2 FUNDAMENTAL RELAY-OPERATING PRINCIPLES AND CHARACTERISTICS

Protective relays are the "tools" of the protection engineer. As in any craft, an intimate knowledge of the characteristics and capabilities of the available tools is essential to their most effective use. Therefore, we shall spend some time learning about these tools without too much regard to their eventual use.

GENERAL CONSIDERATIONS

All the relays that we shall consider operate in response to one or more electrical quantities either to close or to open contacts. We shall not bother with the details of actual mechanical construction except where it may be necessary for a clear understanding of the operation. One of the things that tend to dismay the novice is the great variation in appearance and types of relays, but actually there are surprisingly few fundamental differences. Our attention will be directed to the response of the few basic types to the electrical quantities that actuate them.

OPERATING PRINCIPLES

There are really only two fundamentally different operating principles: (1) electromagnetic attraction, and (2) electromagnetic induction. Electromagnetic attraction relays operate by virtue of a plunger being drawn into a solenoid, or an armature being attracted to the poles of an electromagnet. Such relays may be actuated by d-c or by a-c quantities. Electromagnetic-induction relays use the principle of the induction motor whereby torque is developed by induction in a rotor; this operating principle applies only to relays actuated by alternating current, and in dealing with those relays we shall call them simply "induction-type" relays.

DEFINITIONS OF OPERATION

Mechanical movement of the operating mechanism is imparted to a contact structure to close or to open contacts. When we say that a relay "operates," we mean that it either closes or opens its contacts-whichever is the required action under the circumstances. Most relays have a "control spring," or are restrained by gravity, so that they assume a given position when completely de-energized; a contact that is closed under this condition is called a "closed" contact, and one that is open is called and "open" contact. This is standardized nomenclature, but it can be quite confusing and awkward to use. A much better nomenclature in rather extensive use is the designation *"a"* for an "open" contact, and *"b"* for a "closed" contact. This nomenclature will be used in this book. The present standard method for showing "a" and *"b"* contacts on connection diagrams is illustrated in Fig. 1. Even though an *"a"* contact may be closed under normal operating conditions, it should be shown open as in Fig. 1; and similarly, even though a *"b"* contact may normally be open, it should be shown closed.

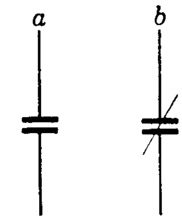

Fig. 1. Contact symbols and designations

When a relay operates to open a *"b"* contact or to close an *"a"* contact, we say that it "picks up," and the smallest value of the actuating quantity that will cause such operation, as the quantity is slowly increased from zero, is called the "pickup" value. When a relay operates to close a *"b"* contact, or to move to a stop in place of a *"b"* contact, we say that it "resets"; and the largest value of the actuating quantity at which this occurs, as the quantity is slowly decreased from above the pickup value, is called the "reset" value. When a relay operates to open its *"a"* contact, but does not reset, we say that it "drops out," and the largest value of the actuating quantity at which this occurs is called the "drop-out" value.

OPERATION INDICATORS

Generally, a protective relay is provided with an indicator that shows when the relay has operated to trip a circuit breaker. Such "operation indicators" or "targets" are distinctively colored elements that are actuated either mechanically by movement of the relay's operating mechanism, or electrically by the flow of contact current, and come into view when the relay operates. They are arranged to be reset manually after their indication has been noted, so as to be ready for the next operation. One type of indicator is shown in Fig. 2. Electrically operated targets are generally preferred because they give definite assurance that there was a current flow in the contact circuit. Mechanically operated targets may be used when the closing of a relay contact always completes the trip circuit where tripping is not dependent on the closing of some other series contact. A mechanical target may be used with a series circuit comprising contacts of other relays when it is

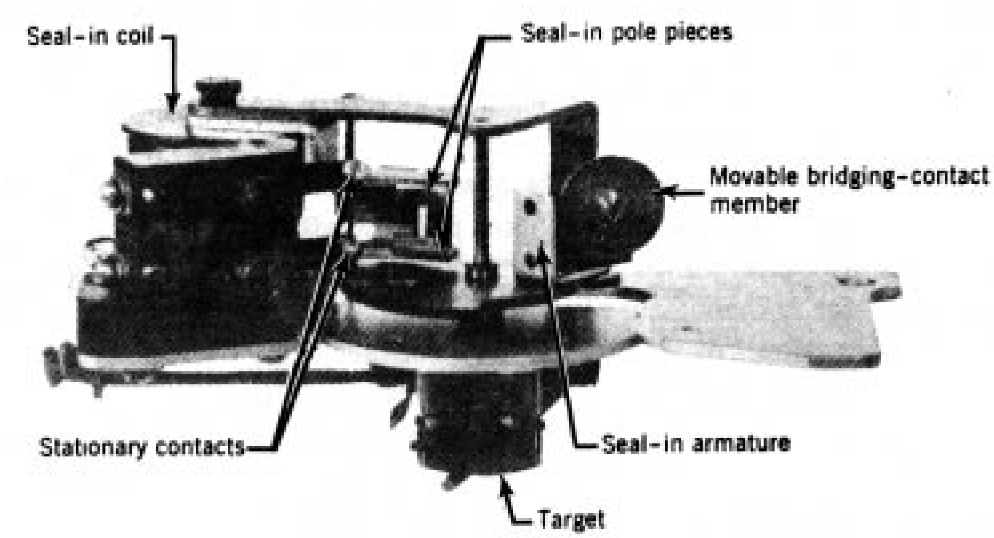

Fig. 2. One type of contact mechanism showing target and seal-in elements.

desired to have indication that a particular relay has operated, even though the circuit may not have been completed through the other contacts.

SEAL-IN AND HOLDING COILS, AND SEAL-IN RELAYS

In order to protect the contacts against damage resulting from a possible inadvertent attempt to interrupt the flow of the circuit tripcoil current, some relays are provided with a holding mechanism comprising a small coil in series with the contacts; this coil is on a small electromagnet that acts on a small armature on the moving contact assembly to hold the contacts tightly closed once they have established the flow of trip-coil current. This coil is called a "seal-in" or "holding" coil. Figure 2 shows such a structure. Other relays use a small auxiliary relay whose contacts by-pass the protective-relay contacts and seal the circuit closed while tripping current flows. This seal-in relay may also display the target. In either case, the circuit is arranged so that, once the trip-coil current starts to flow, it can be interrupted only by a circuit-breaker auxiliary switch that is connected in series with the trip-coil circuit and that opens when the breaker opens. This auxiliary switch is defined as an " *a* " contact. The circuits of both alternatives are shown in Fig. 3.

Figure 3 also shows the preferred polarity to which the circuit-breaker trip coil (or any other coil) should be connected to avoid corrosion because of electrolytic action. No coil should be connected only to positive polarity for long periods of time; and, since here the circuit breaker and its auxiliary switch will be closed normally while the protective-relay contacts will be open, the trip-coil end of the circuit should be at negative polarity.

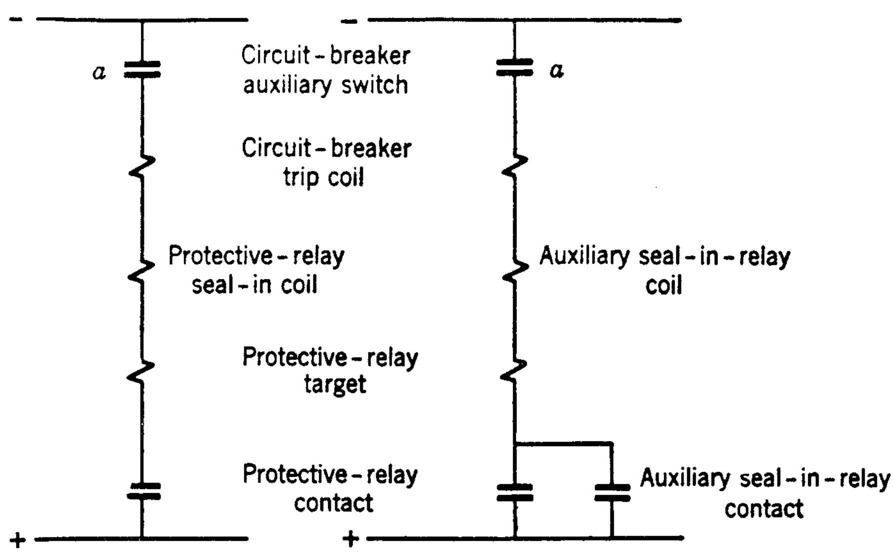

Fig. 3. Alternative contact seal-in methods.

ADJUSTMENT OF PICKUP OR RESET

Adjustment of pickup or reset is provided electrically by tapped current coils or by tapped auxiliary potential transformers or resistors; or adjustment is provided mechanically by adjustable spring tension or by varying the initial air gap of the operating element with respect to its solenoid or electromagnet.

Some relays have adjustable time delay, and others are "instantaneous" or "high speed." The term "instantaneous" means "having no intentional time delay" and is applied to relays that operate in a minimum time of approximately 0.1 second. The term "high speed" connotes operation in less than approximately 0.1 second and usually in 0.05 second or less. The operating time of high-speed relays is usually expressed in cycles based on the power-system frequency; for example, "one cycle" would be 1/60 second in a 60-cycle system. Originally, only the term "instantaneous" was used, but, as relay speed was increased, the term "high speed" was felt to be necessary in order to differentiate such relays from the earlier, slower types. This book will use the term "instantaneous" for general reference to either instantaneous or high-speed relays, reserving the term "high-speed" for use only when the terminology is significant.

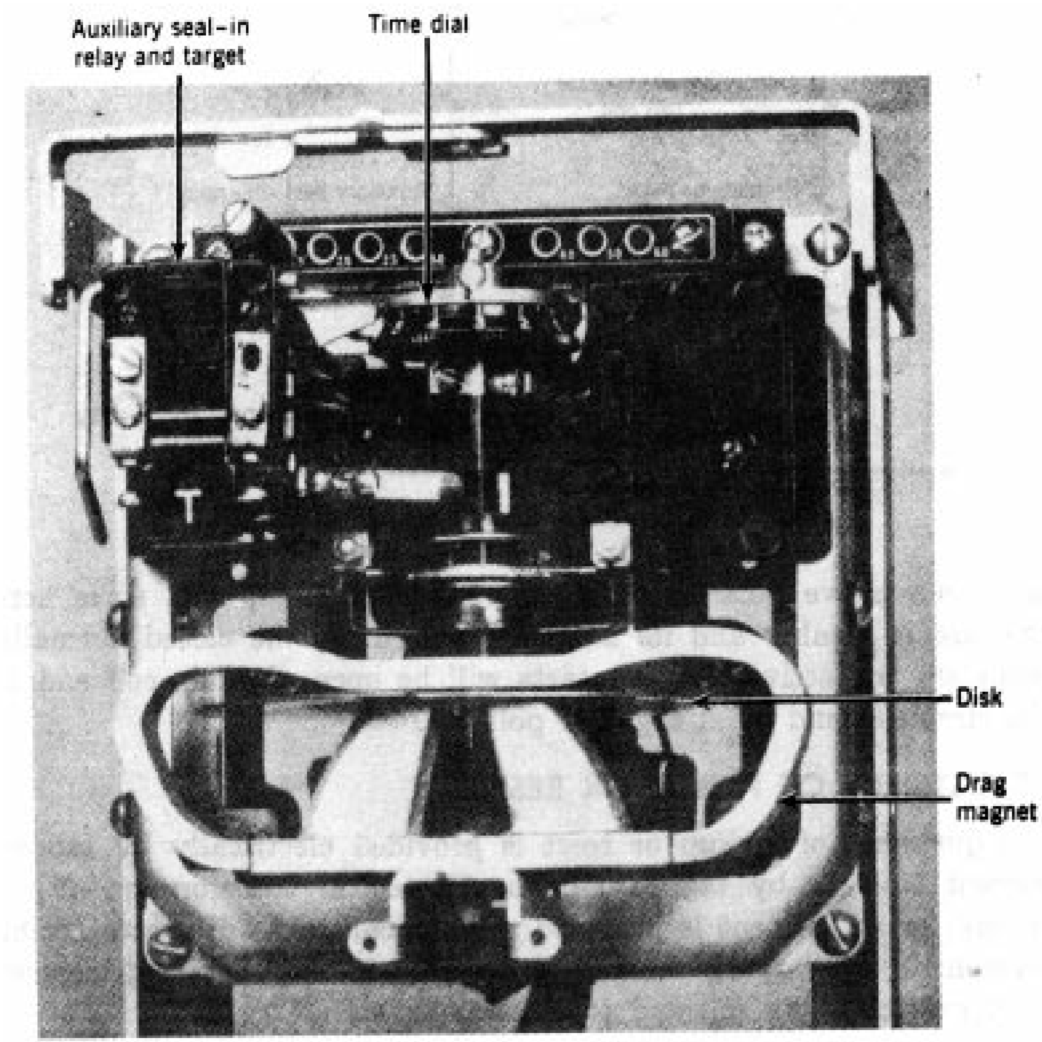

Fig. 4. Close-up of an induction-type overcurrent unit, showing the disc rotor and drag magnet.

Occasionally, a supplementary auxiliary relay having fixed time delay may be used when a certain delay is required that is entirely independent of the magnitude of the actuating quantity in the protective relay.

Time delay is obtained in induction-type relays by a "drag magnet," which is a permanent magnet arranged so that the relay rotor cuts the flux between the poles of the magnet, as shown in Fig. 4. This produces a retarding effect on motion of the rotor in either direction. In other relays, various mechanical devices have been used, including dash pots, bellows, and escapement mechanisms.

The terminology for expressing the shape of the curve of operating time versus the actuating quantity has also been affected by developments throughout the years. Originally, only the terms "definite time" and "inverse time" were used. An inverse-time curve is one in which the operating time becomes less as the magnitude of the actuating quantity is increased, as shown in Fig. 5. The more pronounced the effect is, the more inverse is the curve said to be. Actually, all time curves are inverse to a greater or lesser degree. They are most inverse near the pickup value and become less inverse as the actuating quantity is increased. A definite-time curve would strictly be one in which the operating time was unaffected by the magnitude of the actuating quantity, but actually the terminology is applied to a curve that becomes substantially definite slightly above the pickup value of the relay, as shown in Fig. 5.

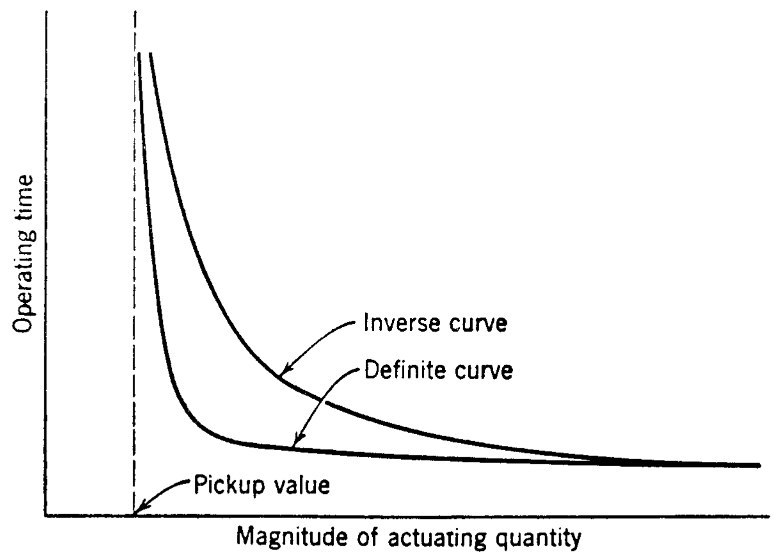

Fig. 5. Curves of operating time versus the magnitude of the actuating quantity.

As a consequence of trying to give names to curves of different degrees of inverseness, we now have "inverse," "very inverse," and "extremely inverse." Although the terminology may be somewhat confusing, each curve has its field of usefulness, and one skilled in the use of these relays has only to compare the shapes of the curves to know which is best for a given application. This book will use the term "inverse" for general reference to any of the inverse curves, reserving the other terms for use only when the terminology is significant.

Thus far, we have gained a rough picture of protective relays in general and have learned some of the language of the profession.

References to complete standards pertaining to circuit elements and terminology are given in the bibliography at the end of this chapter.[1] With this preparation, we shall now consider the fundamental relay types.

SINGLE-QUANTITY RELAYS OF THE ELECTROMAGNETIC-ATTRACTION TYPE

Here we shall consider plunger-type and attracted-armature-type a-c or d-c relays that are actuated from either a single current or voltage source.

OPERATING PRINCIPLE

The electromagnetic force exerted on the moving element is proportional to the square of the flux in the air gap. If we neglect the effect of saturation, the total actuating force may be expressed:

$$F = K_1 I^2 - K_2,$$

where F = net force.

K_1 = a force-conversion constant.

I = the rms magnitude of the current in the actuating coil.

K_2 = the restraining force (including friction).

When the relay is on the verge of picking up, the net force is zero, and the operating characteristic is:

$$K_1 I^2 = K_2,$$

or

$$I = \sqrt{\frac{K_2}{K_1}} = \text{constant}$$

RATIO OF RESET TO PICKUP

One characteristic that affects the application of some of these relays is the relatively large difference between their pickup and reset values. As such a relay picks up, it shortens its air gap, which permits a smaller magnitude of coil current to keep the relay picked up than was required to pick it up. This effect is less pronounced in a-c than in d-c relays. By special design, the reset can be made as high as 90% to 95% of pickup for a-c relays, and 60% to 90% of pickup for d-c relays. Where the pickup is adjusted by adjusting the initial air gap, a higher pickup calibration will have a lower ratio of reset to pickup. For overcurrent applications where such relays are often used, the relay trips a circuit breaker which reduces the current to zero, and hence the reset value is of no consequence. However, if a low-reset relay is used in conjuction with other relays in such a way that a breaker is not always tripped when the low-reset relay operates, the application should be carefully examined. When the reset value is a low percentage of the pickup value, there is the possibility that an abnormal condition might cause the relay to pick up (or to reset), but that a return to normal conditions might not return the relay to its normal operating position, and undesired operation might result.

TENDENCY TOWARD VIBRATION

Unless the pole pieces of such relays have "shading rings" to split the air-gap flux into two out-of-phase components, such relays are not suitable for continuous operation on alternating current in the picked-up position. This is because there would be excessive vibration that would produce objectionable noise and would cause excessive wear. This tendency to vibrate is related to the fact that a-c relays have higher reset than d-c relays; an a-c relay without shading rings has a tendency to reset every half cycle when the flux passes through zero.

DIRECTIONAL CONTROL

Relays of this group are used mostly when "directional" operation is not required. More will be said later about "directional control" of relays; suffice it to say here that plunger or attracted-armature relays do not lend themselves to directional control nearly as well as induction-type relays, which will be considered later.

EFFECT OF TRANSIENTS

Because these relays operate so quickly and with almost equal current facility on either alternating current or direct current, they are affected by transients, and particularly by d-c offset in a-c waves. This tendency must be taken into consideration when the proper adjustment for any application is being determined. Even though the steady-state value of an offset wave is less than the relay's pickup value, the relay may pick up during such a transient, depending on the amount of offset, its time constant, and the operating speed of the relay. This tendency is called "overreach" for reasons that will be given later.

TIME CHARACTERISTICS

This type of relay is inherently fast and is used generally where time delay is not required. Time delay can be obtained, as previously stated, by delaying mechanisms such as bellows, dash pots, or escapements. Very short time delays are obtainable in d-c relays by encircling the magnetic circuit with a low-resistance ring, or "slug" as it is sometimes called. This ring delays changes in flux, and it can be positioned either to have more effect on air increase if time-delay pickup is desired, or to have more effect on air-gap-flux decrease if time-delay reset is required.

DIRECTIONAL RELAYS OF THE ELECTROMAGNETIC-ATTRACTION TYPE

Directional relays of the electromagnetic-attraction type are actuated by d-c or by rectified a-c quantities. The most common use of such relays is for protection of d-c circuits where the actuating quantity is obtained either from a shunt or directly from the circuit.

Figure 6 illustrates schematically the operating principle of this type of relay. A movable armature is shown magnetized by current flowing in an actuating coil encircling the armature, and with such polarity as to close the contacts. A reversal of the polarity of the

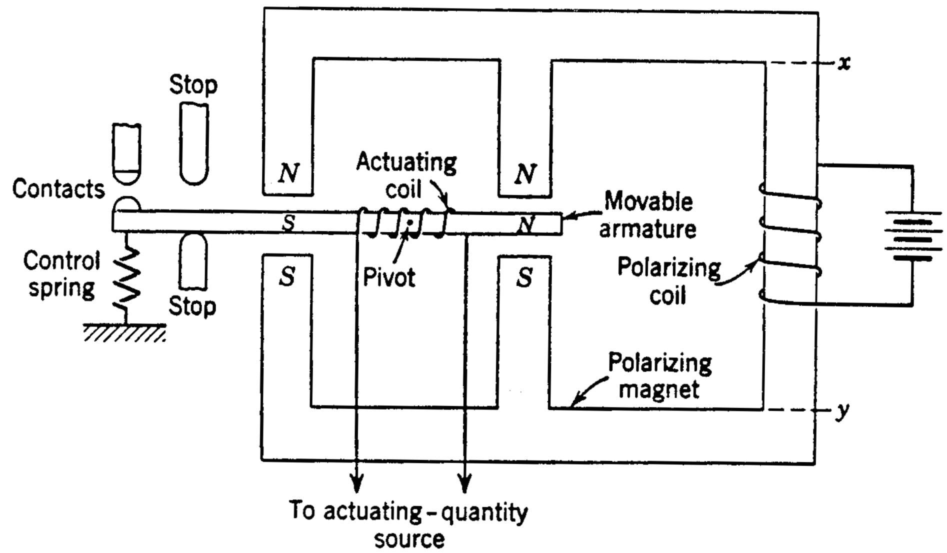

Fig. 6. Directional relay of the electromagnetic-attraction type.

actuating quantity will reverse the magnetic polarities of the ends of the armature and cause the contacts to stay open. Although a "polarizing," or "field," coil is shown for magnetizing the polarizing magnet, this coil may be replaced by a permanent magnet in the section between x and y. There are many physical variations possible in carrying out this principle, one of them being a construction similar to that of a d-c motor.

The force tending to move the armature may be expressed as follows, if we neglect saturation:

$$F = K_1 I_p I_a - K_2,$$

$$F = \text{net force}$$

where K_1 = a force-conversion constant.

I_p = the magnitude of the current in the polarizing coil.

I_a = the magnitude of the current in the armature coil.

K_2 = the restraining force (including friction).

At the balance point when $F = 0$, the relay is on the verge of operating, and the operating characteristic is:

$$I_p I_a = \frac{K_2}{K_1} = \text{constant}$$

I_p and I_a, are assumed to flow through the coils in such directions that a pickup force is produced, as in Fig. 6. It will be evident that, if the direction of either I_p or I_a (but not of both) is reversed, the direction of the force will be reversed. Therefore, this relay gets its name from its ability to distinguish between opposite directions of actuating-coil current flow, or opposite polarities. If the relative directions are correct for operation, the relay will pick up at a constant magnitude of the product of the two currents.

If permanent-magnet polarization is used, or if the polarizing coil is connected to a source that will cause a constant magnitude of current to flow, the operating characteristic becomes:

$$I_a = \frac{K_2}{K_1 I_p} = \text{constant}$$

I_a still must have the correct polarity, as well as the correct magnitude, for the relay to pick up.

EFFICIENCY

This type of relay in much more efficient than hinged-armature or plunger relays, from the standpoint of the energy required from the actuating-coil circuit. For this reason, such directional relays are used when a d-c shunt is the actuating source, whether directional action is required or not. Occasionally, such a relay may be actuated from an a-c quantity through a full-wave rectifier when a low-energy a-c relay is required.

RATIO OF CONTINUOUS THERMAL CAPACITY TO PICKUP

As a consequence of greater efficiency, the actuating coil of this type of relay has a high ratio of continuous current or voltage capacity to the pickup value, from the thermal standpoint.

TIME CHARACTERISTICS

Relays of this type are instantaneous in operation, although a slug may be placed around the armature to get a short delay.

INDUCTION-TYPE RELAYS–GENERAL OPERATING PRINCIPLES

Induction-type relays are the most widely used for protective-relaying purposes involving a-c quantities. They are not usable with d-c quantities, owing to the principle of operation. An induction-type relay is a split-phase induction motor with contacts. Actuating force is developed in a movable element, that may be a disc or other form of rotor of non-magnetic current-conducting material, by the interaction of electromagnetic fluxes with eddy currents that are induced in the rotor by these fluxes.

Figure 7 shows how force is produced in a section of a rotor that is pierced by two adjacent a-c fluxes. Various quantities are shown at an instant when both fluxes are directed downward and are increasing in magnitude. Each flux induces voltage around itself in the rotor, and currents flow in the rotor under the influence of the two voltages. The current produced by one flux reacts with the other flux, and vice versa, to produce forces that act on the rotor.

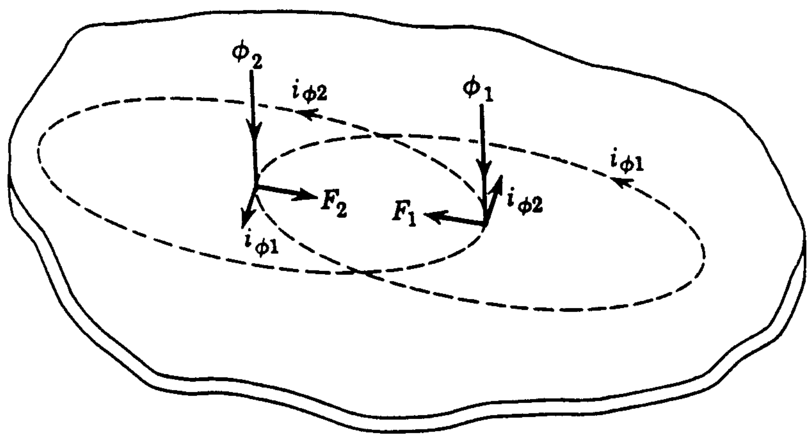

Fig. 7. Torque production in an induction relay.

The quantities involved in Fig. 7 may be expressed as follows:

$$\phi_1 = \Phi_1 \sin \omega t$$

$$\phi_2 = \Phi_2 \sin (\omega t + \theta),$$

where θ is the phase angle by which ϕ_2 leads ϕ_1. It may be assumed with negligible error that the paths in which the rotor currents flow have negligible self-inductance, and hence that the rotor currents are in phase with their voltages:

$$i\phi_1 \;\alpha\; \frac{d\phi_1}{dt} \;\alpha\; \Phi_1 \cos \omega t$$

$$i\phi_2 \;\alpha\; \frac{d\phi_2}{dt} \;\alpha\; \Phi_2 \cos (\omega t + \theta)$$

We note that Fig. 7 shows the two forces in opposition, and consequently we may write the equation for the net force (F) as follows:

$$F = (F_2 - F_1) \;\alpha\; (\phi_2 i_{\phi 1} - \phi_1 i_{\phi 2}) \qquad (1)$$

Substituting the values of the quantities into equation 1, we get:

$$F \;\alpha\; \Phi_1 \Phi_2 \,[\sin (\omega t + \theta) \cos \omega t - \sin \omega t \cos (\omega t + \theta)] \qquad (2)$$

which reduces to:

$$F \;\alpha\; \Phi_1 \Phi_2 \sin \theta \qquad (3)$$

Since sinusoidal flux waves were assumed, we may substitute the rms values of the fluxes for the crest values in equation 3.

Apart from the fundamental relation expressed by equation 3, it is most significant that the net force is the same *at every instant.* This fact does not depend on the simplifying assumptions that were made in arriving at equation 3. The action of a relay under the influence of such a force is positive and free from vibration. Also, although it may not be immediately apparent, the net force is directed from the point where the leading flux pierces the rotor toward the point where the lagging flux pierces the rotor. It is as though the flux moved across the rotor, dragging the rotor along.

In other words, actuating force is produced in the presence of out-of-phase fluxes. One flux alone would produce no net force. There must be at least two out-of-phase fluxes to produce any net force, and the maximum force is produced when the two fluxes are 90° out of phase. Also, the direction of the force-and hence the direction of motion of the relay's movable member-depends on which flux is leading the other.

A better insight into the production of actuating force in the induction relay can be obtained by plotting the two components of the expression inside the brackets of equation 2, which we may call the "per-unit net force." Figure 8 shows such a plot when θ is assumed to be 90°. It will be observed that each expression is a double-frequency sinusoidal wave completely offset from the zero-force axis.

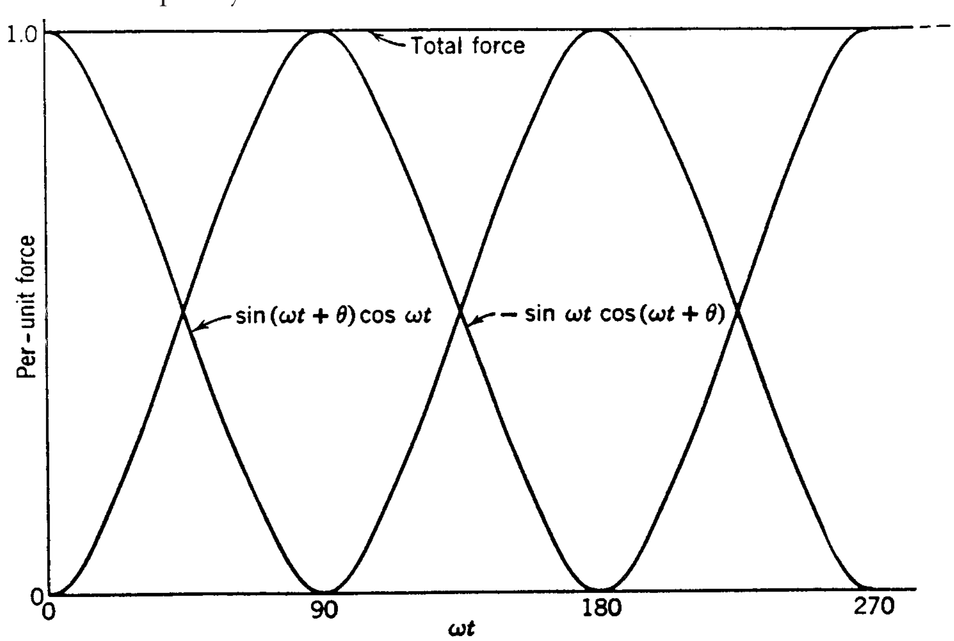

Fig. 8. Per-unit net force.

The two waves are displaced from one another by 90° in terms of fundamental frequency, or by 180° in terms of double frequency. The sum of the instantaneous values of the two waves is 1.0 at every instant. If θ were assumed to be less than 90°, the effect on Fig. 8 would be to raise the zero-force axis, and a smaller per-unit net force would result. When θ is zero, the two waves are symmetrical about the zero-force axis, and no net force is produced. If we let θ be negative, which is to say that ϕ_2 is lagging ϕ_1, the zero-force axis is raised still higher and net force in the opposite direction is produced. However, for a given value of θ, the net force is the same at each instant.

In some induction-type relays one of the two fluxes does not react with rotor currents produced by the other flux. The force expression for such a relay has only one of the components inside the brackets of equation 2. The *average* force of such a relay may still be expressed by equation 3, but the instantaneous force is variable, as shown by omitting one of the waves of Fig. 8. Except when θ is 90° lead or lag, the instantaneous force will actually reverse during parts of the cycle; and, when $\theta = 0$, the average negative force equals the average positive force. Such a relay has a tendency to vibrate, particularly at values of θ close to zero.

Reference 2 of the bibliography at the end of this chapter gives more detailed treatment of induction-motor theory that applies also to induction relays.

TYPES OF ACTUATING STRUCTURE

The different types of structure that have been used are commonly called: (1) the "shaded-pole" structure; (2) the "watthour-meter" structure; (3) the "induction-cup" and the "double-induction-loop" structures; (4) the "single-induction-loop" structure.

Shaded-Pole Structure. The shaded-pole structure, illustrated in Fig. 9, is generally actuated by current flowing in a single coil on a magnetic structure containing an air gap. The air-gap flux produced by this current is split into two out-of-phase components by a so-called "shading ring," generally of copper, that encircles part of the pole face of each pole at the

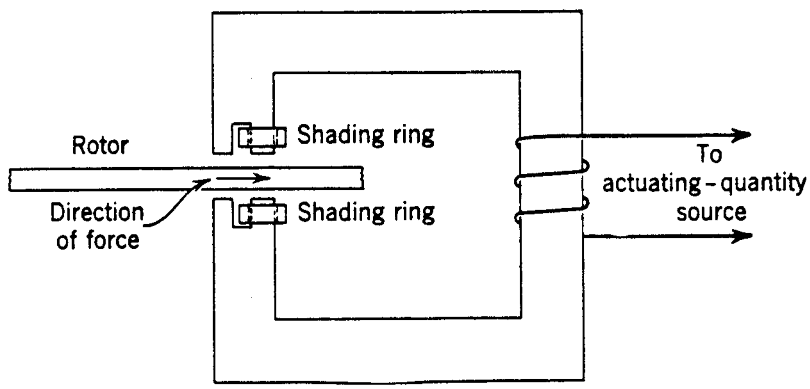

Fig. 9. Shaded-pole structure.

air gap. The rotor, shown edgewise in Fig. 9, is a copper or aluminum disc, pivoted so as to rotate in the air gap between the poles. The phase angle between the fluxes piercing the disc is fixed by design, and consequently it does not enter into application considerations.

The shading rings may be replaced by coils if control of the operation of a shaded-pole relay is desired. If the shading coils are short-circuited by a contact of some other relay, torque will be produced; but, if the coils are open-circuited, no torque will be produced because there will be no phase splitting of the flux. Such torque control is employed where "directional control" is desired, which will be described later.

Watthour-Meter Structure. This structure gets its name from the fact that it is used for watthour meters. As shown in Fig. 10, this structure contains two separate coils on two different magnetic circuits, each of which produces one of the two necessary fluxes for driving the rotor, which is also a disc.

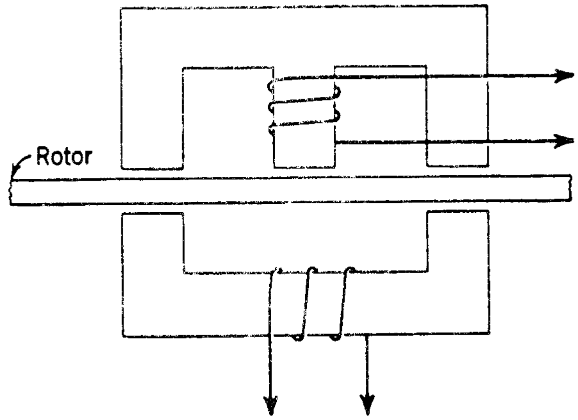

Fig. 10. Watthour-meter structure.

Induction-Cup and Double-Induction-Loop Structures. These two structures are shown in Figs. 11 and 12. They most closely resemble an induction motor, except that the rotor iron is stationary, only the rotor-conductor portion being free to rotate. The cup structure

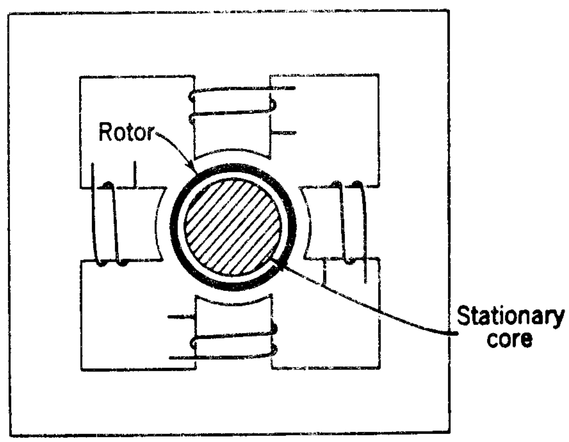

Fig. 11. Induction-cup structure.

employs a hollow cylindrical rotor, whereas the double-loop structure employs two loops at right angles to one another. The cup structure may have additional poles between those shown in Fig. 11. Functionally, both structures are practically identical.

These structures are more efficient torque producers than either the shaded-pole or the watthour-meter structures, and they are the type used in high-speed relays.

Single-Induction-Loop Structure. This structure, shown in Fig. 13, is the most efficient torque-producing structure of all the induction types that have been described. However, it has the rather serious disadvantage that its rotor tends to vibrate as previously described for a relay in which the actuating force is expressed by only one component inside the brackets of equation 2. Also, the torque varies somewhat with the rotor position.

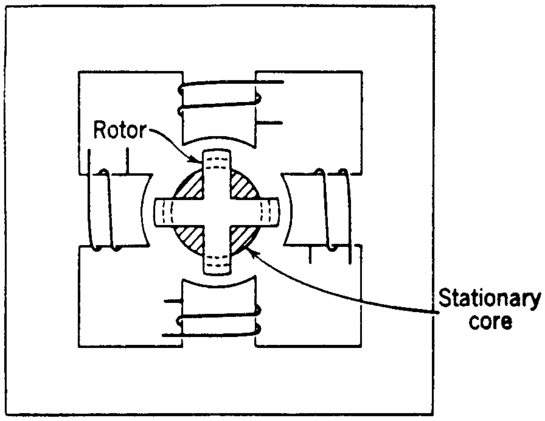

Fig. 12. Double-induction-loop structure.

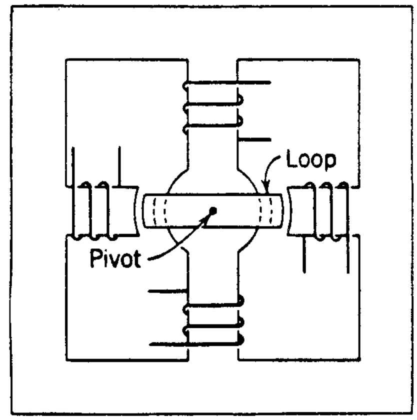

Fig. 13. Single-induction-loop structure.

ACCURACY

The accuracy of an induction relay recommends it for protective-relaying purposes. Such relays are comparable in accuracy to meters used for billing purposes. This accuracy is not a consequence of the induction principle, but because such relays invariably employ jewel bearings and precision parts that minimize friction.

SINGLE-QUANTITY INDUCTION RELAYS

A single-quantity relay is actuated from a single current or voltage source. Any of the induction-relay actuating structures may be used. The shaded-pole structure is used only for single-quantity relays. When any of the other structures is used, its two actuating circuits are connected in series or in parallel; and the required phase angle between the two fluxes is obtained by arranging the two circuits to have different X/R (reactance-to-resistance) ratios by the use of auxiliary resistance and/or capacitance in combination with one of the circuits. Neglecting the effect of saturation,the torque of all such relays may be expressed as:

$$T = K_1 I^2 - K_2$$

where I is the rms magnitude of the total current of the two circuits. The phase angle between the individual currents is a design constant, and it does not enter into the application of these relays.

If the relay is actuated from a voltage source, its torque may be expressed as:

$$T = K_1 V^2 - K_2$$

where V is the rms magnitude of the voltage applied to the relay.

TORQUE CONTROL

Torque control with the structures of Figs. 10, 11, 12, or 13 is obtained simply by a contact in series with one of the circuits if they are in parallel, or in series with a portion of a circuit if they are in series.

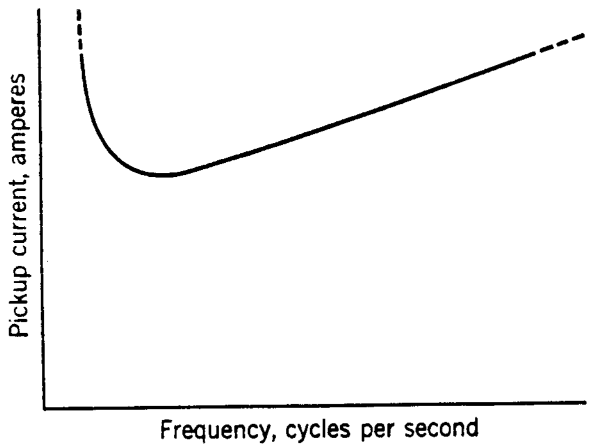

Fig. 14. Effect of frequency on the pickup of a single-quantity induction relay.

EFFECT OF FREQUENCY

The effect of frequency on the pickup of a single-quantity relay is shown qualitatively by Fig. 14. So far as possible, a relay is designed to have the lowest pickup at its rated frequency. The effect of slight changes in frequency normally encountered in power-system operation may be neglected. However, distorted wave form may produce significant changes in pickup and time characteristics. This fact is particularly important in testing relays at high currents; one should be sure that the wave form of the test currents is as good as that obtained in actual service, or else inconsistent results will be obtained.[3]

EFFECT OF D-C OFFSET

The effect of d-c offset may be neglected with inverse-time single relays. High-speed relays may or may not be affected, depending on the characteristics of their circuit elements. Generally, the pickup of high-speed relays is made high enough to compensate for any tendency to "overreach," as will be seen later, and no attempt is made to evaluate the effect of d-c offset.

RATIO OF RESET TO PICKUP

The ratio of reset to pickup is inherently high in induction relays; because their operation does not involve any change in the air gap of the magnetic circuit. This ratio is between 95% and 100% friction and imperfect compensation of the control-spring torque being the only things that keep the ratio from being 100%. Moreover, this ratio is unaffected by the pickup adjustment where tapped current coils provide the pickup adjustment.

RESET TIME

Where fast automatic reclosing of circuit breakers is involved, the reset time of an inverse-time relay may be a critical characteristic in obtaining selectivity. If all relays involved do not have time to reset completely after a circuit breaker has been tripped and before the breaker recloses, and if the short circuit that caused tripping is reestablished when the breaker recloses, certain relays may operate too quickly and trip unnecessarily. Sometimes the drop-out time may also be important with high-speed reclosing.

TIME CHARACTERISTICS

Inverse-time curves are obtained with relays whose rotor is a disc and whose actuating structure is either the shaded-pole type or the watthour-meter type. High-speed operation is obtained with the induction-cup or the induction-loop structures.

DIRECTIONAL INDUCTION RELAYS

Contrasted with single-quantity relays, directional relays are actuated from two different independent sources, and hence the angle θ of equation 3 is subject to change and must be considered in the appliastion of these relays. Such relays use the actuating structures of Figs. 10, 11, 12, or 13.

TORQUE RELATIONS IN TERMS OF ACTUATING QUANTITIES

Current-Current Relays. A current-current relay is actuated from two different current-transformer sources. Assuming no saturation, we may substitute the actuating currents for the fluxes of equation 3, and the expression for the torque becomes:

$$T = K_1 I_1 I_2 \sin \theta - K_2 \tag{4}$$

where I_1 and I_2 = the rms values of the actuating currents.

θ = the phase angle between the rotor-piercing fluxes produced by I_1 and I_2.

An actuating current is not in phase with the rotor-piercing flux that it produces, for the same reason that the primary current of a transformer is not in phase with the mutual flux. (In fact, the equivalent circuit of a transformer may be used to represent each actuating circuit of an induction relay.) But in some relays, such as the induction cylinder and double-induction-loop types, the rotor-piercing (or mutual) fluxes are at the same phase angle with respect to their actuating currents. For such so-called "symmetrical" structures, θ of equation 4 may be defined also as the phase angle between the actuating currents. For the wattmetric type of structure, the phase angle between the actuating currents may be significantly different from the phase angle between the fluxes. For the moment, we shall assume that we are dealing with symmetrical structures, and that θ may be defined as the phase angle between I_1 and I_2 of equation 4.

However, it is usually desirable that maximum torque occur at some value of θ other than 90°. To this end, one of the actuating coils may be shunted by a resistor or a capacitor. Maximum torque will still occur when the coil currents are 90° out of phase; but, in terms of the currents supplied from the actuating sources, maximum torque will occur at some angle other than 90°.

Figure 15 shows the vector relations for a relay with a resistor shunting the I_1 coil. I_1 will now be defined as the total current supplied by the source to the coil and resistor in parallel. If the angle θ by which I_2 leads I_1 is defined as positive, the angle ϕ by which the coil component of I_1 lags I_1 will be negative, and the expression for the torque will be:

$$T = K_1 I_1 I_2 \sin (\theta - \phi) - K_2$$

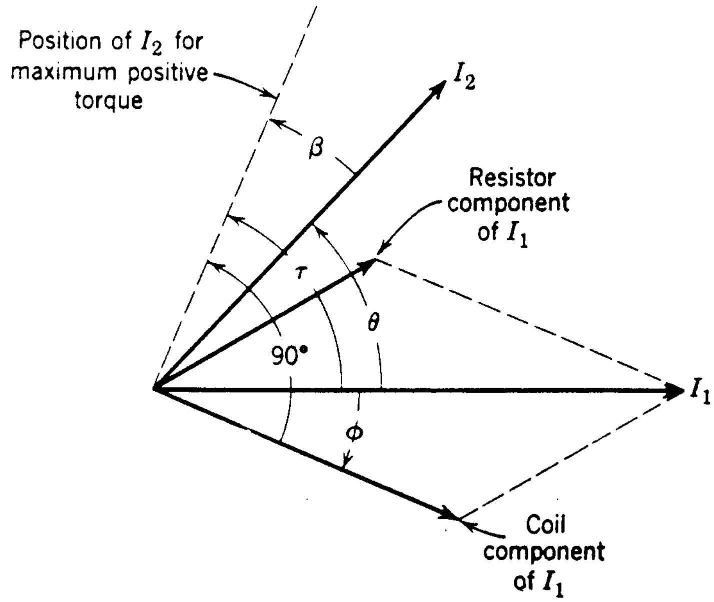

Fig. 15. Vector diagram for maximum torque in a current-current induction-type directional relay.

For example, if we let $\theta = 45°$ and $\phi = -30°$, the torque for the relations of Fig. 15 will be:

$$T = K_1 I_1 I_2 \sin 75° - K_2$$

The angle "τ" of Fig. 15 is called the "angle of maximum torque" since it is the value of θ at which maximum positive torque occurs. It is customary to specify this angle rather than ϕ when describing this characteristic of directional relays. The two angles are directly related by the fact that they add numerically to 90° in symmetrical structures such as we have assumed thus far. But, if we use τ as the design constant of a directional relay rather than ϕ, we can write the torque expression in such a way that it will apply to all relays whether symmetrical or not, as follows:

$$T = K_1 I_1 I_2 \cos(\theta - \tau) - K_2$$

where τ is positive when maximum positive torque occurs for I_2 leading I_1, as in Fig. 15. Or the torque may be expressed also as:

$$T = K_1 I_1 I_2 \cos \beta - K_2$$

where, β is the angle between I_2 and the maximum-torque position of I_2, or, $\beta = (\theta - \tau)$. These two equations will be used from now on because they are strictly true for any structure.

If a capacitor rather than a resistor is used to adjust the angle of maximum torque, it may be connected to the secondary of a transformer whose primary is connected across the coil and whose ratio is such that the secondary voltage is much higher than the primary voltage. The purpose of this is to permit the use of a small capacitor. Or, to accomplish the same purpose, another winding with many more turns than the current coil may be put on the same magnetic circuit with the current coil, and with a capacitor connected across this winding.

Current-Voltage Relays. A current-voltage relay receives one actuating quantity from a current-transformer source and the other actuating quantity from a voltage-transformer source. Equation 5 applies approximately for the currents in the two coils. However, in terms of the actuating quantities, the torque is strictly:

$$T = K_1 VI \cos(\theta - \tau) - K_2$$

where V = the rms magnitude of the voltage applied to the voltage coil *circuit*.

I = the rms magnitude of the current-coil current.

θ = the angle between I and V.

τ = the angle of maximum torque.

For whatever relation between I and V that we call θ positive, we should also call τ positive for that same relation. These quantities are shown in Fig. 16, together with the voltage-coil current I_V and the approximate angle ϕ by which I_V lags V.

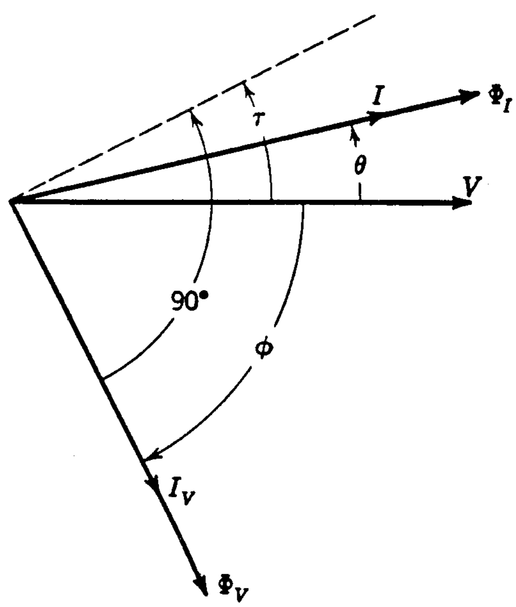

Fig. 16 Vector diagram for maximum torque in a current-voltage induction-type directional relay.

The value of ϕ is of the order of 60° to 70° lagging for most voltage coils, and therefore τ will be of the order of 30° to 20° leading if there is no impedance in series with the voltage coil. By inserting a combination of resistance and capacitance in series with the voltage coil, we can change the angle between the applied voltage and I_V to almost any value either lagging or leading V without changing the magnitude of I_V. A limited change in ϕ can be made with resistance alone, but the magnitude of I_V will be decreased, and hence the pickup will be increased. Hence, the angle of maximum torque can be made almost any desired value. By other supplementary means, which we shall not discuss here, the angle of maximum torque can be made any desired value. It is emphasized that V of equation 6 is the voltage applied to the voltage-coil *circuit*; it is the voltage-coil voltage only if no series impedance is inserted.

Voltage-Voltage Relays. It is not necessary to consider a relay actuated from two different voltage sources, since the principles already described will apply.

THE SIGNIFICANCE OF THE TERM "DIRECTIONAL"

A-c directional relays are used most extensively to recognize the difference between current being supplied in one direction or the other in an a-c circuit, and the term "directional" is derived from this usage. Basically, an a-c directional relay can recognize certain differences in phase angle between two quantities, just as a d-c directional relay recognizes differences in polarity. This recognition, as reflected in the contact action, is limited to differences in phase angle exceeding 90° from the phase angle at which maximum torque is developed, as already described.

THE POLARIZING QUANTITY OF A DIRECTIONAL RELAY

The quantity that produces one of the fluxes is called the "polarizing" quantity. It is the reference against which the phase angle of the other quantity is compared. Consequently, the phase angle of the polarizing quantity must remain more or less fixed when the other quantity suffers wide changes in phase angle. The choice of a suitable polarizing quantity will be discussed later, since it does not affect our present considerations.

THE OPERATING CHARACTERISTIC OF A DIRECTIONAL RELAY

Consider, for example, the torque relation expressed by equation 6 for a current-voltage directional relay. At the balance point when the relay is on the verge of operating, the net torque is zero, and we have:

$$VI \cos(\theta - \tau) = \frac{K_2}{K_1} = \text{constant}$$

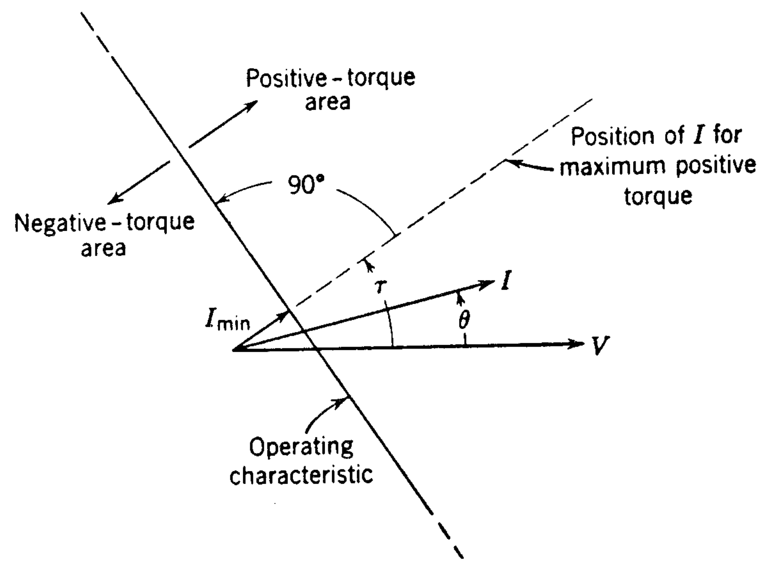

Fig. 17. Operating characteristic of a directional relay on polar coordinates.

This operating characteristic can be shown on a polar-coordinate diagram, as in Fig. 17. The polarizing quantity, which is the voltage for this type of relay, is the reference; and its magnitude is assumed to be constant. The operating characteristic is seen to be a straight line offset from the origin and perpendicular to the maximum positive-torque position of the current. This line is the plot of the relation:

$$I \cos(\theta - \tau) = \text{constant}$$

which is obtained when the magnitude of V is assumed to be constant, and it is the dividing line between the development of net positive and negative torque in the relay. Any current vector whose head lies in the positive-torque area will cause pickup; the relay will not pick up, or it will reset, for any current vector whose head lies in the negative-torque area.

For a different magnitude of the reference voltage, the operating characteristic will be another straight line parallel to the one shown and related to it by the expression:

$$VI_{\min} = \text{constant}$$

where $I_{\min}$, as shown in Fig. 17, is the smallest magnitude of all current vectors whose heads terminate on the operating characteristic. $I_{\min}$, is called "the minimum pickup current," although strictly speaking the current must be slightly larger to cause pickup. Thus, there is an infinite possible number of such operating characteristics, one for each possible magnitude of the reference voltage.

The operating characteristic will depart from a straight line as the phase angle of the current approaches 90° from the maximum-torque phase angle. For such large angular departures, the pickup current becomes very large, and magnetic saturation of the current element requires a different magnitude of current to cause pickup from the one that the straight-line relation would indicate.

The operating characteristic for current-current or voltage-voltage directional relays can be similarly shown.

THE "CONSTANT-PRODUCT" CHARACTERISTIC

The relation $VI_{\min}$ = constant for the current-voltage relay (and similar expressions for the others) is called the "constant-product" characteristic. It corresponds closely to the pickup current or voltage of a single-quantity relay and is used as the basis for plotting the time characteristics. This relation holds only so long as saturation does not occur in either of the two magnetic circuits. When either of the two quantities begins to exceed a certain magnitude, the quantity producing saturation must be increased beyond the value indicated by the constant-product relation in order to produce net positive torque.

EFFECT OF D-C OFFSET AND OTHER TRANSIENTS

The effect of transients may be neglected with inverse-time relays, but, with high-speed relays, certain transients may have to be guarded against either in the design of the relay or in its application. Generally, an increase in pickup or the addition of one or two cycles (60-cycle-per-second basis) time delay will avoid undesired operation. This subject is much too complicated to do justice to here. Suffice it to say, trouble of this nature is extremely rare and is not generally a factor in the application of established relay equipments.

THE EFFECT OF FREQUENCY

Directional relays are affected like single-quantity relays by changes in frequency of both quantities. The angle of maximum torque is affected, owing to changes in the X/R ratio in circuits containing inductance or capacitance. The effect of slight changes in frequency such as are normally encountered, however, may be neglected. If the frequencies of the two quantities supplied to the relay are different, a sinusoidal torque alternating between positive and negative will be produced; the net torque for each torque cycle will be zero, but, if the frequencies are nearly equal and if a high-speed relay is involved, the relay may respond to the reversals in torque.

TIME CHARACTERISTICS

Disc-type reIays are used where inverse-time characteristics are desired, and cup-type or loop-type relays are used for high-speed operation. When time delay is desired, it is often provided by another relay associated with the directional relay.

THE UNIVERSAL RELAY-TORQUE EQUATION

As surprising as it may seem, we have now completed our examination of all the essential fundamentals of protective-relay operation. All relays yet to be considered are merely combinations of the types that have been described. At this point, we may write the universal torque equation as follows:

$$T = R_1 I^2 + K_2 V^2 + K_3 VI \cos(\theta - \tau) + K_4$$

By assigning plus or minus signs to certain of the constants and letting others be zero, and sometimes by adding other similar terms, the operating characteristics of all types of protective relays can be expressed.

Various factors that one must generally take into account in applying the different types have been presented. Little or no quantitative data have been given because it is of little consequence for a clear understanding of the subject. Such data are easily obtained for any particular type of relay; the important thing is to know how to use such data. In the following chapters, by applying the fundamental principles that have been given here, we shall learn how the various types of protective relays operate.

PROBLEMS

1. A 60-cycle single-phase directional relay of the current-voltage type has a voltage coil whose impedance is 230 + $j560$ ohms. When connected as shown in Fig. 18, the relay develops maximum positive torque when load of a leading power factor is being supplied in a given direction.

It is desired to modify this relay so that it will develop maximum positive torque for load in the same direction as before, but at 45° lagging power factor. Moreover, it is desired to maintain the same minimum pickup current as before.

Draw a connection diagram similar to that given, showing the modifications you would make, and giving quantitative values. Assume that the relay has a symmetrical structure.

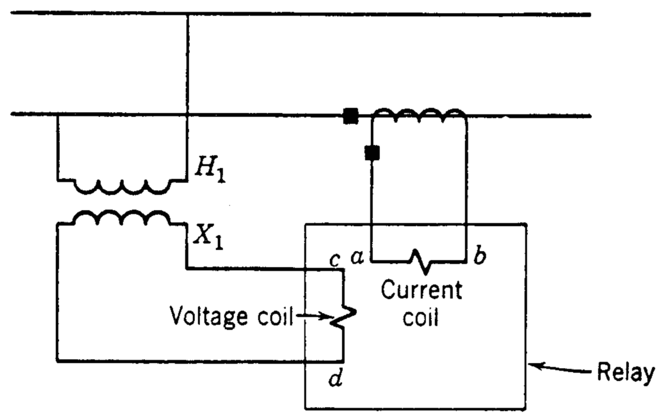

Fig. 18. Illustration for Problem 1.

2. Given an induction-type directional relay in which the frequency of one flux is n times that of the other. Derive the equation for the torque of this relay at any instant if at zero time the relay is developing maximum torque.

3. What will the torque equation of an induction-type directional relay be if one flux is direct current and the other is alternating current?

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