the primary current to flow. Instead of having but two electromotive forces to overcome, as would be the case for a simple circuit, the primary electromotive force must in this case not only overcome the electromotive force of resistance and self-induction in the primary, but also the back electromotive force induced in the primary by the current in the secondary. The electromotive force to overcome resistance of the primary is always in phase with the primary current and is represented by O H. The component necessary to overcome the primary self-induction is equal and opposite to the electromotive force of self-induction and is therefore ninety degrees ahead of the primary current and is represented by the vector H J ninety degrees ahead of O A and equal to $2 \pi n L_1 I_1$. The triangle O H J is the triangle of the primary electromotive forces when no current flows in the secondary. In such a case the necessary impressed electromotive force upon the primary is O J; but when the secondary current is allowed to flow, as in the case under consideration, there must be a component of the primary electromotive force to overcome the back electromotive force due to the secondary current. This electromotive force must be equal and opposite to O F and is represented by the line O G, equal to $-2 \pi n M I_2$. Having thus developed our diagram, the primary electromotive force desired is easily found, since it is the geometrical sum of the three components O H, H J, and O G. The resultant of O H and H J gives O J, and the resultant of O J and O G gives O K, which represents the required primary impressed electromotive force, being in the case considered about twenty-four volts and leading the current by approximately twelve degrees.

From Fig. 1 it is readily seen that since the component of the primary electromotive force O G necessary to overcome the back electromotive force due to the secondary is in the direction of the primary current O A the effect of a current in the secondary is to divide the primary electromotive force into three components, which apparently reduces the self-induction of the primary and increases its resistance by bringing the resultant electromotive force O K more in phase with the primary current, whereby the primary current is increased and more power thus obtained. To further illustrate this point, reference is again made to Fig. 1. In the case just considered, wherein the secondary of the coil was assumed to be on short circuit, it will be noticed that the electromotive force of self-induction in the primary was apparently reduced by the back electromotive force of the secondary from H J to H X and the resistance increased from O H to O Y, while the electromotive force came quite into phase with the current, thus bringing the power factor nigh unto unity. Now let us assume the secondary to have a line in circuit of such resistance that the total secondary resistance becomes eight thousand ohms instead of eighty-five ohms. This is about the equivalent of a two-thousand-mile circuit, as ordinarily used for the telephonic transmission of speech. The diagram of the same induction-coil under these conditions is indicated in dot-and-dash lines in Figs. 1 and 2 with prime and second indices. The apparent result is that the secondary electromotive force rises from 31.45 volts to eighty volts, as shown by O C′, while the secondary current falls from .37 ampere to .01 ampere, the back electromotive force falls from 30.78 volts to .83 volt, as shown by O F′. The lag in the secondary is also reduced from about sixty-seven degrees to about one degree, with an equal shift in the phase relation of the back electromotive force. The result is shown in the position of O G′, with the resultant of O J and O G′, which is O K′, as the necessary impressed primary electromotive force equal to about thirty-three volts and leading the current by about seventy-two degrees instead of twelve degrees, with a power factor proportionately reduced.

The values of the various vectors just given are based upon the assumption that the primary electromotive force has been raised so as to maintain a power-current of one ampere in the primary and that the power factor of the primary remained the same as when the secondary was on short circuit. In practice we have a decreasing or at best a constant primary electromotive force to deal with. Under these circumstances let us consider the primary electromotive force as twenty-four volts. Now with the voltage remaining constant the effect of increasing the secondary resistance as aforesaid is as follows: The secondary current is reduced proportionally to the secondary resistance and swings nearly into phase with the secondary electromotive force. The back electromotive force, which is dependent upon the value of the secondary current, decreases with the secondary current and is advanced by the same phase angle. The component of the primary necessary to overcome this back electromotive force is proportionately reduced in value and advanced in phase. Now as the back electromotive force decreases in value and advances in phase angle the primary impedance increases in value and the impressed primary electromotive force advances or leads over the primary current by a like angle. In the case given the primary impedance is increased from twenty-four ohms on short-circuited secondary to thirty-three ohms with the external secondary circuit as given, and, what is more important, the phase angle between the primary electromotive force and the primary current is increased from twelve degrees in the first instance to seventy-two degrees in the latter. With the given primary voltage the primary current is reduced from one ampere to .72 ampere, which gives us for the secondary electromotive force according to the equation 59.8 volts instead of the apparent eighty volts. The energy of the primary circuit is reduced from 23.47 watts $=E_1 I_1 \cos.\phi$, to 5.33 watts, with a corresponding reduction in the energy of the secondary circuit or main line. Since the magnetic field, by means of which alone energy is transferred from the primary to the secondary of a transformer, is dependent upon the value of the primary current and its power factor and the secondary voltage is directly proportional to the energy of the magnetic field, it follows, then, that any reduction in the secondary or line current as a result of an increased resistance or length of line causes a corresponding increase in the impedance of the primary, and therefore a reduction in the primary current, which in turn operates to further reduce the secondary or line current by reducing the secondary potential, which is equal to $2\pi n M I'$. Thus it is seen that to the primary impedance and secondary resistance is due most of the inefficiency of telephonic induction-coils or transformers. On account of primary self-induction and hysteresis losses it is impracticable to avail ourselves of a magnetic field of sufficient intensity to warrant an efficient transformation. On account of secondary resistance—and long-distance telephonic induction-coils may be said to operate on resistances equivalent to open circuit—we are not allowed to take advantage of a back electromotive force which further reduces the transformation ratio. This is true to such an extent that the transformer referred to in Fig. 1 shows by computation a loss of about eighty per cent. between the primary and the secondary watt energy, even with the secondary on short circuit; $=E_1 I_1 \cos\ \phi - E_2 I_2 \cos.\ \Theta_2$.

Having the problem stated, consider now the proposition of controlling the primary self-induction and rendering it independent of the secondary or line current. I have found that this can be done by the use of capacity in the primary circuit, or preferably multiples thereof, whereby the primary self-induction may be wholly or partially neutralized in the given branches of the primary for any desired frequency, thus greatly increasing the primary current, and thereby the secondary current in the main line. As is well known, the reactions due to self-induction and electrostatic capacity are diametrically opposed. It therefore follows that for any circuit containing both self-induction and capacity it is possible to so adjust the values of each as to make the one neutralize the other. When this is done, a current will flow through the circuit the same as if it were free from any impedance whatsoever. This is the condition of resonance and is possible only when

$$2\pi n L - \frac{1}{2\pi n c} = \text{zero}$$

for any given period of frequency. For any periodicity above or below this the two values will not cancel and perfect resonance will not obtain. I have found, however, that when a circuit is made resonant for any particular frequency—say two hundred and fifty p. p. s.—the effects are experienced by all frequencies above two hundred and fifty, but in a gradually-decreasing value, as will be explained later in this specification.

It is proposed to neutralize the impedance of the primary circuit by dividing the primary into two or more branched or multiple circuits and inserting a sufficient capacity and inductance into each branch or multiple thereof to satisfy the conditions of resonance for the frequencies to be affected, whereby larger primary currents and more power may be obtained. Neutralizing the self-induction of the primary does not affect the magnetic field of the coil or the mutual induction upon which depends the secondary electromotive force and current. On the other hand, it enables us to obtain larger currents through the primaries to utilize more iron in the magnetic circuit and to transform more energy into the secondary. This will be better understood by reference to Fig. 2, which is an enlarged portion of Fig. 1. From this diagram it will be seen that with the secondary on short circuit the primary self-induction is reduced by the back electromotive force O F of the secondary from H J to H X, whereas with the secondary connected into a circuit equaling eight thousand ohms the back electromotive force is reduced to O F′ and so advanced in phase that the primary self-induction becomes H X′, which practically equals that of secondary on open circuit. The result of this has already been described. Now suppose that a capacity reactance be included in the primary circuit to oppose the reactance of self-induction equal to the vector J Z. Then

$$2 \pi n L - \frac{1}{2 \pi n c} = H X,$$

which gives the same impedance for the primary as when the secondary was on short circuit. O K′ becomes O K″. The primary takes practically twice the amount of current as before and transforms an equivalent amount of energy into the secondary circuit or main line, due to an increased ratio of transformation, and this as the result of only partial resonance.

I shall consider now some numerical examples for the purpose of showing the operation of the general rule.

Consider a primary circuit including an induction or transmitter coil of the following constants:

$R_1 = .5$ ohm,
R_1 external $= 9.5$ ohms,
$L_1 = .022$ henry,
$E_1 = 10$ volts.

From the curves of Fig. 3 it will be seen that this circuit and coil, listed therein as circuit No. 4, offers an impedance of about thirty-four ohms to a current of two hundred and fifty p. p. s. and that for a frequency of seven hundred and fifty p. p. s. the impedance is over one hundred and three ohms.

Fig. 4 shows a series of curves of current resulting from the impedances in the circuits given in Fig. 3 corresponding to the circuits and constants given under the impressed electromotive force of ten volts. Thus in Fig. 4, circuit 4, it is seen that for an impedance of thirty-four ohms $= \sqrt{R^2 + (2 \pi n L)^2}$ and a frequency of $n = 250$ we get only .29 ampere, while for seven hundred and fifty p. p. s. we get .097 ampere. This is upon the assumption of secondary on line of eight thousand ohms or approaching open circuit.

Let us introduce into the primary a capacity C. The primary impedance is then determined by the equation

$$I m = \sqrt{R^2 + \left(2 \pi n L - \frac{1}{2 \pi n c}\right)^2}.$$

Assuming $n = 250$ p. p. s. and that

$$2 \pi n L - \frac{1}{2 \pi n c} = 0,$$

then the impedance reduces to zero and the current rises to the value given by $I = \frac{E}{R}$. In the case under consideration this neutralization is approximately obtained by a capacity of eighteen microfarads and the primary current rises from .29 ampere to one ampere as a result of this capacity in the circuit. Reference to Fig. 3 will also show that for a frequency of seven hundred and fifty p. p. s. the current resulting from the partial resonance amounts to .108 ampere against .097 ampere for the same circuit without the capacity, thus indicating clearly the benefits of primary resonance for telephonic currents even where the circuit is attuned or syntonized to but one frequency. Now we may divide the primary circuit into a plurality of circuits and include in each branch the primary of an induction-coil, together with the capacity necessary to tune it for any given frequency, as illustrated in Fig. 4, wherein the current values for identical circuits, with R and L constants the same in each, are shown for different periodicities without capacity and with the circuits tuned for the frequencies of two hundered and fifty p. p. s., three hundred and seventy-five p. p. s., and five hundred p. p. s., respectively. Fig. 4 also shows in dotted lines curves representing the values of current in the secondary circuit, wherein the secondaries are connected in multiple, giving the vector sum of the currents in the different coils. Curve "a," Fig. 4, represents the resultant of coils 1 and 2 in multiple, curve "b" the resultant of 1, 2, and 3 connected in multiple into the secondary circuit, which is considered under short circuit at a transformation ratio of one to one neglecting losses. These curves are significant.

Figs. 5 and 6 illustrate the graphical method of determining the sum of these currents, each vector of which is drawn to a given scale representing the currents and their relative phase angles. Referring to Fig. 5, wherein the values are based upon a frequency of two hundred and fifty p. p. s., it will be noted that as a result of circuit 1 being resonant for this frequency the current I_1 has a value of one ampere, whereas circuits 2 and 3, represented by currents I_2 and I_3, owing to their very high impedance for this frequency give very small values of current and of such relative phase relation as to but slightly increase the resultant current I_R. The fact is elicited, however, that for a frequency of two hundred and fifty, only circuit No. 1 will give any material current into the secondary and that though the coils are in multiple the impedances are so great for this frequency and the phase relations are such that coil 1 is reinforced instead of being short-circuited by coils 2 and 3. Now as the frequencies advance the currents from the different coils come nearer and nearer into phase, and as a consequence the resultant approaches the simple sum of the several currents, as is illustrated by Fig. 6. These values may also be obtained analytically. For two coils in multiple the formula for the resultant current is

$$I_R = \sqrt{a^2 + a'^2 + 2\,a\,a' \cos.\ \phi};$$

where a and a' represent the value of the two currents and ϕ the phase angle between them. For the resultant of three or more currents find the resultant of the first two, then combine this resultant with the third, and so on for the series.

Having illustrated the general theory and underlying principles upon which the resonance features of my invention are based, I shall now give so far as may be necessary the detail of method and apparatus for carrying this theory into effect.

In the art of telephony the mechanical energy of the voice is translated into electrical energy through the agency of a diaphragm in operative relation to a variable-resistance medium in closed circuit with a constant-potential source of electrical energy and a transformer. The changes in the variable resistance following the vibrations of the diaphragm creates a unidirectional variable current through the closed circuit including the primary of the induction-coil. This primary current being unidirectional, it follows that a condenser cannot be placed in series with the primary coil—a necessary requisite under the given conditions—for the circuit being a constant potential one nothing may be gained by placing a condenser in multiple with the primary of the coil. To transform the primary unidirectional current into an alternating secondary current for the purpose of utilizing the principle of resonance in the secondary, then transferring this current to line by means of another transformer, involves the losses of both transformers, together with the dielectric losses of the condensers, which may more than equalize the gains consequent upon a proper tuning for the essential voice frequencies. These facts and the very complex nature of the frequencies and phase relations of a voice-current have apparently led to the belief by telephonic authorities that the principles of resonance cannot be successively applied to telephonic circuits except for the purpose of counteracting the capacity of the main line, and thereby reducing the attenuation factor of transmission. I have discovered a method, however, whereby a capacity may be successfully placed in series with the primary of a transmitter induction-coil and the circuit tuned for any desired frequency or frequencies, which will be better understood by reference to Fig. 7. Referring to this figure, it will be seen that we have a variable resistance 1 in series with a constant-potential source of energy 2 in the main branch of a circuit which divides at 3 and 4 into two branches. One of these branches contains a variable resistance 1, while the other branch contains the primary of an induction-coil or transformer 5 in series with a capacity 6 of such value as to neutralize the inductance of the circuit and make this branch of the circuit resonant for a given frequency. It will be noted that while the circuit divides at 3 and 4 into two branches the source of energy supplying a unidirectional current can only cause a current to flow through the branch containing the variable resistance 1, the current through the other branch being stopped by the condenser 6. This is the normal condition of the circuit. Consider now the result of varying the resistance 1. Under normal conditions about ninety-eight per cent. of the total resistance of the circuit formed by 1, 2, 3, and 4 lies in the variable resistance 1 itself. Therefore ninety-eight per cent. of the drop of potential in the circuit will be between the points 3 and 4, or, in other words, there will be a difference of potential between these points equivalent to ninety-eight per cent. of the potential of the battery or source of energy 2. While no current flows normally through the branch of the circuit containing the primary coil 5 and condenser 6, the condenser is charged to the same potential that exists between 3 and 4. It follows that if the resistance 1 be suddenly lowered, as is the case with a telephonic transmitter when a sound-wave strikes the diaphragm thereof, the potential between the points 3 and 4 is proportionately lowered, and being now of a lower potential than the condenser 6 the condenser discharges, causing a current to flow, as shown by the arrows, through the point 4, the transmitter 1, the point 3, and the induction-coil 5, to the other side of the condenser, and this current not only flows under a potential equal to the maximum variation of the resistance of the system, but flows through a circuit whose impedance has been neutralized or reduced by resonance to practically its ohmic equivalent and at a time when the transmitter resistance is at its minima, thus enormously increasing the available current in the primary coil 5, which in turn proportionately increases the voltage or potential of the secondary circuit. When the transmitter returns to its normal position, the potential of the condenser 6 is again raised to equal the potential between 3 and 4, and as the diaphragm passes through its normal position and to maxima in the opposite direction, thereby raising the resistance of the circuit, there is a proportionally-increased difference of potential across 3 and 4 and also across the condenser-terminals, causing it to take a maximum charge and to discharge again upon a decrease in the potential across 3 and 4, due to another reduction in the resistance 1, and thus with each excursion of the diaphragm to and fro the resistance of the transmitter 1 is alternately increased and decreased, raising or lowering the difference of potential across the terminals of the condenser, which in being alternately charged and discharged produces a current through the primary coil 5. It will also be noted that by this method an absolutely alternating current is utilized in the primary coil, which varies from a positive maxima through zero to a negative maxima, thus insuring better transformer efficiency and better definition of wave form as a result of permitting the use of a greater amount of iron in the core of the primary coil, and the variation of the magnetic flux in the core of the coil from maxima through zero to maxima again instead of merely reducing the value of a magnetic flux of constant polarity from maxima to a certain percentage of itself. This is a distinct step in the art.

From the circuits traced in Fig. 7 it is evident that points 3 and 4 may be divided into a plurality of circuits each containing the primary of an induction-coil with the necessary inductance and capacity requisite to make each branch resonant for the desired frequency.

By winding the primaries of the induction-coils with an increased number of turns the transformer efficiency may not only be increased, but the inductance of the primary coil itself may largely serve to tune the circuit. It is probably advisable, however, to insert separate inductances in the circuits, so as to use the largest amount of inductance in the primary circuit that is practicable without unduly increasing its resistance, for the reason that by so doing smaller capacities will be required for the necessary tuning, and reliable condensers are not only cumbersome and bulky, but also very expensive.

As has been stated in the foregoing, a circuit is tuned or made resonant for a given frequency when

$$2 \pi n L - \frac{1}{2 \pi n c} = o,$$

from which by an easy transposition we may solve for either of the three essential quantities n, L, or C necessary for resonance when the other two are given. For example,

$$2 \pi n L - \frac{1}{2 \pi n c} = o;$$

then by transposition

$$L = \frac{\frac{1}{2 \pi n c}}{2 \pi n} = \frac{1}{4 \pi^2 n^2 c} = L.$$

As inductance is a factor which has to be determined ordinarily by computation, the expression therefor is here given, which is

$$L = \frac{4 \pi t^2 A \mu}{l\, 10^9},$$

where

t — number of turns in the coil.

A — area of magnetic core in square c. m. cross-section.

l — mean length magnetic circuit.

μ — permeability of iron core.

In this connection it should be stated that satisfactory results are to be obtained in tuning for resonance only by the use of mica or air condensers, as I have found by disappointing and painstaking experiments that paraffin condensers are not to be relied upon, owing to dielectric hysteresis and low insulation, which varies within wide limits with changes of temperature.

Having now covered the several fundamental elements of my system entering into the application of resonance principles to the primary circuit for any desired frequency or frequencies and the method of producing the same, I shall now advance to the next step in the direction of increasing the effective main-line potential, so as to give a maximum line-current.

As is well known, in order to effect the long-distance transmission of a telephonic transmitter-current it is necessary to step up the low-potential current of the primary; but there is a limit in thus obtaining the necessary main-line potential, beyond which we may not go and wherein much is lost to telephony. To throw lights upon this point, let us briefly consider the secondary electromotive force in a transformer. As stated in the foregoing, this electromotive force is equal to the primary electromotive force multiplied by the ratio of transformation. This, however, is not all, for the electromotive force so obtained is merely an apparent electromotive force. The ratio of transformation γ may be expressed as

$$\gamma = \frac{2\pi n \cdot M}{\sqrt{4\pi^2 n^2 L_1^2 + R_1^2}};$$

but in telephonic transformers R_1 is usually negligible as compared with $2\pi n L$ and the magnetic leakage very low. It therefore follows that the coefficient of self-induction, being proportional to the square of the number of turns we may say that $\gamma = \frac{t_2}{t_1}$, approximately. This leads us to consider the fictitious nature of the secondary electromotive force so obtained as affecting secondary current. By derivation we may determine the secondary current in general by the equation

$$I_2 = \frac{\frac{t_2}{t_1} E_1}{R_2 + \left(\frac{t_2}{t_1}\right)^2 R_1}.$$

The denominator in this equation shows us the limitations of transformation for effective secondary potential. Furthermore, it not only shows us that the apparent secondary potential must be divided by the secondary impedance, but that the primary resistance is a factor transferred to the secondary and that the transformation ratio is also a factor in the divisor which increases as the square, while the secondary resistance increases directly. To illustrate, consider a transformer with $t_1 = 400$, $t_2 = 2{,}400$, $R_2 =$ 60 ohms. From the equation we would get a certain secondary current. Suppose the secondary turns t_2 be doubled, or made four thousand eight hundred, what would be the result? It is admitted that we should obtain an apparent secondary potential of twice the original value; but since we have increased the secondary resistance to one hundred and twenty ohms and the square of the transformation ratio $\left(\frac{t_2}{t_1}\right)^2$ from $\left(\frac{t_2}{t_1}\right)^2 = 36$ to $\left(\frac{t_2}{t_1}\right)^2 =$ 144 it is readily seen by substitution that in so far as secondary current is concerned we have lost by the operation. This is one reason why telephonic transformers have not been operated on a transformation ratio beyond a certain moderate value. Another reason is that a high transformation ratio has heretofore meant high secondary impedance, which resulted in a greater drop of potential across the secondary terminals than across the receiver-terminals, considering the receiving station or terminal of the circuit. This not only reduces the effective current through the receiver, thus impairing the transmission, but seriously interferes with the voice harmonics or overtones as a result of wave reflection and dissymmetry of wave propagation, due to the position of the secondary impedance in relation to the receiver in the circuit, and it is well known by telephone engineers that by shunting out the secondary of high potential coils the efficiency of the receiver is raised by fifty per cent. or more. This again refers us to and accounts in part for the low-efficiency transmitter induction-coils in general use on the long-distance lines of the American Telephone and Telegraph Company. Now in my invention the essential effective transformation ratio is obtained by tuning the primary circuits for larger currents, which from the expression for secondary electromotive force, $E_2 = 2\pi n M I_1$, gives us the same results as would be obtained by increasing the mutual induction M by raising the transformation ratio. Moreover, this is done without interfering with the efficiency of the receiver. In addition to this I have discovered that by placing the secondaries of the plurality of primary circuits already referred to in multiple and relating them to compensating transformers the terminal impedances of the line may be reduced to practically zero and the receiver efficiency improved by about one hundred per cent. This will be better understood by reference to Figs. 8 and 9.

Referring now to Fig. 8, let us consider the alternator 10 as the equivalent of the secondary source of electromotive force 10 in Fig. 9 and that 10′ is another generator at the distant end of the circuit similarly arranged, the rest of Fig. 8 being identical with Fig. 9 and with similar indices. Alternator 10 is supposed to be generating an electromotive force, which is considered at the moment when the current is in a positive direction following the arrows. The transformers Tr_1 and Tr_2 are taken as identical with a transformation ratio of one to one with one hundred per cent. efficiency, primary and secondary turns wound together on the same core and connected as shown in the diagram. Consider now the current flowing in the direction of the arrows. Upon reaching the terminal 12 of transformer Tr_1 it passes through the line-coil or primary in a direction around the core, as shown, creating a magnetic flux through the core and an induced electromotive force in the other or secondary winding which flows in the opposite direction around the core of the transformer and into the line at 14. A similar action takes place in transformer Tr_2, which generates an electromotive force in its secondary in the same direction as that in the secondary of Tr_1, which on account of the two secondaries being connected places these two secondary electromotive forces in series. Now it is evident that the current from generator 10 upon reaching 14 has two paths, the one through the main circuit and the generator 10′ and the other through the two secondaries 15 and 16. It is also obvious that the secondary path through windings 15 and

16 is impassable, because this path contains an electromotive force of its own, due to mutual induction, opposed to the direction of the current. In fact, this second path has an electromagnetic force twice as great as the electromagnetic force in coil 13 and itself produces a current which is placed in multiple with the current in the line primary. In addition to this it is evident that secondary coils 15 and 16 being in series and of a potential twice as great as that in the main a current is also forced back through the primary coil 13 and the generator 10 and the potential of the generator reduced in the main line by half its former value. Reversing the diagram and considering 10′ as the generator and 10 as the other terminal, we shall also reverse the status of the system, and the potential through the circuit between 11 and 12 and through generator 10 will be twice that given by generator 10′. These results are of course predicated upon ideal relations and efficiencies and in actual practice would be modified by the losses in the transformers and the relative values of transformer and generator constants. Thus it is seen that by the use of compensating transformers we may raise or lower the line voltage or by properly adjusting the transformers or their constants of transformation we may maintain the original potential of the source, while reducing its internal impedance to incoming currents as a result of the shunt to incoming currents through coils 15 and 16. It should be observed, however, that incoming currents are not only shunted in multiple with the source 10, but are raised in potential to twice that of generator 10′, thus reducing the impedance of the terminal from two causes, and thereby increasing the current through the circuit. It will be noted that I have shown and described two compensating transformers in relation to the source of electromotive force—one on each side thereof. Now this is not essential, and in practice one transformer properly adjusted as to constants and transformation ratio so as to equal the line electromotive force is found preferable, as shown at B in Figs. 9, 10, and 11. Both methods, however, are effective and have advantages varying with circumstances. This brings me to Fig. 9, which is a diagrammatic representation of a local battery type of my system in conventional symbols, which will be readily understood. From this figure, where similar references indicate similar parts at each terminal of the line, it will be seen that the principles disclosed and explained with reference to Figs. 7 and 8 are applied to the operation of Fig. 9. Referring now to Fig. 9 specifically, A and B are the two distant terminals of the line. 1 is a telephonic transmitter of any approved type. 2 is a source of constant potential in circuit with transmitter 1, derived from which, branching from points 3 and 4, are two branch circuits containing inductances L_1 and L'_1, primary coils 5 and 7, and capacities 6 and 8. This is identical with Fig. 7, already explained, whereby primary coils 5 and 7 are made resonant for the desired frequencies, as disclosed and illustrated in the foregoing. Now primary coils 5 and 7 act by induction upon secondaries 9 and 10, setting up therein electromotive forces which act upon the compensator-transformers Tr_1 and Tr_2 in the manner previously described in reference to Fig. 8, which is identical with the secondary terminal system of Fig. 9. Therefore we have a system whereby the transformer efficiency is increased by resonance one hundred per cent. or more, while at the same time neutralizing the effective impedance of the equivalent secondaries, and thereby increasing the sensitiveness of the receiver 19 by one hundred per cent., making a net gain over old methods of at least two hundred per cent., as verified by my experiments.

Figs. 10 and 11 are diagrammatic representations of central energy or common battery types of my system with distant terminals A and B and corresponding central offices C O, which will be readily followed from what has already been disclosed and a knowledge of common battery systems in general. Like indices refer to like or equivalent parts in Fig. 9. Fig. 11 is a modification of Fig. 10, showing the method of applying the principles of my invention to subscribers' stations in a common battery system instead of at the central office, as under some circumstances may be desirable.

The apparatus is not claimed herein.

This case is filed as a divisional application of my former application, entitled "Art of telephony," filed July 23, 1904, Serial No. 217,846, pursuant to a requirement by the Patent Office so as to separate apparatus and method claims.

It will be obvious that many changes and variations can be made in the detail of my system without departing from the spirit of my invention.

Therefore, without limiting myself to the details shown, what I claim, and desire to secure by Letters Patent of the United States, is—

1. The step in the art of the electrical transmission and reproduction of sound which consists in making the terminal transmitter circuit or circuits wholly or partially resonant for the essential frequencies to be transmitted, thereby increasing the efficiency of transformation, and the energy transferred to the secondary circuit, substantially as set forth.

2. The step in the art of the electrical transmission of sound which consists in attuning the terminal or transmitter circuit for the es-

sential current frequencies to be transmitted, thereby increasing the primary current and the ratio of transformation and the energy transferred to the line, substantially as set forth.

3. The step in the art of the electrical transmission and reproduction of sound which consists in adjusting the electrical constants of the terminal or transmitter circuits to a condition of resonance and consonance for the essential current frequencies to be transmitted, thereby increasing the efficiency of transformation, and the energy transferred to the main line, and the intensity of the sound reproduced, substantially as set forth.

4. The step in the art of the electrical transmission and reproduction of sound which consists in making the terminal primary and secondary circuits wholly or partially consonant for the essential frequencies to be transmitted, thereby increasing the efficiency of transformation and transmission, and reproduction, substantially as set forth.

5. The step in the art of the electrical transmission and reproduction of sound-waves which consists in adjusting the constants of resistance, inductance and capacity of the primary circuit or circuits, so as to decrease the primary impedance and increase the primary current, thereby increasing the ratio of transformation, the potential of the secondary and the intensity of the transmitted sound-waves, substantially as set forth.

6. The step in the art of the electrical transmission and reproduction of sound, or voice, waves which consists in increasing the ratio of transformation and the line-potential by electrical consonance, while reducing the terminal impedance to incoming sound or voice waves, and thereby increasing the line-current and the sensitiveness of the receiver and the efficiency of reproduction, substantially as set forth.

7. In the art of the electrical transmission and reproduction of sound, the method of producing resonance in the transmitter circuit or circuits, which consists in placing the primary coil in a derived circuit, properly tuned as to inductance and capacity, between points of variable potential due to variations in the resistance of the transmitter-electrodes, whereby the capacity is charged and discharged through the said primary coil with increase and decrease of resistance in the transmitter, substantially as set forth.

8. In the art of the electrical transmission and reproduction of sound, the method of tuning for the essential voice or sound frequencies, which consists in placing the primary coils, in series with capacities, in shunt or derived circuits between points whose potential varies as a function of the vibration of the transmitter-diaphragm, and in adjusting the constants of the said shunt or derived circuits to resonance for the desired frequencies, whereby a current is caused to flow through the said primary coils, due to the charging and discharging of the said capacities with increase and decrease of potential across the terminals of the said shunt or derived circuits, substantially as set forth.

9. In the art of the electrical transmission and reproduction of sound, the method of producing an alternating current in the primary coil which consists in placing the primary coil and a capacity in a derived or shunt circuit between points whose potential varies as a function of the vibration of the transmitter-diaphragm, whereby an alternating current is caused to flow through the said primary coil due to the charging and discharging of the said capacity as the potential varies across the terminals of the said derived or shunt circuit, substantially as set forth.

10. In the art of the electrical transmission and reproduction of sound by means of electrical waves, the method of improving wave definition and characteristics which consists in generating alternating currents in the primary coil with positive and negative maxima and zero values, whereby the range of variation of the magnetic flux in the magnetic circuit of the coil is greatly increased, and the wave form, definition and quality materially improved, substantially as set forth.

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

D. MACLAUCHLIN-THERRELL.

Witnesses:

GEO. T. CAREY,

M. C. KING.