Dec. 12, 1933. E. F. VAAGE 1,938,732

SYSTEM FOR IMPROVING THE SHIELDING EFFECT OF GROUND WIRES AND SHIELD WIRES

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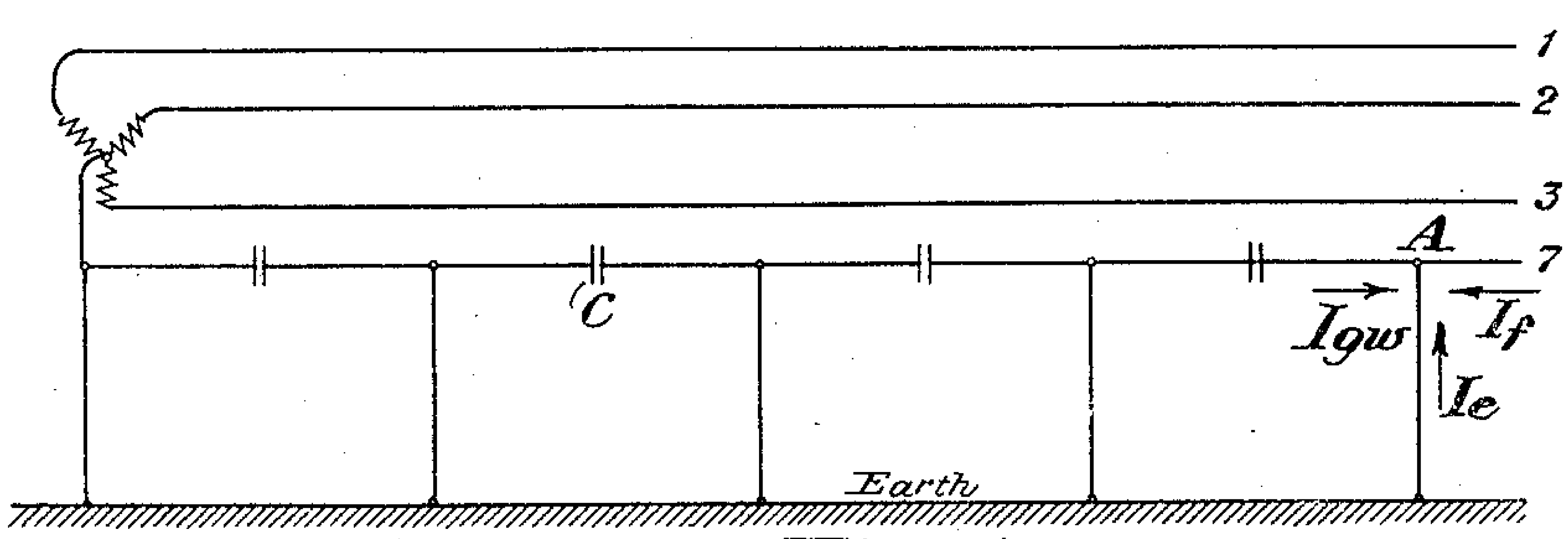

Fig. 1

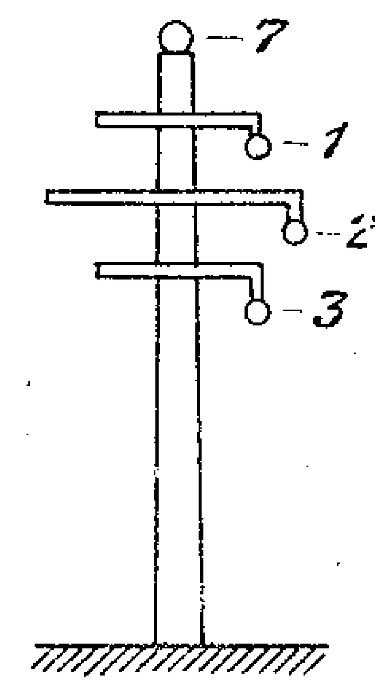

Fig. 2

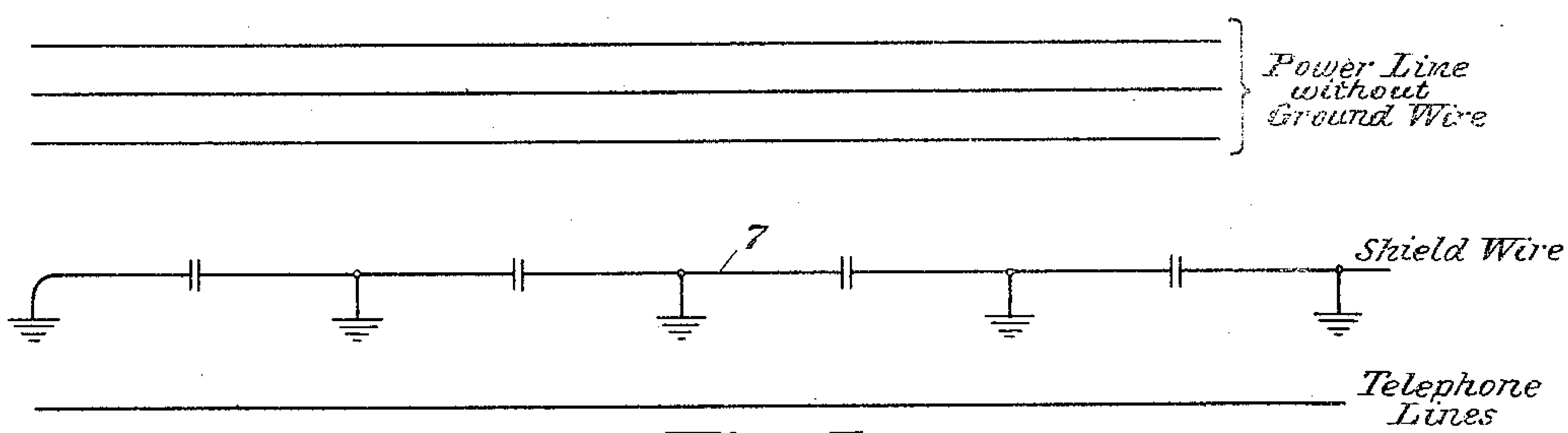

Fig. 3

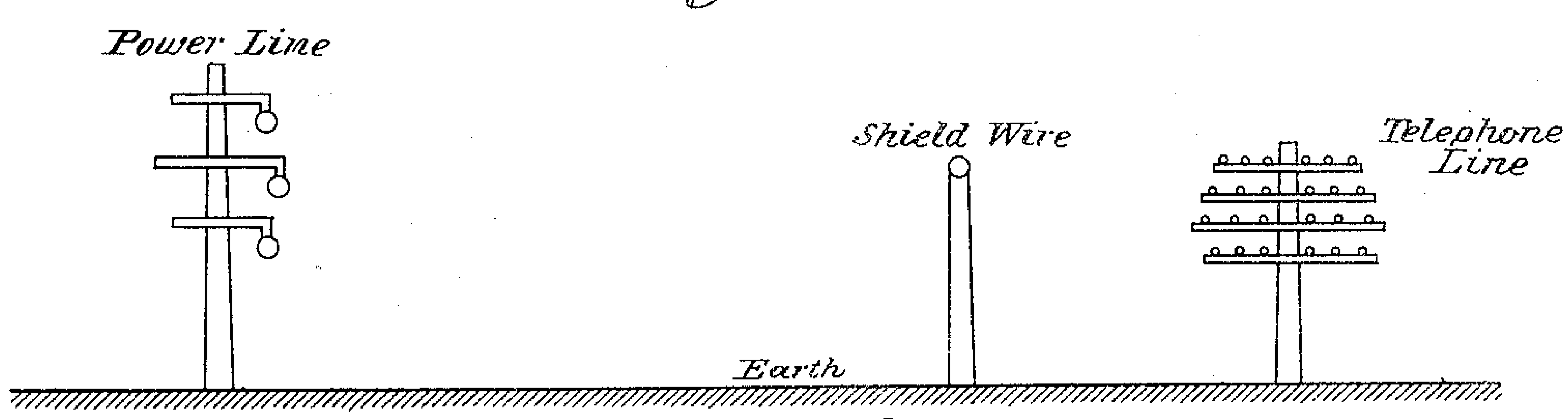

Fig. 4

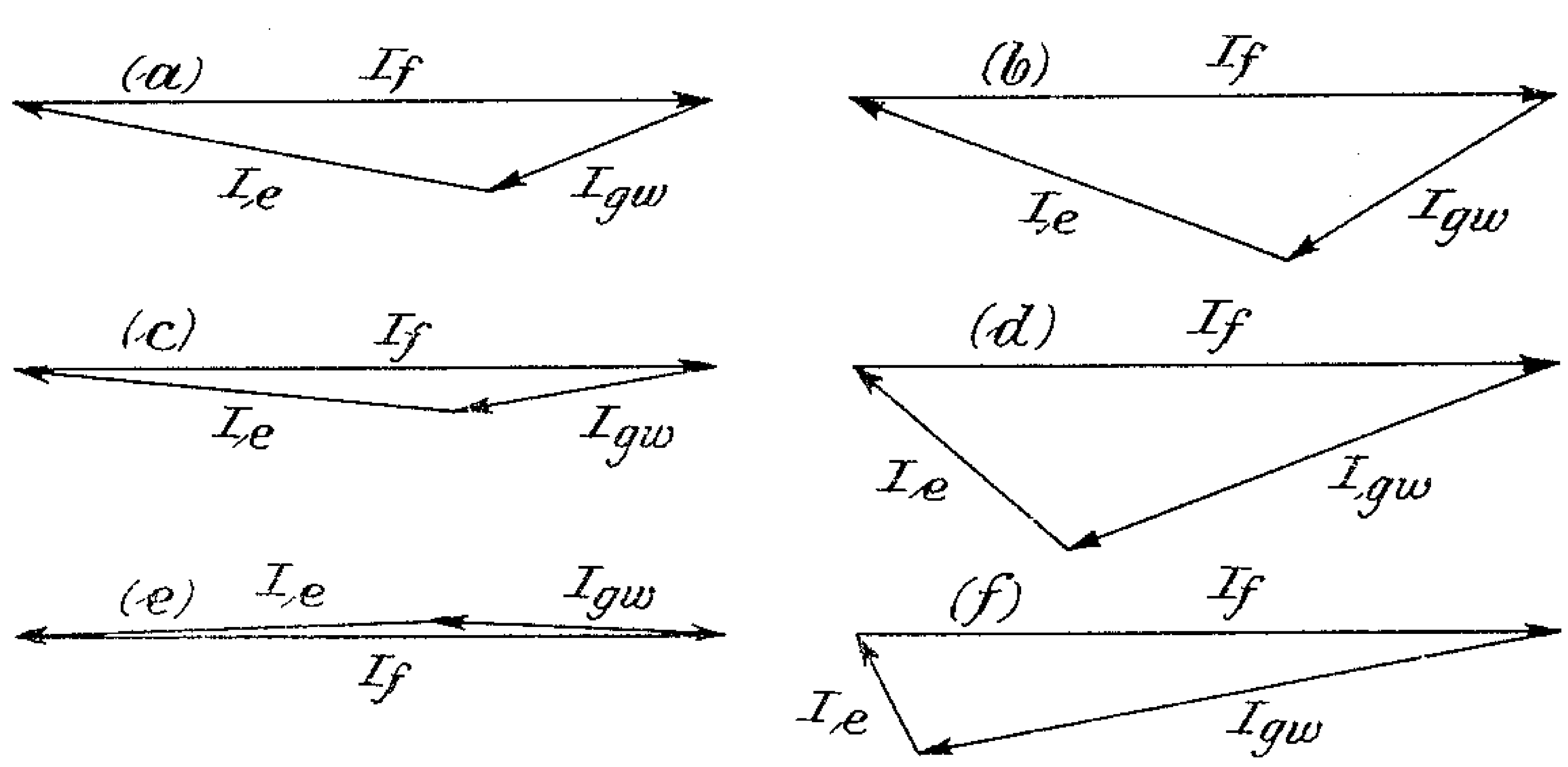

Fig. 5

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SYSTEM FOR IMPROVING THE SHIELDING EFFECT OF GROUND WIRES AND SHIELD WIRES

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10 Claims. (Cl. 171—97)

Among the objects of my invention are to provide new and improved apparatus and a corresponding method for reducing the interference in telephone lines due to currents in neighboring power circuits. Another object of my invention is to provide apparatus and method for increasing the effectiveness of a shielding ground-wire to reduce interference in a telephone circuit near a power line. Still another object is to reduce the interference effect from a power line to a telephone line by interposing series condensers and alternately disposed earth connections in the associated ground-wire. All these objects and other objects and advantages of my invention will become apparent on consideration of a limited number of specific embodiments of the invention which I have chosen for disclosure by way of example in the following specification taken with the appended claims and the drawing. It will be understood that the following disclosure relates principally to these particular illustrative examples of practice according to the invention, and that the scope of the invention will be indicated in the appended claims.

Referring to the drawing,

Figure 1 is a diagrammatic side elevation of a set of three-phase power wires and associated ground return wire adapted for the practice of my invention. Fig. 2 is a corresponding cross-section; Fig. 3 is a diagrammatic side elevation of a power line and a telephone line protected by a ground wire according to my invention; Fig. 4 is a corresponding cross-section; and Fig. 5 is a set of vector diagrams showing the improvement that may be attained by the use of my invention.

In Figs. 1 and 2, the three conductors 1, 2 and 3 are the several conductors of a three-phase power transmission line. As is well known, in such a system the ideal condition is to keep the vector values of the currents in the three conductors of the same absolute magnitude and 120° apart. If this condition is realized the vector sum of the three currents will be zero, and no additional return conductor need be provided, and the inductive effect on a neighboring conductor will be small if its distance is considerable compared to the distance apart of the three conductors 1, 2 and 3.

In practice, there frequently are earth connections at the neutral points of three-phase transmission systems. Even so, there would be no earth return current if the ideal conditions mentioned above were maintained. However, these conditions cannot be realized in practice, and therefore there will be an earth return current for the system which may be very large at times where one or two of the power conductors become accidentally grounded.

In the absence of ground-wires, the vector sum of the currents in the three conductors 1, 2 and 3 will be equal and opposite to this return current in the earth. This vector sum current is called the "residual current". Such currents are particularly serious in producing inductive interference in the neighboring telephone lines.

It is the common practice to place one or more so-called ground-wires on the same pole line with the three-phase conductors 1, 2 and 3. Such ground-wire or wires give protection to the power line from lightning and tend to reduce inductive interference with neighboring telephone lines. In Figs. 1 and 2, there is one such ground return wire, which is indicated by the numeral 7 and it is earthed at its ends and at various intermediate points, one such point being indicated as A in Fig. 1. It carries part of the return current, the remaining part thereof flowing in the earth. Since this ground-wire 7 is placed comparatively near the three-phase conductors 1, 2 and 3, it neutralizes the inductive effect of the residual current to the extent that it carries a part of the earth return current. It has been a known practice, prior to my invention, to make the ground wire conductively continuous, with shunt connections to ground at intervals.

I have determined that by interposing series condensers, such as C, in the ground-wire, alternating with the intermediate ground connections when such are present, and giving the proper values to the C's, a much greater proportion of the return current can be caused to flow in the ground-wire and a correspondingly less proportion in the earth. Thus, the inductive effect of the residual current in the three-phase conductors 1, 2 and 3 will be neutralized in greater part, and the interference effect on neighboring telephone lines will be correspondingly reduced.

Consider the grounded point A of the conductor 7 in Fig. 1. According to Kirchhoff's law, the sum of the three currents flowing toward the point A must be zero, taking the direction toward the point as positive for each such current. That is, let I_F represent the total residual current, as above defined; and let I_e represent the current that flows in the earth and I_{gw} represent the current that flows in the ground-wire. Then,

$$I_F+I_e+I_{gw}=O \qquad (1)$$

The current in a single ground-wire with low earthing resistance is given by the formula:

$$I_{gw}=-\frac{Z_{17}}{Z_{77}}I_F \qquad (2)$$

where Z_{77} is the self-impedance of the ground-wire with earth return and Z_{17} is the mean mutual impedance between such ground-wire and the several three-phase wires.

For a system having more than one ground-wire, the formula will be different from the foregoing. If there are two ground-wires, then

$$I_{gw}=-\frac{2Z_{17}}{Z_{77}+Z_{78}}I_F \qquad (3)$$

and for a system having three ground-wires,

$$I_{gw}=-\frac{3Z_{17}}{Z_{77}+2Z_{78}}I_F \qquad (4)$$

where Z_{17} and Z_{77} have the meanings corresponding to those stated for Equation (2), and Z_{78} is the mean mutual impedance between the ground-wires.

For the case of a single ground-wire

$$I_e=-I_F-I_{gw}=-\left(1-\frac{Z_{17}}{Z_{77}}\right)I_F \qquad (5)$$

Similarly to the derivation of Equation (5) for a single ground-wire, it may be deduced from Equations (1) and (3) that the earth current for two ground-wires is

$$I_e=-\left(1-\frac{2Z_{17}}{Z_{77}+Z_{78}}\right)I_F \qquad (6)$$

and for the case of three ground-wires

$$I_e=-\left(1-\frac{3Z_{17}}{Z_{77}+2Z_{78}}\right)I_F \qquad (7)$$

Comparing from Equation (5) to Equation (6), and then from Equation (6) to Equation (7), it can readily be seen that increasing the number of ground-wires reduces the earth return current. This is because, for the system considered, the absolute value of Z_{17} is considerably less than that of Z_{77}, whereas the absolute values of Z_{17} and Z_{78} are nearly equal. Hence, in passing from Equation (5) to Equation (6), and from Equation (6) to Equation (7), we change the fraction after the minus sign within the parentheses by adding nearly the same quantity to its numerator and denominator, thus causing the fraction to increase and approach unity and thereby making the entire expression within the parentheses smaller and smaller.

Accordingly, the conclusion is that the desirable end of decreasing the earth current is attained in a degree by increasing the number of ground-wires. But these same Formulas (5), (6) and (7) also make it apparent that the earth current can be reduced by reducing the self-impedance Z_{77} of each ground-wire and making Z_{77} approach Z_{17} in value. Indeed, in Equation (5) the earth current would be zero if $Z_{17}—Z_{77}$. Such equality of Z_{17} and Z_{77} will not be possible, on account of the resistance component of Z_{77}. But as will be shown presently, the condition of equality can be approached to a substantial degree by the use of a condenser or condensers in series in the ground-wire.

The capacity of such condensers can be determined as follows:

Equation (5) after the insertion of a condenser can be written:

$$I_e=-\frac{(R_{77}-R_{17})+j(X_{77}-X_C-X_{17})}{R_{77}+j(X_{77}-X_C)}I_F \qquad (8)$$

The absolute magnitude for unit residual current is expressed by:

$$\left|I^2_e\right|=\frac{(R_{77}-R_{17})^2+(X_{77}-X_C-X_{17})^2}{R^2_{77}+(X_{77}-X_C)^2} \qquad (9)$$

Differentiating (9) with respect to $(X_{77}-X_C)$ it is found that, to make I_e a minimum, the following relation should exist:

$$X_{77}-X_C=\frac{1}{2X_{17}}\left[R^2_{17}+X^2_{17}-2R_{77}R_{17}+\sqrt{(R^2_{17}+X^2_{17}-2R_{77}R_{17})^2+4R^2_{77}X^2_{17}}\right] \qquad (10)$$

Let the expression in (10) be written:

$$X_{77}-X_C=A \qquad (11)$$

and since

$$X_C=\frac{1}{\omega C} \qquad (12)$$

the required size of the condenser in farads will be:

$$C=\frac{1}{\omega(X_{77}-A)} \qquad (13)$$

where A is given by Equation (10). In a similar manner the optimum capacity to use with two or more ground wires can be found.

The foregoing principles will be illustrated by a few specific examples. Consider a certain 132-kv. three-phase line having a single ground wire. The numerical values of the impedances Z_{77} and Z_{17} in ohms per mile are given by the following equations:

$$Z_{77}=R_{77}+jX_{77}=0.808+j1.41 \qquad (14)$$

$$Z_{17}=R_{17}+jX_{17}=0.09+j0.55 \qquad (15)$$

Computing the ground wire and the earth current from (2) and (5) respectively, the result, when no condenser is used in series with the ground wire, is:

$$I_{gw}=-\frac{0.09+j0.55}{0.808+j1.41}I_F=-0.343\underline{/20.5^\circ}I_F \qquad (16)$$

$$I_e=-\frac{0.718+j0.86}{0.808+j1.41}I_F=-0.69\underline{/-10^\circ}I_F \qquad (17)$$

Now from (10) and (13) solve for the required capacity to make I_e a minimum. This is found to be 6,000 microfarads per mile, and the self-impedance of the ground wire reduces to:

$$Z_{77}=0.808+j0.97 \qquad (18)$$

Using this value for the computation of the ground wire and earth current these become:

$$I_{gw}=-\frac{0.09+j0.55}{0.808+j0.97}I_F=-0.44\underline{/30.5^\circ}I_F \qquad (19)$$

$$I_e=-\frac{0.718+j0.419}{0.808+j0.97}I_F=-0.663\underline{/19.8^\circ}I_F \qquad (20)$$

The above example shows a reduction in the percentage earth current of 3.9 per cent.

Continuing to deal with the specific example mentioned above, assume that the ground wire is of stranded copper having a cross-section of 211,600 circular mils for which the self impedance Z_{77} is $0.361+j1.41$. Then from Equations (2) and (5) the ground-wire current and earth current without condenser are:

$$I_{gw}=-\frac{0.09+j0.55}{0.361+j1.41}I_F=-0.382\underline{/5.1^\circ}I_F \quad (21)$$

$$I_e=-\frac{0.271+j0.86}{0.361+j1.41}I_F=-0.619\underline{/-3.1^\circ}I_F \quad (22)$$

The required size of the condenser for this case would be, as computed from Equations (10) and (13):

$$C=3470 \text{ microfarad per mile} \quad (23)$$

Then connecting the condenser or condensers in series with the ground wire the self-impedance per mile reduces to:

$$Z_{77}=0.361+j0.647 \quad (24)$$

And the ground wire current and earth current become:

$$I_{gw}=-\frac{0.09+j0.55}{0.361+j0.647}I_F=-0.741\underline{/19.8^\circ}I_F \quad (25)$$

$$I_e=-\frac{0.271+j0.097}{0.361+j0.647}I_F=-0.390\underline{/-41.3^\circ}I_F \quad (26)$$

which is a gain of 35 per cent in shielding on the basis of the same residual current.

If the ground wire were of a still larger size, say 500,000 circular mils, its self-impedance would be:

$$Z_{77}=0.204+j1.41 \quad (27)$$

The required size of the condenser for this case would be:

$$C=3150 \text{ microfarad per mile} \quad (28)$$

The following table shows the results for the three above mentioned sizes of ground wires:

Size of wires	I_{gw} percent of I_F		I_e percent of I_F	
	Without condenser	With condenser	Without condenser	With condenser
136,000 cir. mils	34.3	44.0	69.0	66.3
211,600 cir. mils	38.2	74.1	61.9	39.0
500,000 cir. mils	39.1	92.0	60.8	19.1

It will be seen from the above table that for the highest conductivity ground wire assumed it is possible to reduce the percentage of earth current 69 per cent, while for the lowest conductivity ground wire, which has a resistance component comparable in magnitude with the reactance component of the mutual impedance, there is only a 4 per cent gain in shielding.

The vector diagrams of the quantities in the above table are shown in Fig. 5 of the drawing. Diagrams (*a*) and (*b*) are for a ground wire of 136,000 circular mils, respectively without and with condenser; (*c*) and (*d*) are for 216,000 circular mils, respectively without and with condenser; and (*e*) and (*f*) are for 500,000 circular mils, respectively without and with condenser.

Referring to Figs. 3 and 4, these show a three-phase power line having no ground wire and a telephone line or lines. Supposing the telephone line is subject to troublesome induction from the power line, a grounded shield wire may be interposed as shown. Its beneficial effect may be enhanced by interposed condensers according to the principles disclosed in the foregoing and more specifically demonstrated below.

It can be proved that the shielding factor for a shield wire is:

$$\mu=1-\frac{Z_{st}.Z_{ps}}{Z_{pt}.Z_{ss}} \quad (29)$$

where μ=ratio of induced voltage in telephone line in presence of shield wire to induced voltage in absence of shield wire.

Z_{st}=mutual impedance between the shield and telephone line.

Z_{ps}=mutual impedance between the power and shield wire.

Z_{ss}=self-impedance of shield wire.

The expression in (29) can also be written:

$$\mu=1-\frac{A}{B} \quad (30)$$

where

$$A=A_1+jA_2 \quad (31)$$

$$B=B_1+jB_2 \quad (32)$$

therefore:

$$\mu=\frac{B-A}{B}=\frac{(B_1-A_1)+j(B_2-A_2)}{B_1+jB_2} \quad (33)$$

Equation (33) after inserting a condenser can be written:

$$\mu=\frac{B_1-A_1+j(B_2-X_C-A_2)}{B_1+j(B_2-X_C)} \quad (34)$$

But this is the same form of expression as Equation (8) for ground wires, and therefore, the same method of determining the optimum value of capacity as was used in the case of ground wires can be applied.

As indicated in the examples cited heretofore the size of the condensers will be of the order of 3000 to 6000 microfarads per mile. From a practical standpoint it would be somewhat difficult and expensive to supply and install condensers of such values in the ground wires of power lines. However, electrolytic condensers, protected against lightning could be used with telephone shield wires.

I claim:

1. In combination, a power line, a grounded return conductor therefor, and a plurality of like condensers in series along said conductor, said condensers having the proper capacity value to effect a substantial reduction in the proportion of the return current flowing in the earth.

2. In the operation of a power line and a grounded return conductor, the method of increasing the proportion of the return current flowing in the said conductor which involves the development of a substantial capacity reactance at points along said conductor, and shunting the current along said conductor between it and ground.

3. In combination, a polyphase power line, a grounded return conductor associated therewith, and condensers in series and alternate grounds along said conductor to increase the proportion of the return current flowing therein.

4. In combination, a power line, a return conductor associated therewith and grounded at intervals along its length, and series condensers in said conductor alternating with the ground connections, said condensers having the proper capacity values to substantially increase the proportion of the return current flowing in said conductor.

5. In combination, a polyphase power line

subject to a substantial degree of residual current, a grounded return conductor associated therewith, and alternating series condensers and shunt ground connections along said conductor to increase the proportion of return current flowing in said conductor.

6. In combination, a polyphase power line subject to a residual current therein, a plurality of return conductors associated therewith, said conductors being grounded at intervals along their length, and condensers in series in said conductors and in alternation with said grounds to increase the proportion of return current flowing therein.

7. In combination, a power line, a grounded return conductor therefor, an electrolytic condenser in series in said conductor, and protective means to safeguard said condenser against lightning and accidental high voltages.

8. In combination, a power line, a telephone line subject to induction therefrom, a shielding wire to protect the telephone line from such induction, grounds at intervals along said shielding wire, and condensers interposed in series in alternation with said grounds.

9. In combination, a power line, a neighboring telephone line subject to induction therefrom, an interposed shielding wire, said shielding wire being grounded at intervals, and condensers in series in said wire alternating with the grounds.

10. In the operation of a polyphase power line and a grounded return conductor, the method of increasing the proportion of the return current flowing in the said conductor, which involves shunting the return current between the said conductor and ground at points distributed along the length of said conductor and at alternately disposed points along its length developing a substantial capacity reactance in series in said conductor.

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