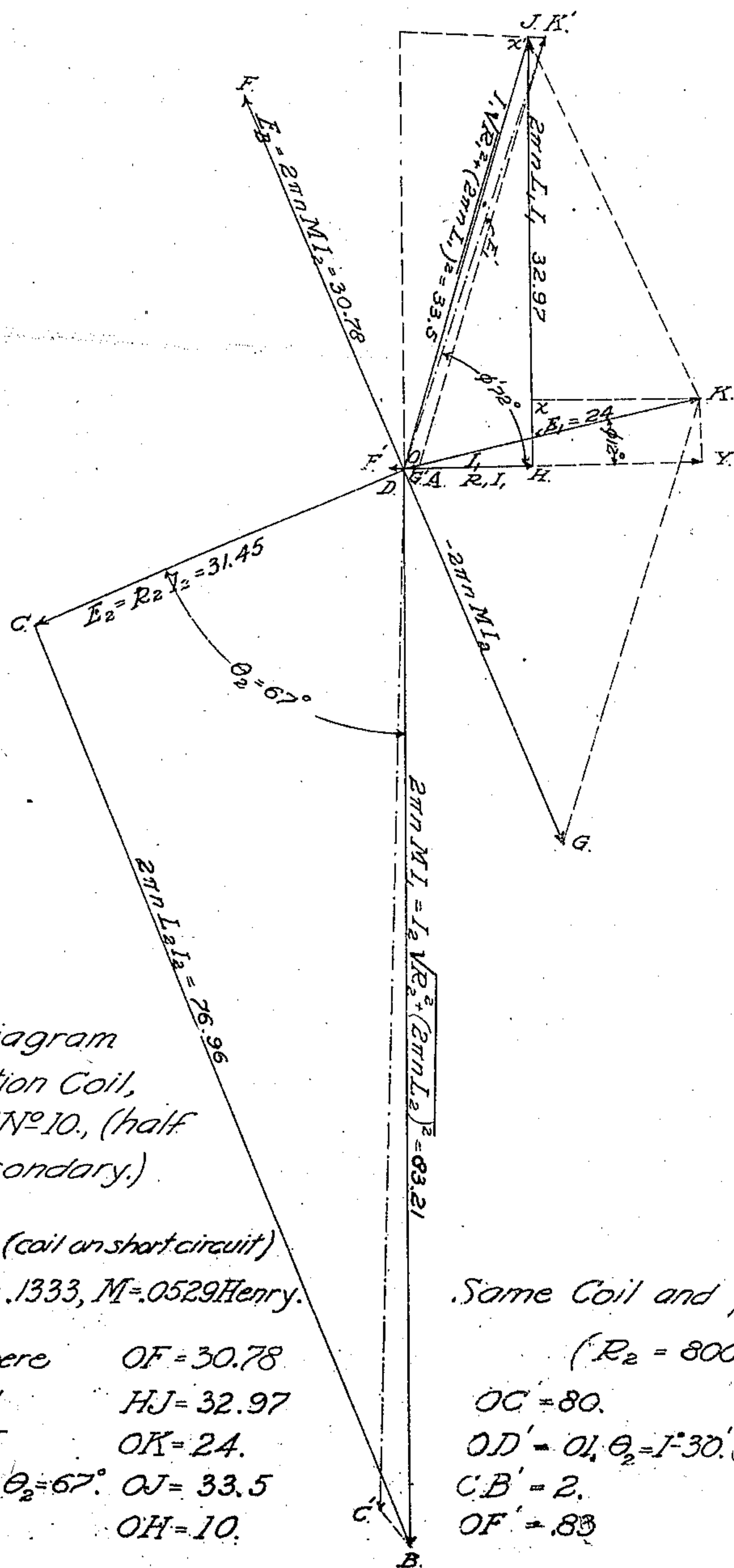


No. 865,215.

PATENTED SEPT. 3, 1907.

D. M. THERRELL.  
ART OF TELEPHONY.  
APPLICATION FILED JULY 23, 1904.

6 SHEETS—SHEET 1.



Polar Diagram  
of Induction Coil,  
Type-Bell No 10, (half  
of secondary.)

$R_1 = .5 \text{ ohm.}$

$R_2 = 85 \text{ ohms (coil on short circuit)}$

$I_1 = .021, I_2 = .1333, M = .0529 \text{ Henry.}$

$OA = 1 \text{ ampere} \quad OF = 30.78$

$OB = 83.21 \quad HJ = 32.97$

$OC = 31.45 \quad OK = 24.$

$OD = .372, \theta_2 = 67^\circ \quad OJ = 33.5$

$CB = 76.96 \quad OH = 10.$

Same Coil and primary current.

( $R_2 = 8000 \text{ ohms}$ )

$OC = 80. \quad OK = 33.$

$OD' = .01, \theta_2 = 1^\circ 30'. \quad OY = \text{app't resistance}$

$CB' = 2. \quad HX = \text{app't reactance}$

$OF' = .83$

Fig 1

WITNESSES.

*R. E. Robinson*

*R. E. Robinson*

INVENTOR.

*D. M. Therrell*

No. 865,215.

D. M. THERRELL.  
ART OF TELEPHONY.  
APPLICATION FILED JULY 23, 1904.

PATENTED SEPT. 3, 1907.

6 SHEETS—SHEET 2.

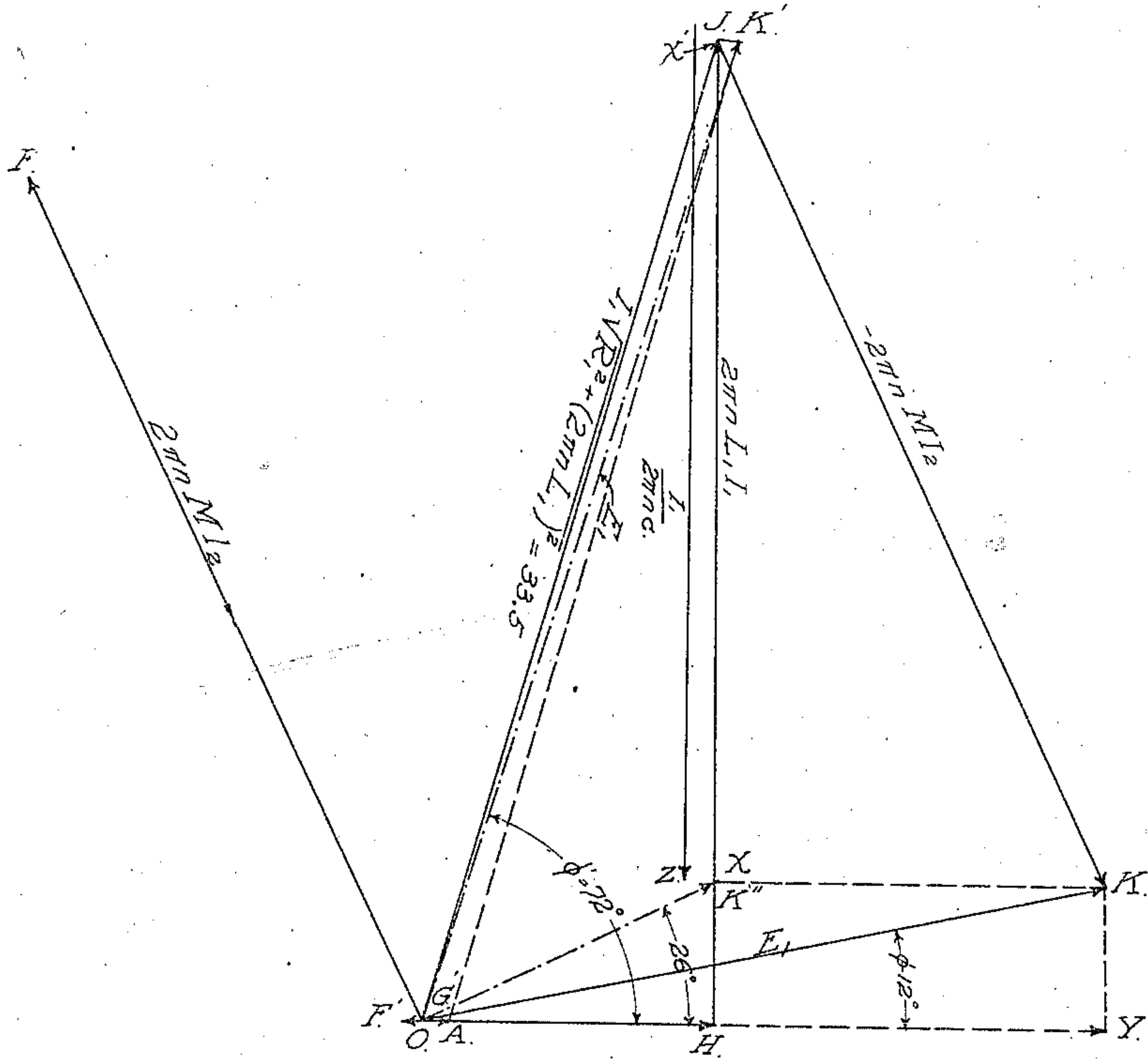


Fig 2.

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

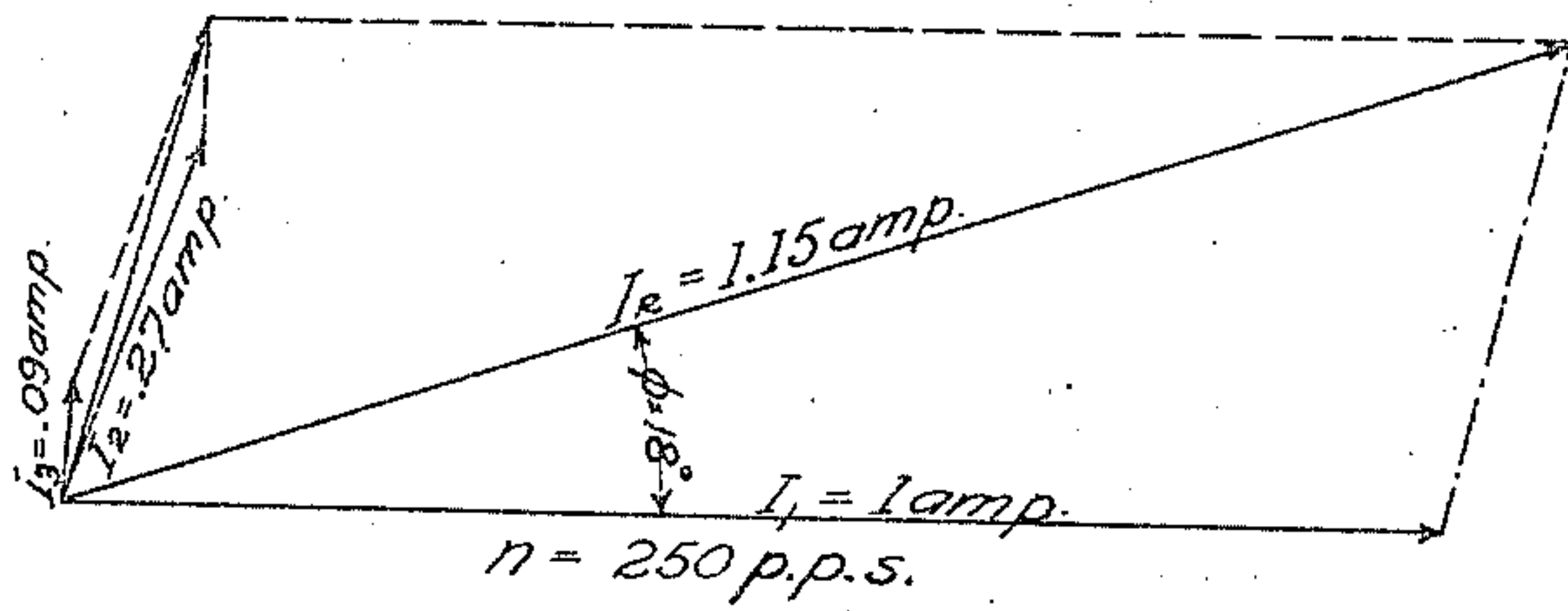


Fig 5.

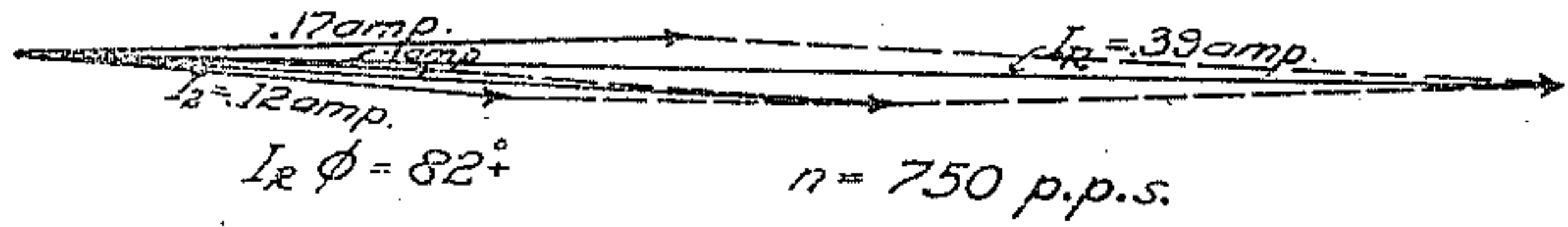


Fig 6.

WITNESSES.

H. Basch  
R. E. Robinson

*INVENTOR.*

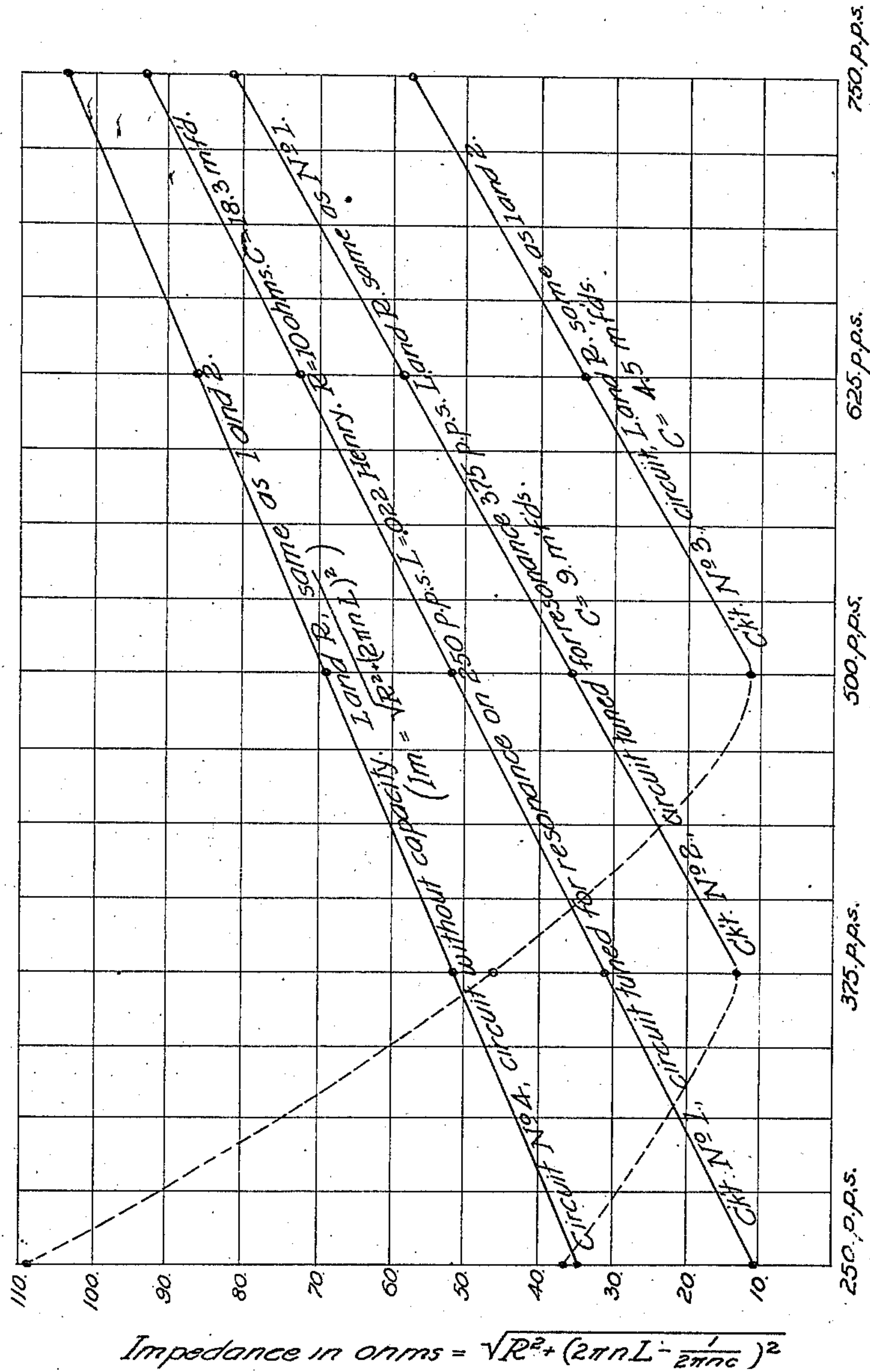
Madachin Mmber

No. 865,215.

D. M. THERRELL.  
ART OF TELEPHONY.  
APPLICATION FILED JULY 23, 1904.

PATENTED SEPT. 3, 1907.

6 SHEETS—SHEET 3.



$n$  = Periods per second.  
Fig 3.

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

WITNESSES.

*S. Bartok*  
*R. E. Robinson*  
*Geo J. Carey*

INVENTOR.

*D. M. Therrell*

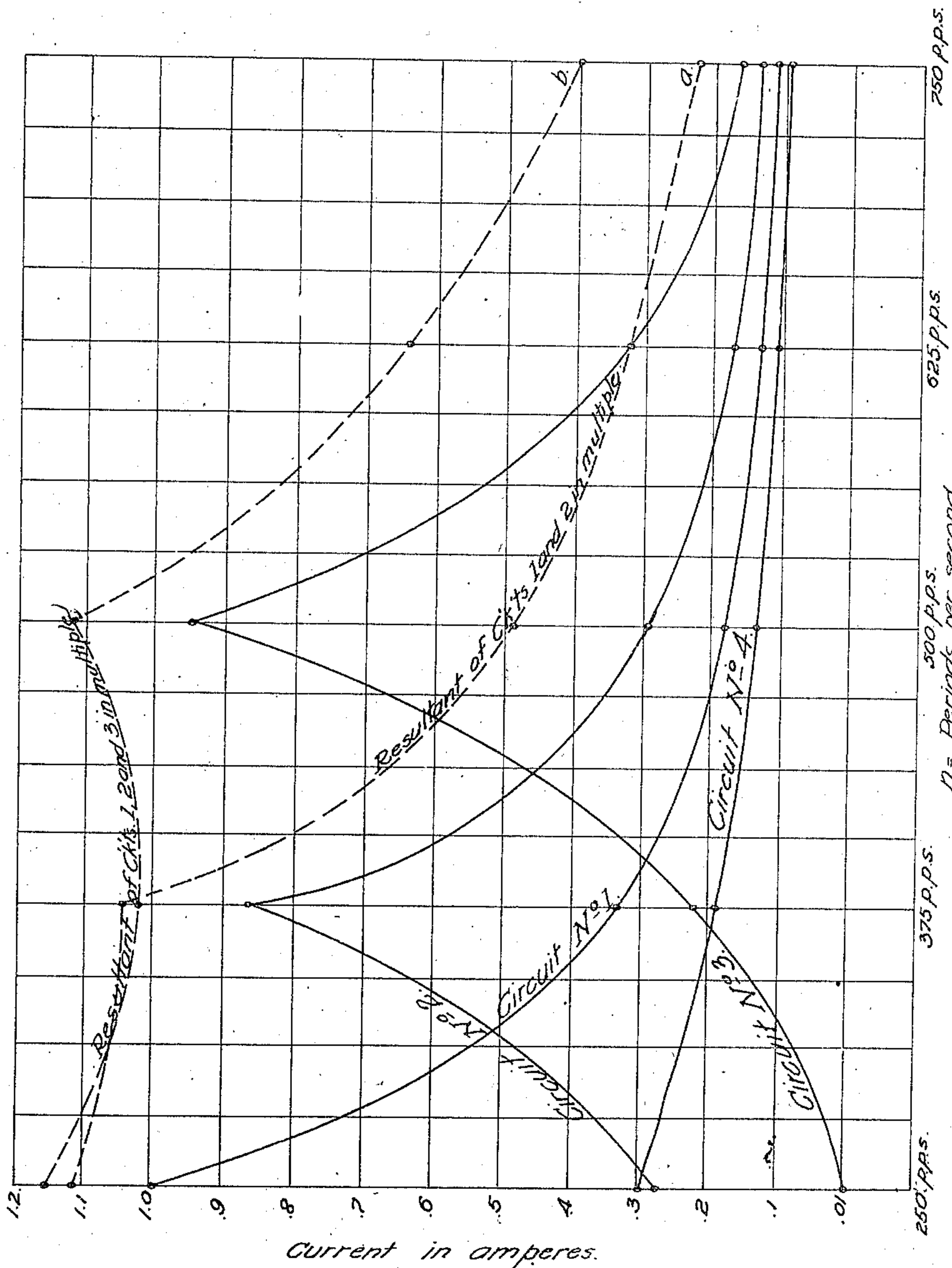


No. 865,215.

D. M. THERRELL.  
ART OF TELEPHONY.  
APPLICATION FILED JULY 23, 1904.

PATENTED SEPT. 3, 1907.

6 SHEETS—SHEET 4.



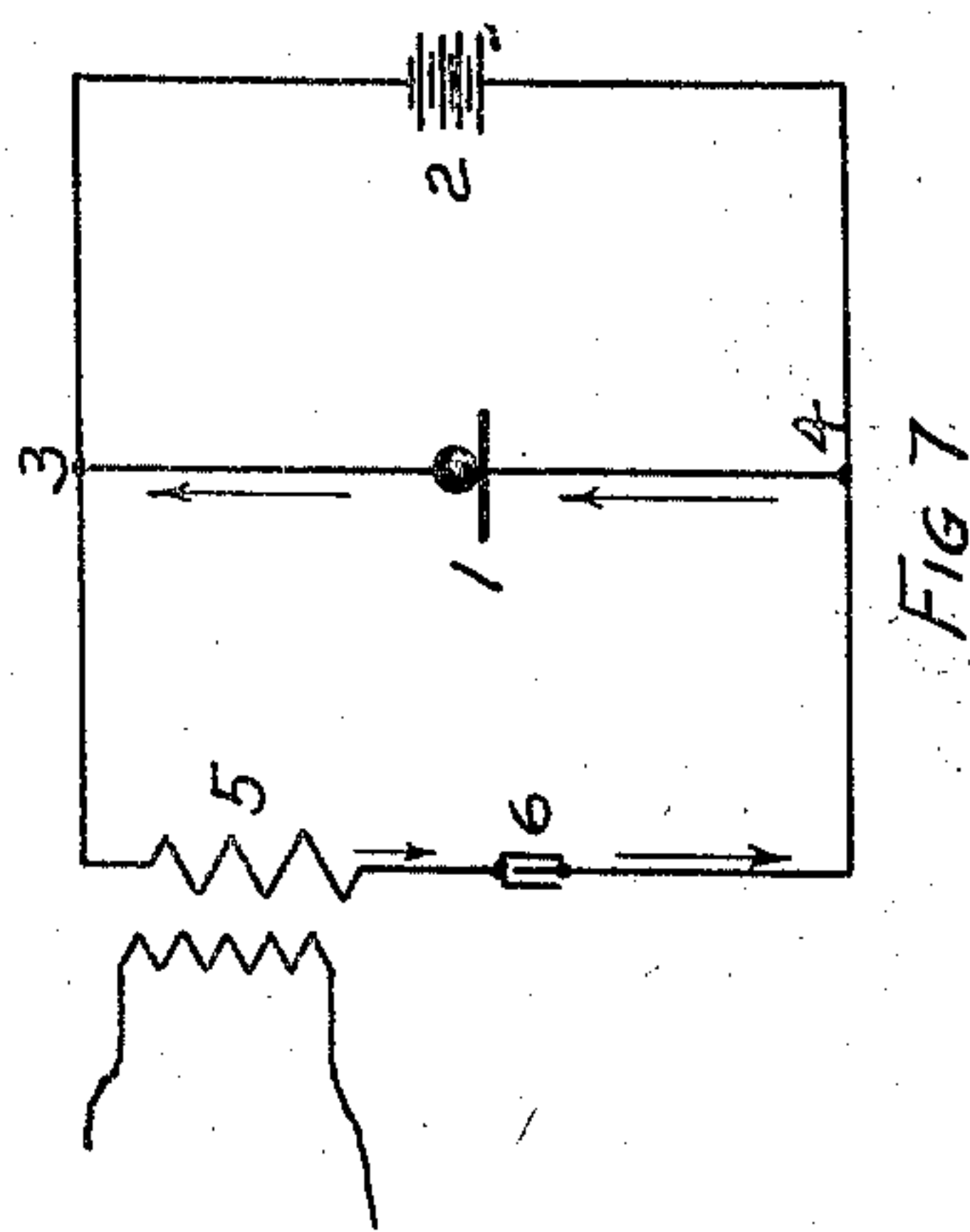
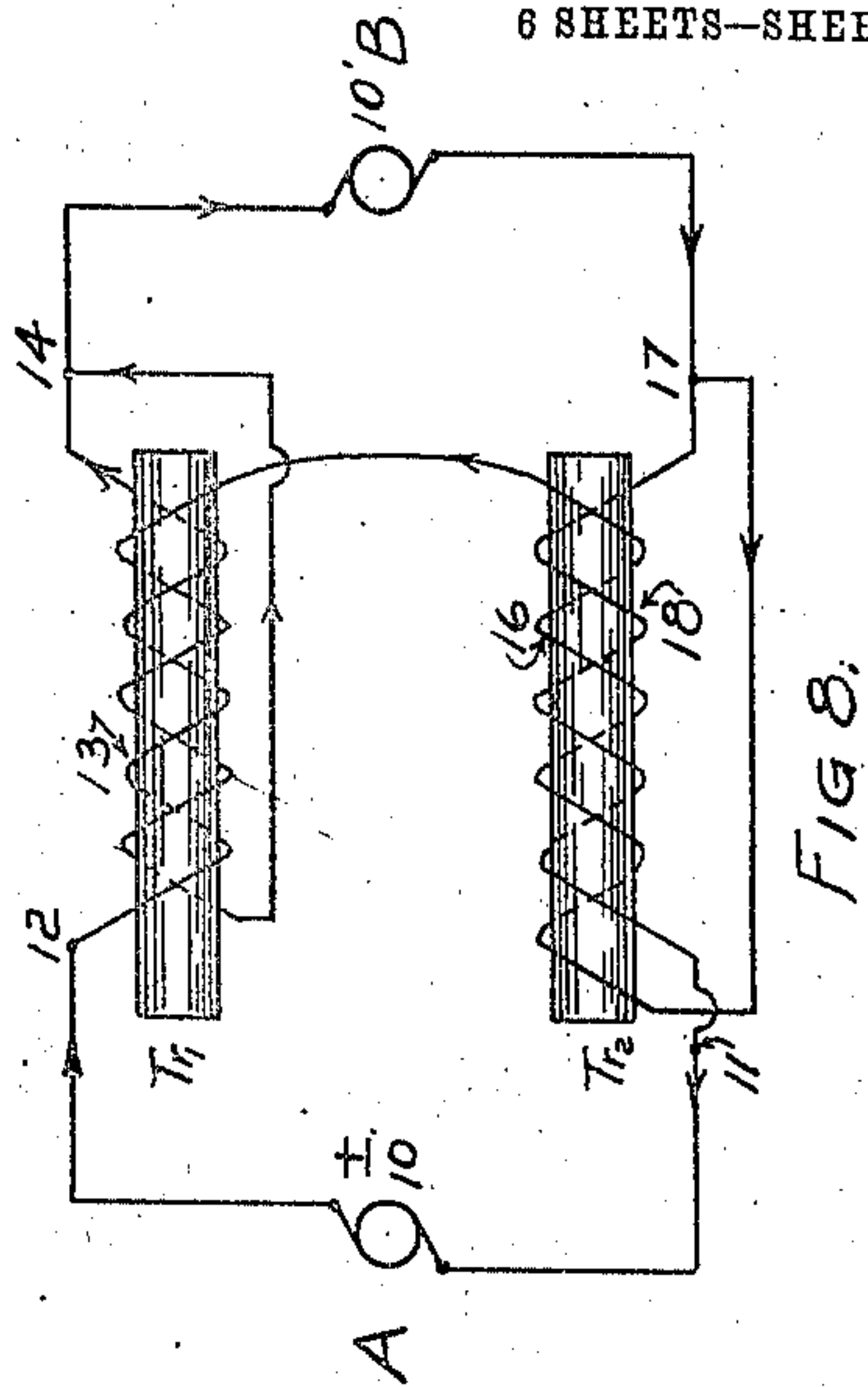
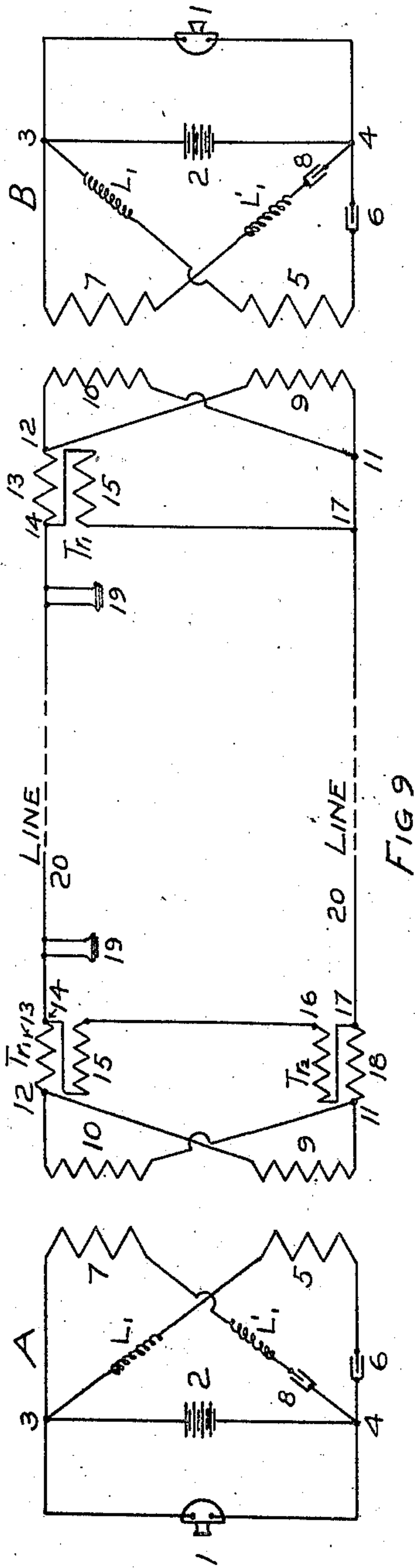
Curves showing value of currents for circuits 1, 2 and 3, and 4, and in broken lines, also, resultant of secondary current, with P and S, of Nos. 1, 2 and 3 connected in multiple.  $E_1 = 10$  volts primary. Transformation ratio 1:1. Secondary on short circuit.

WITNESSES.

*E. Barlow*  
*R. E. Robinson*  
*Geo. J. Carey*

INVENTOR.

*D. MacLachlin Therrell*



Witness C. F. Trimble  
D. M. Therrell

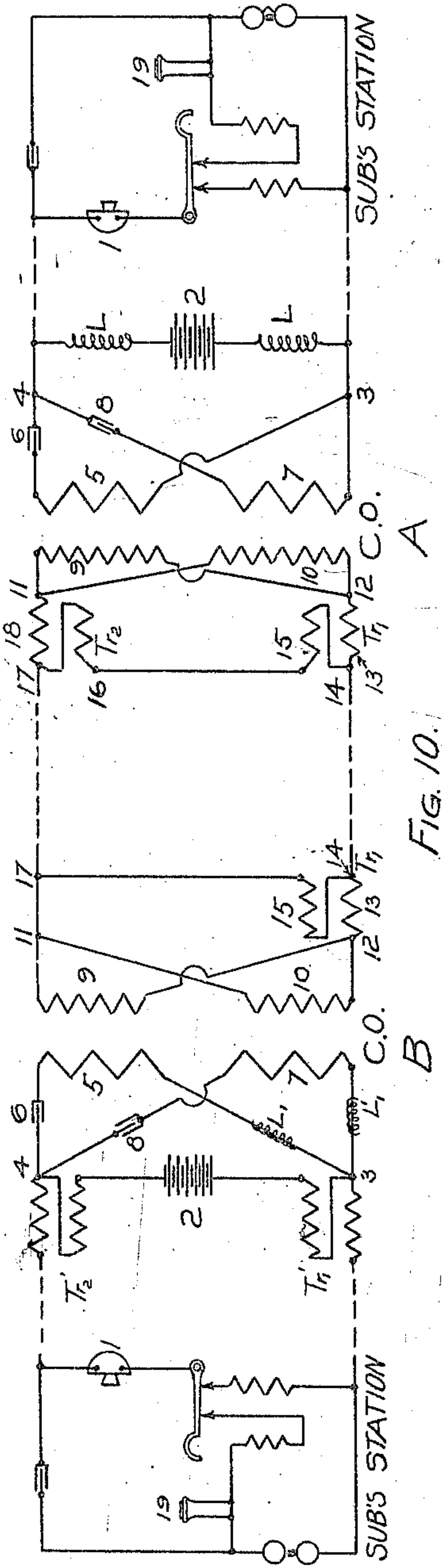
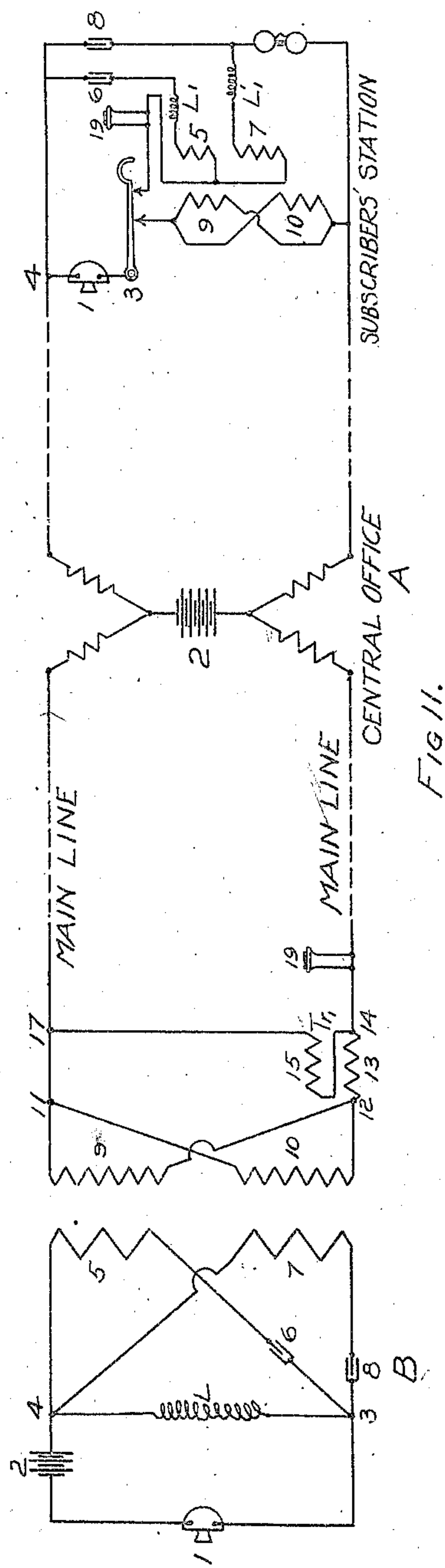
Inventor

Maximilian Therrell

D. M. THERRELL.  
ART OF TELEPHONY.

APPLICATION FILED JULY 23, 1904.

6 SHEETS—SHEET 6.



Inventor

Witness C. F. Trimble  
B. Browne

D. Macaulay



# UNITED STATES PATENT OFFICE.

DANIEL MACLAUHLIN THERRELL, OF CHARLESTON, SOUTH CAROLINA.

## ART OF TELEPHONY.

No. 865,215.

Specification of Letters Patent.

Patented Sept. 3, 1907.

Application filed July 23, 1904. Serial No. 217,846.

*To all whom it may concern:*

Be it known that I, DANIEL MACLAUHLIN 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. Right here has been the stumbling block in the way of telephone engineers, up to the present time.

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  $I^2 R$  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 para-



mount 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  
 5 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  
 10 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  
 15 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  
 20 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.  
 25 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  
 30 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  
 35 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  
 40 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  
 45 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  
 50 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 8,000 ohms in secondary circuit, showing the method of neutralizing the primary self-induction by a capacity reactance.  
 55 Fig. 3. is a set of curves (drawn to rectangular co-ordinates), 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  
 60 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  
 65 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  
 70 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 trans-  
 75 formers, 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. Fig. 10. and 11. are conventional diagrams of  
 80 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  
 85 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 specifications  
 90 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  
 95 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  
 100 there are  $sN$ -lines threading, or linked with the circuit. The quantity,  $sN$ , 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 electro-  
 105 motive 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 cur-  
 110 rent 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  
 115 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 there-  
 120 with. 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 pro-  
 125 portional 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  
 130



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 magneto-motive 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 period per second.  $C$ =capacity.  $I_1$ =primary current.  $I_2$ =secondary current.  $E_1$ =primary e. m. f.  $E_2$ =secondary e. m. f.  $L_1$ =primary inductance.  $L_2$ =secondary inductance.  $M$ =mutual inductance.  $N$ =total flux of magnetic field.  $R$ =ohmic resistance.  $Im$ =impedance.  $\phi$ =primary phase angle.  $\theta_2$ =secondary phase angle.  $p. p. s.$ =periods per second.  $\gamma$ =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 8000 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 1 ampere, flowing through an average resistance, including the transmitter of, say 10 ohms, represented by  $OA$ , and  $OH$ , 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  $\theta_2$ , such that,

$$\tan \theta_2 = \frac{2\pi n L_2}{R_2} \quad 70$$

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

$$E_2 = R_2 I_2 \text{ and } I_2 = \frac{2\pi n M I_1}{\sqrt{R_2^2 + (2\pi n L_2)^2}} \quad 75$$

By the graphical construction for simple circuits, we know that the right triangle  $O. C. B.$  upon  $B.$  as an 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  $O. F.$ ,  $90^\circ$  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 24 volts, and leading the current by approximately 12°.

From Fig. 1, it is readily seen that since the component of the primary e. m. f. O. G. necessary to overcome the back e. m. f. 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 e. m. f. into three components, which apparently reduces the self induction of the primary and increases its resistance by bringing the resultant e. m. f. 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 e. m. f. of self-induction in the primary was apparently reduced by the back e. m. f. of the secondary from H. J. to H. X and the resistance increased from O. H. to O. Y., while the e. m. f. came quite into phase with the current, thus bringing the power factor high unto unity. Now, let us assume the secondary to have a line in circuit of such resistance that the total secondary resistance becomes 8000 ohms instead of 85 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 e. m. f. rises from 31.45 volts to 80 volts, as shown by O. C'; while the secondary current falls from .37 ampere to .01 ampere; the back e. m. f. falls from 30.78 volts to .83 volt as shown by O. F'. The lag in the secondary is also reduced from about 67° to about 1°, with an equal shift in the phase relation of the back e. m. f. 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 e. m. f. equal to about 33. volts and leading the current by about 72° instead of 12°, with a power factor proportionately reduced.

The values of the various vectors just given are based upon the assumption that the primary e. m. f. has been raised so as to maintain a power current of 1 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 e. m. f. to deal with. Under these circumstances, let us consider the primary e. m. f. as 24 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 e. m. f.; the back e. m. f. 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 e. m. f., is proportionately reduced in value and advanced in phase. Now as the back e. m. f. decreases in value and advances in phase angle, the primary impedance increases in value, and the impressed primary

e. m. f. advances or leads over the primary current, by a like angle. In the case given, the primary impedance is increased from 24 ohms on short-circuited secondary to 33. ohms with the external secondary circuit as given, and what is more important the phase angle between the primary e. m. f. and the primary current, is increased from 12° in the first instance, to 72° 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 e. m. f. according to the equation 59.8 volts instead of the apparent 80 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  $2\pi n M I_1$ . 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 93 percent between the primary and the secondary current, even with the secondary on short circuit.

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 or 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 250 p. p. s., the effects are experienced by all frequencies above 250, 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 e. m. f. 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 e. m. f. O. F., of the secondary, from H. J. to H. X., whereas with the secondary connected into a circuit equaling 8000 ohms the back e. m. f. 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

$$2\pi nL - \frac{1}{2\pi nc} = H. X.,$$

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 a 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 ohm,  $L_1 = .022$  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 34 ohms to a current of 250 p. p. s., and that for a frequency of 750 p. p. s., the impedance is over 103 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 e. m. f. of 10 volts. Thus in Fig. 4, circuit 1, it is seen that, for an impedance of 34 ohms

$$= \sqrt{R^2 + (2\pi nL)^2},$$

and a frequency of,  $n = 250$ , we get only .29 ampere, while for 750 p. p. s., we get .097 ampere. This is upon the assumption of secondary on line of 8000 ohms,

or approaching open circuit. Let us introduce into the primary a capacity, C. The primary impedance is then determined by the equation,

$$I_m = \sqrt{R^2 + \left(2\pi nL - \frac{1}{2\pi nc}\right)^2}.$$

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

$$2\pi nL - \frac{1}{2\pi nc} = 0,$$

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 18 microfarads and the primary current rises from .29 ampere to 1 ampere as a result of this capacity in the circuit. Reference to Fig. 3 will also show that for a frequency of 750 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 250 p. p. s., 375 p. p. s. and 500 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 1:1 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 250 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 1 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 250, 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

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

- 5 where  $a$ , and  $a'$ , represent the value of the two currents and  $\phi$  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.
- 10 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.
- 15 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.
- 20 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
- 25 be placed in series with the primary coil, a necessary requisite under the given conditions, and 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
- 30 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
- 35 have apparently led to the belief, by telephonic authorities, that the principles of resonance cannot be successfully 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,
- 40 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
- 50 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,
- 55 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
- 60 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. 65 Under normal conditions about 98 percent of the total resistance of the circuit formed by 1, 2, 3 and 4, lies in the variable resistance 1 itself. Therefore 98 percent of the drop of potential in the circuit will be between the points 3 and 4; or in other words, there will be a 70 difference of potential between these points equivalent to 98 percent 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 75 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 80 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 85 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 95 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 100 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 105 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 115 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 120 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 125 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

$$2\pi nL - \frac{1}{2\pi nc} = 0.$$

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:

$$2\pi nL - \frac{1}{2\pi nc} = 0,$$

then by transposition,

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

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

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

where  $l$  = number of turns in the coil,  $A$  = area of magnetic core in square c. m. cross section,  $l$  = mean length magnetic circuit,  $\mu$  = 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 light 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 e. m. f. multiplied by the ratio of transformation. This, however, is not all, for the e. m. f. so obtained is merely an apparent e. m. f. The ratio of transformation  $\gamma$ , may be expressed as,

$$\gamma = \frac{2\pi nM}{\sqrt{4\pi^2 n^2 L^2 + R_1^2}}$$

But, in telephonic transformers,  $R_1$  is usually negli-

gible as compared with  $2\pi nL$ , 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,

$$\gamma = \frac{l_2}{l_1}$$

approximately. This leads us to consider the fictitious nature of the secondary e. m. f. so obtained as affecting secondary current. By derivation, we may determine the secondary current in general, by the equation

$$I_2 = \frac{l_2 E_1}{R_2 + \left(\frac{l_2}{l_1}\right)^2 R_1}$$

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

$$l_1 = 400, l_2 = 2400, R_2 = 60 \text{ ohms.}$$

From the equation, we would get a certain secondary current. Suppose the secondary turns,  $l_2$ , be doubled, or made 4800, 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 120 ohms, and the square of the transformation ratio,

$$\left(\frac{l_2}{l_1}\right)^2, \text{ from } \left(\frac{l_2}{l_1}\right)^2 = 36, \text{ to } \left(\frac{l_2}{l_1}\right)^2 = 144.$$

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 50 percent, 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 cir-



5 circuits for larger currents, which from the expression  
 for secondary e. m. f.,  $E_2 = 2\pi nMI$ , 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 plu-  
 10 rality of primary circuits already referred to, in mul-  
 tiple, and relating them to compensating transformers,  
 the terminal impedances of the line may be reduced  
 to practically zero and the receiver efficiency im-  
 proved by about 100 percent. This will be better un-  
 derstood by reference to Figs. 8 and 9.

Referring now to Fig. 8, let us consider the alterna-  
 15 tor 10, as the equivalent of the secondary source of  
 e. m. f. 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 gen-  
 20 erating an e. m. f., 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 1:1, with  
 100 percent. efficiency, primary and secondary turns  
 25 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 reach-  
 ing the terminal 12 of transformer  $Tr_1$  it passes through  
 the line coil, or primary, in a direction around the core,  
 30 as shown, creating a magnetic flux through the core  
 and an induced e. m. f. 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  $Tr_2$   
 35 which generates an e. m. f. in its secondary in  
 the same direction as that in the secondary of  
 $Tr_1$ , which on account of the two secondaries be-  
 ing connected, places these two secondary e. m. f's.  
 in series. Now, it is evident that the current  
 40 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 wind-  
 45 ings 15 and 16, is impassable because this path con-  
 tains an e. m. f. of its own, due to mutual induction,  
 opposed to the direction of the current. In fact, this  
 second path has an e. m. f. twice as great as the e. m. f.  
 in coil 13, and itself produces a current, which is placed  
 in multiple with the current in the line primary. In  
 50 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 poten-  
 tial of the generator reduced in the main line by half its  
 55 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 gen-  
 60 erator 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 con-  
 stants. Thus it is seen that by the use of compensating  
 65 transformers, we may raise or lower the line voltage,

or by properly adjusting the transformers, or their con-  
 stants of transformation, we may maintain the original  
 potential of the source while reducing its internal im-  
 pedance to incoming currents, as a result of the shunt  
 to incoming currents through coils 15 and 16. It 70  
 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 75  
 the circuit.

It will be noted that I have shown and described two  
 compensating transformers in relation to the source of  
 e. m. f., one on each side thereof. Now, this is not es-  
 80 sential, and in practice one transformer properly ad-  
 justed as to constants and transformation ratio, so as to  
 equal the line e. m. f., is found preferable, as shown at  
 B., in Figs. 9 and 10. Both methods, however, are ef-  
 fective, and have advantages varying with circum-  
 stances. This brings me to Fig. 9 which is a diagram- 85  
 matic representation of a local battery type of my sys-  
 tem, in conventional symbols, which will be readily un-  
 derstood. 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 90  
 with reference to Figs. 7 and 8, are applied to the opera-  
 tion 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 95  
 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 pri-  
 mary coils 5 and 7 are made resonant for the desired fre- 100  
 quencies, as disclosed and illustrated in the foregoing.  
 Now, primary coils 5 and 7 act by induction upon sec-  
 ondaries 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 105  
 to Fig. 8, which is identical with the secondary ter-  
 minal system of Fig. 9. Therefore, we have a system  
 whereby the transformer efficiency is increased by res-  
 onance 100 percent. or more, while at the same time,  
 neutralizing the effective impedance of the equivalent 110  
 secondaries and thereby increasing the sensitiveness of  
 the receiver 19, by 100 percent., making a net gain over  
 old methods of at least 200 percent., as verified by my  
 experiments.

Figs. 10 and 11 are diagrammatic representations of 115  
 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 120  
 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. 125

I do not in this application claim the art or method of  
 telephony described, as that is claimed in my other  
 application, companion hereto, entitled "Art of te-  
 lephony", filed August 2, 1905, Serial Number 272375,  
 which application is a division hereof, pursuant to the 130



requirement of the Patent Office, so as to separate the apparatus from the 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. In the art of the electrical transmission and reproduction of sound, means for producing resonance in the transmitter circuit, substantially as set forth.
2. In the art of the electrical transmission and reproduction of sound, means for producing and determining electrical resonance in the transmitter circuit, substantially as set forth.
3. In the art of the electrical transmission and reproduction of sound, means for producing electrical resonance in the primary circuit or circuits, whereby the current is increased in the said circuit or circuits, substantially as set forth.
4. In the art of the electrical transmission and reproduction of sound, means for producing electrical consonance in the primary and secondary circuits, substantially as set forth.
5. In the art of the electrical transmission and reproduction of sound, means for producing and determining electrical consonance in the transmitter circuits, whereby the current is increased, substantially as set forth.
6. In the art of the electrical transmission and reproduction of sound, means for attuning the transmitter circuit to the essential frequencies of the sound to be transmitted, substantially as set forth.
7. In the art of the electrical transmission and reproduction of sound, means for electrically attuning the transmitter circuit for the essential harmonic frequencies of the sound to be transmitted, whereby the current is increased in the said transmitter circuit, substantially as set forth.
8. In the art of the electrical transmission and reproduction of sound, means for electrically attuning the transmitter and line circuits for the essential frequencies to be transmitted, substantially as set forth.
9. In the art of the electrical transmission and repro-

duction of sound, means for electrically attuning the transmitter and line circuits for the essential frequencies to be transmitted, whereby the current is increased in the said circuits, substantially as set forth.

10. In the art of the electrical transmission and reproduction of sound, means for reducing the terminal impedance to incoming line currents, substantially as set forth.

11. In the art of the electrical transmission and reproduction of sound, means for reducing the terminal impedance of the line to incoming voice or sound currents, whereby the line current is increased, substantially as set forth.

12. In the art of the electrical transmission and reproduction of sound, means for generating alternating currents in a branch of the transmitter circuit containing the primary coil, substantially as set forth.

13. In the art of the electrical transmission and reproduction of sound, means for generating alternating currents in circuits derived from the transmitter circuit and containing the primary coils of a plurality of transformers, substantially as set forth.

14. In the art of the electrical transmission and reproduction of sound, the combination of a transmitter, a source of energy and a transformer in a circuit attuned for the essential sound or voice frequencies and in operative relation to the main line and receivers, substantially as set forth.

15. In the art of the electrical transmission and reproduction of sound, the combination of a transmitter, a source of energy and transformers in derived circuits attuned for the essential voice or sound frequencies and in operative relation to the main line and receivers, substantially as set forth.

16. In the art of the electrical transmission and reproduction of sound, the combination of a transmitter, a source of energy and transformers in circuits attuned for the essential sound or voice frequencies and in operative relation to the main line and receivers and compensating transformers in the main line, substantially as set forth.

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

D. MACLAUCHLIN THERRELL.

Witnesses:

GEO. T. CAREY,  
K. C. MCCOY.