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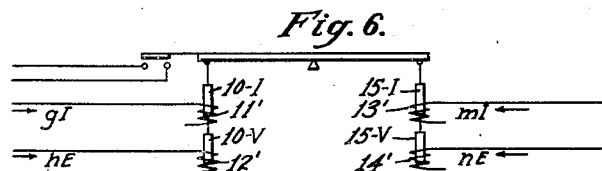
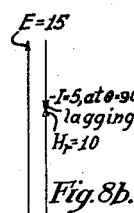
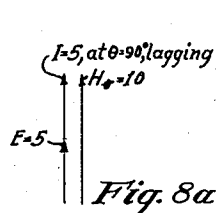
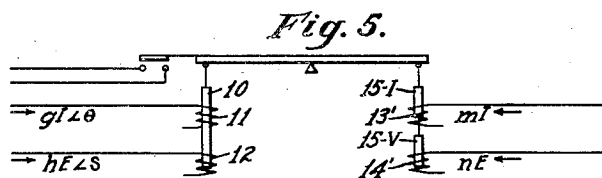
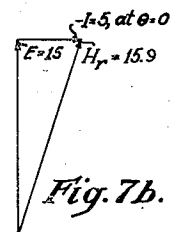
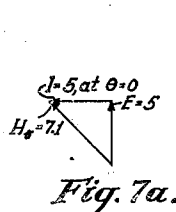
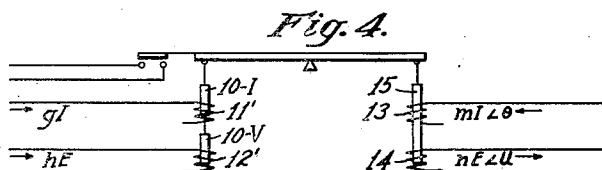
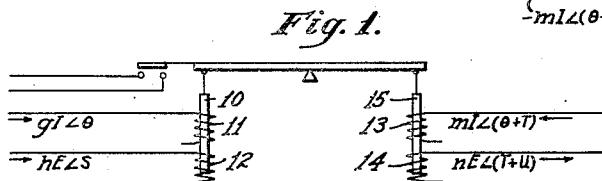
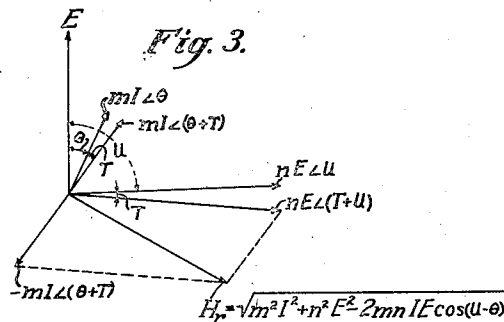
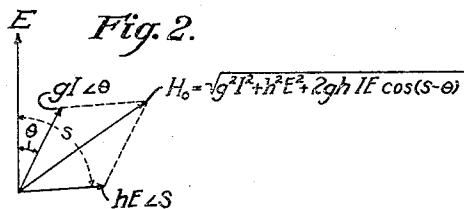
S. L. GOLDSBOROUGH

2,404,955

LONG-LINE FAULT-DETECTOR AND RELAYING-SYSTEM

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2 Sheets-Sheet 1



WITNESSES:
Edward Michale
Rev. L. Groome

INVENTOR
Shirley L. Goldsborough.
BY O. R. Buchanan
ATTORNEY

UNITED STATES PATENT OFFICE

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LONG-LINE FAULT DETECTOR AND
RELAYING SYSTEM

Shirley L. Goldsborough, Basking Ridge, N. J.,
assignor to Westinghouse Electric Corporation,
East Pittsburgh, Pa., a corporation of Pennsylvania

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My invention relates to protective relays and relaying systems for long alternating-current transmission-lines in which the fault-current may be less than the load-current, where there is need for a sensitive fault-detector element which can definitely distinguish between load and faults.

One object of my invention is to provide a three-zone high-speed impedance-relay system with a third-zone element having a voltage-restrained directional characteristic, or, more specifically, having a response to admittance or mhos, as distinguished from impedance or ohms, with a directional characteristic such that the critical admittance or mhos, to which the relay responds at its balance-point, is equal to, or approaches, a constant, times the cosecant of the power-factor angle of the fault-current.

A more specific object of my invention is to utilize such a directional mho-relay as the third-zone impedance-element of a high-speed impedance-relay protective-system, for the purpose in assisting in providing third-zone backup protection, controlling the timing relay, initiating carrier-current transmission when carrier-current protection is provided, assisting in providing out-of-step discrimination when out-of-step protection is provided and, in short, doing any or all of the things which a third-zone impedance or reactance element has done, in the past, or might be expected to do, in the future.

More specifically, I utilize my directional mho-relay, in connection with a conventional directional relay, to initiate the operation of the timer-relay which establishes the times at which second-zone and third-zone relay-protection is provided.

It is a further object of my invention to provide a new kind of alternating-current impedance relay, or modified-impedance or reactance relay, having a restraining-force which is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage. The operating-force of the relay may be responsive either to a line-current, or to a line-voltage, or to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage. The line-currents (or line-voltages) which control the operating and restraining forces may be either the same or different line-currents (or line-voltages, as the case may be).

A still more specific object of my invention is to provide a modified impedance relay having

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a response to both current and voltage on both ends, or on both the operating side and the restraining-side of the relay, utilizing different delta line-voltages on the respective ends, and having the operating force of the relay responsive to the line-current in one phase-conductor, and to the delta line-voltage across the other two phase-conductors of a three-phase transmission line which is being protected.

With the foregoing and other objects in view, my invention consists in the relays, elements, combinations, systems, and methods hereinafter described and claimed and illustrated in the accompanying drawings, in which:

Figure 1 is a general diagram of a current- and voltage-operated and restrained balanced-beam relay, in accordance with my invention, from which the general mathematical equations are derived;

Figs. 2 and 3 show the angular relationships on the operating and restraining sides, respectively, in a general case;

Figs. 4, 5, and 6 are modifications of the general relay-form shown in Fig. 1, but in which the responses to current and voltage have been separated, on one or both sides of the relay;

Figs. 7a and 7b show the vector-relationships on the operating and restraining sides, respectively, of my relay, when the line-current is in phase with the line-voltage, in a form of embodiment in which the product of the line-mhos and the sine of the power-factor phase-angle of the line-current is a constant, at the balance-point of the relay;

Figs. 8 and 8b are similar views showing the vector-conditions of the relay when the line-current lags the line-voltage by exactly 90°, the current- and voltage-magnitudes of the relay-response being so chosen that the relay is just at its balance-point under these conditions;

Fig. 9 is a Cartesian-coordinate diagram of the relationships between the line-resistance R and the line-reactance X at the balance-point of the relay referred to in Figs. 7a, 7b, 8a, and 8b, with indications of the manner in which the constants of the relay may sometimes be advantageously modified, while still preserving the approximate characteristics of a relay in which the balance-point mhos vary with the cosecant of the line-current angle;

Fig. 10 is a polar diagram of the balance-point mhos, plotted as the radius vector, varying in accordance with the line-current angle θ , in the form of relay which was referred to in connection with Figs. 7a, 7b, 8a, and 8b, in which the balance-

point mhos, times $\sin \theta$, will be either a constant, with the locus of its end-point lying in a straight line, or with various slight modifications of this form of response;

Fig. 11 is a vector-diagram of the line-currents and delta line-voltages of a three-phase line, showing how the phase-AB voltage collapses when there is a line-to-line fault on this phase;

Fig. 12 is a diagrammatic view of circuits and apparatus illustrating the alternating-current energization of a phase-A relay having a response to both current and voltage, on both sides of the relay, the restraining-side voltage being the phase-AB voltage, but the operating-side voltage being phase-BC voltage, thereby avoiding the damaging effects of a collapsed phase-AB voltage; and

Fig. 13 is a diagrammatic view of circuits and apparatus illustrating a three-zone high-speed impedance-relay protective-system, utilizing my directional mho-relay as the third-zone element.

In the following derivations, we will regard lagging angles as positive, and leading angles as negative, so that lagging reactance X will be positive.

Representing the line-current as $I < \theta$, (read "I phase theta"), and the line-voltage as E , we energize our relay with an operating coil or coils 11 and 12, operating on a common armature or magnetic circuit 10, as shown in Fig. 1, producing an operating field-strength of

$$H_0 = gI < \theta + hE < S \quad (1)$$

and a restraining coil or coils 13 and 14, operating on a common armature 15, producing a restraining field-strength of

$$H_r = mI < (\theta + T) - nE < (T + U) \quad (2)$$

as shown, in a beam-type relay, in Fig. 1. The angular relationships on the operating side are shown in Fig. 2, and those on the restraining side are shown in Fig. 3.

In these derivations, it will be convenient to consider the coefficients g , h , m and n as positive, taking care of possible polarity-reversals by adding 180° to the arbitrary angles S and U , respectively.

The operating-force F_0 is equal to the square of the field-strength H_0 .

$$F_0 = H_0^2 = g^2 I^2 + h^2 E^2 + 2ghIE \cos (S - \theta) \quad (3)$$

The restraining-force F_r is equal to the square of the field-strength H_r .

$$F_r = H_r^2 = m^2 I^2 + n^2 E^2 - 2mnIE \cos (U - \theta) \quad (4)$$

The relay will operate when the restraining-force F_r is less than the operating-force F_0 , or when

$$m^2 I^2 + n^2 E^2 - 2mnIE \cos (U - \theta) < g^2 I^2 + h^2 E^2 + 2ghIE \cos (S - \theta) \quad (5)$$

Dividing through by I^2 , rearranging terms, and remembering that

$$\frac{E^2}{I^2} = Z^2 = R^2 + X^2, \quad (6)$$

$$\frac{E}{I} \cos \theta = R, \quad (7)$$

$$\frac{E}{I} \sin \theta = X, \quad \text{and} \quad (8)$$

$$\cos (S \pm \theta) = \cos \theta \cos S \mp \sin \theta \sin S \quad (9)$$

we find that the relay will operate when

$$(n^2 - h^2)(R^2 + X^2) - 2ghR \cos S - 2ghX \sin S - 2mnR \cos U - 2mnX \sin U < g^2 - m^2 \quad (10)$$

$$\text{If } (n^2 - h^2) > 0, \quad (11)$$

we may divide through by this quantity without changing the inequality-sign, obtaining a relay-response when

$$\left(R - \frac{gh \cos S + mn \cos U}{n^2 - h^2} \right)^2 + \left(X - \frac{gh \sin S + mn \sin U}{n^2 - h^2} \right)^2 < \frac{h^2 m^2 + g^2 n^2 + 2ghmn \cos (S - U)}{(n^2 - h^2)^2} \quad (12)$$

The locus of all values of the apparent line-resistance R and the apparent line-inductance X at the balance-point of the relay is thus a circle. If the relay is to operate, the apparent or measured line-resistance R and the apparent or measured line-reactance X must fall inside of this circle. The center of the circle is at

$$R_0 = \frac{gh \cos S + mn \cos U}{n^2 - h^2} \quad (13)$$

$$X_0 = \frac{gh \sin S + mn \sin U}{n^2 - h^2} \quad (14)$$

Its radius is

$$Q_0 = \frac{1}{n^2 - h^2} \sqrt{h^2 m^2 + g^2 n^2 + 2ghmn \cos (S - U)} \quad (15)$$

The maximum impedance $X_{\max}$ for which the relay will balance is

$$X_{\max} = X_0 + Q_0 = \quad (16)$$

$$\frac{gh \sin S + mn \sin U + \sqrt{h^2 m^2 + g^2 n^2 + 2ghmn \cos (S - U)}}{n^2 - h^2}$$

If $m=0$, the relay will not have the restraint-side current-response represented by the coil 13 in Fig. 1, and it will then be the same as Lewis' modified impedance-relay of Patent 1,967,093, operating when

$$\left(R_1 - \frac{gh \cos S}{n^2 - h^2} \right)^2 + \left(X_1 - \frac{gh \sin S}{n^2 - h^2} \right)^2 < \frac{g^2 n^2}{(n^2 - h^2)^2} \quad (17)$$

If $m=0$ and $h=0$, the relay becomes a current-operated voltage-restrained impedance-relay, the same as the present applicant's impedance-relay of Patent 1,934,662, operating when

$$R_2^2 + X_2^2 < \frac{g^2}{n^2} \quad (18)$$

If $m=0$ and $n=0$, the relay would have no restraining-force, and it would be inoperative as an impedance or modified-impedance or reactance relay.

If $m=0$ and $g=0$, the relay would balance two voltage-responses, and it would be inoperative as an impedance or modified-impedance or reactance relay.

If $n=0$, the relay will not have the restraint-side voltage-response which is represented by the coil 14, in Fig. 1, and the quantity $(n^2 - h^2)$ will be $-h^2$, or less than zero, contrary to inequality (11), thus reversing the inequality-sign in inequality (12). The relay will be an inverted modified-impedance relay. It will drop out, only when the indicated line-impedance is small, and it will respond whenever the apparent line-resistance R and the apparent line-reactance X are outside of the circle, or when

$$\left(R_3 + \frac{g \cos S}{h} \right)^2 + \left(X_3 + \frac{g \sin S}{h} \right)^2 > \frac{m^2}{h^2} \quad (19)$$

If $n=0$ and $g=0$, the relay becomes a voltage-operated current-restrained relay, which is an

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inverted impedance-relay, which will drop out, only when the indicated line-impedance is small. It will respond when R and X are outside of the circle, or when

$$R_4^2 + X_4^2 > \frac{m^2}{h^2} \quad (20)$$

If $n=0$ and $h=0$, the relay would balance two current-responses, and it would be inoperative as an impedance or modified-impedance or reactance relay.

If $h=0$, the relay will not have the operating-side voltage-response represented by the coil 12 in Fig. 1, and it will then have a modified-impedance response, operating when

$$\left(R_3 - \frac{m \cos U}{n}\right)^2 + \left(X_3 - \frac{m \sin U}{n}\right)^2 < \frac{g^2}{n^2} \quad (21)$$

A relay in conformity with Equation 21 is described and claimed in my continuation-in-part application Serial No. 547,561, filed August 1, 1944, with particular reference to the adjustment of the operating-coil current-response g to control the radius g/m , the adjustment of the angle U between the restraint-voltage and the unity-power-factor restraint-current to determine the slope of the line drawn from the origin to the circle-center, and the adjustment of the restraint-coil current-response m to control the displacement of the circle-center from the origin.

If $h=0$ and $g=0$, the relay would have no operating-force, and would never operate.

If $g=0$, the relay will not have the operating-side current-response represented by the coil 11 in Fig. 1, and it will have a modified-impedance response, operating when

$$\left(R_6 - \frac{mn \cos U}{n^2 - h^2}\right)^2 + \left(X_6 - \frac{mn \sin U}{n^2 - h^2}\right)^2 < \frac{h^2 m^2}{(n^2 - h^2)^2} \quad (22)$$

It is an aspect of my invention, therefore, to provide a new kind of impedance relay, or modified-impedance or reactance relay, having operating and restraining forces as set forth in Equations 3 and 4, with any real values of the constants except $m=0$ or $n=0$. With $m=0$, the general type of relay is old, in so far as it is operative at all as an impedance relay or modified-impedance or reactance relay, and aside from specific new relations of the design-constants which are pointed out hereinafter. With $n=0$, the relay is inoperative as an impedance or modified-impedance or reactance relay. In other words, I provide an alternating-current relay having a restraining-force which is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage. The operating-force of the relay may be responsive either to a line-current, or to a line-voltage, or to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage. The line-currents (or line-voltages) which control the operating and restraining forces may be either the same or different line-currents (or line-voltages, as the case may be).

In its broader aspects, if there are both a current-response and a voltage-response, on both sides of a modified-impedance relay of my invention, it can readily be shown that both the operating-force and the restraining force need not be equal to the square of the vector sum of the current-responsive and voltage-responsive

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quantities, but one of said forces, or even both of them, may be separately responsive to the current and voltage, as by having separate magnetic circuits.

Thus, in Fig. 4, the current-responsive operating-coil 11' and the voltage-responsive operating-coil 12' operate on separate armatures 10—I and 10—V, respectively, the relay being otherwise as shown in Fig. 1. The relay thus operates when

$$m^2 I^2 + n^2 E^2 - 2mnIE \cos (U - \theta) < g^2 I^2 + h^2 E^2 \quad (23)$$

or when

$$\left(R_7 - \frac{mn \cos U}{n^2 - h^2}\right)^2 + \left(X_7 - \frac{mn \sin U}{n^2 - h^2}\right)^2 < \frac{h^2 m^2 + g^2 (n^2 - h^2)}{(n^2 - h^2)^2} \quad (24)$$

Or, as shown in Fig. 5, the current-responsive restraint-coil 13' and the voltage-responsive restraint-coil 14' may operate on separate armatures 15—I and 15—V, respectively, the relay being otherwise as shown in Fig. 1. The relay then operates when

$$m^2 I^2 + n^2 E^2 < g^2 I^2 + h^2 E^2 + 2ghIE \cos (S - \theta) \quad (25)$$

or when

$$\left(R_8 - \frac{gh \cos S}{n^2 - h^2}\right)^2 + \left(X_8 - \frac{gh \sin S}{n^2 - h^2}\right)^2 < \frac{g^2 n^2 - m^2 (n^2 - h^2)}{(n^2 - h^2)^2} \quad (26)$$

Or, as shown in Fig. 6, the current and voltage-responsive coils 11', 12', 13' and 14', on both sides of the relay, may each have its separate armature 10—I, 10—V, 15—I and 15—V, respectively, yielding a relay-response when

$$m^2 I^2 + n^2 E^2 < g^2 I^2 + h^2 E^2 \quad (27)$$

or when

$$R_9^2 + X_9^2 < \frac{g^2 - m^2}{n^2 - h^2} \quad (28)$$

One particularly advantageous form of my invention is a directional mho-relay, according to Equation 5, in which the angles S and U are approximately $+90^\circ$, and in which the current-response constants g and m are approximately equal. The fact that the angles S and U are approximately $+90^\circ$ indicates that the voltage-responsive relay-currents $hE < S$ and $nE < U$ lag approximately 90° behind the line-voltage E , which is another way of saying that the relaying current $gI < (\theta - S)$ lags behind the line-voltage E by an angle $(\theta - S)$. The fact that the current-response coefficients g and m are equal indicates that the same relaying-current, and the same number of relaying turns, are used on both the operating and restraining sides of the relay. It is to be noted that the restraining side of the relay must have a voltage-responsive field-strength or ampere-turns nE , which is larger than the corresponding quantity, hE , on the operating side, which means to say that either the number of restraining turns is greater, if the same voltage-responsive relaying currents are utilized on both sides of the relay, or the voltage-responsive relaying current on the restraint-side is larger than the voltage-responsive relaying current on the operating-side, if the same number of turns is used on both voltage-currents. I have used a relationship

$$n = 3h \quad (29)$$

although I am not, of course, limited to this particular relationship.

With $S=U=90^\circ$, and $g=m$, Equations 12, 17, 21, and 22 take the general form

$$R^2 + (X - X_0)^2 < X_0^2 \quad (30)$$

The equation for the locus of the apparent or measured line-resistance R and the apparent or measured or line-reactance X , at the balance-point of the relay, under the conditions represented by Equation 30, is a circle 21, as shown in Fig. 9, with the relay responding for line-impedance conditions falling within the circle.

In polar coordinates, it is more convenient to plot the reciprocal of impedance, or admittance M , measured in mhos, against the power-factor angle θ . The polar equation for the conditions $S=U=90^\circ$, and $g=m$, is most conveniently determined from Equation 5, by determining the value of $I/E=M$, in terms of θ . It takes the general form,

$$M > kcsc \theta \quad (31)$$

where k is a constant. The locus of the end of the radius vector M , satisfying Equation 31, is a straight line 22, parallel to the 0° position, as shown in Fig. 10.

In case the delta line-voltage E_{AB} is utilized for the restraint of the phase-A impedance-elements, as has been customary, a difficulty may be encountered in a relay having the same value of line-current response on both the operating and restraining sides of my relay, or $g=m$, in the form of my invention which is represented by Equations 30 and 31, and by the lines 21 and 22 in Figs. 9 and 10. This difficulty sometimes makes itself felt in the event of a phase-to-phase fault on the phase AB. This will best be understood by reference to Fig. 11, in which the normal phases and magnitudes of the three delta line-voltages E_{AB} , E_{BC} , and E_{CA} , are shown with reference to the line-current I_A at unity power-factor. In the event of a fault on phase-AB, the phase-AB voltage collapses to E_{AB}' , or to a value close to zero. In a relay with equal operating- and restraining-responses, or $g=m$, the effects of the line-currents cancel each other, so that the relay responds to

$$EI \sin \theta = E^2 \quad (32)$$

$$\text{or } \frac{I}{E} \sin \theta = k \quad (33)$$

When E approaches 0, this response becomes indeterminate and unreliable.

When the difficulty just mentioned is experienced, there are several things which can be done about it. Instead of making the two current-responses exactly equal, on opposite sides of the relay, we can make the operating-side current-response slightly larger than the restraining-side current-response, as indicated by the equation

$$g = m + a \quad (34)$$

The effect of this change is to make the radius of the circle 21, in Fig. 9, a little larger than X_0 , as shown by the circle 23 in Fig. 9. Or, in polar coordinates, the effect of making $g = m + a$, is to reduce the value of the balance-point mhos, or M , by a very small quantity which varies with M^2 , so that, as M approaches infinity, at the smaller values of the power-factor angle θ , the amount by which M is cut short increases very rapidly. The result is an inwardly bending curve of the type shown at 24 in Fig. 10, in which the balance-point of the relay at unity power-factor occurs at a finite value of the apparent or measured line mhos M_0 , as shown in Fig. 10.

Another modification which can be made in my directional mho-relay, which for some purposes approximates the effect of making $g = m + a$, is to keep $g = m$, but to make S and U slightly less than 90° . The effect of this change is to shift the center of the R -and- X circle clockwise, or from C_0 to C_0' , as shown in Fig. 9, resulting in the circle 25, the amount of shift being perhaps exaggerated, for clearness of illustration. In the polar diagram, the effect of starting out with S and U less than 90° is to tilt the straight-line mho-envelope 22 clockwise, as shown at 26, so that the relay-response, at unity power-factor, is at a finite value of the line-mhos, as indicated at M_0' in Fig. 10.

For protecting a transmission-line in which the load-current lags behind the line-voltage by as much as 30° when the line-current has the highest value which it could have under fault-free conditions, it would be possible to utilize a slightly smaller current-response on the operating side of the relay than on the restraint-side, or

$$g = m - a \quad (35)$$

The effect of this change, while still keeping S and U equal to 90° , would be to curve the locus of the end of the radius vector outwardly, as shown at 27 in Fig. 10.

Another variation of my invention, which is particularly applicable in cases where the difficulty of erroneous or uncertain operation is encountered because of the collapse of the line-voltage, E_{AB} , which is utilized to restrain my directional mho-relay, is to utilize a voltage-responsive actuating-force component, on the operating side of the relay, which is responsive to a delta line-voltage which does not collapse under any conditions under which the relay, such as the phase-A relay, is expected to respond. This provides the relay with a positive operating-force which assures its operation.

Thus, in Fig. 12, I have shown a form of embodiment of my relay M , in which the operating-side voltage-response is to the quadrature-related delta line-voltage E_{BC} , which lags 90° behind the line-current I_A at unity power-factor, whereas, on the restraint-side of the relay, the voltage-response is to the delta line-voltage E_{AB} , which is subject to collapse in the event of a phase-to-phase fault to which the phase-A relay should respond, under the conditions depicted in Fig. 11.

In Fig. 12, I have also shown a variation which is always possible in securing a field-strength or magnetizing-force which is responsive to the vectorial sum of a current-function and a voltage-function. In Fig. 1 and other figures, this vectorial combination of the current and voltage was effected by putting two coils on the same magnetic circuit, so as to operate on the same armature 13 or 15, and energizing one coil in response to current, and the other coil in response to voltage. In Fig. 12, I illustrate the other alternative of adding these two currents, or their voltages, together, so that I produce a single relaying-current, which is proportional to the vectorial sum of two voltages, or other two electrical quantities, one being responsive to the line-current, and the other being responsive to the line-voltage.

Thus, in Fig. 12, I show two three-winding transformers 30, each having a voltage-responsive primary winding 31, a current-responsive primary winding 32, and a single secondary winding 33. The relay M has a single operating coil 34 and a single restraining coil 35, these coils being

energized from the secondary windings 33 of the respective three-winding transformers 30. In these three-winding transformers 30, it is necessary to use a considerable impedance in series with each of the respective voltage-windings 31, in order that the external impedance of the voltage-winding circuit should be fairly large compared to the magnetizing impedance of the winding 31. This is necessary so that the voltage-coil 31 of each transformer will not resist any flux-change in the iron core of the transformer, as a result of changes in the instantaneous ampere-turns of the current-coil 32. With the proper series resistance in the circuit of the voltage-coil 31, the current-responsive and voltage-responsive fluxes combine properly in the iron of the transformer, thus resulting in a proper vectorial summation of the fluxes.

In the case of the three-winding transformer 30 on the operating side of the relay M, the external impedance in the voltage-coil circuit is a resistance 36, which makes the primary current in the voltage-responsive coil 31 substantially in phase with the delta line-voltage E_{bc} , which lags behind the phase-A line-current I_A by 90° at unity power-factor, corresponding to $S=90^\circ$ in my formulas, which is what is wanted. In the other three-winding transformer 30, which is used on the restraint-side of the relay M, the impedance in the voltage-coil circuit is a capacitor 37, or it may be a capacitor 37 and a resistance 38 in series, in such proportion as to cause the primary current in the voltage-coil 31 to lead the delta line-voltage E_{ab} by 60° . Since the line-voltage E_{ab} already leads the line-current I_A by 30° at unity power-factor, this brings the primary current in the voltage-responsive coil 31, on the restraint-side of the relay M, 90° in advance of the line-current I_A , corresponding to $U=90^\circ$ in my formulas, which is what is desired.

It will be understood, from Fig. 12, that only the phase-A relay-connections are shown. Ordinarily, similar equipment will be provided for the other two phases. Only phase-A of the line-current transformer 39 is shown. The entire three phases of the potential-transformer 40 are shown, because all three of the voltage-phases are utilized in the relay.

In the operation of the relay shown in Fig. 12, it will thus be seen that the relay operates in precisely the same manner as the general relay which was described in connection with Fig. 1, and for which the various formulas were derived, so long as the three-phase line-voltage remains balanced. In case of an unbalanced collapse of the three-phase line-voltage, however, as in the case of a phase-AB fault, as depicted in Fig. 11, my relay of Fig. 12 utilizes an uncollapsed voltage E_{bc} on the operating side of the relay, so as to maintain an adequate and reliable force tending to make the relay respond, as it should, notwithstanding the collapse of the phase-AB line-voltage as a result of a phase-to-phase fault on the line.

In addition to providing a novel form of relay-energization and response, my invention also involves a novel relaying-system, or use, of a directional mho-relay which approximates a mho-response to a constant, times the cosecant of the power-factor angle θ . This form of relaying-system is shown in Fig. 13, wherein the three-phase line to be protected is shown at 41, its three phases being marked A, B, and C. It is connected to a three-phase bus 42 by means of a circuit-breaker 43 which is provided with a trip-

coil TC and a make-contact 43A. Only the phase-A relaying-equipment is shown in Fig. 13. It comprises an ordinary directional element D, having make-contacts which are sufficiently designated by the relay-designation D. It has first- and second-zone balanced-beam impedance relays Z1 and Z2 which are of conventional design, and which need no further description. Each of these impedance-relays has a make-contact which is sufficiently designated by referring to the relay-designation Z1 or Z2, as the case may be.

Each of the impedance-relays Z1 and Z2 has a current-responsive operating-coil 44, and two voltage-responsive restraint-coils 45 and 45', with a phase-shifting capacitor 46 in series with one of them, so as to make the relay-currents therein 90° out of phase with each other, thus obtaining a substantially constant pull throughout each cycle, in a manner which is well understood.

The design and energization of the impedance-relays Z1 and Z2 has been particularly referred to, in connection with Fig. 13, because the relaying-equipment which is shown in Fig. 13 also includes one of my directional mho-relays M, which is constructed in a precisely similar manner, with an operating coil 34 and two restraint-coils 35 and 35', with a capacitor 46' in series with one of the restraint-coils 35', for precisely the same reason of producing a steady restraining-force operating on the relay. The directional mho-relay M has a single make-contact which is sufficiently designated by reference to the relay-designation M.

The energization of the directional mho-relay M in Fig. 13 is the same as that which was shown and described in Fig. 12, except that the response to the line-voltage has been omitted on the operating-side, so that the operating-coil 34 of the relay M is energized directly in series with the line-current transformer 39 in Fig. 13. The relay thus responds to the condition where $h=0$, in Equations 5, 12, and 21. The relay-response of the directional mho-relay M in Fig. 13 may be similar to any of the curves 21 to 27 in Figs. 9 and 10, which have already been discussed.

In Fig. 13, the directional mho-relay M is utilized in place of the sensitive, third-zone impedance-element of a previously used impedance-relay system. This may be understood by considering the tripping circuit 50 which is utilized to energize the trip-coil TC of the circuit-breaker 43. The energization of the tripping circuit begins with the directional-relay contact D, from which it extends, through a circuit-conductor 51, to the second-zone impedance-relay contact Z2, from which the circuit continues through a conductor 52. The D-controlled conductor 51 also leads to the mho-relay contact M, and thence to a conductor 53, which energizes an auxiliary timer-relay TX, having a contact which initiates the operation of a timer-relay T, which thus starts to operate when the auxiliary timer-relay TX is energized. The timer T has two sets of contacts T2 and T3, for providing a shorter time-interval, represented by the T2-contacts, for second-zone operation, and a longer time-interval, represented by the T3-contacts, for third-zone operation.

There are three paths or circuits by which the trip-coil TC of the circuit-breaker 43 may be energized. The first circuit is conventional. It consists of an instantaneous circuit which is completed from the positive battery-terminal

(+), through the D-contact, the conductor 51, the Z1-contact, the conductor 50, the trip-coil TC, and the breaker-switch 43A, to the negative battery-terminal (-).

The second energizing-circuit for the trip-coil TC, in Fig. 13, involves a novel feature in accordance with my invention, in that the operation of the second-zone impedance-type relay Z2 is monitored by my directional mho-relay M, as well as by a conventional directional response, which is indicated, in Fig. 13, by the directional element D. The mho-relay M is able to distinguish between load-currents and fault-currents, and it is thus able to monitor the Z2-relay, since the Z2-relay has no phase-angle discrimination between load and fault currents. At the same time, the conventional directional element D supervises the directional mho-element M, which is desirable because the mho-element loses its directional characteristics for close-in faults, because of the predominance of the current-responsive torque on the front end 34 of the beam, for the case where $h=0$, (as in Fig. 13), or in the case where the voltage on the front end of the beam is supplied by the uncollapsed quadrature voltage (as in Fig. 12).

The second energizing-circuit for the trip-coil TC, as shown in Fig. 13, includes the D-contact, the conductor 51, the Z2-contact, the conductor 52, and then the second-zone timer-contact T2 which becomes closed upon the expiration of a predetermined fixed time after the initial energization of the conductor 53, which responds to an operation of the M-relay. The second-zone tripping operation is thus under the control of the directional mho-relay M, which provides the timing, monitored by the directional element D and the second-zone impedance-element Z2. From the second-zone timer-contact T2, the tripping-circuit continues directly through the tripping-conductor 50, the trip-coil TC, and finally the auxiliary breaker-switch 43a.

The third-zone tripping circuit, in Fig. 13, is altogether under the control of the directional mho-relay M, monitored only by the conventional directional element D. This tripping circuit can be traced from the D-contact, the conductor 51, the M-contact, the conductor 53, the third-zone timer-contact T3, and the tripping-circuit 50.

While I have illustrated my invention in several illustrative and preferred forms of embodiment, and have explained its various features of construction and operation, I desire it to be understood that I am not limited altogether to the illustrated structures, combinations, and proportions of parts, as various changes may be made, within the scope of my invention, particularly in its broader aspects. I desire, therefore, that the appended claims shall be accorded the broadest construction consistent with their language.

I claim as my invention:

1. An electro-responsive device adapted for use on an alternating-current system and comprising a movable part, means for providing a restraining-force which is responsive to

$$I_r^2 + E_r^2 - 2I_r E_r \cos(U - \theta)$$

and means for providing an operating-force which is responsive to

$$I_0^2 + E_0^2 + 2I_0 E_0 \cos(S - \theta)$$

where I_r and E_r are the effective restraint-side ampere-turns responsive to a line-current and a line-voltage, respectively, I_0 and E_0 are the effective operating-side ampere-turns responsive to a

line current and a line-voltage, respectively, θ is the power-factor angle of the line, and S and U are phase-shifting angles.

2. A single-phase electro-responsive fault-detecting device adapted for use on a three-phase system and comprising a movable part, means for providing a restraining-force which is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a delta line-voltage which is susceptible of collapse under fault-conditions to which the device should respond, and means for providing an operating-force which is responsive to the vectorial sum of a reversed alternating-current function of the same line-current and an alternating-current function of a delta line-voltage which is not susceptible of collapse under fault-conditions to which the device should respond, the restraining voltage-component leading the restraining current-component by approximately 90° , and the operating voltage-component lagging behind the operating current component by approximately 90° , under unity-power-factor line-current conditions.

3. A modified-reactance fault-detecting relay-element adapted for the protection of an alternating-current line, said relay-element comprising line-energized relay-means for producing at least two separate relay-fluxes and for developing, from said fluxes, a response to predetermined line-impedance values, characterized by the line-energized relay-means for producing at least one of said relay-fluxes including line-energized circuit-means for carrying at least two derived alternating-current relaying-quantities, at least one of said quantities being responsive to a line-current, at least another one of said quantities being responsive to a line-voltage, and further characterized by said line-energized relay-means having such energizing-constants that the locus of the measured line-resistance R and the measured line-reactance X , at the balance-point of the relay, is approximately at

$$R^2 + (X - X_0)^2 = X_0^2$$

where X_0 is a constant.

4. A mho-responsive fault-detecting relay-element adapted for the protection of an alternating-current line, said relay-element comprising line-energized relay-means for producing at least two separate relay-fluxes and for developing, from said fluxes, a response to predetermined line-impedance values, characterized by the line-energized relay-means for producing at least one of said relay-fluxes including line-energized circuit-means for carrying at least two derived alternating-current relaying-quantities, at least one of said quantities being responsive to a line-current, at least another one of said quantities being responsive to a line-voltage, and further characterized by said line-energized relay-means having such energizing-constants that the locus of the measured line-admittance in mhos, at various line-power-factor angles θ , at the balance-point of the relay is approximately at

$$M = kcsc \theta$$

where k is a constant.

5. A zone-type high-speed relay-system for alternating-current lines, comprising, in combination, instantaneously operating fault-responsive trip-circuit means, time-delayed fault-responsive trip-circuit means including a timing-relay, a plurality of fault-responsive elements of different sensitivities cooperating with said instantaneous

and time-delayed trip-circuit means, the most sensitive fault-detecting element of said combination being a modified reactance element substantially as defined in claim 3, and means initiated by a response of said modified-reactance element for initiating the operation of said timing-relay.

6. A zone-type high-speed relay-system for alternating-current lines, comprising, in combination, instantaneously operating first-zone fault-responsive trip-circuit means, including a first-zone fault-responsive element, time-delayed second-zone trip-circuit means, including a second-zone fault-responsive element and a timing-relay, and a still more sensitive fault-detecting element, substantially as defined in claim 12, for initiating the operation of said timing-relay.

7. A modified-reactance fault-detecting relay-element adapted for the protection of an alternating-current line, said relay-element being of a type comprising line-energized relay-means, responding to a line-derived voltage and a line-derived current, for producing at least two separate relay-fluxes and for developing, from said fluxes, a relay-response having a circle for the locus of the balance-point of the relay, when the measured line-resistance R and the measured line-reactance X , at said balance-point, are plotted in rectangular coordinates, said relay-element having such energizing-constants that the center of the circle is displaced from the origin in a line which approximately coincides with the X -axis for lagging line-reactances, by a displacement-distance which is approximately equal to the radius of the circle, whereby said relay-element has a directional characteristic.

8. A mho-responsive fault-detecting relay-element adapted for the protection of an alternating-current line, said relay-element comprising line-energized relay-means, responding to a line-derived voltage and a line-derived current, for producing at least two separate relay-fluxes and for developing, from said fluxes, a relay-response to line-admittance values, when the locus of all line-admittance values at the balance-point of the relay is plotted in polar coordinates at various values of the power-factor angle of the line-current, said line-energized relay-means having such energizing-constants that said locus is responsive approximately linearly to the line-admittance times the sine of the power-factor angle, whereby said relay-element has a directional characteristic.

9. A zone-type protective-relay assembly for an alternating-current line, comprising a trip-circuit means for effecting a line-switching operation, and a plurality of fault-responsive elements of different sensitivities for supervising the energization of said trip-circuit means, characterized by at least one of said fault-responsive elements comprising a relay as defined in claim 3.

10. A zone-type protective-relay assembly for an alternating-current line, comprising a trip-circuit means for effecting a line-switching operation, and a plurality of fault-responsive elements of different sensitivities for supervising the energization of said trip-circuit means, characterized by at least one of said fault-responsive elements comprising a relay as defined in claim 4.

11. A zone-type protective-relay assembly for an alternating-current line, comprising a trip-circuit means for effecting a line-switching oper-

ation, and a plurality of fault-responsive elements of different sensitivities for supervising the energization of said trip-circuit means, characterized by at least one of said fault-responsive elements comprising a relay as defined in claim 7.

12. A zone-type protective-relay assembly for an alternating-current line, comprising a trip-circuit means for effecting a line-switching operation, and a plurality of fault-responsive elements of different sensitivities for supervising the energization of said trip-circuit means, characterized by at least one of said fault-responsive elements comprising a relay as defined in claim 8.

13. An electro-responsive device adapted for use on an alternating-current system and comprising a movable part, means for providing a restraining-force which is responsive to both a line-current and a line-voltage, and means for providing an operating-force which is responsive to both a line-current and a line-voltage, at least one of said forces being responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage, characterized by both the restraining-force and the operating-force being responsive to the same line-current, the current-responsive operating flux-component being slightly larger than the current-responsive restraining flux-component.

14. An electro-responsive device adapted for use on an alternating-current system and comprising a movable part, means for providing a restraining-force which is responsive to both a line-current and a line-voltage, and means for providing an operating-force which is responsive to both a line-current and a line-voltage, at least one of said forces being responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage, characterized by both the restraining-force and the operating-force being responsive to the same line-current, the current-responsive operating flux-component being slightly smaller than the current-responsive restraining flux-component.

15. A single-phase electro-responsive fault-detecting device adapted for use on a three-phase system and comprising a movable part, means for providing a restraining-force which is responsive to both a line-current and a delta line-voltage which is susceptible of collapse under fault-conditions to which the device should respond, and means for providing an operating-force which is responsive to the same line-current and a delta line-voltage which is not susceptible of collapse under fault-conditions to which the device should respond.

16. The invention as defined in claim 15, characterized by at least one of said forces being responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage, both the restraining-force and the operating-force being responsive, in substantially equal degrees, to the same line-current, the voltage-responsive component of said vectorial sum being out of phase with the current-responsive component thereof by approximately 90° under unity-power-factor line-current conditions.

SHIRLEY L. GOLDSBOROUGH.