Nov. 7, 1933. S. L. GOLDSBOROUGH 1,934,662

HIGH SPEED IMPEDANCE RESPONSIVE RELAY

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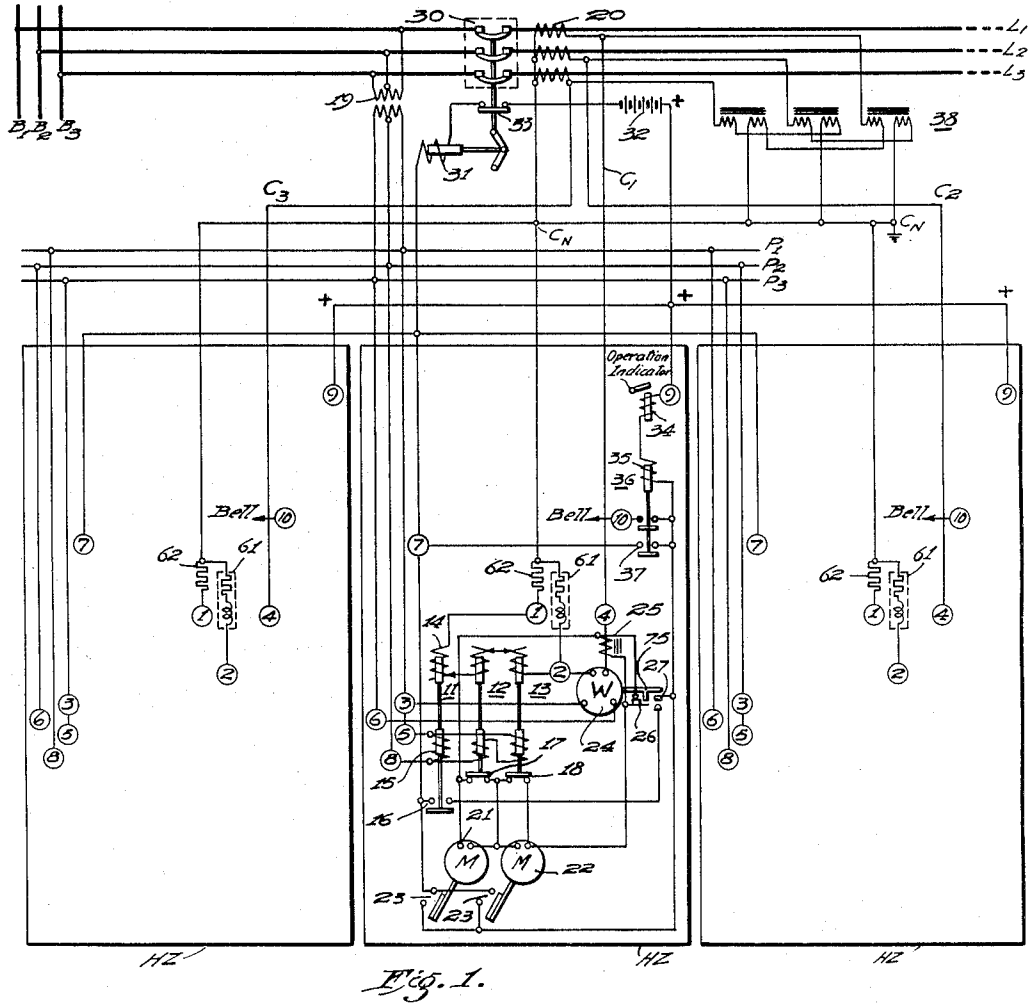


Fig. 1.

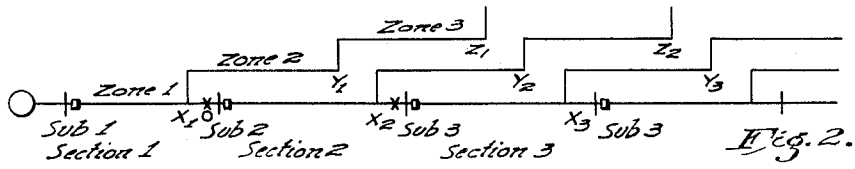


Fig. 2.

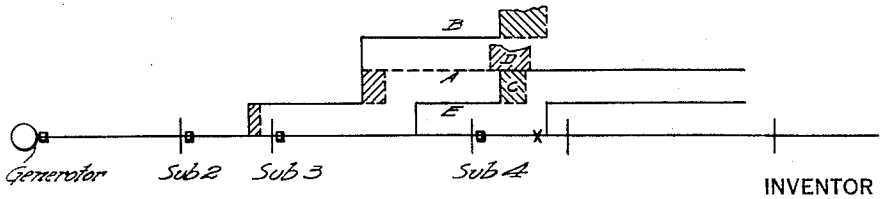


Fig. 3.

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HIGH SPEED IMPEDANCE RESPONSIVE RELAY

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Fig. 4.

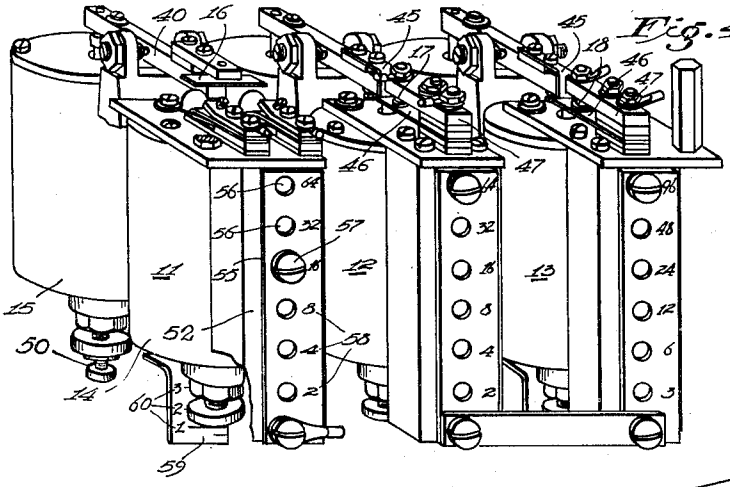


Fig. 6.

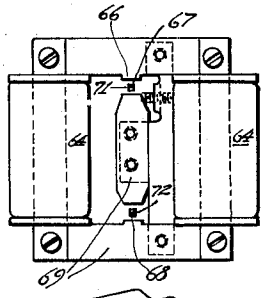


Fig. 5.

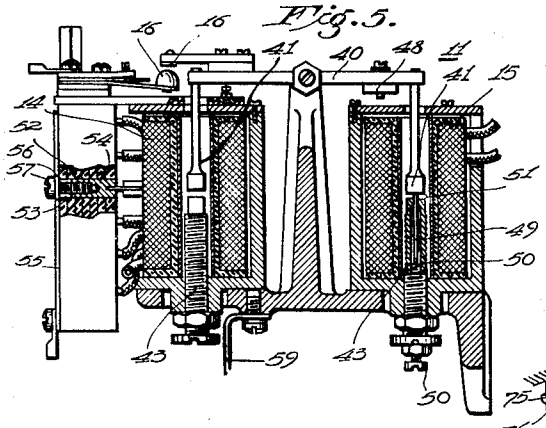
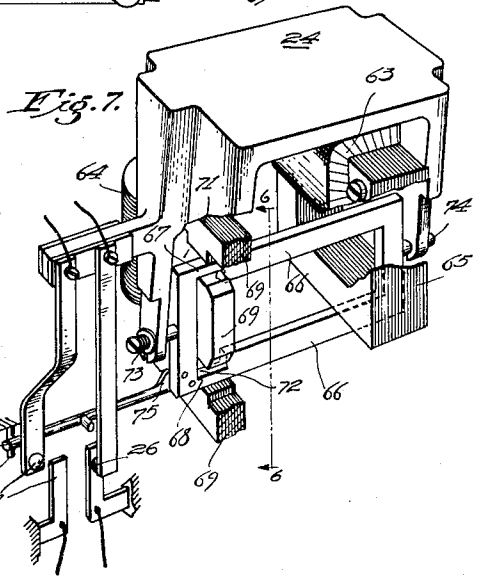


Fig. 7.



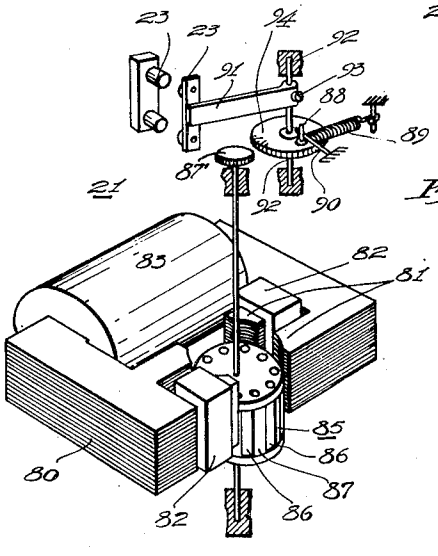


Fig. 8.

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Patented Nov. 7, 1933

1,934,662

UNITED STATES PATENT OFFICE

1,934,662

HIGH-SPEED IMPEDANCE-RESPONSIVE RELAY

Shirley L. Goldsborough, East Orange, N. J., assignor to Westinghouse Electric & Manufacturing Company, a corporation of Pennsylvania

Application May 1, 1930. Serial No. 448,937

21 Claims. (Cl. 175—294)

My invention relates to relays and relaying systems particularly designed for use with quick-acting circuit-breakers for the purpose of increasing the stability of transmission lines, or the ability of such lines to transmit power without loss of synchronism during fault conditions.

The question of system stability has been given a great deal of study by transmission engineers. Considerable thought has been expended on the problem of how to transmit greater amounts of power and still maintain the system in synchronism during accidental faults on the transmission lines, power transformers, generators and associated apparatus. A number of ways of increasing the stability limit of power systems have been suggested, all of which are only partial solutions of the problem. It has been found, however, that probably the most effective method of raising the stability limit consists in clearing short circuits very quickly, as set forth in an application of R. D. Evans et al., Serial No. 403,390, filed October 30, 1929, and assigned to the Westinghouse Electric and Manufacturing Company. It can be shown that the amount of power which can be transmitted with stability is more or less a function of the rapidity with which short circuits are cleared from the system. The reduction of the total breaker and relay time of operation to .1 sec. results in a large increase in the stability limit.

My present invention relates to a high-speed inpedance-responsive relay which is sold by the Westinghouse Electric and Manufacturing Company as the type HZ relay. It has been developed to solve the problem of a high-speed relay for use in connection with high-speed breakers to effect the rapid clearing of line faults. This relay is capable of operating in 1 cycle or less on a 60-cycle system. Selectivity is attained by the employment of the impedance principle. This principle has been chosen as it offers the simplest way of obtaining high-speed discrimination.

This relay is designed primarily for the high-speed sectionalizing of transmission lines upon the occurrence of three-phase, phase-to-phase, and double ground faults.

Because of the resistance which may be present in a single-phase ground, the use of relays of the impedance type for ground protection is not entirely satisfactory, and, therefore, my present relay is not generally recommended for this purpose. However, in cases where the transmission line is built on steel towers, with ground wires, and where the soil conditions are favorable, my present relay may be used to protect against single-phase grounds.

My relays may be used on single lines in a closed loop or on parallel-circuit lines with equally satisfactory results.

With the foregoing and other objects in view, my invention consists in the relay, relaying system, combinations, subcombinations, and elements hereinafter described and claimed and illustrated in the accompanying drawings, wherein

Figure 1 is a wiring diagram of the circuits and apparatus embodying my invention as applied to the protection of one end of a sectionalized three-phase transmission line against faults which include a short circuit between two or more wires of the transmission line,

Figs. 2 and 3 are charts illustrating the time-distance characteristic of my relays and the method of setting the relays for different line-section conditions,

Fig. 4 is a perspective view showing my three impedance elements which are utilized in each of my high-speed relays,

Fig. 5 is a cross sectional view of one of the impedance elements,

Fig. 6 is a detail sectional view of a part of the directional element, the second plane being indicated by the line 6—6 in Fig. 7,

Fig. 7 is a simplified perspective view of the directional element, and

Fig. 8 is an enlarged, partially diagrammatic, perspective view of the time-switch element.

The apparatus which is commonly sold under the name of a high-speed impedance relay, type HZ, consists of a glass-enclosed box or board having a number of so-called elements mounted thereon or therein, and each having ten terminals which are numbered one to ten, both in actual practice and in Fig. 1 of the accompanying drawings. For a three-phase line, I utilize three high-speed impedance relays, designated HZ in Fig. 1 of the drawings, said relays being connected across different delta phases of the transmission line L_1, L_2 and L_3 which is connected to a bus B_1, B_2 and B_3. As the three relays are identical, a description of one will suffice for all, and one is shown in detail in Fig. 1.

Each relay comprises three instantaneously operating high-speed impedance-responsive relay-elements 11, 12 and 13, each having a current-responsive actuating coil 14 and a voltage-responsive restraining coil 15. The first impedance element 11 has a pair of normally open contacts 16, whereas the second and third relay

elements 12 and 13 have normally closed contacts 17 and 18, respectively.

Energy for the voltage windings of all of the relay elements is supplied from potential transformer buses P_1, P_2 and P_3 which are shown as deriving power from the potential transformer 19. The current-responsive windings of the several relays are energized from a star-connected current transformer 20 having a neutral terminal C_N and phase terminals C_1, C_2 and C_3.

The impedance relay-elements 11, 12 and 13 are constructed to operate as quickly as possible upon an over-balancing of the voltage coil 15 by the current coil 14. These relays thus respond to a critical ratio of voltage to current, and hence to a critical impedance, or apparent impedance, of the delta phase of the line to which the relay is connected. When the line impedance becomes less than a predetermined value, therefore, the impedance relay-element operates. The second and third impedance elements 12 and 13 are set to operate at a higher critical impedance than the first relay element, and hence their voltage coils 15 may be connected in series with each other and in parallel to the voltage coil of the first element 11.

It will be noted, from Fig. 1, that the current coils 14 of the three impedance elements 11, 12 and 13 are connected in series with the current transformer on the line L_1, whereas the voltage coils 15 are energized across the delta phase P_1—P_2 which corresponds to the line phase L_1—L_2.

Each relay HZ is also provided with two synchronous timers or time switches 21 and 22, which are indicated schematically as motors in Fig. 1 but which have a more complicated construction, as will be described hereinafter in connection with Fig. 8. Each synchronous timer has a pair of normally open contacts 23 which are closed at the end of a time period according to the setting of the timer element, as will subsequently be described.

Each impedance relay HZ is also provided with a directional element 24 which is schematically indicated in Fig. 1 as a contact making wattmeter, the current windings of which are energized in series with the current coils 14 of the impedance elements, and the voltage windings of which are energized across the potential transformer phases P_1—P_3 corresponding to the line phase L_1—L_3.

Since practically all applications, where high speed is essential, require a directional element, the standard HZ relay is equipped with this element and the relays without the directional element will not at present be available. For the few cases where no directional element is required, the standard relay may be used and the directional contacts blocked closed or open, as the case may be.

In order to provide a suitable source of energization for the timing motors 21 and 22, even during a three-phase short circuit close to the relaying point, at which time the potential-transformer voltage becomes substantially zero, I energize my timing motors from the fault current, itself, instead of from the line voltage, as heretofore. To this end, a current transformer 25 is provided having a primary winding in series with the current coils 14 of the impedance elements and the current windings of the wattmeter or directional element 24. The secondary winding of the current transformer 25 is connected to the timing motors 21 and 22 connected in series, and is short circuited by a pair of closed contacts 26 on the directional element 24, which are closed at all times except when current is flowing away from the bus B_1, B_2 and B_3 into the line L_1, L_2 and L_3. The timing motor 21 is also short circuited by the normally closed contacts 17 of the second impedance element 12. The second timing motor 22 is short circuited by the normally closed contacts 18 of the third impedance element 13.

It will thus be seen that neither one of the timing motors 21 or 22 can be energized unless its associated impedance element is overbalanced, and unless, also, the current is flowing into a fault to the right of the relay element as drawn in Fig. 1.

The directional wattmeter element 24 is also provided with a set of normally open contacts 27 which are connected in series with the normally open contact 16 of the first impedance element 11.

It will be understood that my relaying system is applicable to a sectionalized transmission line having a plurality of line-sections in series, only one end of one section being shown in Fig. 1. Each section of the line is provided, at each end, with suitable relay equipment, and also with an oil circuit breaker 30 which is provided with a trip coil 31, the latter being energized from a suitable source, such as a large storage battery 32 which is capable of sending a very heavy momentary tripping current into the trip coil 31. The circuit breaker is preferably provided with back contacts 33 which are closed when the circuit breaker is closed and which open when the circuit breaker is opened or partially opened, said back contacts being connected in series with the tripping coil to interrupt the trip-coil circuit. The trip-coil circuit is completed either by the contacts 16 of the first impedance element 11, in series with the contacts 27 of the directional wattmeter element 24, or by one of the contact elements 23 of the two time switches 21 and 22. This tripping circuit also includes an operation indicator 34 and the actuating coil 35 of an electromagnetic contactor switch 36 which has a pair of normally open contacts 37 which are closed as soon as the tripping circuit is energized, thereby short circuiting all of the lighter contacts on the quickly moving elements 11 and 24, so as to relieve these contacts of the duty of carrying the heavy tripping current. The contactor switch 36, when it closes, also energizes terminal number ten of the relay, which is adapted to be connected to an alarm bell, if desired.

The contactor switch is provided in order to increase the capacity and the certainty of action of the several tripping contacts 16, 27 and 23. The shunting contacts 37 of the contactor switch 36, will not open under any circumstances until the tripping circuit is opened by the auxiliary switch 33 on the breaker.

Summarizing the phase connections of the middle relay HZ of Fig. 1, it will be noted that the current-responsive windings of all of the elements are responsive to the line current in phase L_1. The voltage coils of the impedance elements 11, 12 and 13 are energized from the delta phase L_2—L_1 which leads the current in line L_1 by 30° at unity power factor. The relative polarity between the current and the distance-element voltage does not matter since the connection between the two is purely mechanical, and the

above voltage may be reversed, making it lag the current by 150° at unity power factor.

The voltage windings of the directional element 24 are energized from the delta phase L_3—L_1 which lags behind the current in the line L_1 by 30° when the line power factor is 100%. The advantage of connecting the directional element in this manner is that, for anything except a three-phase fault, the directional voltage of the relay operating will be equal to, or in excess of, the normal line-to-neutral voltage.

One of the following methods should be used to insure that relays are properly connected:

a. Connect the current coils of a single-phase wattmeter in series with the current winding of a relay. With power flowing in either direction, if the current is lagging so that the power factor is between 100% and 50% and if the 30° connection is to be used, select a pair of voltage leads which give the highest reading on the wattmeter. The two leads selected should be connected to the relay potential terminals. Inspect contacts on the directional element, which should be opened when the power is flowing towards the bus bars. If the contacts close when power flows towards the bus bars, the potential leads on each relay should be reversed.

b. Connect the current coils of a single-phase power-factor meter in series with the current coils of a relay. Select a pair of potential leads which give 86.6% of power-factor lead on the power-factor meter when the line power factor is 100%. These two leads should be connected to the relay potential terminals. See that the directional contacts are open with power flowing into the station.

While the connections have been specifically described for only one of the three relay elements HZ, it will be understood, by inspection of Fig. 1, that the other two relays are connected, in a similar manner, to the other two line phases L_3 and L_2, respectively, with corresponding changes in the voltage connections in accordance with the instructions already given.

Before considering, in detail, the structural design and the method of setting my type HZ relay, a number of factors to be considered will be discussed.

The point on the line where a short circuit will cause the voltage element to just balance the current element of an impedance-responsive element is called its balance point. For instance, the balance point of the first impedance element in Fig. 2 is at X_1. This balance point will shift slightly, depending upon the type of fault. Suppose we adjust the first impedance element to balance at point X_1, Fig. 2, for a wire-to-wire short circuit, Then, for a symmetrical three-wire short circuit, the balance point will shift approximately 15% further out, or to the right. This comes about from the fact that, for the same current and same location, the ratio of the delta voltage drops of a three-phase fault and a line-to-line fault is 1.73/2. Since the three-phase fault does not produce as much voltage-drop as the line-to-line fault, the three-phase fault must occur 15% farther to the right in order to effect a balance between the current and voltage elements.

The balance point of the first impedance element should be adjusted at approximately 75% of the length of the line-section in which the relay is located. Then the balance point for a three-phase short will shift the balance point to 86.3% of the section length.

A line-to-line-to-ground fault will produce a shift of the balance point in the same direction as the three-phase fault shifts it in an amount depending upon the ratio of the negative-sequence impedance X_2 to the zero-sequence impedance X_0 of the system to the fault. (These terms are explained in a series of articles by Wagner and Evans in The Electric Journal March, 1928, pages 151–157; April, 1923, pages 194–197; June, 1928, pages 307–311, particularly pages 308–309; July, 1928, pages 359–362; September, 1929, pages 425–431, particularly page 428; and December, 1929, pages 571–581, particularly pages 571–574.)

However, the ratio X_2/X_0 is generally less than unity and, in that case, the shift is less than 15%. Since we have to allow for a 15% shift for a three-phase short, the shift due to a double ground can be neglected until the X_2/X_0 ratio becomes greater than one. In this event, the shift can be eliminated by filtering out the zero-sequence component of current.

The means for filtering out the zero-sequence component of current may take the form shown in my copending application Serial No. 406,828, filed November 13, 1929, or it may take the form of a small interconnected star grounding transformer, as shown at 38, and described in one of the above-mentioned Wagner and Evans articles in the Electric Journal, December 1929, Volume 26, page 574. This consists of three small one-to-one transformers connected so that the zero phase-sequence currents neutralize each other magnetically, so that no impedance is offered to the flow of said zero-sequence currents. On the other hand, a small transformer or set of transformers is a substantially infinite impedance for the positive or negative phase-sequence components of the current, since it permits only the negligibly small magnetizing currents to flow in these phase-sequence components. It will be understood that, in many cases, the means 38 for providing a low-impedance path for zero phase-sequence currents need not be provided.

Assuming a single line having sections of equal impedance, the balance point of the second impedance element should be adjusted about midway into the next section for a line-to-line fault. For a three-phase fault, it will then shift to the right 15% of the distance from sub 1, or substation 1, to a point Y_1, making its three-phase balance position 73% of the length of the second line-section. In general, the second impedance element should be adjusted for a balance point Y_1 close enough to sub 2 for a line-to-line short, so that a three-phase short will not shift it too close to the balance point X_2 of the first impedance element at the near end (sub 2) of the second line-section.

The back-up element, or third impedance element, should be adjusted so that its balance point Z_1 is just inside the third line-section for a line-to-line short circuit, or at about 25% of the length of the third line-section. Then, for a three-phase short, the balance point will be at 58% of the length of the third line-section.

The time interval for which to set the synchronous timers will depend on the speed of the circuit-breakers. For a breaker opening in 6 cycles, it would be satisfactory to set the first timer at 10 cycles and the back-up timer at 20 cycles.

Where a short section follows a long section, as in Fig. 3, it becomes difficult to obtain strict selectivity on the back-up element without grad-

ing the time settings on successive relays. Where a long section follows a short section, this difficulty is not experienced.

Referring to Fig. 3, the section "sub 3 to sub 4" is much longer than section "sub 2 to sub 3", and it is seen that, if we make the back-up element of the relay at sub 2 have the time curve shown by dotted line A, it will overlap the back-up time of the relay at sub 3. Thus, for a three-phase short circuit at X, in case the breaker at sub 4 fails, the relays at both sub 3 and sub 2 will trip. If this rather remote possibility of insufficient back-up selectivity is considered undesirable, it can be overcome by raising the time of the back-up relay element at sub 2 to the value indicated by the full-line B. This will allow sufficient time for breaker at sub 3 to open before the back-up relay element at sub 2 can close.

When making settings on parallel line sections, they can be considered as single line sections of variable length. This will affect the shift of the second and third element balance points, and may make it necessary to grade the time intervals on the back-up element.

The following rules will be helpful in making settings where parallel line sections are involved.

Where a single line follows a parallel line section, the second element of relays on the parallel lines should be set with the assumption that all but one parallel line are disconnected. The back-up element should be set with all lines in.

Where the parallel lines follow the single line on which relays are to be set, the second impedance element should be set upon the assumption that all parallel lines are in. The back-up element should be set upon the assumption that all parallel lines except one are disconnected.

In choosing the settings for type HZ relays, the most satisfactory procedure is to lay off to scale a number of line sections and then draw the time-distance curves for each relay in such a manner that the 15% shift due to the three-phase fault will not cause the first and second impedance zones to overlap. It is feasible to allow the back-up zones to overlap, as first class selectivity on the back-up protection is not generally necessary. After the time-distance curves have been adjusted graphically, the balance points and time delays of the relays will be known, and the impedance elements may be adjusted as explained hereinafter.

It is seen that the time does not vary directly as the distance from the fault, but increases definite amounts at definite points. In zone 1, the relay operates in 1 cycle or less. In zone 2, the relay operates with definite time delay which is adjustable and which is predetermined with reference to the speed of breaker operation plus the time of relaying. Zone 3 provides back-up protection in case a breaker in the next section fails to clear the trouble.

Referring to the detailed construction of the impedance elements shown in Figs. 4 and 5 of the accompanying drawings, it will be noted that each of these elements comprises a centrally pivoted contact-carrying beam 40 of a non-magnetic material, such as brass, carrying, at each end, a plunger or armature 41 of magnetic material, preferably of a magnetic material having low remanence and a high maximum permeability at low flux densities, such as hipernic, which is an alloy of approximately 50% nickel, 50% iron and varying quantities of manganese up to 1%. The low remanence is desired in order that the armature will have no hysteresis or residual magnetism so that it will lose its flux quickly and completely as soon as the magnetizing force is removed, which is necessary in order to obtain a very quick action. The high maximum permeability at low flux densities is desirable in order to obtain a strong positive action as soon as the pulls on the two ends of the contact-carrying beam 40 are overbalanced, even though the currents are weak.

The plunger or armature 41 on the contact end of the beam 40 is pulled down by the action of the current coil 14, whereas the plunger or armature 41 at the other end of the beam is pulled down by the voltage coil 15 which thus opposes the current coil. Both coils are provided with axially adjustable hipernic cores 43 which are screw-threaded to provide the axial adjustment.

The plungers and the beam are made light, so that, once the pull on the current side becomes greater than the pull on the voltage side, the beam moves very quickly and closes the bridging contacts 16, in the case of the first impedance element 11, or opens the contacts 17 or 18, in the case of the second and third impedance elements 12 and 13. This contact-opening action, as indicated in Fig. 4, is secured by the provision of a micarta finger 45 attached to the contact-carrying end of the beam and pressing down on a leaf spring 46 which carries the bottom contact member of the normally closed contact 17 or 18, the top contact-carrying member being rigidly supported by an insulating block 47.

The pivoted beam 40 may be provided with a balancing weight 48, as will be obvious.

The plunger or armature 41, which extends into the voltage coil 15, is provided with a non-magnetic pin extension 49 which depends downwardly into a suitable bore in the core screw 43 of this voltage coil. This pin 49 thus serves to center the plunger or armature 41 within the voltage coil 15. The pin 49 also serves as a stop to limit the pulling action of the voltage coil, by means of the resting of the pin 49 against the top of an adjusting screw 50 which projects up through the bottom of the core screw 43 of the voltage coil. Adjustment of the screw 50 thus serves to control the air gap 51 between the bottom of the plunger 41 and the top of the core 43 of the voltage coil 15. This adjustment is commonly made at the factory and not thereafter disturbed.

The current coil 14 and its core screw 43 are adapted to be adjusted by the user of the apparatus. To this end, a tap-changing block is provided comprising a non-conducting block 52 which is provided with a row of perforations 53, each of which is partially filled by a tap-changing terminal 54 which extends part way into the perforations 53 from the back of the insulating block 52. The front of the block 52 is provided with a metal strip 55 having corresponding perforations 56 through any one of which a tap screw 57 may be inserted according to the number of turns which is desired.

By providing taps so that, when moving from one tap to the next higher tap, a geometric progression is made in the number of effective turns of the current coil, and by providing for axial adjustment of the core 43 of the current coil 14, I am enabled to provide for a continuous adjustment of the pull of the current coil over the entire range, including any possible intermediate value. I have also provided a system of mark-

ing which effectively correlates these two adjustments. Thus, a series of numbers, as indicated at 58, are assigned to the series of taps on the tap-changing block, and indicated on the face of the block, as shown in Fig. 4, and a vertical-adjustment scale 59 is also provided to indicate the axial adjustment of the core 43 of the current coil 14, and a series of numbers, usually from one to three, are assigned to the vertical scale of the adjusting screw, as indicated at 60 in Fig. 4, the highest number being at the top, corresponding to the shortest air gap between the plunger and the core of the current coil.

The use of this system of markings of the settings of the current coil may be explained as follows:

Since the impedance of the voltage circuit of the relay is the same at all times, it is merely necessary to increase or decrease the pull of the current coil 14 in order to effect a balance for a larger or smaller impedance, respectively.

The most satisfactory method of arriving at the top settings is by use of a formula. This formula is as follows:

$$TS=\frac{39.4\ L Z R_c K}{R_v}$$

where L is the length of the line up to the so-called "balance point" at which the impedance element tips over, and Z is the unit impedance of the line. R_c is the current transformer ratio. R_v is the potential transformer ratio. T is the number on the relay tap block, as indicated by the scale 58, and S is the number on the vertical core-screw scale 60. K is a constant determined by the design of a transient shunt, and the impedance angle of the transmission line, as will be subsequently described.

For example, assume K=1, that is, no shunt is used. After having obtained the value of TS, T should be obtained by dividing TS by the largest number on the scale S which will yield an even tap number. For instance, if the product TS should come out 36, it is seen that S=2.25 and T=16 gives this product. These taps should be used rather than S=1.125, T=32.

The settings for the second and third impedance elements are obtained in the same manner, using the proper values of L Z.

When a sudden short circuit occurs on a transmission line, a number of transient phenomena take place during the first few cycles. These transients appear in the current wave, but do not generally occur in the voltage wave. This means that the transient will be able to influence the balance of the impedance elements. The most troublesome transient, and the only one which need be compensated for, is the direct-current transient, which occurs in the asymmetrical short-circuit current. The value of this transient depends upon the point of the voltage wave at which the short occurs, and its effect is to shift the balance point of the impedance element. This transient may make the value of the short-circuit current during the first cycle as much as 1.8 times its symmetrical value. This would mean a considerable shifting of the balance point to the right. In order to prevent this shifting, a device called a transient shunt is used to filter out the direct-current transient, as set forth in an application of L. N. Crichton, Serial No. 422,965, filed January 23, 1930, and assigned to the Westinghouse Electric and Manufacturing Company.

The transient shunt consists of an impedance device 61 with a phase angle which is the same as that of the transmission-line impedance, said impedance device 61 being connected in shunt with the current coils 14 of the impedance elements and a series resistor 62. The transient passes through the shunt, and the voltage drop produced across the shunt feeds the relay coils 14. The resistance 62, which is required as a cooperative part of the transient shunt, is placed in series with the relay coils, rather than being embodied in the coils themselves, so that the current taps may be changed without materially changing the impedance to the relay current. The presence of the transient in the current coils of the directional element and synchronous timers, does no harm, and hence it is not shunted out of these coils.

The impedance of the transient shunt is generally such as to by-pass about two thirds of the total current.

A new type of directional element 24 has been necessitated in order to secure the high speed necessary to enable the directional element to operate preferably faster than the first instantaneous impedance element, which operates substantially always within one cycle and sometimes as fast as about one half cycle on a 60-cycle system. For such high-speed service, it has been shown that a small contact-making induction watt-meter, such as has been used heretofore, having a rotating disc which is dragged around by eddy-current action, is inherently too slow to be made to operate satisfactorily in a high-speed relay.

It is necessary, in my high-speed relay, to use a directional element operating on the galvanometer principle, by which I mean an instrument having a magnetizable needle or armature which orients itself according to the direction of the field, or one having a coil through which current is flowing, which reacts with a field to produce movement in the one direction or the other, according to the direction of flow of the current with respect to the field.

As shown in Figs. 6 and 7, my substantially instantaneous directional relay-element 24 comprises two alternating-current windings or coils 63 and 64, the direction of whose currents is to be compared. The winding marked 63 is energized as a voltage coil connected to terminals 3 and 6 of the relay and energized, as shown for the central relay in Fig. 1, from the line phases L_1 and L_3. This voltage-coil winding 63 of the directional element is wound as the primary winding of a potential transformer having a closed magnetic core 65, one leg of which is loosely embraced by a single loop 66 of aluminum or copper, constituting the secondary winding of the transformer. Current is thus induced in the loop 66 which is substantially in phase with the voltage applied to the voltage coil of the directional element.

The loop 66 is much larger than is necessary merely to embrace a leg of the potential transformer core 65, so as to provide two substantially parallel inductor portions 67 and 68 which cooperate with the field produced by the current winding 64 as follows:

The current winding 64 is wound as the stator member of the galvanometer having a magnetic circuit 69 which is broken by two air gaps 71 and 72. The magnetic material used in the circuit 69 may be hipernic, or only a part of it may be hipernic, in order to secure the advantages mentioned hereinabove as inherent in this material. The two parallel inductor sides 67 and 68

of the loop 66 are disposed in the two air gaps 71 and 72, respectively, so that said sides lie transversely across the flux in said air gaps.

The loop 66 is pivotally supported on an axis parallel to, and substantially midway between, the parallel loop portions 67 and 68 lying in said air gaps 71 and 72, as by means of two bearings 73 and 74. The loop 66 is thus so mounted that it will swing through a small angle when the inductor sides 67 and 68 are displaced transversely in the current-coil field or air gaps 71 and 72 by reason of the reaction between the current in the loop and the flux in the air gap. The loop carries an extending arm 75 which may be of micarta plate, or other insulating material, which rests against a stop 76 in one position of the relay, and which hits against the contact members 26 and 27 when the relay rotates a very short distance in the other direction, thereby opening the contacts 26 and closing the contacts 27.

By reason of the fact that the directional element is connected to current and voltage sources of such relative phases that the current leads the voltage by 30 degrees when the line power factor is 100%, it follows that, when a fault occurs, the fault current, which is very strongly lagging, will still have a component either in phase with or in phase opposition to the voltage applied to the voltage coil, so that a quick and positive operation will be obtained. This directional element has true wattmeter characteristics and is extremely fast without undue energy consumption.

In its essential features, the directional element comprises a current coil 64 and a coil 63 which is energized by a reference current, with respect to which the phase or direction of the current in the current coil is to be compared. While I have indicated this reference coil 63 as being energized from the line voltage, it is to be understood, of course, that other sources of reference currents which are used for directional relay-elements may obviously be used, but these are not specifically described herein, as they constitute the subject-matter of other applications, such as the hereinabove-mentioned Evans et al. application, Serial No. 403,390; an application of L. N. Crichton et al., Serial No. 437,924, filed March 20, 1930, and assigned to the Westinghouse Electric and Manufacturing Company; and my application entitled High-speed directional relay element, Serial No. 448,938, filed May 1, 1930.

While I have indicated that the voltage which is applied to the reference coil 63 of the directional element 24 should preferably lag behind the line current by 30 degrees when the power factor of the line is unity, it is to be understood that other angles could be used, if convenient, just so that the short-circuit current of the line, when the power factor is very low, shall not be nearly at right angles to the phase of the voltage applied to the reference coil 63.

In adjusting the directional element, it is desirable that the contacts shall be so adjusted that both sets of contacts are actuated at the same time by the contact arm 75. It is usual to provide about 1/64'' clearance between the contacts and the micarta arm 75 when the latter is resting against its stop 76, and to adjust the stationary contacts so that they will have about 1/32'' separation when open.

The synchronous timer 21 or 22, as shown more clearly in an enlarged and somewhat diagrammatic view in Fig. 8, preferably consists of a small subsynchronous-speed timing motor, such as that which is described in an application, Serial No. 557,294 of O. F. Rowe, filed April 29, 1922, and assigned to the Westinghouse Electric and Manufacturing Company. It consists of a two-pole stator core 80 having split pole pieces 81 carrying shading coils 82 or equivalent dephasing means energized from a single-phase stator coil 83. The rotor member of the timing motor consists of an open-slot squirrel-cage armature 85 having 12 slots 86 forming as many salient poles 87 which lock into step with the split poles of the stator member at a subsynchronous speed corresponding to the 12-pole rotor member instead of the 2-pole stator member.

The armature 85 is mounted for axial and rotatable movement and normally rests in a position below the position of exact alignment with the stator poles when the motor is deenergized. When the motor is energized, the armature is drawn upwardly by the magnetic attraction of the field, thereby causing a pinion 87' which is carried by the armature shaft to come into mesh with a reduction gear 88, thereby providing a declutchable means which permits the armature to become instantly disengaged from the reduction gear as soon as the motor is deenergized, without waiting for the armature to give up its kinetic energy. The reduction gear 88 is provided with a reset spring 89 which instantly returns it to its initial position, in abutment against a suitable stop 90, as soon as the armature is declutched therefrom.

The moving element of the switch contacts 23 of the timing element 21 or 22 is carried by a contact arm 91 which is adjustably clamped to the low-speed shaft 92 of the reduction gear by means of a bolt or set screw 93.

The time delay introduced by my synchronous timers can be adjusted by loosening the screw 93 which clamps the contact arm 91 to the gear shaft 92 and moving the arm to the correct position, as indicated by a suitable scale 94 on the gear.

The timing motor has a constant speed, as near as can be detected, over a considerable range of fault-current values and will operate on a current as small as three amperes. If necessary, however, the maximum current delivered to the timing motor by the current transformer 25 may be limited by so designing the transformer that it will become saturated by unusually high fault currents.

The operation of my relay may be briefly summarized as follows:

By means of the core screw and taps on the current coil, the pull of this coil can be adjusted so that it just balances the pull of the voltage when a short circuit occurs at X_1 in Fig. 2. Under this condition, the contacts cannot be closed. If a short occurs to the left of X_1, the current pull overcomes the voltage pull and closes the contacts. These contacts are in series with the contacts on the directional element so that the breaker is not tripped unless the power flow is in the right direction. If the trouble occurs at point O, the first impedance element cannot close its contacts, as the ratio E/I is too high. However, the second impedance element is adjusted to balance for a short at Y_1 and, therefore, operates with trouble at O. The operation of this element opens a short circuit across the synchronous timer 21 which is energized by the current transformer 25. The synchronous timer

closes its contacts after a definite time delay and trips the breaker. The third impedance element is adjusted to balance with trouble at Z_1. With trouble anywhere between the relaying station and the balance point Z_1, this third impedance element energizes the second synchronous timer which is set for a longer time delay. This third element is provided only for back-up protection and would be able to trip the breaker only in case the breaker at sub 2 should fail to operate, because, otherwise, the fault would be cleared and the timer deenergized before its contacts could close.

It should be observed that the operation of the synchronous timers is possible only in case the power flow is in the right direction, as the directional element contacts must be opened in order to energize the timers.

It is important that my type-HZ relay herein described shall be provided with a potential for the impedance elements which is proportional to the high-tension potential. This generally means that potential must be taken directly from the high-tension bus except in cases where a power transformer is available and there is no possibility of feeding fault current from the low-tension to the high-tension bus.

It is usually desirable to connect the potential transformers for my relays directly to the line which the relays protect, but, on very high-voltage lines, the cost of high-tension potential-transformers may prohibit their use. In such cases, however, high-tension potential may still be obtained if circuit-breakers equipped with condenser-type bushings are used. A network has been developed which is connected between the last conducting layer on the bushing and ground; and which will supply a voltage satisfactory for relaying, both as regards ratio and phase angle, as set forth in an application of J. F. Peters, Serial No. 227,449, filed October 20, 1927, a second application of J. F. Peters, Serial No. 269,460, filed April 12, 1928, and an application of J. F. Peters and R. E. Marbury, entitled Method of deriving power from high-voltage lines, Serial No. 448,989, filed May 1, 1930, all assigned to the Westinghouse Electric and Manufacturing Company.

The maximum permissible volt-ampere burden which such a network can supply increases with the voltage of the line, and, on the lower-voltage lines, it may be necessary to use the output of the two bushings on the same phase, connecting them in parallel. Below an operating voltage of about 88 kilovolts, the volt-ampere capacity of such a potential network device becomes too low for relay operation, even when two condenser bushings are connected in parallel.

If it is intended to use my high-speed HZ relays with three-phase potential transformers, consideration must be given to the design of these transformers. Three-phase potential transformers having a "shell-type" core are satisfactory for use with the HZ relays, but transformers of the three-legged "core type" or those with a tertiary winding should not be used. With transformers of the latter types, the voltages supplied to the HZ relays would not be correctly representative of the line voltage for phase-to-phase or phase-to-ground faults, since some of the flux of the unfaulted phase or phases would circulate through the leg upon which the faulted phase is wound and thus would affect the secondary voltage.

The individual elements of my relay system are separately claimed in three divisional applications, Serial Nos. 654,661; 654,662; and 654,663, all filed on February 1, 1933, and directed, respectively, to the impedance relay element, the directional relay element, and the timing relay element.

In the foregoing specification and in the appended claims, the term "impedance element" or "impedance-responsive element", when used without further qualification, refers to any relay-element which picks up at a predetermined "impedance" or an apparent or arbitrary component of impedance or quantity obtained by dividing any voltage component or quantity by any current component or quantity.

While I have carefully described my new high-speed relay and explained its design and operation in a single preferred form of embodiment, it will be obvious that various changes and modifications may be resorted to without departure from the essential intent and spirit of the invention. I desire, therefore, that the appended claims be accorded the broadest construction consistent with their language and the prior art.

I claim as my invention:

1. A relay assemblage ready for installation for the purpose of controlling the clearing of faults from an electric transmission line, characterized by fault-current terminals and voltage terminals, at least three substantially instantaneous impedance-responsive elements set for response to different impedances, two time-switch elements, means adapted to set said two time-switch elements in operation, respectively, in response to the two impedance elements which respond to the highest impedances, means including common tripping connections adapted for the purpose of controlling the clearing of faults in response to either the impedance element which responds to the lowest impedance, or to either of the two time-switch elements, and a substantially instantaneous directional element for rendering the other elements ineffective at all times except when the fault current is flowing in a predetermined direction.

2. A relay comprising fault-current terminals and voltage terminals, three impedance-responsive elements set to respond to different impedances, two time-switch elements set in operation, respectively, by the two impedance elements which respond to the highest impedances, and a directional element for rendering the other elements ineffective at all times except when the fault current is flowing in a predetermined direction.

3. The combination with an electric power line having a circuit breaker, of a protective relay for controlling the operation of said circuit breaker, said relay comprising a first fault-responsive element operating substantially instantaneously in response to near-by faults on the power line, a second fault-responsive element responding to similar faults on the power line even though they are located somewhat further away from the relay, a time-switch element set in operation by said second fault-responsive element, means for operating the circuit breaker in response to either said first fault-responsive element or said time-switch element, said time switch element completing its operation in a time slightly longer than is necessary for the circuit breaker to interrupt the line-current for any faults responded to by said first fault-responsive element, and a directional element of a substantially-instantaneously-operating-galvanometer

type for rendering the other elements ineffective at all times except when the current is flowing in a predetermined direction.

4. The combination with an electric power line having a circuit breaker, of a protective relay for controlling the operation of said circuit breaker, said relay comprising a first fault-responsive element operating substantially instantaneously in response to nearby faults on the power line, a second fault-responsive element responding to similar faults on the power line even though they are located somewhat further away from the relay, a third fault-responsive element responding to similar faults on the power line even though they are located still farther away from the relay, fault-responsive timing means comprising a first pair and a second pair of time-switch contacts associated, respectively, with said second fault-responsive element and said third fault-responsive element for rendering said second and third fault-responsive elements inoperative to effect the operation of the circuit breaker until their respective time-switch contacts are operated, means for operating the circuit breaker either in response to said first fault-responsive element or in response to either of said second and third fault-responsive elements in conjunction with their respective time-switch contacts, said first pair of time-switch contacts completing their operation in a time slightly longer than is necessary for the circuit breaker to interrupt the line-current for any faults responded to by said first fault-responsive element, said second pair of time-switch contacts completing their operation in a time slightly longer than is necessary for the circuit breaker to interrupt the line-current for any faults responded to by said second fault-responsive element and its associated first pair of time-switch contacts, and a directional element of a substantially-instantaneously-operating-galvanometer type for rendering the other elements ineffective at all times except when the current is flowing in a predetermined direction.

5. A sectionalized transmission line comprising a plurality of line-sections in series, each line-section having a circuit breaker and a relay at each end, said relay comprising, in general, a first fault-responsive means for operating substantially instantaneously in response to near-by faults, a second fault-responsive means for operating only after a time in response to similar faults even though they are located somewhat farther away from the relay, means for operating the circuit breaker in response to either said first fault-responsive means or said second fault-responsive means, and a directional element of a substantially-instantaneously-operating-galvanometer type for rendering both of said fault-responsive means ineffective at all times except when the current is flowing into the line-section in which the relay is located, characterized by the facts that the first fault-responsive means of each relay is set to respond to faults which are substantially never farther away than the end of its particular line-section, the second fault-responsive means of each relay is set to respond to faults in the next line-section beyond the one in which the relay is located but not to respond to faults as far away as the extreme limit of response of the first fault-responsive relay means located at the near end of said next line-section, and the time of operation of said second fault-responsive means of each relay being sufficient to enable the circuit breaker at the near end of said next line-section to first clear the fault in response to its first fault-responsive relay-means if it is going to.

6. The invention as specified in claim 5, further characterized by the fact that some or all of the relays have a third fault-responsive relay means for operating only after a still longer time in response to faults occurring as far away as the third line-section, which is two sections beyond the line-section in which the relay is located, and having a time of operation which is at least sufficient to enable the circuit breaker at the near end of the second line-section, which is adjacent to the line-section in which the relay is located, to first clear a fault in said third line-section in response to its second fault-responsive relay-means if it is going to.

7. A relaying system comprising at least one of each of the following elements; a substantially instantaneous impedance-responsive relay-element of a balanced-plunger type having a non-magnetic intermediately pivoted beam, a magnetizable armature depending from each end thereof, a voltage coil and a current coil embracing the respective armatures and provided with magnetizable cores, said armatures and cores being of a material having low remanence and a high maximum permeability at low flux densities, means for varying the number of turns on said current coil, and means for axially adjusting the core of said current coil; a substantially instantaneous directional relay-element of a galvanometer type comprising two alternating-current windings the direction of whose currents is to be compared, one of said windings being wound as the primary winding of a magnetic-core transformer the secondary winding of which consists of a single loop loosely embracing one leg of the core, the other of said windings being wound as the stator of a galvanometer having two air gaps across which its flux is passed, two substantially parallel sides of said loop lying transversely across said flux in said air gaps, and means for pivotally supporting said loop on an axis substantially parallel to, and substantially midway between, the substantially parallel loop portions lying in said air gaps; an electric time-switch relay-element comprising a two-pole single-phase stator member having split pole pieces and dephasing coils, an axially and rotatably movable motor-armature associated therewith, a declutchable reduction gear driven by said motor-armature when said stator member is energized, and disengaged therefrom by axial movement of the motor-armature as soon as the stator member is deenergized and while the motor-armature is still revolving, and a switch contact device, yieldably restrained by a reset element, driven by said reduction gear when the latter is clutched to the motor-armature and connecting means whereby said directional relay-element, in one position thereof, renders said instantaneous impedance-responsive relay-element and said time-switch relay-element ineffective.

8. A relay comprising a substantially instantaneous fault-responsive relay-element and a substantially instantaneous directional element associated therewith for rendering the same ineffective except when the current is flowing in a predetermined direction, said directional element being of a galvanometer type characterized by two alternating-current windings the direction of whose currents is to be compared, one of said windings being wound as the primary winding of a magnetic-core transformer the secondary wind-

ing of which consists of a single loop loosely embracing one leg of the core, the other of said windings being wound as the stator of a galvanometer having two pole pieces, two sides of said loop being spaced from the respective pole pieces in operative relation thereto, means for pivotally mounting said loop so that said loop-sides may move laterally across said pole pieces, a pair of cooperating switch contact members at least one of which is biased toward a predetermined position with respect to the other cooperating contact member, and means on said loop for striking said biased contact member and displacing the same from its predetermined biased position.

9. The combination with an electric power line having a circuit breaker, of a protective relay for controlling the operation of said circuit breaker, said relay comprising a first fault-responsive element operating substantially instantaneously in response to near-by faults, a second fault-responsive element responding to similar faults even though they are located somewhat farther away from the relay, a time-switch element set in operation by said second fault-responsive element, and means for operating the circuit breaker in response to either said first fault-responsive element or said time-switch element; said time switch element completing its operation in a time slightly longer than is necessary for the circuit breaker to interrupt the line-current for any faults responded to by said first fault-responsive element; said time-switch element comprising a self-starting electric motor having an axially and rotatably movable armature biased to an axial position not in exact alinement with the field member when the motor is energized but drawn axially by the magnetic attraction of the field member when the motor is energized, a declutchable reduction gear driven by said armature when the motor is energized, and disengaged therefrom by axial movement of the armature as soon as the motor is deenergized and while the armature is still revolving, and a switch contact device, yieldably restrained by a reset element, driven by said reduction gear when the latter is clutched to the armature.

10. A sectionalized three-phase electric power line comprising a plurality of line-sections in series, each line-section having, at each end, a circuit breaker and three high-speed single-phase impedance-responsive relays for controlling the operation of said circuit breaker upon the occurrence of three-phase faults, double line-to-ground faults or line-to-line faults across any one of the three respective delta phases of the line, each of said relays comprising, in general, a substantially instantaneously operating impedance-responsive relay-element having a balance point at approximately 75% of the section length for a line-to-line fault and a second impedance-responsive delayed-action device having a balance point about midway in the next line-section for a line-to-line fault.

11. The invention as defined in claim 10, characterized by means for supplying the relays from a three-phase current-transformer source from which the zero-phase sequence current-component has been substantially filtered out.

12. A high-speed impedance-responsive relay comprising fault-current terminals and voltage terminals, at least two impedance relay-elements each having oppositely pulling current and voltage coils, a substantially instantaneously operating directional element having two pairs of contacts, an electric-motor-actuated time-switch having at least one pair of contacts, a current transformer for energizing said time-switch motor from the fault current, one pair of contacts of said directional element short-circuiting said current transformer except when current is flowing in a predetermined direction, one of the impedance relay-elements having normally closed contacts normally short-circuiting said time-switch motor, the other impedance relay-element being substantially instantaneously operating and having normally open contacts, said last mentioned contacts being connected in series with a second pair of directional-element contacts which are open except when current is flowing in the aforesaid predetermined direction.

13. The invention as specified in claim 3, characterized by an electromagnetic contactor switch operative, whenever the circuit breaker is actuated by a closure of relay contacts, to short-circuit said relay contacts, and an auxiliary switch on said circuit breaker for interrupting the actuating current thereof when the circuit breaker is at least partially open.

14. The combination, with a three-phase transmission line, of a relay comprising; an impedance-responsive element having a current coil energized from, and in accordance with the phase and magnitude of, the current in one of the line-conductors, and a voltage coil energized from, and in accordance with the phase and magnitude of, the delta line voltage which leads said current by 30° when the line is operating at unity power-factor; and a directional element having a current coil in series with the impedance-element current coil, and a voltage coil energized from, and in accordance with the phase and magnitude of, the delta line voltage which lags 30° behind said current when the line is operating at unity power factor.

15. A relay for a three-phase transmission line, characterized by an impedance element having a current coil energized from, and in accordance with the phase and magnitude of, the current in one of the line-conductors, and a voltage coil energized from, and in accordance with the phase and magnitude of, the delta line voltage which leads said current by 30° when the line is operating at unity power factor.

16. A relay for a three-phase transmission line, characterized by a directional element having a current coil energized in response to a current-transforming device connected in the line, a reference coil the voltage of which is to be compared with the phase of said current, and means for supplying said reference coil with a reference voltage which does not vary materially in phase during the fault-clearing period and which has a phase intermediate between the unity-power-factor phase of the current in said current coil and the phase of said current during fault conditions on the line.

17. The combination, with a three-phase transmission line, of a relay comprising; an impedance-responsive element having a current coil, means for causing said current coil to be energized from a current-transforming device connected in the line, a voltage coil, and means for causing said voltage coil to be energized from, and in accordance with the phase and magnitude of, a derived line voltage which leads the current in said current coil when the line is operating at unity power-factor; and a directional element adapted to control the effectiveness of the other elements, said directional element having

a current coil, means for causing said last-mentioned current coil to be energized from a current-transforming device connected in the line, a voltage coil, and means for causing said last-mentioned voltage coil to be energized from, and in accordance with the phase and magnitude of, a derived line voltage which lags behind the current in said directional-element current coil when the line is operating at unity power factor.

18. A relay for a three-phase transmission line, characterized by an impedance element having a current coil energized from a current-source derived from the line, and a voltage coil energized from, and in accordance with the phase and magnitude of, a derived line voltage which leads the current in said current coil when the line is operating at unity power factor.

19. The combination with an electric power line having a circuit breaker, of a protective relay for controlling the operation of said circuit breaker, said relay comprising a first fault-responsive element operating substantially instantaneously in response to near-by faults, a second fault-responsive element responding to similar faults even though they are located somewhat farther away from the relay, a time-switch element set in operation by said second fault-responsive element, and means for operating the circuit breaker in response to either said first fault-responsive element or said time-switch element; said time-switch element completing its operation in a time slightly longer than is necessary for the circuit breaker to interrupt the line-current for any faults responded to by said first fault-responsive element; said time switch-element comprising a self-starting electric motor of substantially constant speed, a normally disengaged switch member, means responsive to the energization and deenergization of the motor for mechanically engaging and disengaging said switch member to and from driving connection with the motor, respectively, and re-set means for yieldingly biasing said switch member to its initial position.

20. A relaying system comprising at least one of each of the following elements; a substantially instantaneous impedance-responsive relay-element of a balanced-plunger type having a non-magnetic intermediately pivoted beam, a magnetizable armature depending from each end thereof, a voltage coil and a current coil embracing the respective armatures and provided with magnetizable cores, said armatures and cores being of a material having low remanence and a high maximum permeability at low flux densities, means for varying the number of turns on said current coil, and means for axially adjusting the core of said current coil; a substantially instantaneous directional relay-element of a galvanometer type comprising two alternating-current windings the direction of whose currents is to be compared, one of said windings being wound as the primary winding of a magnetic-core transformer the secondary winding of which consists of a single loop loosely embracing one leg of the core, the other of said windings being wound as the stator of a galvanometer having two air gaps across which its flux is passed, two substantially parallel sides of said loop lying transversely across said flux in said air gaps, and means for pivotally supporting said loop on an axis substantially parallel to, and substantially midway between, the substantially parallel loop portions lying in said air gaps; and an electric time-switch relay-element comprising a self-starting electric motor of substantially constant speed, a normally disengaged switch member, means responsive to the energization and deenergization of the motor for mechanically engaging and disengaging said switch member to and from driving connection with the motor, respectively, and re-set means for yieldingly biasing said switch member to its initial position.

21. A relay comprising fault-current terminals and voltage terminals, two substantially instantaneous electro-responsive elements responding to different ratios of relay-voltage to relay-current, a time-switch element set in operation by the electro-responsive element which responds to the highest ratio of relay-voltage to relay-current, and a substantially instantaneous directional element for rendering the other elements ineffective at all times except when the fault current is flowing in a predetermined direction.

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