6 Protective Relays

Introduction—Basic Terminology—Operating Principle of Protective Relays—Classification of Relays—Electro-Magnetic Attraction Relays—Electro-Magnetic Induction Relays—Permanent Magnet Moving Coil Relay—Thermal Relays—Buchholz Relay—Over-Current Relays—Induction Type Directional Power Relay—Induction Type Directional Over-Current and Earth-Fault Relay—Universal Relay Torque Equation—Distance Protection—Impedance Type Distance Relay—Reactance Type Distance Relay—Mho Type Distance Relay—Classification of Distance Relays—Differential Protection—Translay Relay—Negative Phase Sequence or Phase Unbalance Relay—Solved Examples—Exercises—Problems.

6.1. INTRODUCTION

In modern power system to have a normal operation of the system without electrical failure and damage to the equipment two alternatives are available with the designer, one is to design the system so that faults cannot occur and the other is to accept the possibility of faults and take steps to guard against the ill effects of such faults. Although it is possible to eliminate faults to a large extent by careful system design, careful insulation coordination, current operation and maintenance, it is obviously not possible to ensure cent per cent reliability and therefore the possibility of faults must be accepted and the necessity of protection scheme must be realized.

Protection scheme required for the protection of power system components against abnormal conditions such as faults etc. essentially consists of protective relaying and circuit breaker. Protective relay functions as a sensing device, it senses the fault, then determines its location and finally, it sends tripping command to the circuit breaker. The circuit breaker after getting the command from the protective relay, disconnects the faulted element. From this, it can be concluded, that, the protective relay which is the brain behind the scheme, plays a vital role. Therefore, proper care should be taken in designing and selecting an appropriate protective relay which is reliable, efficient and fast in operation. As a matter of fact by clearing the fault fast with the help of fast acting protective relay and associated circuit breaker, the damage to the apparatus is reduced, subsequent hazards like fire, risk to the life are reduced, by removing the particular faulted section, the continuity of supply is maintained through remaining healthy section, by clearing the fault fast, fault arising time is reduced and therefore, the system can be restored to the normal state sooner, transient state stability limit of the system is greatly improved, permanent damage to the equipment is avoided and possibility of developing most simple fault such as single phase–to–ground into more severe fault such as double phase-to-ground fault is reduced.

All the above objectives can be achieved only if the protective relay is reliable, maintainable and sensitive enough to distinguish between normal and abnormal (or faulty) conditions. The relay must come into action whenever there is a fault and must not operate if there is no fault. A number of relays are employed for the protection of the power system. Some of them are primary relays meaning that they are the first line of defence. Such relays sense the fault and send signal to the proper circuit breaker to trip and clear the fault. The fault may not be cleared if the circuit breaker fails to open or relay maloperates. The circuit breaker failure is because of two reasons, first, failure of supply to its trip coil and second, struck mechanical lever. The relay failure is because of three reasons such as wrong setting, bad contacts and open-circuit in the relay coil. In such cases, a second line of defence is provided by the back-up relays. These back-up relays have longer operating time even though they sense the fault along with the primary relays. Back-up relays are arranged in two ways viz., they are located at the same place as the primary relay (local back-up) and operate the same breaker or they are located at different stations and operate different breakers. The latter scheme has higher reliability.

In order to attain the desired reliability, the power system network is divided into different protection zones. The overall system protection is divided into (*i*) generator protection (*ii*) transformer protection (*iii*) bus protection (*iv*) transmission line protection and (*v*) feeder protection.

The relays employed for protection of apparatus and transmission lines are (*i*) over-current relays (*ii*) under-voltage relays (*iii*) under-frequency relays (*iv*) directional relays (*v*) thermal relays (*vi*) phase sequence relays such as negative sequence or zero sequence relays (*vii*) differential relays including percentage–differential relays (*viii*) distance (or impedance) relays such as plane impedance relays, angle impedance i.e., ohm (or reactance) relays, angle admittance i.e., Mho's relays, offset or restricted relays (*ix*) pilot relays such as wire-pilot, carrier channel pilot or microwave pilot relays. All the existing relaying schemes employ either one or more of these relaying schemes with slight modifications.

The protective relays do not eliminate the possibility of fault occurrence on the power system rather their action starts only after the fault has occurred on the system. It would be ideal if protection could anticipate and prevent fault occurrence but this is obviously impossible except where the original cause of a fault creates some effect which can operate a protective relay. So far only type of relay falls within this class, this is the gas detector (Buchholz relay) employed for protection of transformers. Such a relay operates when the oil level in the conservator pipe of a transformer is lowered due to accumulation of gas caused by a poor connection or by an incipient breakdown of insulation (slowly developing fault).

The function of the protective relays, as already discussed, is to sense the fault and then to energize the circuit breaker trip coil. Circuit breakers normally employed for protection of transmission lines and equipment are (*i*) air circuit breakers (*ii*) oil circuit breakers (*iii*) minimum-oil circuit breakers (*iv*) air-blast circuit breakers (*c*) SF_6 circuit breakers and (*vi*) vacuum switches. All of these breakers have been described in chapter 5.

The first of the above is employed for the apparatus protection, the second is used for the feeder protection and the third and the fourth are employed for the EHV/UHV transmission lines. The air-blast circuit breakers on EHV/UHV lines have become standard practice. In place of air, SF_6 is used and these SF_6 circuit breakers have several advantages, as described in Art 5.14.4. For important lines breakers are also provided with a reclosing feature.

The main features of a good protective relaying are (*i*) reliability (*ii*) selectivity (*iii*) sensitivity (*iv*) simplicity (*v*) speed and (*vi*) economy, all have been described in Art 1.8.

6.2. BASIC TERMINOLOGY

It is desirable to define and explain some important terms concerned with protective relaying for the sake of familiarity.

Protective Relay. It is an electrical device designed to initiate isolation of a part of an electrical installation, or to operate an alarm signal, in the event of an abnormal condition or a fault.

Energizing Quantity. It is an electrical quantity, i.e., current or voltage either alone or in combination with other electrical quantities, required for the operation of the relay.

Trip Circuit. It is a circuit that controls the circuit breaker for opening operation and comprises of trip coil, relay contacts, auxiliary switch, seal-in-coil, battery supply etc.

Characteristic Quantity. This is a quantity to which the relay is designed to respond, e.g., current in an over-current relay, impedance in an impedance relay, phase angle in a directional relay etc. Some relays have a calibrated response to one or more quantities, called the **characteristic quantities.**

Operating Force or Torque. It is a force (or torque) which tends to close the relay contacts.

Restraining Force or Torque. It is a force (or torque) which opposes the operating force (or torque) and tends to prevent the closure of relay contacts.

Setting. It is an actual value of the energizing or characteristic quantity at which the relay is designed to operate under given conditions.

Power Consumption (or Burden) of a Relay. It is the value of power consumed by the relay circuits at the rated current or voltage and expressed in VA for ac and watts for dc.

Pick-up. A relay is said to pick up when it moves from the *off* position to the *on* position or the operation of the relay is called the *relay pick-up*.

Operating or Pick-up Level. It is the value of actuating quantity (current or voltage) which is on threshold (border) above which the relay operates and closes its contacts. So long as the current in the relay is less than the pick-up value, the relay does not operate and the breaker controlled by it remains in the closed position. However, when the relay coil current is equal or exceeds the pick-up value, the relay operates to energise the trip coil which opens the circuit breaker.

Drop-out or Reset Level. This is the value of current or voltage etc. below which a relay opens its contacts and comes back to its original position. The ratio of the drop-out or reset value to the pick-up or operating value is called the drop-out or reset ratio.

Flag or Target. It is a visual device, usually spring-or gravity-operated, for indicating the operation of a relay.

Operating Time. It is given by the time which elapses between the instant when the actuating quantity exceeds the pick-up value to the instant when the relay contacts close.

Reset Time. It is given by the time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay returns to its original position.

Seal-in-Coil. It is a coil that is provided not to allow the relay contacts to open when the current is flowing through them.

Maximum Torque Angle (MTA) or Characteristic Angle of Relay. This is the design angle of the relay that will yield maximum torque.

Overshoot Time. This is the time during which stored operating energy is dissipated after the characteristic quantity has been suddenly restored from a specified value to the value which it had at the initial position of the relay.

Fault Clearing Time. Time elapsed between the instant of occurrence of fault and instant of final arc extinction in circuit breaker is called the *fault clearing time.*

Breaker Time. Time interval between closure of trip circuit and final arc extinction in circuit breaker is called the *breaker time.*

Relay Time. The interval between occurrence of fault and closure of relay contacts is called the *relay time.*

Relay time plus breaker time is equal to *fault clearing time.*

Consistency. It is accuracy with which the relay can repeat its electrical or time characteristics.

Reach. A distance relay operates whenever the impedance seen by the relay is less than a pre-specified value. This impedance or the corresponding distance is known as the *reach* of the relay.

Reach of a relay may be defined as the limiting distance covered by the protection, the faults beyond which are not within the reach of the protection and should be covered by the other relay.

Over-reach. The tendency of the relay to operate at impedances larger than its setting is known as over-reach. This can occur with some high speed relays if the current applied is not symmetrical, as is frequently the case during the first few cycles following a fault.

Under-reach. The extra impedance introduced by an arc into the fault loop affects the distance measured by the relay and causes it to under-reach. Under–reach is just reverse of over-reach and may be defined as the failure of distance relay to operate within the set protected distance (say 90%).

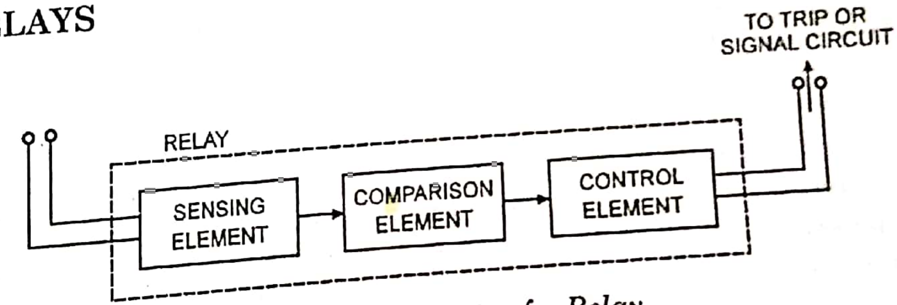
6.3. OPERATING PRINCIPLE OF PROTECTIVE RELAYS

All the relays employed for protection against short-circuits operate by virtue of the current and/or voltage supplied to them by CTs or PTs. Failures in the system are indicated by the individual or relative changes in the currents or voltages supplied to the protective relaying equipment. For every type and location failure, there is some distinctive difference in these quantities and there are various types of protective relays available, each of which is designed to recognise a particular difference and to operate in response to it. The difference may be in terms of the magnitude, frequency, phase angle, rate of change, harmonics or waveshape, duration of the conditions etc.

The main principle employed in the operation of the relay is either electro-magnetic attraction or electro-magnetic induction. In an electro-magnetic attraction relay, a plunger is drawn into a solenoid or an armature is attracted to the poles of an electro-magnet. Such relays can be operated either by dc or ac. In the case of electro-magnetic induction relays, the principle of induction motor is used and the torque is developed by electro-magnetic induction. Such relays are operated by the ac quantities only.

6.4. CLASSIFICATION OF RELAYS

The protective relay may be defined as an electrical device interposed between the main circuit and the circuit breaker in such a manner that any abnormality in the circuit acts on the relay, which in turn, if the abnormality is of a dangerous character, causes the breaker to open and so to isolate the faulty element. The relay ensures the safety of the circuit equipment from any damage which might be otherwise caused by the fault.



Basic Elements of a Relay
Fig. 6.1

All the relays have three essential fundamental elements, as illustrated in fig 6.1.

1. ***Sensing element,*** sometimes also called the measuring element, responds to the change in the actuating quantity; the current in a protected system in case of over-current relay.

2. ***Comparing element*** serves to compare the action of the actuating quantity on the relay with a pre-selected relay setting.

3. ***Control element*** on a pick up of the relay, accomplishes a sudden change in the control quantity such as closing of the operative current circuit.

Relays may be classified as to which kind of *physical quantity* the *sensing element* respond to and may be classed as *electrical* (actuated by some electrical quantity such as current, voltage, power etc.); *mechanical* (actuated by pressure, velocity of outflow of a liquid or gas etc.) *thermal* (actuated by heating effect), *optical*, *acoustical*, and other types of relays.

In power system protective relaying, the most widely applied are electrical type relays. Generally speaking the electrical protective relays can be broadly, classified into two categories: (*i*) electro-magnetic relays and (*ii*) static relays. In this chapter electro-magnetic relays will be discussed. The study of static relays will be taken up in chapter 7.

According to principle of operation and construction the relays may be classified such as electro-magnetic attraction type, electro-magnetic induction type, electro-dynamic type, moving coil type, electro-thermal type, physico-electric type and static relays.

Electro-magnetic attraction relays are of two types namely attracted armature type and solenoid type. In an *attracted armature type relay* operation depends on the movement of an armature under the influence of attractive force due to magnetic field set up by the current flowing through the relay winding while in a *solenoid type relay* operation depends on the movement of an iron plunger core along the axis of solenoid. Moving iron, moving plunger, attracted armature hinged, and balanced beam types of relays fall under this category. Such relays are actuated by dc or ac quantities.

In an *electro-magnetic induction type relay* operation depends on the movement of a metallic disc or cylinder free to rotate by the interaction of induced currents and the alternating magnetic fields producing them.

In an *electro-dynamic type relay* moving member consists of a coil free to rotate in an electro-magnetic field as in case of a moving coil instrument.

In a *moving coil type relay* moving member consists of a coil free to rotate in the air gap of a permanent magnet.

In an *electro-thermal type relay* movement depends up on the action of heat produced by the current flowing through the element of the relay.

Buchholz relay is an example of *physico-electric relay.*

Static relays employ thermionic valves, transistors or amplifiers and will be discussed in the next chapter.

According to their functions in the relay protective scheme, relays may be divided into main, auxiliary (or supplementary) and signal relays. The *main relays* are the protective elements which respond to any change in the actuating quantity, e.g., current, voltage, power etc. The *auxiliary* or *supplementary relays* are those which are controlled by other relays to perform some auxiliary or supplementary function such as introduction of a time delay, multiplying the number of contacts, increasing the making or breaking capacity of the contacts of another relay, passing a command pulse from one relay to another relay, acting upon a circuit breaker closing or opening coil, energizing a signal or an alarm, etc. *Signal relays* function to register (by flag or target) the operation of some relay or relay protection, and control warning (visible) and alarm (audible) signal devices. The choice of signal relay is governed by the importance of the associated switchgear, the method of control and the number of alarm indications to be displayed.

According to actuating quantity, electrical relays are classified into current, voltage, power, reactance, impedance, frequency relays, and, according to the direction of the change they respond to, as minimum (or under) and maximum (over-) relays. A *maximum (or over-) relay* is one which responds to the actuating quantity when it exceeds a pre-determined value as in the case of an over-current relay which operates when the current exceeds a pre–determined value. A *minimum (or under-) relay* is one which operates when the value of actuating quantity drops below a pre-determined value as in case of an under-voltage relay which operates when the voltage falls below a particular level.

According to the connection of sensing element, relays are classed as primary and secondary relays. *Primary relays* are those whose sensing (or measuring) elements are directly connected in the circuit or element they protect, while the *secondary relays* are those whose measuring elements are connected to the circuit they protect through instrument transformers (CT's or PTs). Normally secondary relays are used in power system protection because of the high values of line voltages and currents.

As to how the relays act upon the circuit breaker, they are subdivided into *direct-acting relay* whose control element acts mechanically to operate a circuit breaker and *indirect*-acting relay whose control element operates an auxiliary (operative) power source circuit to control the circuit breaker.

Primary relays, despite the substantial simplification of the protective schemes afforded by them are employed only in the simplest schemes for low-voltage circuits. The application of primary relays to high-voltage circuits is rendered difficult by complications arising from their conditions of operation and servicing (adjustment, checking, supervision at the high voltage). Protective schemes using indirect-acting primary relays need, furthermore, the use of an operative current. Such arrangements are bulky and costly. Direct-acting secondary relays do not require an operative current, their armatures act directly upon the circuit breaker tripping device. Protection schemes using direct-acting secondary relays, notwithstanding difficulty in checking and adjustment, have found application because of their simple design.

The relay most frequently used is the indirect-acting secondary relay, notwithstanding the greater complexity of the protection scheme and the need for operative power. Such relays allow changes to be made in their settings and can be removed, or cut out of the circuit for repair or checking during operation of the circuit element they protect. Such relays, furthermore, possess a relatively high sensitivity and, due to the fact that the connections to the protected circuit elements are made through instrument transformers, are electrically isolated from the high primary-circuit voltage. They are also to a much lesser degree than primary relays subject to the action of short-circuit currents.

As to time of action relays can be distinguished as relays without time delay and relays with time delay. Among the relays which fall under the category of non-time delay are *non-intertia types* with operating times of several thousandths of a second (milli-seconds)- usually electronic relays; *quick-acting relays* with operating times ranging from 5 to 40 ms, and *ordinary relays* with operating times of 0.04 to 0.2 second. Among the time-delay or time-lag relays are relays with *non-regulable* time delay, obtained mainly by the use of short-circuited windings, eddy-current sleeves etc., and also relays with *regulable* time delay. The latter type is termed time-lag relays. Protective relay schemes use time-lag relays having time delays ranging from about 0.2 s upto 5 to 20 s.

As to type of contacts, relays can be differentiated as relays with normally-open (n-o) and normally-closed (n–c) contacts. The relay contacts are called normally-open (n-o) if they are open (separated) when the relay winding is not energised, and normally-closed (n-c) if they are closed (in contact) when the relay winding is not energised. Use is also made of relays provided with two-way or double-throw contacts and with sliding contacts (which during relay operation close for a brief interval of time. When relays are operated, their contacts may close or open instantaneously or with time delay. Relay contacts, depending upon the type and function of the relay, as well as type and material of the contacts themselves, are capable of satisfactorily withstanding multitudes of operations in operative circuits of the corresponding voltage (usually 12 to 220 V) and switch circuits handling power flows ranging from several to hundreds of volt-amperes (VA).

According to applications the relays may be classified as :

(i) ***Over-Voltage, Over–Current and Over-Power Relay.*** The relay operates when the voltage, current or power rises above a specified value.

(ii) ***Under-Voltage, Under-Current and Under-Power Relay.*** The relay operates when the voltage, current or power falls below a specified value.

(iii) ***Directional or Reverse Current Relay.*** The relay operates when the applied current assumes a specified phase displacement with respect to the applied voltage and the relay is compensated for fall in voltage.

(iv) ***Directional or Reverse Power Relay.*** The relay operates when the applied current and voltage assume specified phase displacement and no compensation is allowed for fall in voltage.

(v) ***Differential Relay.*** The relay operates when some specified phase or magnitude difference between two or more electrical quantities occurs.

(vi) ***Distance Relay.*** In this relay the operation depends upon the ratio of the voltage to the current.

According to timing characteristics the relays can be divided into following classes :

(i) ***Instantaneous Relays.*** In these relays complete operation takes place after a very short (negligible) time duration from the incidence of the current or other quantity resulting in operation. The time of operation of such relays is lesser than 0.2 second.

(ii) ***Definite Time Lag Relays.*** In these relays the time of operation is sensibly independent of the magnitude of the current or of other quantity causing operation.

(iii) ***Inverse-Time Lag Relays.*** In these relays the time of operation is approximately inversely proportional to the magnitude of the current or other quantity causing operation.

(iv) ***Inverse-Definite Minimum Time (IDMT) Lag Relays.*** In these relays the time of operation is approximately inversely proportional to the smaller values of current or other quantity causing operation and tends to be a definite minimum time as the value increases without limit.

In induction type of relays the time lag may be achieved by employing a permanent magnet which is so arranged that the relay rotor cuts the flux between the poles of this magnet. Such a magnet is called the "drag magnet".

In other types of relays this may be achieved in two ways. Firstly, when a series connected overload trip coil is used, an oil dash pot can be attached in which is a piston connected to the lower end of the solenoid plunger of the relay. In case of fault when the plunger is pulled, the piston, immersed in the oil, retards plunger motion, thus provides the necessary drag or delay in the relay operation, as shown in fig. 6.2 (*a*).

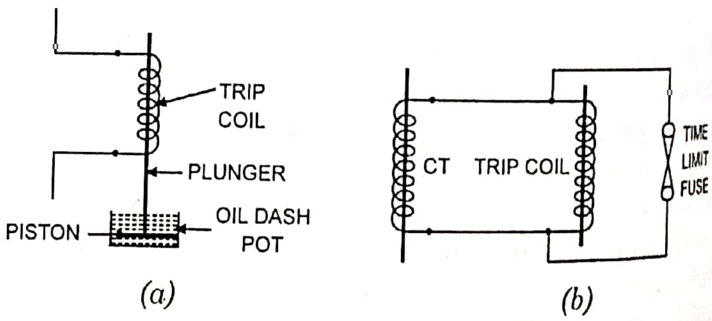
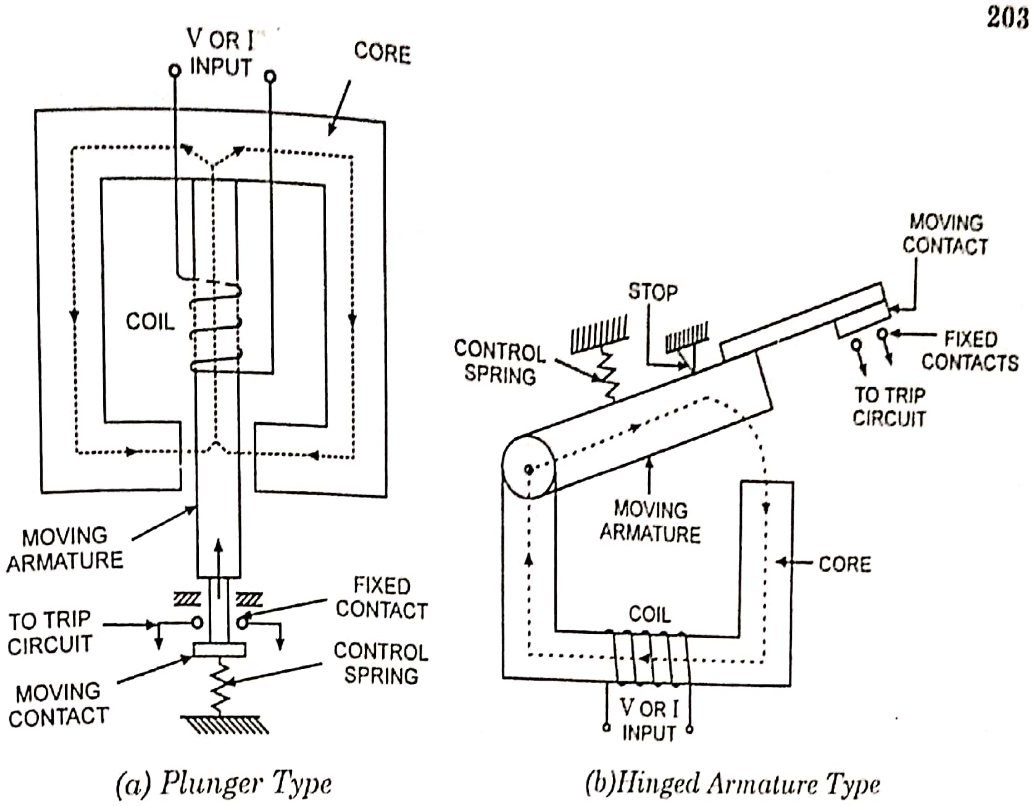


Fig. 6.2

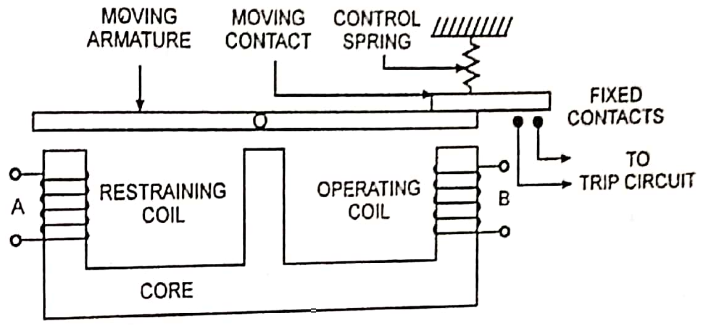
When the trip coil is transformer operated, time delay is achieved by connecting a a time-limit fuse across the trip coil i.e., in parallel. This fuse should have an inverse time-current characteristic and will normally carry the CT secondary current to by-pass the trip coil. As and when sufficient current occurs to "blow" this fuse, the whole current is then transferred to the trip coil which operates to trip the circuit breaker. This is illustrated in fig. 6.2 (*b*).

6.5. ELECTRO-MAGNETIC ATTRACTION RELAYS

These are the simplest type of relays and include plunger (or solenoid), hinged armature, rotating armature (or balanced beam) and moving iron polarized relays–all such relays are shown in fig 6.3. All of these relays operate on the same principle i.e., in such relays the operation is obtained by virtue of an armature being attracted to the poles of an electro-magnet or a plunger being drawn into a solenoid. The electro-magnetic force exerted on the moving element is proportional to the square of flux in the air gap or the square of the current flowing through the coil. It is basically a single actuating quantity relay. Such relays respond to both ac and dc because operating torque is proportional to the square of current flowing through the coil. With dc the torque developed is constant and if it exceeds the restraining torque or force caused by the controlling spring, the relay operates reliably.



(a) Plunger Type (b) Hinged Armature Type



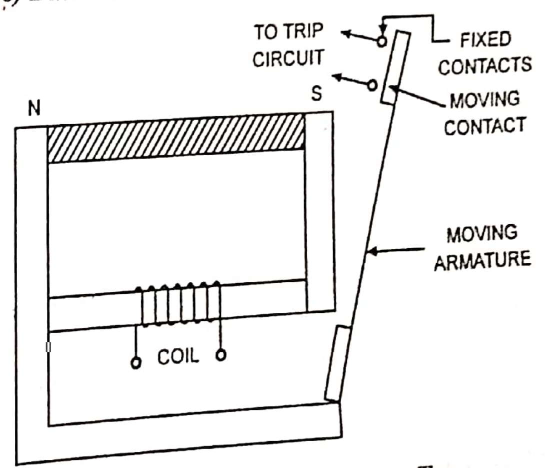
(c) Balanced Beam Type

In case of ac quantity the electro-magnetic force developed is given as

$$F_e = K I^2 = K (I_{max} \sin \omega t)^2$$

$$= \frac{1}{2} K \left[I^2_{max} - I^2_{max} \cos 2\omega t\right] \quad ...(6.1)$$

It shows that the electro-magnetic force consists of two components, one constant independent of time ($\frac{1}{2} K I^2_{max}$) and another dependent upon time and pulsating at double the supply frequency ($\frac{1}{2} K I^2_{max} \cos 2\omega t$). The total electro-magnetic force, therefore, pulsates at double the supply frequency.

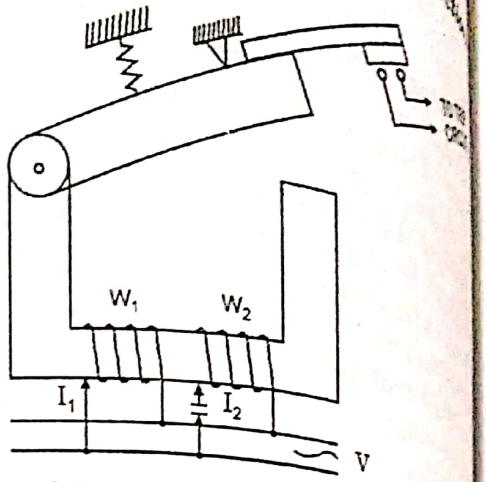


(d) Polarized Moving Iron Type

Electro-Magnetic Attraction Armature Relays
Fig. 6.3

Since the restraining force produced by the spring is constant and the electro-magnetic force developed is pulsating, the relay armature vibrates at double the power supply frequency. This causes the relay to hum and produce noise and also is a source of damage to the relay contacts. This leads to sparking and unreliable operation of the relay operative circuit contacts due to make and break of the circuit.

To overcome this difficulty in ac electro-magnetic attraction relays, the flux developing the electro-magnetic force is splitted into two fluxes acting simultaneously but differing in time phase, so that the resultant deflecting force is always positive and constant. This can be easily achieved either by providing two windings on the electro–magnet having a phase shifting network, as shown in fig 6.4 or by putting shading rings on the poles of the electro-magnet, as shown in fig 6.5. The latter method is more simple and is widely used.

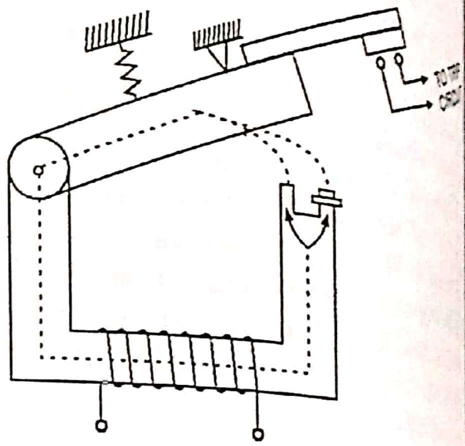


Hinged Armature Electro-Magnetic Relay With Two Windings
Fig. 6.4

Hinged armature relays are mainly employed as auxiliary relays, e.g., tripping relays, ac and dc voltage and current relays.

In the case of a *balanced beam type relay* shown in fig 6.3 (*c*) two quantities $|A|^2$ and $|B|^2$ are compared because electro-magnetic forces developed vary as the square of the ampere-turns. Ratio of reset/operating current for such relays is low. If set for fast operation, it will have a tendency to over–reach on transient conditions.

The sensitivity of the hinged armature relays can be increased for dc operation by the addition of a permanent magnet, as illustrated in fig 6.3 (*d*). This is known as a *polarized moving iron relay*. It is more robust in construction; most of these employ leaf-spring supported armatures.



Hinged Armature Electro-Magnetic Relay With a Shadding Coil on the Pole
Fig. 6.5

Modern attraction armature relays are compact, robust, reliable and fast. VA burden depends on construction, setting etc. For a typical relay it is of the order of 0.2 to 0.6 VA current range of 0.1 to 0.4 A. Such relays are usually instantaneous type but can be made definite time lag or inverse-time lag by using an oil dash pot, an air-escapement chamber clock-work mechanism or by placing a fuse in parallel with the relay. These relays do not have directional feature unless they are provided with additional polarized coil.

The attraction armature relays have fast operation and fast reset because of small length of travel and light moving parts. As these relays are fast and operate on dc as well as ac, they are affected by transients. The transients contain dc component in addition to ac wave. Therefore, though the steady-state value may be less than relays pick-up value, the relay may pick-up during transient state.

Attraction armature relays have many applications in protection of ac and dc equipment. They are, however, sensitive to starting currents, load fluctuations and current surges.

Attraction armature relays can be designed to respond to over–and under–current, over-under voltage, for both dc and ac operations. They are employed as measuring or auxiliary relays.

Balanced beam relay is difficult to be designed over a wide range current because the force is proportional to square of current. Such relays are fast and instantaneous but can be made a definite time lag or inverse–time lag by using an oil dash pot, an air-escapement chamber a clock-work mechanism or by placing a fuse in parallel with the relay. Such relays can have operating time of the order of 0.02 second. High ratio of resetting quantity can be had. VA burden depends on application. In current balance type the VA burden is of the order of 0.2, 0.4, 0.6 VA for 0.1 to 0.6 A current range. This relay is being largely superseded by permanent magnet moving oil relay having better accuracy and lower VA burden.

6.6. ELECTRO-MAGNETIC INDUCTION RELAYS

Electro-magnetic induction relays are the most widely used relays for protective relaying purposes involving only ac quantities. These relays operate on the simple principle of split-phase induction motor. Actuating force is developed on a moving element, that may be a disc or other form of rotor of non-magnetic current-conducting material (such as aluminium), by the interaction of electro-magnetic fluxes with eddy currents that are induced in the rotor by these fluxes.

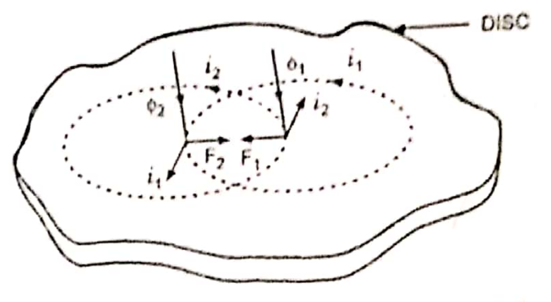
Fig. 6.6 illustrates how force is developed in a section of a rotor that is pierced by two adjacent ac fluxes. Various quantities are shown at an instant when both fluxes are directed downward and are increasing in magnitude. Each flux induce voltage around itself in the rotor, and currents flow in the 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.

The quantities shown in fig 6.6 may be expressed as

$$\phi_1 = \phi_{1max} \sin \omega t$$

$$\phi_2 = \phi_{2\,max} \sin (\omega t + \theta)$$

where θ is the angle by which ϕ_2 leads ϕ_1



Production of Torque in An Induction Relay
Fig. 6.6

It may be assumed with negligible error that the paths in which the rotor currents flow have negligible self inductance, and therefore rotor currents are in phase with their respective induced voltages. The phasor diagram is shown in fig 6.7. Now

$$i_1 \propto e_1 \propto \frac{d\phi_1}{dt} \propto \phi_{1\,max} \cos \omega t$$

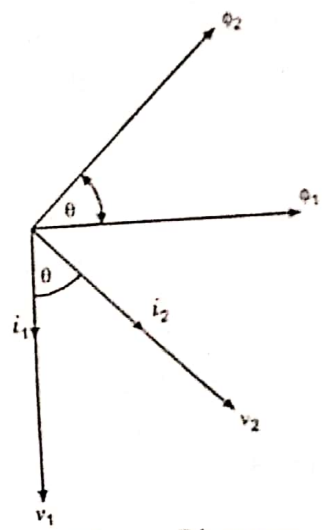
$$i_2 \propto e_2 \propto \frac{d\phi_2}{dt} \propto \phi_{2\,max} \cos (\omega t + \theta)$$

Since the two forces (F_1 and F_2) developed are in opposition, as illustrated in fig 6.6, therefore net force acting on the movable element is given as

$$F = (F_2 - F_1) \propto \phi_2 i_1 - \phi_1 i_2$$

$$\propto \phi_{1max}\, \phi_{2max} [\cos \omega t \sin (\omega t + \theta) - \sin \omega t \cos(\omega t + \theta)] \quad ...(6.2)$$

$$\text{or } F \propto \phi_{1\,max}\, \phi_{2\,max} \sin \theta$$



Phaser Diagram For an Induction Relay
Fig. 6.7

The following points may be noted from expression (6.2)

(i) The net force is same at every instant as the term ωt is not involved in the expression for the force developed. It is most significant. This fact does not depend upon the assumptions made in arriving at expression (6.2). The action of a relay under the influence of such a force is positive and free from vibration.

(ii) The greater the phase angle θ between the two fluxes, the greater is the net force applicable to the movable element. Obviously the force developed will be maximum when phase angle θ is 90°.

(iii) Also the force developed will be more when the resistance R of the annular ring is low because $i \propto \frac{v}{R}$ i.e., the movable element must be of low resistence material such as copper or aluminium. From torque-weight ratio point of view the movable element should be of aluminium alone.

(*ii*) The direction of net force and hence the direction of motion of movable element depends upon which flux is leading.

The different types of structures that have been used for obtaining the phase difference in the fluxes and hence the operating torque in induction relays are (*i*) shaded pole structure (disc type) (*ii*) watt-hour meter or double winding structure (disc type) and (*iii*) induction cup structure.

High, low and adjustable speeds are possible in induction type relays. The ratio of reset to pick-up is inherently high in case of induction relays as compared to attraction armature relays as their operation does not involve any change in the air gap of the magnetic circuit as it is in the case of latter.The ratio lies between 95% and 100%. This is not perfectly 100% because of the friction and imperfect compensation of the control spring torque.

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

Induction type relays are employed extensively for protection against overloads, short-circuits and earth faults on transmission/distribution lines and in industrial plants.

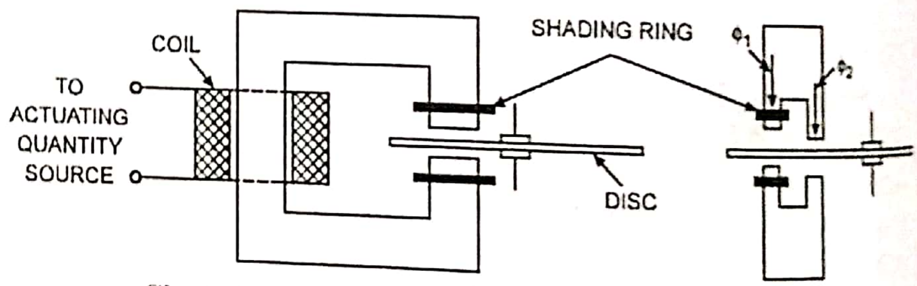
6.6.1. Shaded Pole Structure. The shaded-pole structure, illustrated in fig 6.8, is usually actuated by current flowing in a single coil wound on a magnetic structure containing an air-gap. The air-gap flux produced by the actuating current is split into two fluxes displaced in time and space by a so-called *shading ring* ,generally of copper, that encircles part of the pole face of each pole, as shown in fig 6.8. The disc is normally made of aluminium so as to have low inertia and, therefore, needs less deflecting torque for its movement. The two rings have currents induced in them by the alternating flux of the electromagnet and the magnetic fields developed by these induced currents cause the flux, in the portions of the iron surrounded by the rings to lag in phase by 40° to 50° behind the flux in the unshaded portions of the pole. As already proved, the driving torque is given as

$$T \propto \phi_s \, \phi_u \sin \theta$$

Assuming that the flux in the shaded portion of the pole, ϕ_s and the flux in the unshaded portion of the pole, ϕ_u to be proportional to the actuating current in the coil, I.

$$T \propto I^2 \sin \theta$$

i.e., the driving torque varies as the square of the current flowing through the relay coil.



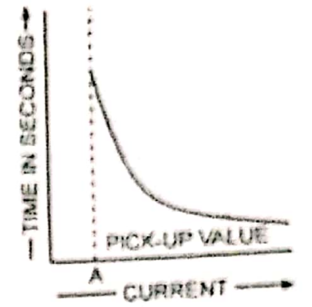
Shaded Pole Construction of Induction Disc Relay

Fig. 6.8

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

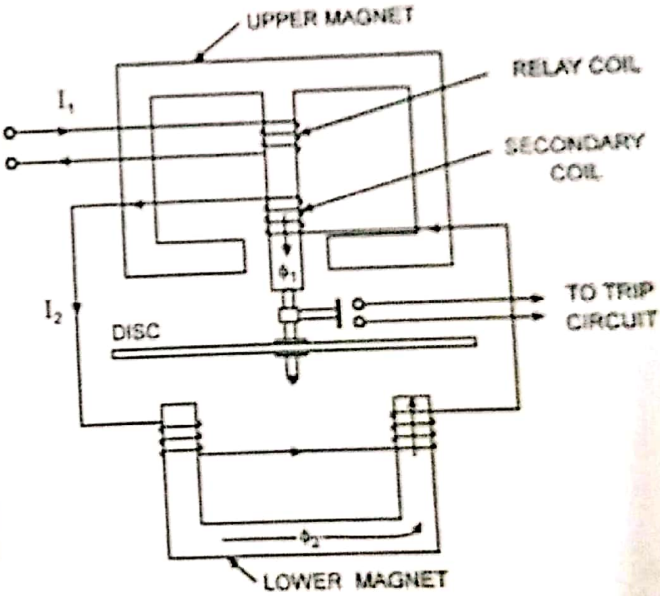
The control torque is provided with the help of a control spring attached to the disc spindle. With the movement of the disc towards closing of the contacts spring torque increases slightly with the winding of the spring. The relay disc is so shaped that as it turns towards the pick-up position (closing of contacts), there is increase in the area of the disc between the poles of the actuating structure which causes increase in eddy currents and, therefore, increase in electrical torque that just balances the increase in the control spring torque. The shape of the disc usually is that of a spiral. Since the shape of disc is not perfectly circular, suitable balance weight is provided on the part of the disc which has smaller area. A permanent magnet of high retentivity steel is provided to give eddy current braking to the disc. This is necessary to reduce to a minimum the over-run of the disc in case the current or voltage providing the driving torque stops before the operation has been completed. A modern induction disc relay will have an over-run of not more than 2 cycles on interruption of 20 times the setting quantity.

Modern induction disc relays are robust and reliable. VA burden depends upon rating. It is of the order of 2.5 VA. The time-current characteristics of induction relays are inverse characteristics, as shown in fig 6.9, i.e., the time reduces as current increases. The current setting can be changed by taking the suitable number of turns. Higher current setting will require smaller number of turns so as to give fixed ampere-turns required for developing the minimum torque for the movement of the disc. The time setting can be changed by changing the relative position of contacts by adjusting the length of travel of moving contacts. This is known as *time multiplier setting*. The higher the time multiplier setting the greater is the operating time. The effect of dc offset may be neglected with inverse time single quantity induction relays, because they are generally slow. The dc offset may affect fast relays. Ratio of reset to pick-up is high (above 95%) because operation does not involve any change in air-gap.



Inverse Characteristic
Fig. 6.9

6.6.2. Watthour-Meter Structure. Watthour meter type induction disc relay gives the same results as given by a shaded pole type. The construction of this relay is similar to the watthour meter commonly used everywhere. It consist of an E-shaped electro-magnet and a U-shaped electro-magnet with a disc free to rotate in between. A phase displacement between the fluxes produced by the two magnets is obtained either by having different resistance and inductance for the two circuits or by energizing them from two different sources whose outputs are relatively displaced in phase. Many variations in the design and construction are possible to suit the required conditions.

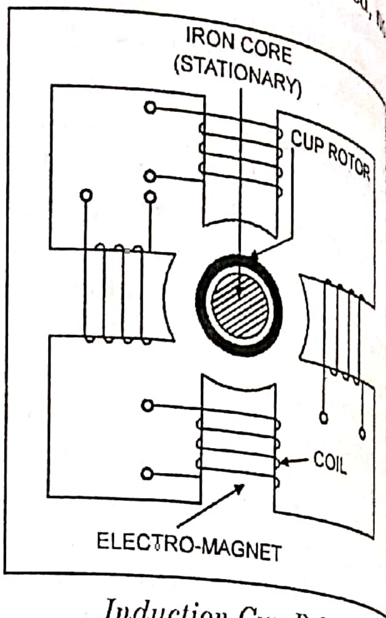


Watthour Meter Type Induction Disc Relay
Fig. 6.10

The E-shaped electromagnet carries two windings; the primary and the secondary. The primary winding carries relay current I_1 while the secondary winding is connected to the windings of U-shaped electro-magnet (fig 6.10). The primary current induces emf in the secondary and so circulates a current I_2 in it. The flux ϕ_2 induced in the U-shaped or lower magnet by the current in the secondary winding of the E-shaped or upper magnet will lag behind flux ϕ_1 by an angle θ. The two fluxes ϕ_1 and ϕ_2 induced in upper and lower magnets respectively differing in phase by angle θ will develop a driving torque on the disc proportional to $\phi_1 . \phi_2 \sin \theta$.

Most of the modern induction relays are of this type. The advantage of this type of construction is that it can provide larger phase angle between ϕ_1 and ϕ_2 and thus higher torque, being proportional to sin θ. An important feature of relay of this type is that its operation can be controlled by opening or closing the secondary winding circuit. If this circuit is opened, torque will be developed and thus the relay can be made inoperative.

6.6.3. Induction-Cup (Electro-magnetic) Relay. These relays operate on the same principle as the induction motor. The relay has two, four or more electromagnets energized by the relay coils. A stationary iron core is placed between these electromagnets (four in number) as illustrated in fig. 6.11. The rotor is a hollow metallic cylindrical cup which is free to rotate in the gap between the electromagnets and the stationary iron core. The rotating field is produced by two pairs of coils wound on four poles as shown. The rotating field induces currents in the cup causing it to rotate in the same direction. The rotation depends on the direction of rotation of the field and the magnitude of the applied voltage and /or currents and the phase angle between them. A control spring, and the back stop or closing of the contacts carried on an arm are attached to the spindle of the cup so as to prevent the continuous rotation.



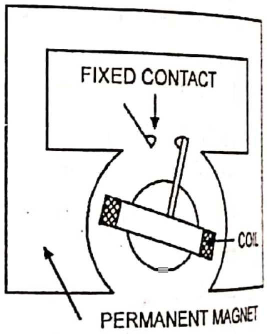
Induction Cup Relay
Fig. 6.11

The operating time characteristic depends on the type of structure. These relays have inverse-time characteristics.

Induction cup structures are more efficient torque producers than either the shaded-pole or the watthour–meter structures. Therefore, such relays are very fast in operation and may have an operating time of less that 0.01 second.

6.7. PERMANENT MAGNET MOVING COIL RELAY

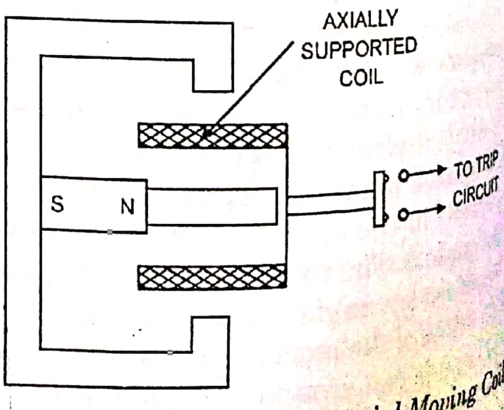
The arrangement is shown in fig 6.12. In this relay, the coil is free to rotate in the magnetic field of a permanent magnet. The torque is developed by the interaction between the field of the permanent magnet and the coil field developed due to flow of actuating current in the coil. The time–current characteristic of such relays is an inverse-time characteristic. The relay responds to dc only but it can be used with ac in conjunction with a rectifier. The characteristic can be varied by adjusting the control spring. The time setting is obtained by adjusting the position of the contact.



Permanent Magnet Moving-Coil Relay
Fig. 6.12

The operating torque is proportional to the actuating current. Such a relay has uniform torque for different positions of the coil and therefore, can be accurately set. Theoretically the reset value is equal to the operating value.

6.7.1. Moving Coil Relay With Axial Moving Coil. Such a relay is shown in fig. 6.13. The coil is supported axially and moves horizontally when energized by the actuating current. Such relay is faster than the rotating coil type owing to small travel and lighter parts. Relay of this type may have an operating time of the order of 0.03 second. Sensitivity can be made as small as 0.1 mW. These relays are delicate and so require careful handling.



Moving Coil Relay With Axial Moving Coil
Fig. 6.13