3 CURRENT, VOLTAGE, DIRECTIONAL, CURRENT (OR VOLTAGE)-BALANCE, AND DIFFERENTIAL RELAYS

Chapter 2 described the operating principles and characteristics of the basic relay elements. All protective-relay types are derived either directly from these basic elements, by combining two or more of these elements in the same enclosing case or in the same circuit with certain electrical interconnections, or by directly adding the torques of two or more such elements to control a single set of contacts. Various external connections and auxiliary equipments are employed that may tend to obscure the true identity of the elements and make the equipment appear complicated. However, if one will examine the equipment, he will invariably recognize the basic elements.

GENERAL PROTECTIVE-RELAY FEATURES

Certain features and capabilities apply generally to all types of protective relays. These will be discussed briefly before we consider the various types of relays.

CONTINUOUS AND SHORT-TIME RATINGS

All relays carry current- and/or voltage-coil ratings as a guide to their proper application. For relays complying with present standards, the continuous rating specifies what a relay will withstand under continuous operation in an ambient temperature of 40° C. Relays having current coils also carry a 1-second current rating, since such relays are usually subjected to momentary overcurrents. Such relays should not be subjected to currents in excess of the 1-second rating without the manufacturer's approval because either thermal or mechanical damage may result. Overcurrents lower than the 1-second-rating value are permissible for longer than 1 second, so long as the I^2t value of the 1-second rating is not exceeded. For example, if a relay will withstand 100 amperes for 1 second, it will withstand $100\sqrt{1/2}$ amperes for 2 seconds. It is not always safe to assume that a relay will withstand any current that it can get from current transformers for as long as it takes a circuit breaker to interrupt a short circuit after the relay has operated to trip the circuit breaker. Also, should a relay fail to succeed in tripping a circuit breaker, thermal damage should be expected unless back-up relays can stop the flow of short-circuit current soon enough to prevent such damage.

CONTACT RATINGS

Protective-relay contacts are rated on their ability to close and to open inductive or non-inductive circuits at specified magnitudes of circuit current and a-c or d-c circuit voltage. As stated in Chapter 2, protective relays that trip circuit breakers are not permitted to

interrupt the flow of trip-coil current, and hence they require only a circuit-closing and momentary current-carrying rating. If a breaker fails to trip, the contacts of the relay will almost certainly be damaged. The circuit-opening rating is applicable only when a protective relay controls the operation of another relay, such as a timing relay or an auxiliary relay; in such a case, the protective relay should not have a holding coil or else it may not be able to open its contacts once they have closed. If a seal-in relay is used, the current taken by the controlled relay must be less than the pickup of the seal-in relay.

When a relay of the "over and-under" type with *"a"* and *"b"* contacts is used to control the operation of some other sevice, the relay can be relieved of any circuit breaking duty by the arrangement of Fig. 1. When the protective relay picks up, it causes an auxiliary relay to pick up and seal itself in around the protective-relay contacts. Other auxiliary-relay contacts may be used, as shown, for control purposes, thereby relieving the protective-relay contacts of this duty. When the protective relay resets, it shorts the auxiliary-relay coil, thereby causing the auxiliary relay to reset.
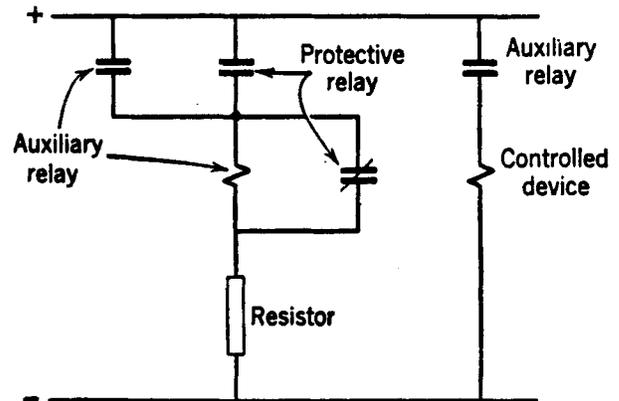

Fig. 1. Control circuit for relay of the "over-and-under" type.

HOLDING-COIL OR SEAL-IN-RELAY AND TARGET RATINGS

Two different current ratings are generally available either in the same relay or in different relays. The higher current rating is for use when the protective relay trips a circuit breaker directly, and the lower current rating is for use when the relay trips a circuit breaker indirectly through an auxiliary relay. In either event, one should be sure that the rating is low enough so that reliable seal-in and target operation will be obtained should two or more protective relays close contacts together, thereby dividing the total available trip-circuit current between the parallel protective-relay-contact circuits. Also, depending on the tripping speed of the breaker, the trip-circuit current may not have time to build up to its steady-state value. The resistances of the seal-in and target coils are given to permit one to calculate the trip-circuit currents.

BURDENS

The impedance of relay-actuating coils must be known to permit one to determine if the relay's voltage- or current-transformer sources will have sufficient capacity and suitable accuracy to supply the relay load together with any other loads that may be imposed on the transformers. These relay impedances are listed in relay publications. This subject will be treated further when we examine the characteristics of voltage and current transformers.

OVERCURRENT, UNDERCURRENT, OVERVOLTAGE, AND UNDERVOLTAGE RELAYS

Overcurrent, undercurrent, overvoltage, and undervoltage relays are derived directly from the basic single-quantity electromagnetic-attraction or induction types described in Chapter 2. The prefix "over" means that the relay picks up to close a set of *"a"* contacts when the actuating quantity exceeds the magnitude for which the relay is adjusted to operate. Similarly, the prefix "under" means that the relay resets to close a set of *"b"* contacts when the actuating quantity decreases below the reset magnitude for which the relay is adjusted to operate. Some relays have both *"b"* and *"a"* contacts, and the prefix before the actuating quantity in their name is "over-and-under." In protective-relay terminology, a "current" relay is one whose actuating source is a current in a circuit supplied to the relay either directly or from a current transformer. A "voltage" relay is one whose actuating source is a voltage of the circuit obtained either directly or from a voltage transformer.

Because all these relays are derived directly from the single quantity types described in Chapter 2, there is no need to consider further their principle of operation.

ADJUSTMENT

Pickup or Reset. Most overcurrent relays have a range of adjustment to make them adaptable to as wide a range of application circumstances as possible. The range of adjustment is limited, however, because of coil-space limitations and to simplify the relay construction. Hence, various relays are available, each having a different range of adjustment. The adjustment of plunger or attracted-armature relays may be by adjustment of the initial air gap, adjustment of restraining-spring tension, adjustable weights, or coil taps. The adjustment of current-actuated induction relays is generally by coil taps, and that of voltage-actuated relays by taps on series resistors or by auxiliary autotransformer taps.

Voltage relays and undercurrent relays do not generally have as wide a range of adjustment because they are expected to operate within a limited range from the normal magnitude of the actuating quantity. The normal magnitude does not vary widely because relay ratings are usually chosen with respect to the ratios of current and voltage transformers so that the relay current is normally slightly less than rated relay current and the relay voltage is approximately rated relay voltage, regardless of the application.

Time. Except for the "over-and-under" types, the operating time of inverse-time induction relays is usually adjustable by choosing the amount of travel of the rotor from its reset position to its pickup position. It is accomplished by adjustment of the position of the reset stop. A so-called "time lever" or "time dial" with an evenly divided scale provides this adjustment.

The slight increase in restraining torque of the control spring, as the reset stop is advanced toward the pickup position, is compensated for by the shape of the disc. A disc whose periphery is in the form of a spiral, or a disc having a fixed radius but with peripheral slots, the bottoms of which are on a spiral, provides this compensation by varying the active area of the disc between the poles. Similarly, holes of different diameter may be used. As the disc turns toward the pickup position when the reset stop is advanced, or whenever the relay

operates to pick up, the increase in the amount of the disc area between the poles of the actuating structure causes an increase in the electrical torque that just balances the increase in the control-spring torque.

When a bellows is used for producing time delay, adjustment is made by varying the size of an orifice through which the air escapes from the bellows.

TIME CHARACTERISTICS

A typical time curve for a high-speed relay is shown in Fig. 2. It will be noted that this is an inverse curve, but that a 3-cycle (60-cycle-per-second basis) operating time is achieved only slightly above the pickup value, which permits the relay to be called "high speed."

Figure 3 shows a family of inverse-time curves of one widely used induction-type relay. A curve is shown for each major division of the adjustment scale. Any intermediate curves can be obtained by interpolation since the adjustment is continuous.
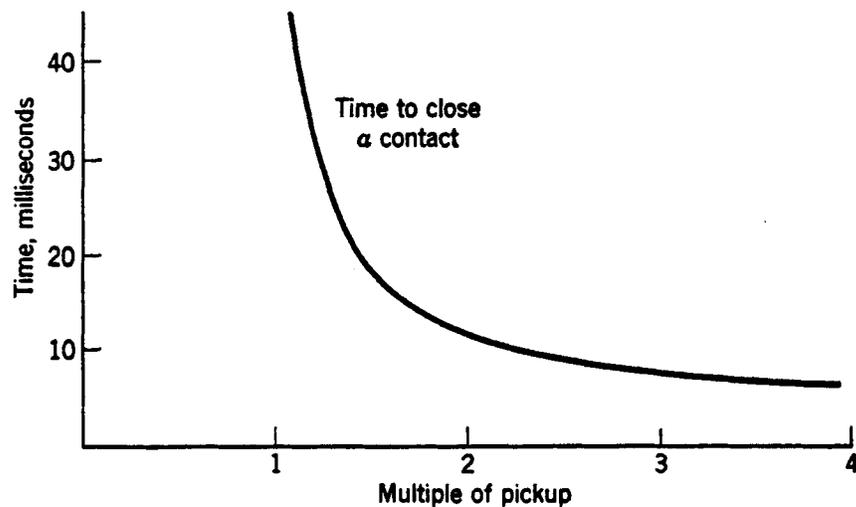

Fig. 2. Time curve of a high-speed relay.

It will be noted that both Fig. 2 and Fig. 3 are plotted in terms of multiples of the pickup value, so that the same curves can be used for any value of pickup. This is possible with induction-type relays where the pickup adjustment is by coil taps, because the ampere-turns at pickup are the same for each tap. Therefore, at a given multiple of pickup, the coil ampere-turns, and hence the torque, are the same regardless of the tap used. Where air-gap or restraining pickup adjustment is used, the shape of the time curve varies with the pickup.

One should not rely on the operation of any relay when the magnitude of the actuating quantity is only slightly above pickup, because the net actuating force is so low that any additional friction may prevent operation, or may increase the operating time. Even though the relay closes its contacts, the contact pressure may be so low that contamination of the contact surface may prevent electrical contact. This is particularly true in inverse-time relays where there may not be much impact when the contacts close. It is the practice to apply relays in such a way that, when their operation must be reliable, their actuating quantity will be at least 1.5 times pickup. For this reason, some time curves are not shown for less than 1.5 times pickup.
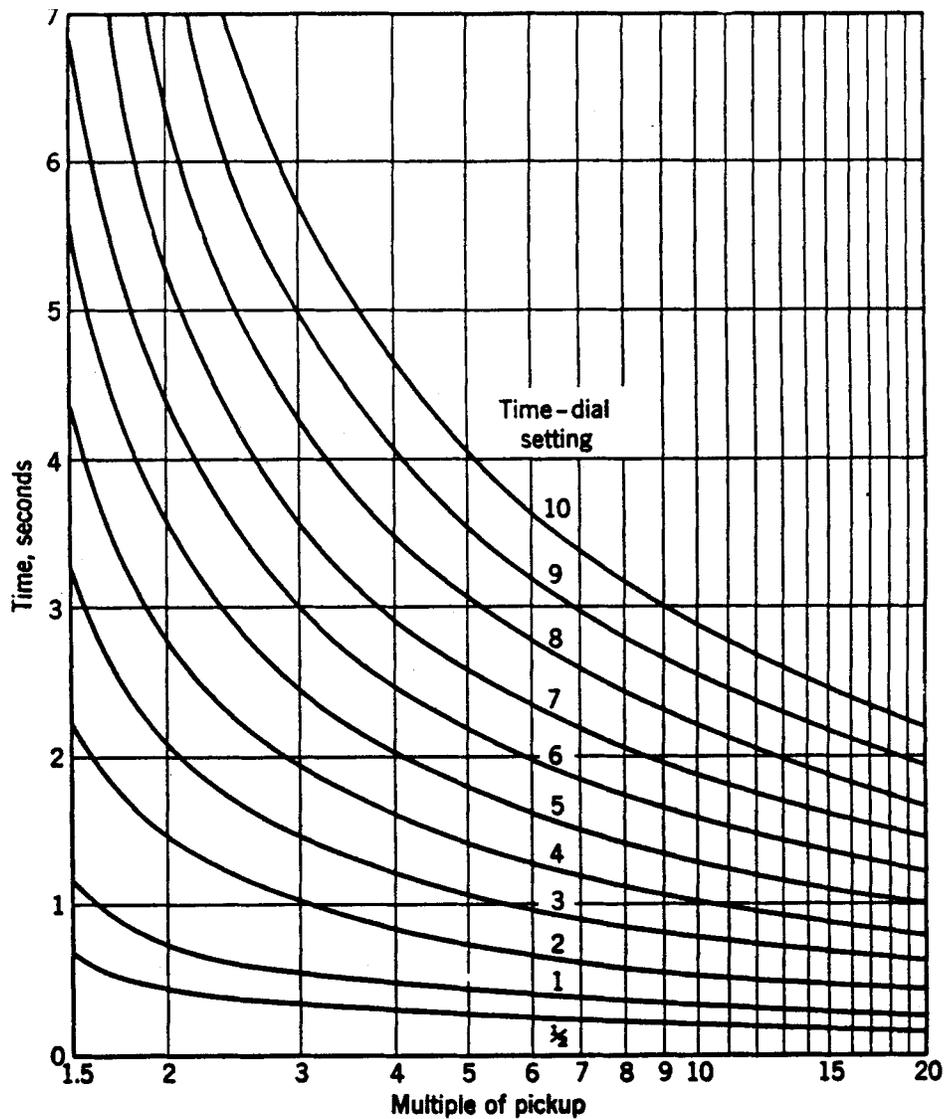
Fig. 3. Inverse-time curves.

The time curves of Fig. 3 can be used to estimate not only how long it will take the relay to close its contacts at a given multiple of pickup and for any time adjustment but also how far the relay disc will travel toward the contact-closed position within any time interval. For example, assume that the No. 5 time-dial adjustment is used, and that the multiple of pickup is 3. It will take the relay 2.45 seconds to close its contacts. We see that in 1.45 seconds, the relay would close its contacts if the No. 3 time-dial adjustment were used. In other words, in 1.45 seconds, the disc travels a distance corresponding to 3.0 time-dial divisions, or three-fifths of the total distance to close the contacts.

This method of analysis is useful to estimate whether a relay will pick up, and, if so, what its time delay will be when the magnitude of the actuating quantity is changing as, for example, during the current-in rush period when a motor is starting. The curve of the rms magnitude of current versus time can be studied for short successive time intervals, and the disc travel during each interval can be found for the average current magnitude during that interval. For each successive interval, the disc should be assumed to start from the position that it had reached at the end of the preceding interval.

For the most effective use of an inverse-time relay, its pickup should be chosen so that the relay will be operating on the most inverse part of its time curve over the range of magnitude of the actuating quantity for which the relay must operate. In other words, the minimum value of the actuating quantity for which the relay must operate should be at least 1.5 times pickup, but not too much more. This will become more evident when we consider the application of these relays.

The time curves illustrated in manufacturers' publications are average curves, and the time characteristics of individual relays vary slightly from the published curves. Ordinarily, this variation will be negligible, but, when the most accurate adjustment of a relay is required, it should be determined by test.

OVERTRAVEL

Owing to inertia of the moving parts, motion will continue when the actuating force is removed. This characteristic is called "overtravel." Although overtravel occurs in all relays, its effect is usually important only in time-delay relays, and particularly for inverse-time overcurrent relays, where selectivity is obtained on a time-delay basis. The basis for specifying overtravel is best described by an example, as follows. Suppose that, for a given adjustment and at a given multiple of pickup, a relay will pick up and close its contacts in 2.0 seconds. Now suppose that we make several tests by applying that same multiple of pickup for time intervals slightly less than 2.0 seconds, and we find that, if the time interval is any longer than 1.9 seconds, the relay will still close its contacts. We would say, then, that the overtravel is 0.1 second. The higher the multiple of pickup, the longer the overtravel time will be. However, a constant overtravel time ofapproximately 0.1 second is generally assumed in the application of inverse-time relays; the manner of its use will be described when we consider the application of these relays.

RESET TIME

For accurate data, the manufacturer should be consulted. The reset time will vary directly with the time-dial adjustment. The method of analysis described under "Time Characteristics" for estimating the amount of disc travel during short time intervals, combined with the knowledge of reset time, will enable one to estimate the operation of inverse-time relays during successive application and removal of the actuating quantity, as when a motor is "plugged," or when a circuit is tripped and then automatically reclosed on a fault several times, or during power surges accompanying loss of synchronism.

COMPENSATION FOR FREQUENCY OR TEMPERATURE CHANGES IN VOLTAGE RELAYS

A voltage relay may be provided with a resistor in series with its coil circuit to decrease changes in pickup by decreasing the effect of changes in coil resistance with heating. Such a resistor will also help to decrease the effect on the characteristics of change in frequency. A series capacitor may be used to obtain series resonance at normal frequency when operation on harmonics is to be avoided.

COMBINATION OF INSTANTANEOUS AND INVERSE-TIME RELAYS

Frequently, an instantaneous relay and an inverse-time relay are furnished in one enclosing case because the two functions are so often required together. The two relays are independently adjustable, but are actuated by the same quantity, and their "a" contacts may be connected in parallel.

D-C DIRECTIONAL RELAYS

Such relays are derived directly from the basic electromagnetic-attraction type described in Chapter 2. The various types and their capabilities are as follows.

CURRENT-DIRECTIONAL RELAYS

The current-directional relay is identical with the basic type described in Chapter 2. It is used for protection in d-c power circuits, its armature coil being connected either directly in series with the circuit or across a shunt in series with the circuit, so that the relay will respond to a certain direction of current flow. Such relays may be polarized either by a permanent magnet or by a field coil connected to be energized by the voltage of the circuit. A field coil would be used if the relay were calibrated to operate in terms of the magnitude of power (watts) in the circuit.

With adjustable calibration, the relay would also have overcurrent (or overpower) or undercurrent (or underpower) characteristics, or both, in addition to being directional.

VOLTAGE-DIRECTIONAL RELAYS

Voltage-directional relays are the same as current-directional relays except for the number of turns and the resistance of the armature coil, and possibly except for the polarizing source. Such relays are used in d-c power circuits to respond to a certain polarity of the voltage across the circuit or across some part of the circuit. If the relay is intended to respond to reversal of the circuit-voltage polarity, it is polarized by a permanent magnet, there being no other suitable polarizing source unless a storage battery is available for the purpose. Otherwise, either permanent-magnet polarization or a field coil energized from the circuit voltage would be used.

When such a relay is connected across a circuit breaker to permit closing the breaker only when the voltage across the open breaker has a certain polarity, the relay may be called a "differential" relay because it operates only in response to a predetermined difference between the magnitudes of the circuit voltages on either side of the breaker.

VOLTAGE-AND-CURRENT-DIRECTIONAL RELAYS

The voltage-and-current-directional relay has two armature coils. Such a relay, for example, controls the closing and opening of a circuit breaker in the circuit between a d-c generator and a bus to which another source of voltage may be connected, so as to avoid motoring of the generator. The voltage armature coil is connected across the breaker and picks up

the relay to permit closing the breaker only if the generator voltage is a certain amount greater than the bus voltage. The current armature coil is connected in series with the circuit, or across a shunt, and resets the relay to trip the breaker whenever a predetermined amount of current starts to flow from the bus into the generator.

VOLTAGE-BALANCE-DIRECTIONAL RELAYS

A relay with two voltage coils encircling the armature may be used to protect a three-wire d-c circuit against unbalanced voltages. The two coils are connected in such a way that their magnetomotive forces are in opposition. Such a relay has double-throw contacts and two restraining springs to provide calibration for movement of the armature in either direction. When one voltage exceeds the other by a predetermined amount, the armature will move one way to close one set of contacts; if the other voltage is the higher, the armature will close the other set of contacts.

Such a relay may also be used to respond to a difference in circuit-voltage magnitudes on either side of a circuit breaker, instead of the single-coil type previously described.

CURRENT-BALANCE-DIRECTIONAL RELAYS

A relay like a voltage-balance type except with two current coils encircling the armature may be used for current-balance protection of a three-wire d-c circuit, or to compare the loads of two different circuits.

DIRECTIONAL RELAYS FOR VACUUM-TUBE OR RECTIFIED A-C CIRCUITS

Both the single-coil and the two-coil types of voltage relays previously described have been used to respond to the output of vacuum-tube or rectifying circuits. Such relays are generally called "polarized" relays, the term "directional" having no significance since the actuating quantity is always of the same polarity; the directional type of relay is used only for its high sensitivity. A relay used for this purpose may be polarized by a permanent magnet or from a suitable d-c source such as a station battery.

Another sometimes-useful characteristic of a d-c directional relay actuated from a rectified a-c source is that the torque of the relay is proportional to the first power of the actuating quantity. Thus if two or more armature coils should be energized from different rectified a-c quantities, the relay torque would be proportional to the arithmetic sum (or difference, if desired) of the rms values of the a-c quantities, regardless of the phase angles between them. Such operation cannot be obtained with a-c relays.

POLARIZING MAGNET VERSUS FIELD COIL

Except where a permanent magnet is the only suitable polarizing source available, a field coil is generally preferred. It has already been said that a field coil is required if a relay is to respond to watts. A coil provides more flexibility of adjustment since series resistors can be used to vary the polarizing mmf. Also, it is necessary to remove polarization to permit some types of relays to reset after they have operated, and this requires a field coil.

SHUNTS

The rating of a shunt and the resistance of the leads from the shunt to a current-directional relay affect the calibration of the relay. It is customary to specify the rating of the shunt and the resistance of the leads necessary for a given range of calibration of the relay.

TIME DELAY

As mentioned in Chapter 2, d-c directional relays are inherently fast. For some applications, an auxiliary time-delay relay is necessary to prevent undesired operation on momentary reversals of the actuating quantity.

A-C DIRECTIONAL RELAYS

In Chapter 2, a-c directional relays were said to be able to distinguish between the flow of current in one direction or the other in an a-c circuit by recognizing differences in the phase angle between the current and the polarizing quantity. We shall see that the ability to distinguish between the flow of current in one direction or the other depends on the choice of the polarizing quantity and on the angle of maximum torque, and that all the variations in function provided by a-c directional relays depend on these two quantities. This will become evident on further examination of some typical types.

POWER RELAYS

Relays that must respond to power are generally used for protecting against conditions other than short circuits. Such relays are connected to be polarized by a voltage of a circuit, and the current connections and the relay characteristics are chosen so that maximum torque in the relay occurs when unity-power-factor load is carried by the circuit. The relay will then pick up for power flowing in one direction through the circuit and will reset for the opposite direction of power flow.

If a single-phase circuit is involved, a directional relay is used having maximum torque when the relay current is in phase with the relay voltage. The same relay can be used on a three-phase circuit if the load is sufficiently well balanced; in that event, the polarizing voltage must be in phase with the current in one of the three phases at unity-power-factor load. (For simplicity, the term "phase" will be used frequently where the term "phase conductor" would be more strictly correct.) Such an in-phase voltage will be available if phase voltage is available; otherwise, a connection like that inneutral voltage is' not available.
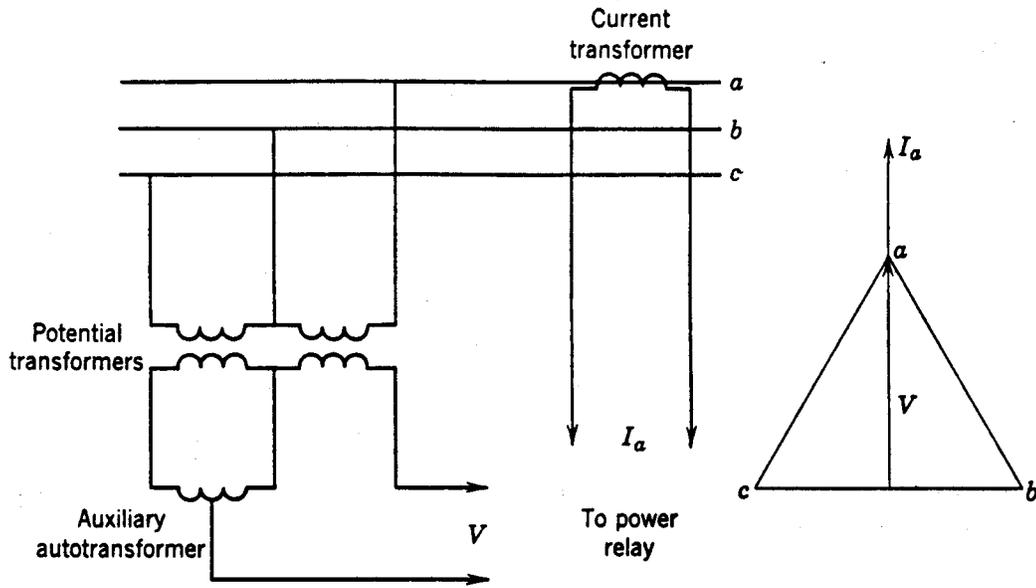
Fig. 4. Connections and vector diagram for a power relay where phase-to-neutral voltage is not available.

Fig. 4 will provide a suitable polarizing voltage. Or, a relay having maximum torque when its current leads its voltage by 30° can be connected to use V_{ac} and I_a, as in Fig. 5.
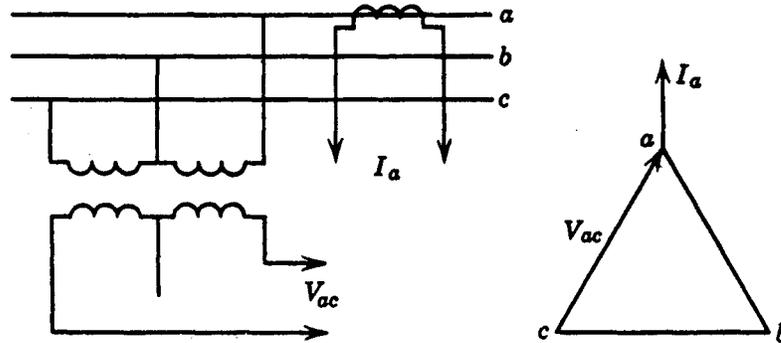

Fig. 5. Connections and vector diagram for a power relay wing phase-to-phase voltage.

The conventions and nomenclature used throughout this book in dealing with three-phase voltage and current vector diagrams is shown in Fig. 6. The voltages of Fig. 6 are defined as follows:

$$V_{ab} = V_a - V_b$$

$$V_{bc} = V_b - V_c$$

$$V_{ca} = V_c - V_a$$

From these definitions, it follows that:

$$V_{ba} = -V_{ab} = V_b - V_a$$

$$V_{cb} = -V_{bc} = V_c - V_b$$

$$V_{ac} = -V_{ca} = V_a - V_c$$

When the load of a three-phase circuit may be sufficiently unbalanced so that a single-phase relay will not suffice, or when a very low minimum pickup current is required, a polyphase relay is used, having, actually or in effect, three single-phase relay elements whose torques are added to control a single set of contacts. The actuating quantities of such a relay may be any of several combinations, the following being frequently used:
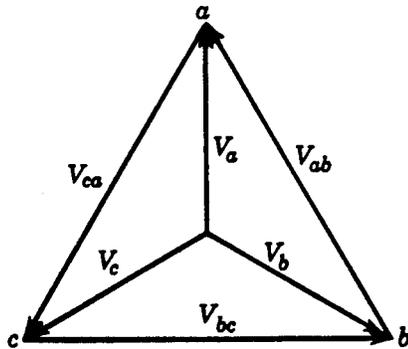

Fig. 6. Conventions and nomenclature for three-phase voltage vector diagrams.

Element No.	Voltage	Current
1	V_{ac}	I_a
2	V_{cb}	I_c
3	V_{ba}	I_b

However it may be accomplished, a power relay will distinguish between the flow of power in one direction or the other by developing positive (or pickup) torque for one direction, and negative (or reset) torque for the other. The unity-power-factor component of the current will reverse as the direction of power flow reverses, as illustrated in Fig. 7 for a relay connected as in Fig. 5.

Power relays are used generally for responding to a certain direction of current flow under approximately balanced three-phase conditions and for approximately normal voltage magnitudes. Consequently, any combination of voltage and current may be used so long as the relay has the necessary angle of maximum torque so that maximum torque will be developed for unity-power-factor current in the three-phase system. Power relays are
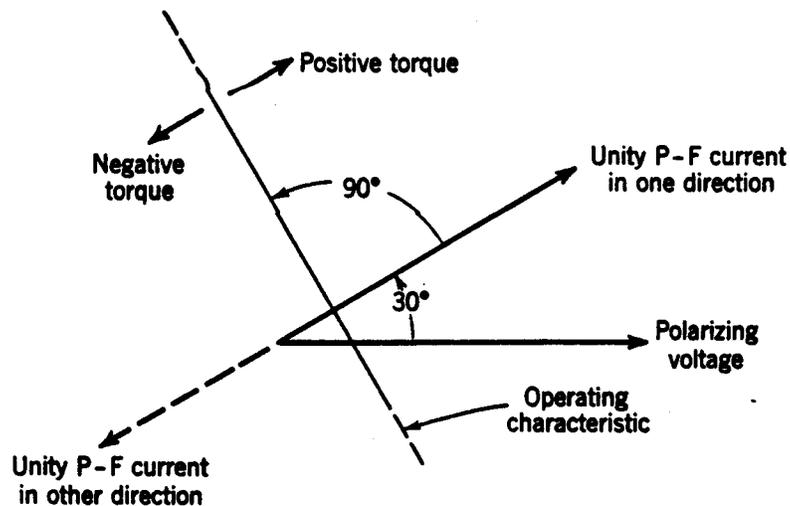

Fig. 7. A typical power-relay operating characteristic.

available having adjustable minimum pickup currents. They may.be calibrated either in terms of minimum pickup amperes at rated voltage or in terms of minimum pickup watts. Therefore, such relays may be adjusted to respond to any desired amount of power being supplied in a given direction. In effect, these relays are watthour meters with their dial mechanisms replaced by contacts, and having a control spring. Some power relays have actually been constructed directly from watthour-meter parts.

Power relays usually have time-delay characteristics to avoid undesired operation during momentary power reversals, such as generator synchronizing-power surges or power reversals when short circuits occur. This time delay may be an inherent inverse-time characteristic of the relay itself, or it may be provided by a separate time-delay relay.

DIRECTIONAL RELAYS FOR SHORT-CIRCUIT PROTECTION

Because short circuits involve currents that lag their unity-power-factor positions, usually by large angles, it is desirable that directional relays for short-circuit protection be arranged to develop maximum torque under such lagging-current conditions. The technique for obtaining any desired maximum-torque adjustment was described in Chapter 2. The problem is straightforward for a single-phase circuit. Exactly the same technique can be applied to three-phase circuits, but there are a number of possible solutions, and not all of them are good. The problem is somewhat different from that with power relays. With power relays, we are dealing with approximately balanced three-phase conditions, and where the polarizing voltage is maintained approximately at its normal value; any of the alternative ways of obtaining maximum torque at unity-power-factor-load current is equally acceptable from a functional standpoint. If three-phase short circuits were the only kind with which we had to contend, any of the many possible arrangements for obtaining maximum torque at a given angle would also be equally acceptable. But the choice of connections for obtaining correct directional discrimination for unbalanced short circuits (i.e., phase-to-phase, phase-to-ground, and two-phase-to-ground) is severely restricted.

Three conventional current-and-voltage combinations that are used for phase relays are illustrated by the vector diagrams of Fig. 8, in which the quantities shown are for one of three single-phase relays, or for one of the three elements of a polyphase relay. The other two relays or elements would use the other two corresponding voltage-and-current combinations. The names of these three combinations, as given in Fig. 8, will be recognized as describing the phase relation of the current-coil current to the polarizing voltage under balanced threephase unity-power-factor conditions.

The relations shown in Fig. 8 are for the relay or element that provides directional discrimination when short circuits occur involving phases a and b. Note that the voltage V_{ab} is not used by the relay or element on which dependence for protection is placed. For such a short circuit, one or both of the other two relays will also develop torque. It would be highly undesirable if one of these others should develop contact-closing torque when the conditions were such that it would cause unnecessary tripping of a circuit breaker. It is to avoid this possibility, and yet to assure operation when it is required, that the many possible alternative connections are narrowed down to the three shown. Even with these, there are circumstances when incorrect operation is sometimes possible unless additional steps are taken to avoid it; this whole subject will be treated further when we consider the application of such relays to the protection of lines. It will probably be evident, however, that, since in a polyphase relay the torques of the three elements are added, it is only necessary that the net torque be in the right direction to avoid undesired operation. The bibliography[1] gives reference material for further study of polyphase directional-relay connections and their effect on relay behavior, but it is a bit advanced, in view of our present status.
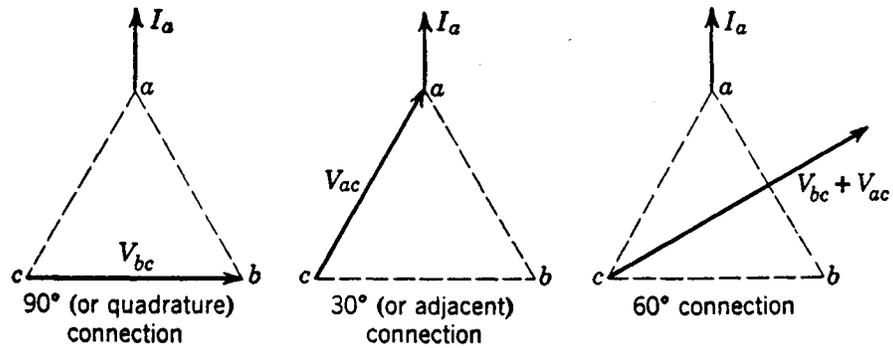
Fig. 8. Conventional connections of directional phase relays.

With directional relays for protection against short circuits involving ground, there is no problem similar to that just described for phase relays. As will be seen later, only a single-phase relay is necessary, and the connections are such that, no matter which phase is involved, the quantities affecting relay operation have the same phase relation. Moreover, a ground relay is unaffected by other than ground faults because, for such other faults, the actuating quantities are not present unless the CT's (current transformers) fail to transform their currents accurately.

Except for circuit arrangements for providing the desired maximum-torque relations, a directional relay for ground protection is essentially the same as a single-phase directional relay for phase-fault protection. Such relays are available with or without time delay, and for current or voltage polarization, or for polarization by both current and voltage simultaneously.

Directional relays for short-circuit protection are generally used to supplement other relays. The directional relays permit tripping only for a certain direction of current flow, and the other relays determine (1) if it is a short circuit that is causing the current to flow, and (2) if the short circuit is near enough so that the relays should trip their circuit breaker. Such directional relays have no intentional time delay, and their pickup is non-adjustable but low enough so that the directional relays will always operate when their associated relays must operate. Some directional relays combine the directional with the fault-detecting and locating function; then, the directional relay will have adjustable pickup and either instantaneous or inverse-time characteristics.

Some directional relays have adjustment of their maximum-torque angle to permit their use with various connections of voltage transformer sources, or to match their maximum-torque angle more accurately to the actual fault-current angle.

DIRECTIONAL-OVERCURRENT RELAYS

Directional-overcurrent relays are combinations of directional and overcurrent relay units in the same enclosing case. Any combination of directional relay, inverse-time overcurrent relay, and instantaneous overcurrent relay is available for phase- or ground-fault protection.

"Directional control" is a design feature that is highly desirable for this type of relay. With this feature, an overcurrent unit is inoperative, no matter how large the current may be, unless the contacts of the directional unit are closed. This is accomplished by connecting

the directional-unit contacts in series with the shading-coil circuit or with one of the two flux-producing circuits of the overcurrent unit. When this circuit is open, no operating torque is developed in the overcurrent unit. The contacts of the overcurrent unit alone are in the trip circuit.

Without directional control, the contacts of the directional and overcurrent units would merely be connected in series, and there would be a possibility of incorrect tripping under certain circumstances. For example, consider the situation when a very large current, flowing to a short circuit in the non-tripping direction, causes the overcurrent unit to pick up. Then, suppose that the tripping of some circuit breaker causes the direction of current flow to reverse. The directional unit would immediately pick up and undesired tripping would result; even if the overcurrent unit should have a tendency to reset, there would be a race between the closing of the directional-unit contacts and the opening of the overcurrent-unit contacts.

Separate directional and overcurrent units are generally preferred because they are easier to apply than directional relays with inherent time characteristics and adjustable pickup. The operating time with separate units is simply a function of the current in the overcurrent unit; the pickup and time delay of the directional unit are so small that they can be neglected. But the operating time of the directional relay is a function of the product of its actuating and polarizing quantities and of the phase angle between them. However, the relay composed of separate directional and overcurrent units is somewhat larger, and it imposes somewhat more burden on its current-transformer source.

CURRENT (OR VOLTAGE) - BALANCE RELAYS

Two basically different types of current-balance relay are used. Based on the production of actuating torque, one may be called the "overcurrent" type and the other the "directional" type.

OVERCURRENT TYPE

The overcurrent type of current-balance relay has one overcurrent element arranged to produce torque in opposition to another overcurrent element, both elements acting on the same moving structure. Figure 9 shows schematically an electromagnetic-attraction ""balanced-beam" type of structure. Another commonly used structure is an induction-type relay having two overcurrent elements acting in opposition on a rotor.

If we neglect the negative-torque effect of the control spring, the torque equation of either type is:

$$T = K_1 I_1^2 - K_2 I_2^2$$

When the relay is on the verge of operating, the net torque is zero, and:

$$K_1 I_1^2 = K_2 I_2^2$$

Therefore, the operating characteristic is

$$\frac{I_1}{I_2} = \sqrt{\frac{K_2}{K_1}} = \text{constant}$$
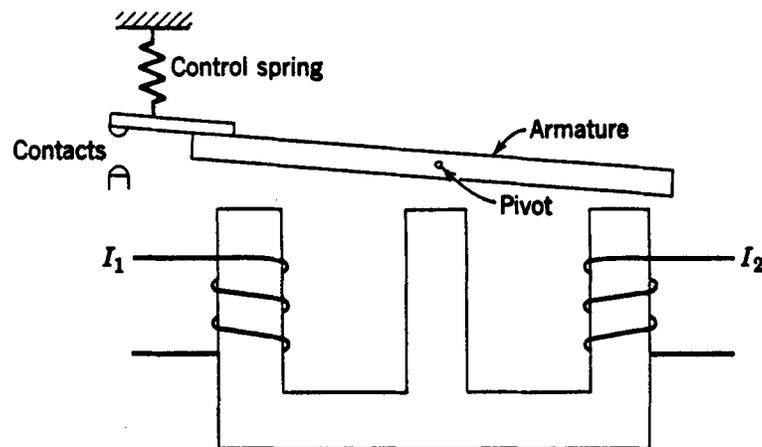
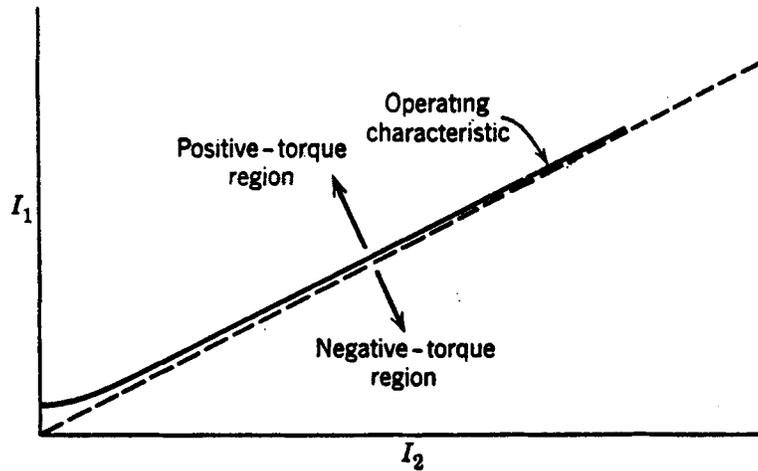**Fig. 9. A balanced-beam type of current-balance relay.**

Fig. 10. Operating characteristic of a current-balance relay.

The operating characteristic of such a relay, including the effect of the control spring, is shown in Fig. 10.

The effect of the control spring is to require a certain minimum value of I_1 for pickup when I_2 is zero, but the spring effect becomes less and less noticeable at the higher values of current. The relay will pick up for ratios of I_1 to I_2 represented by points above the operating characteristic.

Such an operating characteristic is specified by expressing in percent the ratio of I_1 to I_2 required for pickup when the relay is operating on the straight part of the characteristic, and by giving the minimum pickup value of I_1 when I_2 is zero. I_1 is called the "operating"
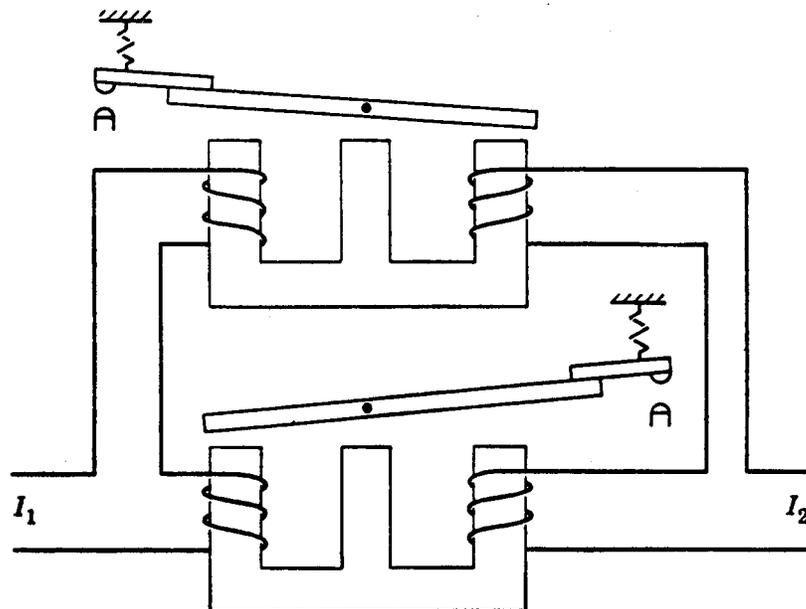
Fig. 11. A two-element current-balance relay

current since it produces positive,, or pickup, torque; I_2 is called the "restraining" current. By proportioning the number of turns on the operating and the restraining coils, one can obtain any desired "percent slope," as it is sometimes called.

Should it be desired to close an *"a"* contact circuit when either of two currents exceeds the other by a given percentage, two elements are used, as illustrated schematically in Fig. 11. For some applications, the contacts of the two elements may be arranged to trip different circuit breakers, depending on which element operates.

By these means, the currents in the different phases of a circuit, in different circuit branches of the same phase, or between corresponding phases of different circuits, can be compared. When applied between circuits where the ratio of one of the currents to the other never exceeds a certain amount except when a short circuit occurs in one of the circuits, a current-balance relay provides inherently selective protection.

Although the torque equations were written on the assumption that the phase angle between the two balanced quantities had no effect, the characteristics of such relays may be somewhat affected by the phase angle. In other words, the actual torque relation may be:

$$T = K_1 I_1{}^2 - K_2 I_2{}^2 + K_3 I_1 I_2 \cos (\theta - \tau)$$

where the effect of the control spring is neglected, and where θ and τ are defined as for directional relays. The constant K_3 is small, the production of directional torque by the interaction between the induced currents and stray fluxes of the two elements being incidental and often purposely minimized by design. With only rare exceptions, the directional effect can be neglected. It is mentioned here in passing merely for completeness of the theoretical considerations. It will not be mentioned again when other relays that balance one quantity against another are considered, but the effect is sometimes there nevertheless.
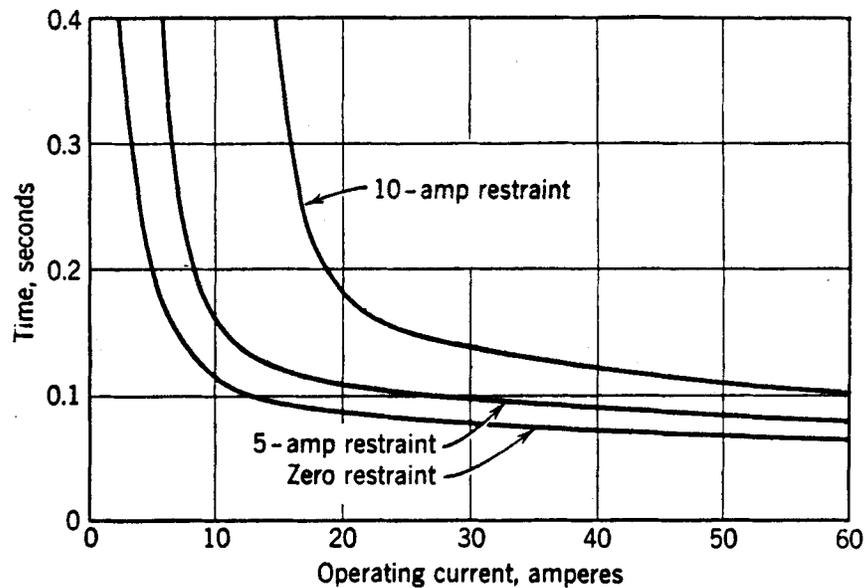

Fig. 12. Time-current curves of a current-balance relay.

It will be evident that the characteristics of a voltage-balance relay may be expressed as for the current-balance relay if we substitute V_1 and V_2 for I_1 and I_2. Also, whereas the current-balance relay operates when one current exceeds a normal value in comparison with the

other current, the voltage-balance relay is generally arranged to operate when one voltage drops below a normal value.

Relays are available having high-speed characteristics or inverse-time characteristics with or without an adjustable time dial. A typical set of time curves is shown in Fig. 12, where the effect of different values of restraining currents on the shape of the time curve is shown for one time adjustment. Such curves cannot be plotted on a multiple basis because the pickup is different for each value of restraining current. It will be noted that each curve is asymptotic to the pickup current for the given value of restraining current.

High-speed relays may operate undesirably on transient unbalances if the percent slope is too nearly 100% and for this reason such relays may require higher percent-slope characteristics than inverse-time relays.

DIRECTIONAL TYPE

The directional type of current-balance relay uses a current-current directional element in which the polarizing quantity is the vector difference of two currents, and the actuating quantity is the vector sum of the two currents. If we assume that the currents are in phase, and neglect the effect of the control spring, the torque is:

$$T = K_1 \ (I_1 + I_2) \ (I_1 - I_2)$$

where I_1 and I_2 are rms values. Therefore, when the two currents are in phase and are of equal magnitude, no operating torque is developed. When one current is larger than the other, torque is developed, its direction depending on which current is the larger. If the two currents are 180° out of phase, the direction of torque for a given unbalance will be the
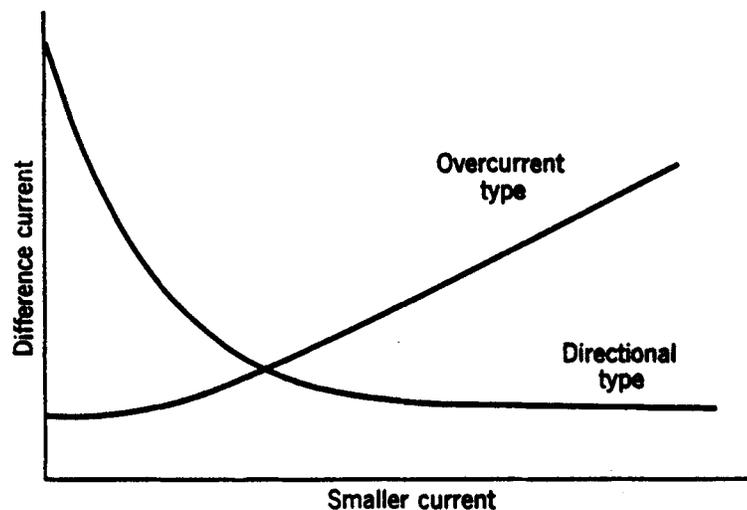

Fig. 13. Comparison of current-balance-relay characteristics.

same as when the currents are in phase, as can be seen by changing the sign of either current in the torque equation. This type of relay may have double-throw contacts both of which are normally open, the control spring being arranged to produce restraint against movement in either direction from the midposition.

This relay is not a current-balance relay in the same sense as the overcurrent type, as shown by a comparison of their operating characteristics in Fig. 13. The directional type is more sensitive to unbalance when the two currents are large, and is less sensitive when they are small. This is advantageous under one circumstance and disadvantageous under another. For parallel-line protection, which is the principal use of the directional type, auxiliary means are not required to prevent undesirable operation on load currents during switching; this is because the pickup is inherently higher when one line is out of service, at which time one of the two currents is zero. On the other hand, the directional type is more apt to operate undesirably on transient current-transformer unbalances when short circuits occur beyond the ends of the parallel lines; this is because the relay is more sensitive to current unbalance under high-current conditions when the errors of current transformers are apt to be greatest.

DIFFERENTIAL RELAYS

Differential relays take a variety of forms, depending on the equipment they protect. The definition of such a relay is "one that operates when the vector difference of two or more similar electrical quantities exceeds a predetermined amount."[2] It will be seen later that almost any type of relay, when connected in a certain way, can be made to operate as a differential relay. In other words, it is not so much the relay construction as the way the relay is connected in a circuit that makes it a differential relay.
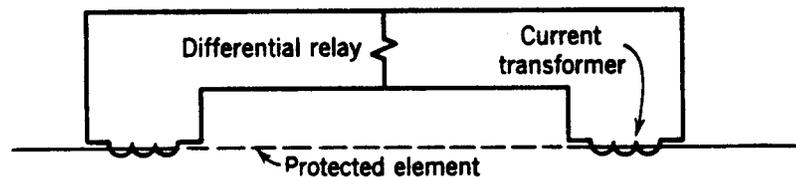

Fig. 14. A simple differential-relay application.

Most differential-relay applications are of the "current-differential" type. The simplest example of such an arrangement is shown in Fig. 14. The dashed portion of the circuit of Fig. 14 represents the system element that is protected by the differential relay. This system element might be a length of circuit, a winding of a generator, a portion of a bus, etc. A current transformer (CT) is shown in each connection to the system element. The secondaries of the CT's are interconnected, and the coil of an overcurrent relay is connected across the CT secondary circuit. This relay could be any of the a-c types that we have considered.

Now, suppose that current flows through the primary circuit either to a load or to a short circuit located at *X*. The conditions will be as in Fig. 15. If the two current transformers have the same ratio, and are properly connected, their secondary currents will merely circulate between the two CT's as shown by the arrows, and no current will flow through the differential relay.
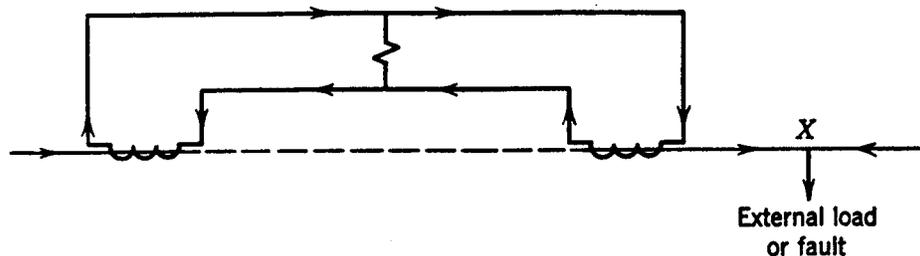

Fig. 15. Conditions for an external load or fault.

But, should a short circuit develop anywhere between the two CT's, the conditions of Fig. 16 will then exist. If current flows to the short circuit from both sides as shown, the sum of the CT secondary currents will flow through the differential relay. It is not necessary that short-circuit current flow to the fault from both sides to cause secondary current to flow through the differential relay. A flow on one side only, or even some current flowing out of one side while a larger current enters the other side, will cause a differential current. In other words, the differential-relay current will be proportional to the vector difference between the currents entering and leaving the protected circuit; and, if the differential current exceeds the relay's pickup value, the relay will operate.
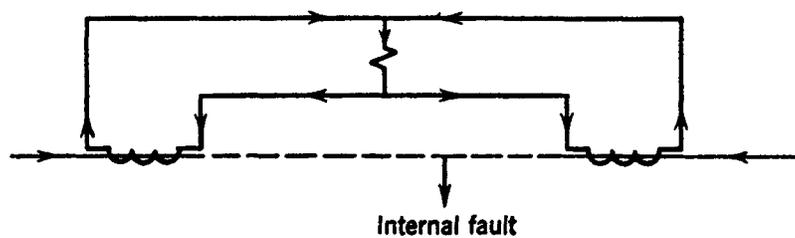

Fig. 16. Conditions for an internal fault.

It is a simple step to extend the principle to a system element having several connections. Consider Fig. 17, for example, in which three connections are involved. It is only necessary, as before, that all the CT's have the same ratio, and that they be connected so that the relay receives no current when the total current leaving the circuit element is equal vectorially to the total current entering the circuit element.

The principle can still be applied where a power transformer is involved, but, in this case, the ratios and connections of the CT's on opposite sides of the power transformer must be such as to compensate for the magnitude and phase-angle change between the power-transformer currents on either side. This subject will be treated in detail when we consider the subject of power-transformer protection.

A most extensively used form of differential relay is the "percentage-differential" type. This is essentially the same as the overcurrent type of current-balance relay that was described earlier, but it is connected in a differential circuit, as shown in Fig. 18. The differential current required to operate this relay is a variable quantity, owing to the effect of the restraining coil. The differential current in the operating coil is proportional to $I_1 - I_2$, and the

Fig. 17 A three-terminal current-differential application

equivalent current in the restraining coil is proportional to $(I_1 + I_2)/2$, since the operating coil is connected to the midpoint of the restraining coil; in other words, if we let N be the number of turns on the restraining coil, the total ampere-turns are $I_1N/2 + I_2N/2$, which is the same as if $(I_1 + I_2)/2$ were to flow through the whole coil. The operating characteristic of such a relay is shown in Fig. 19. Thus, except for the slight effect of the
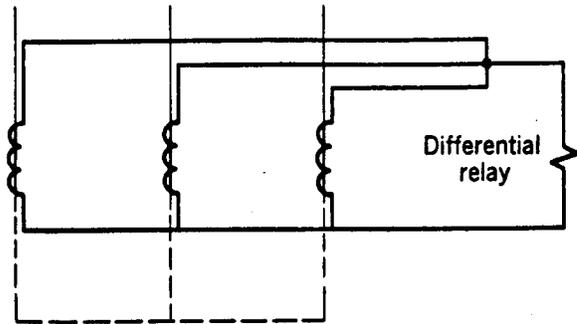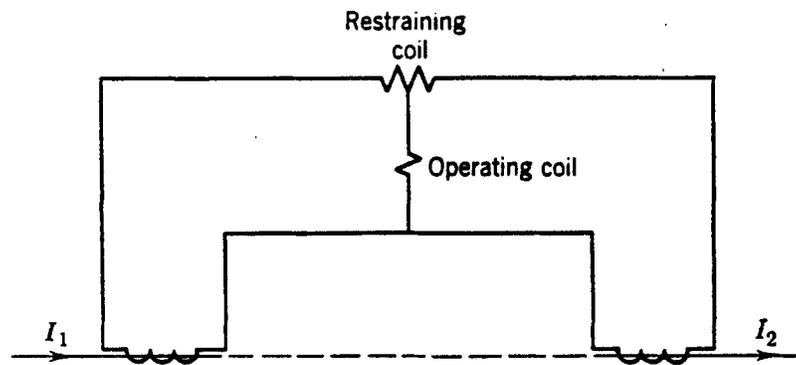

Fig. 18. A percentage-differential relay in a two-terminal circuit.

control spring at low currents, the ratio of the differential operating current to the average restraining current is a fixed percentage, which explains the name of this relay. The term "through" current is often used to designate I_2, which is the portion of the total current that flows through the circuit from one end to the other, and the operating characteristics may be plotted using I_2 instead of $(I_1 + I_2)/2$, to conform with the ASA definition for a percentage differential relay.[2]

The advantage of this relay is that it is less likely to operate incorrectly than a differentially connected overcurrent relay when a short circuit occurs external to the protected zone.
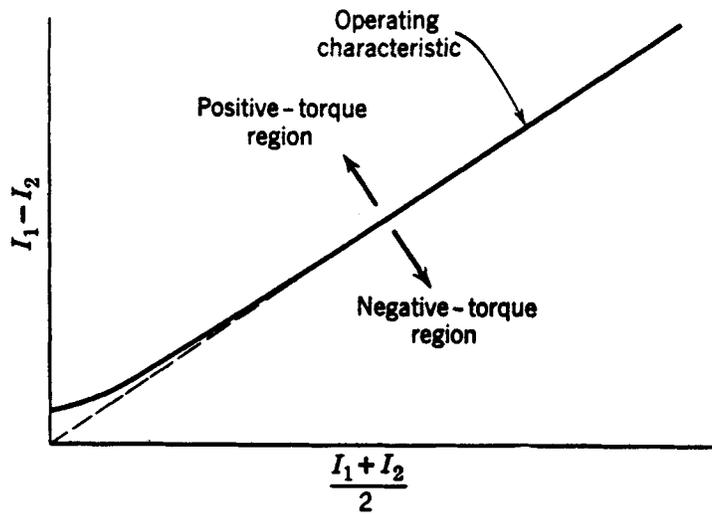
Fig. 19. Operating characteristic of a percentage-differential relay.

Current transformers of the types normally used do not transform their primary currents so accurately under transient conditions as for a short time after a short circuit occurs. This is particularly true when the shortcircuit current is offset. Under such conditions, supposedly identical current transformers may not have identical secondary currents, owing to slight differences in magnetic properties or to their having different amounts of residual magnetism, and the difference current may be greater, the larger the magnitude of short-circuit current. Even if the short-circuit current to an external fault is not offset, the CT secondary currents may differ owing to differences in the CT types or loadings, particularly in power-transformer protection. Since the percentage-differential relay has a rising pickup characteristic as the magnitude of through current increases, the relay is restrained against operating improperly.

Figure 20 shows the comparison of a simple overcurrent relay with a percentage-differential relay under such conditions. An overcurrent relay having the same minimum pickup as a percentage-differential relay would operate undesirably when the differential current barely exceeded the value X, whereas there would be no tendency for the percentage-differential relay to operate.
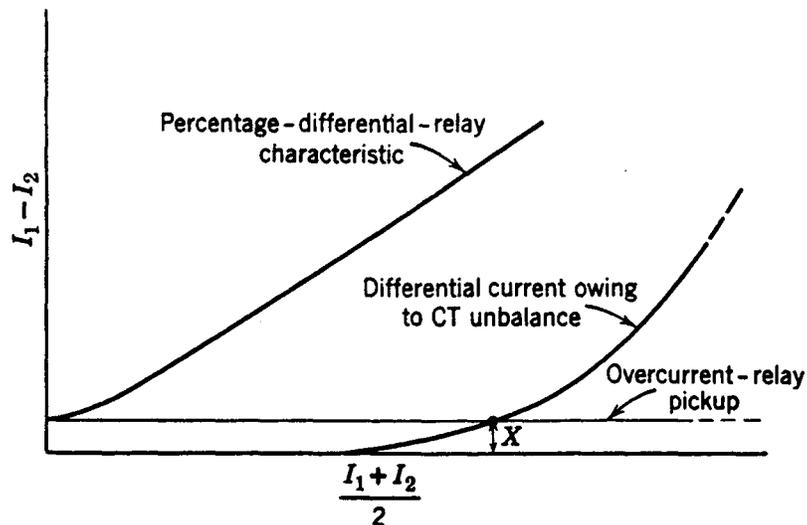

Fig. 20. Illustrating the value of the percentage-differential characteristic.

Percentage-differential relays can be applied to system elements having more than two terminals, as in the three-terminal application of Fig. 21. Each of the three restraining coils of Fig. 21 has the same number of turns, and each coil produces restraining torque independently of the others, and their torques are added arithmetically. The percent-slope characteristic for such a relay will vary with the distribution of currents between the three restraining coils.
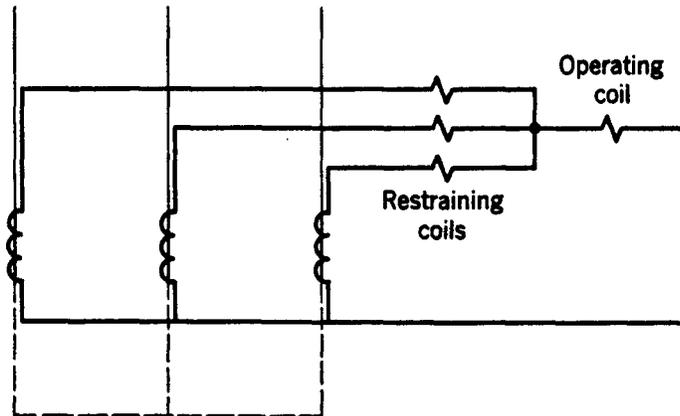

Fig. 21. Three-terminal application of a percentage-differential relay.

Percentage-differential relays are usually instantaneous or high speed. Time delay is not required for selectivity because the percentage-differential characteristic and other supplementary features to be described later make these relays virtually immune to the effects of transients when the relays are properly applied.

The adjustments provided with some percentage-differential relay will be described in connection with their application.

Several other types of differential-relay arrangements could be mentioned. One of these uses a directional relay. Another has additional restraint obtained from harmonics and the d-c component of the differential current. Another type uses an overvoltage relay instead of an overcurrent relay in the differential circuit. Special current transformers may be used having little or no iron in their magnetic circuit to avoid errors in transformation caused by the d-c component of offset current waves. All these types are extensions of the fundamental principles that have been described, and they will be treated later in connection with their specific applications.

There has been great activity in the development of the differential relay because this form of relay is inherently the most selective of all the conventional types. However, each kind of system element presents special problems that have thus far made it impossible to devise a differential-relaying equipment having universal application.

PROBLEMS

1. Given a polyphase directional relay, each element of which develops maximum torque when the current in its current coil leads the voltage across its voltage coil by 20°.

Assuming that the constant in the torque equation is l.0, and neglecting the spring torque, calculate the total torque for each of the three conventional connections for the following voltages and currents:

$$V_{bc} = 90 + j0$$

$$V_{ab} = -30 + j50$$

$$V_{ca} = -60 - j50$$

$$I_a = 25 + j7$$

$$I_b = -15 - j18$$

$$I_c = -2 + j10$$

2. Figure 22 shows a percentage-differential relay applied for the protection of a generator winding. The relay has a 0.l-ampere minimum pickup and a 10% slope (defined as in Fig. 19). A high-resistance ground fault has occurred as shown near the grounded-neutral end of the generator winding while the generator is carrying load. As a consequence, the currents in amperes flowing at each end of the generator winding have the magnitudes and directions as shown on Fig. 22.
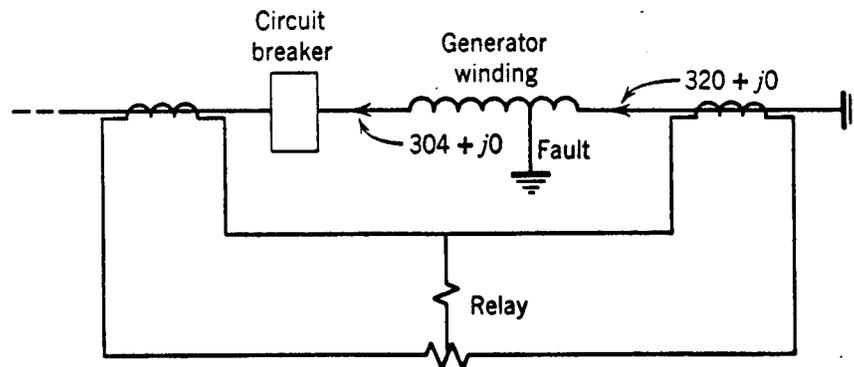

Fig. 22. Illustration for Problem 2.

Assuming that the CT's have a 400/5-ampere ratio and no inaccuracies, will the relay operate to trip the generator breaker under this condition? Would the relay operate at the given value of fault current if the generator were carrying no load with its breaker open? On the same diagram, show the relay operating characteristic and the points that represent the operating and restraining currents in the relay for the two conditions.

3. Given two circuits carrying a-c currents having rms values of I_1 and I_2, respectively. Show a relay arrangement that will pick up on a constant magnitude of the arithmetic (not vector) sum of I_1 and I_2.

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