# SECTION III

# POWER SYSTEM PROTECTION

# 25

# *Introduction to Protective Relaying*

About Protective Relaying — Faults : Causes and Effects — Protective zones — Primary and Back-up Protection — Back-up Protection methods — Desirable qualities of Protective Relaying — Selectivity and Discrimination — Relay time and fault clearing time — Sensitivity — Stability — Reliability — Adequateness — Terms and Definitions in Protective Relaying — Historical Review — Role of Engineer — About further text — Summary — Questions.

## 25.1. ABOUT PROTECTIVE RELAYING

Protective relaying is necessary with almost every electrical plant, and no part of the power system is left unprotected. The choice of protection depends upon several aspects such as type and rating of the protected equipment, its importance, location, probable abnormal conditions, cost, etc. Between generators and the final load points, there are several electrical equipment and machines of various ratings. Each needs certain adequate protection.

The protective relaying senses the abnormal conditions in a part of the power system and gives an alarm or isolates that part from the healthy system.

The relays are compact, self-contained devices which respond to abnormal condition. The relays distinguish between normal and abnormal condition. Whenever an abnormal condition develops, the relays close its contacts. Thereby the trip circuit of the circuit-breaker is closed. Current from the battery supply flows in the trip-coil of the circuit-breaker and the circuit breaker opens and the faulty part is disconnected from the supply. The entire process, 'occurrence of fault-operation of relay-opening of circuit-breaker — removal of faulty part from the system', — is automatic and fast. Circuit-breakers are switching devices which can interrupt normal currents and fault currents. Besides relays and circuit-breakers there are several other important components in the protective relaying scheme, these include : protective current transformers and voltage transformers, protective relays, time-delay relays, auxiliary relays, secondary circuits, trip circuits, auxiliaries and accessories, etc. Each component is important. Protective relaying is a teamwork of these components.

The functions of protective relaying include the following :

— To sound an alarm or to close the trip circuit of circuit-breaker so as to disconnect a component during an abnormal condition in the component, which include over-load, under-voltage, temperature rise, unbalanced load, reverse power, under-frequency, short circuits, etc.

— To disconnect the abnormally operating part so as to prevent the subsequent faults, *e.g.* over-load protection of a machine protects the machine and prevents insulation failure.

— To disconnect the faulty part quickly so as to minimize the damage to the faulty part, *e.g.* If a machine is disconnected immediately after a winding fault, only a few coils may need replacement. If the fault is sustained, entire winding may get damaged and the machine may be beyond repairs.

— To localise the effect of fault by disconnecting the faulty part, from the healthy part, causing least disturbance to the healthy system.

— To disconnect the faulty part quickly so as to improve the system stability, service continuity and system performance. Transient stability can be improved by means of improved protective relaying.

Faults cannot be avoided completely. They can be minimized. Protective relaying plays as importance role in minimizing the faults, and also in minimizing the damage in the event of faults.

## 25.2. FAULTS, CAUSES AND EFFECTS*

A fault in its electrical equipment is defined as a defect in its electrical circuit due to which the flow of current is diverted from the intended path. Faults are causes by breaking of conductors or failure of insulation. Fault impedance is generally low, and fault currents are generally high. During the faults, the voltages of the three phases become unbalanced and the supply to the neighbouring circuits is affected. Fault currents being excessive, they can damage not only the faulty equipment, but also the installation through which the fault current is fed. For example, if a fault occurs in a motor, the motor winding is likely to get damaged. Further, if the motor is not disconnected quickly enough the excessive fault currents can cause damage to the starting equipment, supply connections, etc.

Faults in certain important equipment can affect the stability of the power system. For example, a fault in the bus-zone of a power station can cause tripping of all the generator units in power station and can affect the stability of the interconnected system.

There are several causes of faults occurring in a particular electrical plant. Faults can be minimized by improved system design, improved quality of components, better and adequate protective relaying, better operation and maintenance, etc. However, the faults cannot be entirely eliminated. Fault statistics are systematic records regarding number and causes of faults occurring a particular system. Table 25.1 gives data about such records. These records are useful guides to manufacturers and electricity boards for taking corrective measures.

Faults can be minimized to some extent by taking the following measures :

1. Improvement in the quality of machines, equipment, installation, etc. by improvement in design, manufacturing techniques, materials, quality control, adequate testing, research and development.
2. Improvement in system design, correct lay-out, choice of equipment.
3. Adequate and reliable protection systems ; control.
4. Regular and detailed maintenance by trained personnel.
5. Trained personnel for operation and management of electrical plant.

**Table 25.1. Faults in a System in a Year**

| *Equipment* | *Cause of fault* | *% of Total Faults* |
|---|---|---|
| 1. Overhead lines | 1. Lightning strokes<br>2. Storms, earthquakes, icing<br>3. Birds, trees, kites aeroplanes, snakes, etc.<br>4. Internal over-voltages. | 30—40 |
| 2. Underground cables | 1. Damage during digging<br>2. Insulation failure due to temperature rise<br>3. Failure of joints | 8—10 |
| 3. Alternators (Generator) | 1. Stator faults<br>2. Rotor faults<br>3. Abnormal conditions<br>4. Faults in associated equipment<br>5. Faults in protective system | 6—8 |
| 4. Transformers | 1. Insulation failure (Re. Sec. 12.4)<br>2. Faults in tap-changer<br>3. Faults in bushing<br>4. Faults in protection circuit<br>5. Inadequate protection<br>6. Overloading, Over voltage. | 10—12 |

* Ref. Sec. 1.3 and 12.4 for types and causes of faults.



| *Equipment* | *Cause of fault* | *% of Total Faults* |
|---|---|---|
| 5. CT, PT | 1. Over-voltages<br>2. Insulation failures<br>3. Breaking of conductors<br>4. Wrong connections. | 15—20 |
| 6. Switchgear | 1. Insulation failure<br>2. Mechanical defect<br>3. Leakage of air/oil/gas<br>4. Inadequate rating<br>5. Lack of maintenance. | 10—12 |

## 25.3. IMPORTANCE OF PROTECTIVE RELAYING

Inadequate protection can lead to a major fault that could have been avoided, *e.g.* the thermal over-load protection of motor prevents the over-loading of motor and thereby the insulation failure is avoided. A damaged equipment needs time for repairs and replacement. By adequate protection, the damage can be eliminated or minimized.

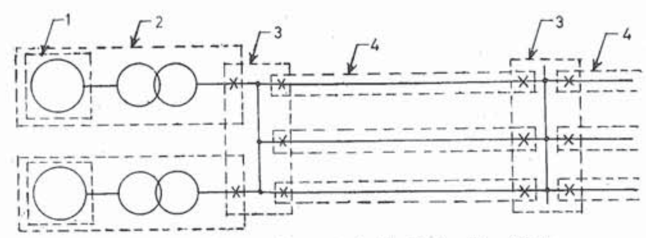
A fault in the equipment in the supply system leads to disconnection of supply to a large portion of the system. If the faulty part is quickly disconnected, the damage caused by the fault is minimum and the faulty part can be repaired quickly and the service can be restored without further delay. Better service continuity has its own merits. Thus the protective relaying helps in improving service continuity and its importance is self-evident.

## 25.4. PROTECTIVE ZONES

The protective relaying of a power system is planned along with the system design. The circuit-breakers are located at appropriate point such that any component of the power system can be disconnected for usual operation and maintenance requirements, and also during abnormal conditions such as short circuits.

Depending upon the rating of the machine, its location, relative importance, probability of faults and abnormal conditions, etc., each power system component (generator, transformer, transmission lines, bus-bar, cables, capacitors, individual loads, etc.) is covered by a protective zone. A part of the system protected by a certain protective scheme is called protective zone or zone of protection. The entire power-system is covered by several protective zones and no part of the system is left unprotected.

Fig. 25.1 (*a*) illustrates the meaning of protective zones. Each zone covers one of two power system components. Neighbouring zones overlap so that no 'dead spot' are left in the protected system (Ref. Fig. 25.1 *b*).




...Boundary of protective zones decided by location of CT's

*x*—Circuit-breaker plus Isolators 1—Generator p.zone
2—Generator transformer unit protective zone 3—Bus bar p.zone
4—Tr. line p.zone.

Fig. 25.1. (*a*). Explaining protective zones.

The boundary of a protective zone is determined by the location of current transformers. Hence, current transformers are located such that the circuit-breakers are covered in the protective zones. (Ref. Fig. 17.24 Sec. 17.11, Fig. 17.2).

G Generator

T Main transformer of unit

TL Transformer Lines

1,1′ Subscript for generator-transformer unit protection system covering circuit-breakers $X, X'$ respectively

2 Subscript for Main Bus Protecting System covering circuit-breaker $X, X'$ and also $Y, Y'$

3.3′ Subscript for transmission line protection systems Covering circuit-breakers $Y, Y'$

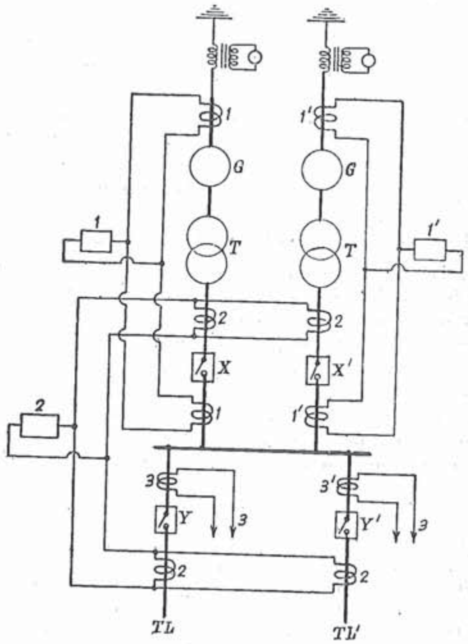



Fig. 25.1. (*b*) Explaining overlapping of neighbouring protective zones in a generation station. in a generation station.

The zones can be precisely identified in unit systems, such as circulating current differential protection of transformers. Unit system is one in which the protection responds to faults in the protected zone alone, and it does not respond to through faults (faults beyond the protected zone). Non-unit systems, such as over-current protection, do not have exact zone boundary.

Each zone has certain protective scheme and each protective scheme has several protective systems.

## 25.5. PRIMARY AND BACK-UP PROTECTION

Primary protection (Main protection) is the essential protection provided for protecting an equivalent/machine. As a precautionary measure, an addition protection is generally provided and is called 'Back-up Protection'. The primary protection is the first to act and the Back-up Protection is the next in the line of defence-meaning, if primary protection fails, the back-up protection comes into action and removes the faulty part from the healthy system. Back-up protection is provided for the following reasons :

If due to some reason, the Main protection fails, the Back-up protection serves the purpose of protection. Main protection can fail due to failure of one of the components in the protective system such as relay, auxiliary relay CT, PT, trip circuit, circuit-breaker, etc. If the primary protection



fails, there must be an additional protection, otherwise the fault may remain uncleared, resulting in a disaster.

When main protection is made inoperative for the purpose of maintenance, testing, etc. the Back-up protection acts like main protection. As a measure of economy, Back-up protection is given against short-circuit protection and generally not for other abnormal conditions. The extent to which back-up protection is provided, depends upon economic and technical considerations. The cost of back-up protection is justified on the basis of probability of failure of individual component in protection system, cost of the protected equipment, importance of protected equipment, location of protected equipment, etc.

The methods of back-up protection can be classified as follows :

1. **Relay Back-up.** Same breaker is used by both main and back-up protection, but the protective systems are different. Separate trip coils may be provided for the same-breaker.

2. **Breaker Back-up.** Different breakers are provided for main and back-up protection, both the breakers being in the same station (Ref. Sec. 43.11).

3. **Remote back-up.** The main and Back-up protections provided at different stations and are completely independent.

4. **Centrally Co-ordinated Back-up.** The system having central control can be provided with centrally controlled back-up. Central control continuously supervises the load flow and frequency in the system. The information about load flow and frequency is assessed continuously. If one of the components in any part of the system fails, (*e.g.* a fault on a transformer, in some station) the load flow in the system is affected. The central coordinating station receives information about the abnormal condition through high frequency carrier signals. The stored programme in the digital computer determines the correct switching operation, as regards severity of fault, system stability, etc. Main protection is at various stations and Back up protection for all stations is at central control centre. The centrally coordinated back-up is a team-work of protective relaying equipment, high frequency carrier current equipment and digital computer (Ref. Sec. 43.14).

The system frequency and active power balance are closely related. Load-frequency control of the Grid is monitored by load control centres.

## 25.6. BACK UP PROTECTION BY TIME GRADING PRINCIPLE

This principle has been used all over the world during last several decades [Fig. 25.2]. The current is measured at various points along the current path, *e.g.*, at source, intermediate locations, consumer end. The tripping time at these locations are graded in such a way that the circuit-breaker/fuse nearest the faulty part operate first, giving primary protection. The circuit-breaker/fuse at the previous station operates only as back-up. Referring to Fig. 25.2, the tripping time at station *C*, *B* and *A* are graded such that for a fault beyond *C* breaker at *C* operates as a primary protection. Meanwhile, the relays at *A* and *B* also may start operating but they are provided with enough time lag so that the circuit-breaker at *B* operates only if the circuit-breaker at *C* does not. (Ref. Sec. 30.2).

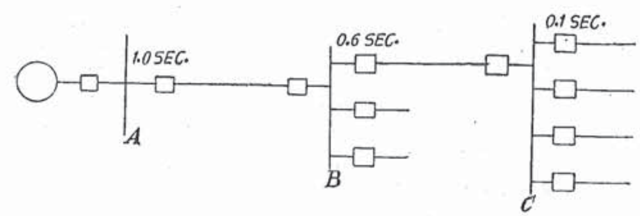



Fig. 25.2. Back up relaying by time-grading.

### 25.6.1. Back-up Protection by Duplication Principle

The principle is very popular in U.S.A. In this form of protection, the important protective devices (protective transformers, protection systems, relays, circuit-breakers, auxiliaries, etc.) are duplicated. Both primary and back-up protections are provided at the same station and are arranged to operate at the same speed, *i.e.* as fast as possible. Such protection is costly and the cost is justified for protection of EHV transmission lines, bus bars, large generators, large transformers, etc. If the cost of separate circuit-breakers is not justified, same circuit-breaker with two independent trip coils can be employed, one for each protection. Sometimes the Main and Back-up protection are based on different principle of operation, *e.g.* differential and over-current, so that if the main protection fails to sense the fault, the back-up protection does not fail to do so.

In protection of generator-transformer unit, differential protection is provided for generator alone plus a second-differential protection is applied to generator-transformer unit, C.B. is common.

The merits of Duplication Back-up principle are :

— Fast and almost simultaneous fault clearing, improved stability.

— Complete reliability can be assured

However, the duplication should be economically justified.

### 25.6.2. Monitoring

Monitoring means checking the performance. Monitoring is used as an alternative to duplicate protection. It is a continuous process of monitoring instrument transformers, relays circuit-breaker trip circuit and other components of primary protection. The monitoring devices continuously switch 'in' and 'out' and determine whether the component is in working order and operational readiness. Circuit-breakers are not actually tripped but are provided a test circuit to facilitate the monitoring. The monitoring is achieved by means of high frequency signals.

Monitoring is also used in protection transmission lines by means of power line carrier telemetering. (Ref. Sec. 44.6)

In large networks load frequency is monitored constantly. Generation is matched with load to maintain constant frequency (50 Hz ± 1%).

The reactive power compensation required and bus-voltages are monitored constantly to ensure voltage stability.

## 25.7. DESIRABLE QUALITIES OF PROTECTIVE RELAYING

Protective relaying should have certain qualities. Some of these quantities cannot be expressed in form of a mathematical expressions, however, they are important. The qualities of protective relaying are named as

— Selectivity, discrimination.

— Sensitivity, power consumption.

— Reliability.

— Adequateness.

— Speed, time.

— Stability.

— System security

The qualities should be carefully considered while selecting protection schemes for power system protection. Cost is also equally important. A better protective system costs more.

### 25.7.1. Selectivity and Discrimination

Selectivity is a quality of being selective. A protective system should be 'selective' in protecting-meaning, the protective relaying should select the faulty part of the system and should isolate, as far as possible, only faulty part from the remaining healthy system. Discrimination is 'the act discriminating' or 'distinguishing the difference between'. 'Discriminating quality of protective relaying enables it to distinguish between' the following :

Normal Condition—Abnormal condition.

Abnormal Condition within the protective zone-Abnormal condition elsewhere.



The protective system should operate only during abnormal conditions and should not operate under normal condition. In other words, the protective relaying system should discriminate between normal condition and abnormal condition. It should select and disconnect only faulty part without disconnecting the remaining healthy part.

Protective relaying should be inoperative and stable during faults and abnormal conditions beyond its protective zone. It should not operate for faults, abnormal conditions beyond its protective zone. Referring to Fig. 25.3, if a fault occurs on transmission line, the protective relaying should isolate only the faulty line without tripping the neighbouring line or the transformer. For fault $F_1$, only circuit-breaker $CB_1$ should open. For fault $F_2$, both $CB_2$ and $CB_3$ should open.

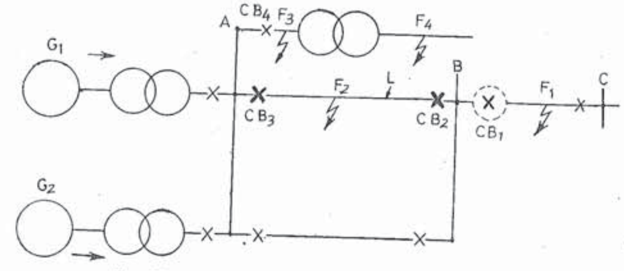



Fig. 25.3. Explaining selectivity and sensitivity.

In Unit-protective systems the selectivity is almost absolute. Such protective systems respond to faults in their protected zone alone. They doe not respond to faults elsewhere. Non-unit systems of protection use some other principle (such as graded time lag, graded current feature, directional feature, distance principle, etc.) for obtaining discrimination. However, in no-unit systems, the selectivity is not exact.

If protective relaying is not selective, and operates for faults beyond its protective zones, a larger portion of the system gets disconnected unnecessarity, causing embarrassment to supplier and consumers.

### 25.7.2. Relay Time and Fault Clearing Time (Ref. Sec. 2.11)

Fault clearing time is the time between the instant of fault and instant of final are interruption (in circuit breaker).

Fault clearing time is the sum of relay-time and circuit breaker-time.

Remember the time events

Fault Clearing Time = [Relay Time] + [Breaker Time]

$$\begin{bmatrix}\text{Fault Instant}\\ \text{to}\\ \text{Closing of}\\ \text{relay contacts}\end{bmatrix} + \begin{bmatrix}\text{Closing of relay}\\ \text{contacts to Final}\\ \text{Arc-extinction}\\ \text{in C.B.}\end{bmatrix}$$

The relay-time is the time between the instant of occurrence of fault and the instant of closure of relay contacts. Or, it is the time between the instant when the operating quantity reaches the pick-up value and the instant of closure of relay contacts.

The circuit breaker time is the total of time taken by operating mechanism to open to circuit breaker contacts and the arching time. It is also called total break time.

The fault clearing time is significant due to the following reasons :

1. Rapid fault clearing minimizes the damage. During short circuit tests on bus bars, with fault duration of 0.07 second, with 60 kA r.m.s. value of current, no damage was observed after the tests. With fault duration of 7 seconds, however, the bus bars were completely destroyed.

2. Rapid fault clearing improves power system stability. For the reason, the slow relays and slow circuit breakers should not be preferred for protection, where stability is important. This applies to protection of EHV transmission lines, protection of large machines like important generator, large transformer, large-motors, etc., and protection in important generating stations and receiving stations.

Though fast fault clearing is desirable, time lag is purposely provided in majority of protection systems for the following purposes :

— To permit discrimination between main and back-up protection.

— To prevent the operation of relay during transients, starting currents, permissibly load fluctuations, etc.

The relay-time of fast relays is of the order of a few cycles and that of inverse time relays can be adjusted between about 6 seconds to 60 seconds. The circuit-breaker time of slow circuit-breakers is of the order of 5 cycles and that of fast circuit-breakers is of the order of 2 cycles to 3 cycles.

Static Relays of 1/2 cycle or one cycle are now available.

### 25.7.3. Sensitivity

Sensitivity of a protective scheme refers to the smallest value of actuating quantity at which the protection starts operating in relation with the minimum value of fault current in the protected zone.

Referring to Fig. 25.3, consider the protection system of the transmission line $L$. The protection system should be so sensitive that it should respond to a fault say $F_2$ for minimum fault current.

Minimum fault current can flow when :

Only one generator (Say $G_1$) is connected in the system, other generator ($G_2$) being disconnected.

— The fault is at the receiving end of the transmission line.

— The fault is an arcing fault, the arc path being through air, the arc resistance is high and fault current low.

The protection should be sensitive enough to act during a fault under such conditions. Sensitivity can be defined in terms of sensitivity factor $K_s$ equal to ratio of minimum short-circuit current and minimum operating current, *i.e.*

$$K_s = \frac{I_s}{I_o}$$

where $K_s$ = Sensitivity factor

$I_s$ = Minimum short-circuit current in the zone

$I_o$ = Minimum operating current of protection

The operation current should not be kept too small for following reasons :

— The protection should not operate on maximum loads.

— The protection should not operate under through fault conditions, or faults some where else in the system.

Hence the sensitivity should be chosen with due considerations to the following :

— Minimum fault current in protected zone

— Operating values required for primary and back-up protection. For example, Fig. 25.3 ; the protective scheme for busbar protection should be such that, it does not respond to fault $F_2$ as a primary protection. Fault $F_2$ should be cleared by $CB_3$. However the bus-bar protection at $A$ should provide a back-up for the protection of line $L$.



### 25.7.4. Stability

Stability is defined as the quality of protective system by the virtue of which, the protective system remains inoperative and stable under certain specified condition such as system disturbance through faults, transients, etc.

Consider protection of transformer. For faults beyond the protected zone, the protection of transformer should remain stable. To achieve such stability, the relay CT's, protective scheme design and type of disturbance are important. To improve stability certain modifications are necessary in relays design and the relay scheme. For example biased differential protection for protection of power transformer is more stable than plain differential protection. Further, to make the transformer protection insensitive to inrush of currents during switching-in, provision like Harmonic Restraint are provided. In many cases, time delay, mechanical and electrical bias, filter circuits etc. are provided to make the relays stable during certain disturbances.

### 25.7.5. Reliability

Reliability means trustworthiness. The protective relaying should not fail to operate in the event of faults in the protected zone. Secondly, there should not be any fault in the components of protective system. Protective system should not operate unnecessarily. Reliability of protective systems is assessed from statistical data. 'Reliability' cannot be easily specified in terms of a mathematical expression with certainty. Statistical survey and records give idea about reliability of protective systems. With increasing size of systems, use of EHV lines, interconnections and use of large generators and transformers, the importance of reliability of protective systems has increased.

The protective system is a teamwork of several components. A failure or defect in any one of them can result in failure of protection system. Hence the basic requirement of reliable protection is reliability of each component including circuit-breaker, relays, CT's, PT's secondary cables, trip circuit, battery system accessories, etc. Next the design of protection system, installation, maintenances, etc., are also very important. These aspects are mentioned in Fig. 25.4. It is clear that the reliability of protective systems depends on diverse aspects and a good reliability is a task to be shared by the protective gear manufacturers, electricity boards and associates.

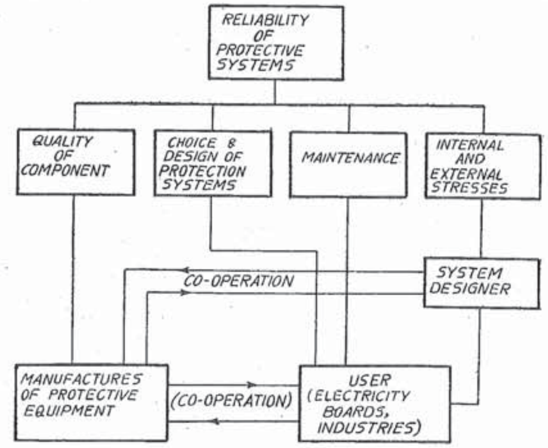



Fig. 25.4. Reliability of protective systems is influenced by several aspects.

### 25.7.6. Adequateness

There can be many abnormal conditions and providing protection against every abnormal condition is economically impossible. However, the protection provided for any machine, should be adequate. The adequateness of protection is judged by considering the following aspects :

— Rating of the protected machine.
— Location of the protected machine.
— Probability of abnormal condition due to internal and external causes.
— Cost of the machine, important.
— Continuity of supply as affected by failure of machine.

for low voltage machine/equipment, at the remote end of the system, an elaborate and costly protective system is not necessary. For example, distribution transformers below, say 500 kVA are protected simply by drop-out fuses. Motors below 100 kW are protected by thermal over-load relays and HRC fuses. In these cases, the cost of CT's and protective relays, circuit-breakers, etc. is not generally justified. Whereas for a large machine, say generator, a very complex protective scheme is necessary. The adequateness of protection should be assessed while planning the protection scheme. Each installation generally needs particular attention, as the protective relaying needs are influenced by local conditions.

## 25.8. SOME TERMS IN PROTECTIVE RELAYING

The meaning and definitions of some terms concerned with protective relaying are given here, for the sake of familiarity.

1. **Relay.** Relay is a device by means of which an electric circuit (trip circuit of alarm circuit), is controlled, (closed), by change in the other circuit. Relays are automatic. There are several types and application of relays. Relays are essential components of protective systems.

2. **Protective Relay.** A protective relay is an electrical relay used for protective of electrical devices. It is a device which closes its contacts, when operating quantity reaches certain predetermined magnitude/phase. Closing of relay contacts initiates an alarm circuit or trip circuit.

3. **Measuring Relay.** A measuring relay operates at a predetermined value of operating quantity by performing the necessary measurement. A relay in which, the operation is independent of measurement is called *all-or-nothing* relay. *All-or-nothing* relays, auxiliary relays, etc, are used to supplement the measuring relay.

4. **Trip Circuit.** The circuit comprising trip coil, relay contacts, auxiliary switch, seal in coil, battery supply, etc; which controls the circuit-breaker for opening operation.

5. **Current Transformers (CT).** These are used for measurement purpose and protective relaying purpose. Accordingly, they are called measuring CT and protective CT. The current ratio of a CT is usually high. The secondary current ratings are of the order of 5 A, 1A, and 0.1 A, the latter being used for static relays. Primary current ratings vary from 10 to 3000 A or more. Ratio error and phase angle are important aspects of CT's. The CT's play an important role in protective relaying. The Volt-Ampere rating of current transformers is low (5—150 VA) as compared with that of power transformers (a few kVA to several MVA).

6. **Voltage Transformers or Potential Transformer (V.T.).** The voltage transformers step-down the primary voltage to a secondary voltage of lower value. The standard rated secondary voltage is 110 V, 240, 440 V. The Volt-Ampere capacity of Potential Transformer is small relative to that of power transformers. The VT's are used for measurement and protection. They are accordingly called as measuring instrument potential transformers and protective potential transformers.

7. **Auxiliary Switch.** A multipoint switch which operates in conjunction with circuit-breaker and connects/disconnects certain protective, indicating and control circuits in each position, (open and close). It is placed in the switch cubicles of circuit-breakers and isolators.

8. **Fault Clearing Time.** Time elapsed between the instant of occurrence of fault and instant of final arc extinction in circuit breaker. It is expressed in milliseconds (ma) or cycles I cycle in 50 Hz system is equivalent to 1/50 second, *i.e.* 0.02 second.



9. **Relay Time.** Time interval between occurrence of fault and closure of Relay contact (Ref. Ch. 2).

10. **Breaker Time.** Time interval between closure of trip circuit and final arc interruption. Relay time plus breaker time is equal to fault clearing time. (Ref. Sec. 25.7.2)

11. **Stability of Power System.** Stability denotes a condition during which all the Synchronous machines in the system are in synchronism, *i.e.* in step with each other. [Ref. Ch. 44]

12. **Earth Fault.** A fault which involves earth (ground); *e.g.*, single line to ground fault, double line to ground fault, arcing grounds.

13. **Phase fault.** A fault which does not involve earth; *e.g*, Line to line fault.

14. **Instantaneous Relay.** A fast relay having relay time of less than 0.2 second and having no intentional time lag.

15. **IDMT Relay.** Inverse definite minimum time relay, is a relay having an inverse characteristic of current *vs.* time, upto certain increased value of current after which the time is definite.

16. **Electro-mechanical Relay.** Conventional relay in which the measurement is performed by moveable parts.

17. **Static Relays.** Relays in which relay measurement or comparison is performed by stationary (static) circuit.

18. **Biased Relay.** A relay whose characteristic is modified by additional mechanical or electromagnetic procession such as a bias-coil, magnet, etc.

19. **Power Consumption of a Relay.** The value of power consumed expressed in VA (for a.c.) or watts (for d.c.) under certain specified conditions.

20. **Pick-up.** The operation of relay is called relay Pick-up. Pick-up value or level is the value of operating quantity which is on threshold (border) above which the relay operates and closes its contacts. Consider an over-current delay. During an injection test, suppose, the current is gradually increased. At a certain value of current, the relay contacts are on the verge of moving such that increase in current causes contacts movement. This value of current is known as pick-up value. Normally the relay setting corresponds to pick-up value.

21. **Reset, drop-out.** The value of current/voltage etc. below which the relay resets and comes back to original position.

22. **Over-current Relay.** A relay which responds to increase in current.

23. **Earth-fault Relay.** A relay which sense earth fault.

24. **Distance Protection.** A protection scheme used for protection of transmission lines in which the relay measurement is based on measuring *V/I* ratio at relaying point which gives a measure of distance between relay location and fault location.

25. **Differential Protection.** A protective system which responds to vector difference (phase/magnitude) between two or more similar electrical quantities.

26. **Protective Scheme.** A set of protective systems covering a particular protective zone, *e.g.* Transmission line protective scheme may comprise overcurrent protection system, earth fault protection system.

27. **Protective System.** A combination of components which together, performs the protective relaying. The components include CT's pilot wires, measuring relays, seconding circuits, trip circuit.

28. **SCDA.** Supervisory Control and Data Acquisition. Computer based system which performs measurement, data acquisition, data transmission, operating and control functions. (Ref. Sec. 50.4)

29. **Auto-reclosure.** The process of automatic reclosing of circuit breaker after its opening. (Ref. Sec. 44.12).

30. **Power Line Carrier (PLC).** High frequency signals sent through the power line conductors (for purpose of communication, monitoring and protection).

31. **Carrier Current Protection.** Protection of transmission line by means of power line carrier signals.

32. **Unit Protection.** Protection system in which the protective zone can be clearly identified by means of CT boundaries. Such protection does not respond to through fault. It responds to only internal faults. (*e.g.* Differential protection of Power Transformer).

33. **Reach. (of Distance Protection of Lines).** The limiting distance 'covered by the protection, the faults beyond which are not within the reach of the protection and should be covered by other relay.

34. **Over-reach. (of Distance Protection).** Operation of (distance) relay for a fault beyond its set protected distance (say 130%).

35. **Under reach (of distance protection).** Failure of distance relay to operate within the set protected distance (say 90%).

36. **Carrier Transfer (Inter tripping).** Carrier signal sent from one end to other end of transmission line so as to trip the circuit-breaker at the other end.

37. **Carrier Blocking.** Carrier signal sent to other end of transmission line so as to reduce the relay time at that end by shunting the step timer.

## 25.9. DISTINCTION BETWEEN RELAY UNIT, PROTECTIVE SCHEME AND PROTECTIVE SYSTEM

A protected equipment (say, a Generator) comes in a particular protected zone. It is protected by a 'Protection scheme'. The protection scheme has a set of protective systems, *e.g.* a large generator may have a protection scheme comprises overcurrent protection, differential protection, earth fault protection, and so many others. Hence, *protection scheme* comprises set of protective systems and the protection schemes is named according to the protected equipment *e.g.*

— generator protection (scheme) — transformer protection (scheme)

(The word 'scheme' is generally omitted).

The term *Protective System,* or simply 'protection' is named according to the principle of operation or abnormal condition. Protective transformers and relays connected in a particular fashion for giving protection against certain abnormal condition/conditions. The protective systems are named as follows :

Names based on abnormal condition :

— Over-current protection (system) — Earth fault protection (system)
— Reverse-power protection (system) — Under-voltage protection (system)
— Under-frequency protection (system), etc.

Names based on principle of operation.

— Differential protection (system) — Distance protection (system)
— Power line carrier protection (system)

(The word system may be omitted).

*Relay Unit* or 'Relay' is a self-contained unit comprising one or more coils, fixed and movable sub-assemblies, or static circuits, provision for plug-setting, time-setting, etc. Relay unit is an important component of the protective system. It is generally named according to its type of construction/principle of operation. It is either electromagnetic or static.

## 25.10. PROTECTIVE CURRENT TRANSFORMERS AND VOLTAGE TRANSFORMERS

Protective relays are generally connected in the secondary circuit of current transformers and voltage transformers (Potential Transformer). The primaries of these transformers are connected in the main power circuit.



The connection of the secondaries of protective current transformers and voltage transformers depend upon the design of protective system. In large installation, several sets of CT's and VT's are necessary for various protection systems.

Protective current transformers and voltage transformers should behave satisfactorily during transient abnormal conditions. Hence their accuracy under transient condition is very important.

## 25.11. ACTUATING QUANTITIES

The discrimination between normal and abnormal condition can be judged by measuring actuating quantity. The electrical relays respond to current/voltage, derived from secondaries of CI's or VT's connected to the protected equipment. During abnormal condition the actuating quantity varies according to the type of fault. For every type and location of abnormal condition, there is a distinct variation in some of the quantities. Hence the actuating quantity for the relays can be one or more of the following parameter of voltage/current derived from CT/VT.

— Magnitude — Frequency
— Rate of change — Wave Shape.
— Phase Angle — Duration (Time)
— Direction — Ratio

In recently developed system, the functions of measurement, protection, control and data acquisition are integrated. Supervisory control and Data Acquisition Systems (SCADA) are used in modern interconnected power system. (Ch. 50).

## 25.12. ELECTRO-MECHANICAL RELAYS AND STATIC RELAYS

The conventional electro-mechanical relays have movable sub-assemblies. The operation of such relays is based upon the following effects of electric current :

— electromagnetic attraction — electromagnetic induction
— thermal effect, heat generated by $i^2rt$.

Some electromechanical relays responds to gas pressure generated due to heat of arc. (Buchholz Relay).

Static relays do not have any movable parts in their measuring system. The measurement is carried out by stationary electronic circuit. Static relays have several merits and are being increasing used for various application. Recently 'Programmable Relays' have been introduced. (Ref. Sec. 43.13).

## 25.13. POWER LINE CARRIER CHANNEL (PLC)

High frequency signals are transmitted through the transmission line conductor for the purpose of communication, protection, signalling and monitoring.

Carrier current equipment are installed at the sending end and receiving end of transmission line sections.

The power line carrier equipment can be used for the following :

— to send tripping signals to the other end of transmission line so as to open the circuit-breaker at that end (Inter-tripping).
— to send signal to the remote end so as to accelerate the relays at the other end of the transmission line (carrier acceleration).
— to send blocking signal to the other end of transmission line so as to prevent tripping of circuit-breaker at that end (carrier blocking).
— carrier current protection of transmission line based on differential principle.

Carrier current signalling is used along with digital computers for network monitoring, central load control, central back-up protection.

### 25.14. PROGRAMMABLE RELAY

Conventional electromagnetic and static relays are hard wired relays. Their wiring is fixed. Only their setting can be manually changed. In recent years, programmable relays are introduced. They have a microprocessor in their circuit. The characteristics and behaviour of the relay can be programmed. The programme can take care of on line computation. Such relays are useful for centrally co-ordinated back-protection (Ref. Sec. 46.12).

### 25.15. SYSTEM SECURITY

Failures cannot be totally avoided. In a large interconnected system, one or two major faults (contingencies) may cause cascade tripping of circuit-breakers resulting in black-out over a large part of the system. Such occurrences can be avoided by installation of computerized SCADA and EMS systems in addition to the protective relaying systems. (Ref. Ch. 50).

System Security is defined as the ability of the system to operate in normal state even with occurrence of certain specified contingencies. (Ref. Sec 50.9).

### 25.16. ROLE OF ENGINEERS

The tasks of engineers include the following :

— Planning of protection.
— Design of protective systems, systems studies.
— Choice of protection, protective equipment.
— installation, setting, commissioning
— maintenance.
— maintaining a check on failures, assessing causes and remedies.

The engineers working in other fields such as machine designers, project engineers, manufacturers of electrical equipment, contractors, railway engineers etc. need knowledge regarding failures of equipment, their causes and remedies, and protective gear applications. Failures may be prevented by proper choice of equipment and good protective systems.

**Summary**

Faults are caused by insulation failure or breaking of conductors. Besides faults, there are other abnormal conditions. Protective systems prevent faults by disconnecting an equipment in the event of abnormal condition. Further, if faults develop, the protective system disconnects faulty parts. Protective system is a team of relays, circuit breaker, CT's PT's and other components. 'Sensitivity, time selectivity stability, adequateness, reliability, are the desirable qualities of protective systems. Selectivity or Discrimination is the property by virtue of which the protective relaying system distinguishes between normal condition and abnormal condition, faults in the protection zone and fault elsewhere. 'Sensitivity' of a protection refers to the minimum operating current in relation with minimum fault current in the protected zone. 'Sensitivity' of a protection refers to the minimum operating current in relation with minimum fault current in the protection zone.

'Relay time' is the time between occurrence of fault and closure of relays contacts. 'Stability' is the property of the protective relaying system by virtue of which, the protective relay remains unoperated during system disturbances and through fault conditions 'Reliability' is trustworthiness. To achieve reliability, the quality of each component, maintenance and every aspect of protective relaying is important. Reliability is improved by co-operation between manufacturers and electricity boards. Static Relays do not have movable parts in their measurement circuit.



## QUESTIONS

1. Describe the faults clearing with reference to the following :
   — Components in protective system.
   — Sequence of operations between occurrence of fault and final arc extinction in circuit-breaker.
   — Fault clearing time.
2. Discuss the cause of faults and need of protective systems.
3. Fig. Q. 3 shows a portion of power system. Draw main and back-up protective zone. Showing the overlappings of neighbouring protective zones; for short-circuit protection.
4. Discuss the role of back-up protection. What are the various methods of giving Back-up protection ? (Ref. Ch. 43)
5. Discuss the back-up protection achieved in graded time over-current protection of radial transmission lines.
6. What are the merits of rapid fault clearing in case of
   1. Distribution systems ?
   2. Transmission systems ?
   Why rapid fault clearing is not possible in graded time over-current protections system ?

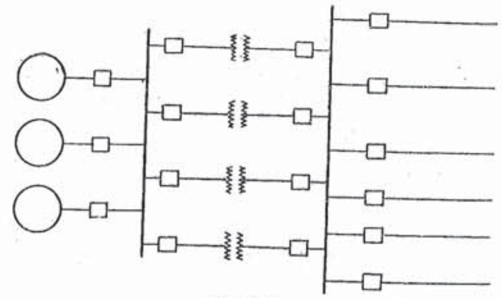


Fig. Q.3.

7. Discuss the factor influencing 'Reliability' of protective system. Suggest, how the reliability can be improved.
8. Define and explain the following :
   — Sensitivity of relay.
   — Relay time, Fault-clearing time.
   — Stability of protective system.
9. Discuss the present trends in power system protection with reference to static relay and digital computers. (Ref. Ch. 46).
10. Explain the term 'Fault clearing time'. How can the stability of a power system be improved, for given circuit configuration ?
11. State the types of faults in power system. Discuss causes the effects of faults. (Ref. Sec. 1.3, and 12.4).
12. Describe essential qualities of protective systems with reference to protection of generator. Illustrate the protective zones in a generating station layout.

**Note :**

1. Ch. 25 Introduction to protective relaying applies to conventional and static protection systems. Ch. 26 refers to electromagnetic and electromechanical relay units only. Ch. 27 to 36 deal with abnormal conditions and protective systems which apply to both conventional and static relays. Ch. 38. to Ch. 43 deal with static relays and protection schemes. *Both electromagnetic and static relays are equally important.*
2. *Integrated Protection and Control System and Modular Configuration of Static Relays.*

   In traditional electromagnetic relays and earlier generations of static relays, a separate relay unit is used for each protective function.

   In the second generation of static relays, several protective functions are provided in a single modular static protection relay system. *e.g.* Motor Protection Relay provides overcurrent, earth fault, undervoltage, stalling protection etc. in a single unit.

   In the third generation of static protection systems, modular microprocessor based integrated configuration is used. The functions of Measurement, Protection, Control, Data Acquisition and transmission are provided a single system. Choice of functions is based on requirements.

# 26

# *Electromagnetic Relays*

Introduction — Definitions — Principle Types of Relays — Attracted Armature Type — Balanced Beam Relay — Induction Disc — Induction cup — Permanent Magnet Moving Coil — Thermal — Gas Operated — Operating Characteristics — Seal — in — Feature — Design Features — Auxiliary Switch — Sealing, Holding, Relay Unit, Protective Systems, Protective Schemes — Pick-up and Drop off — Rectifier Systems — Directional element — All-or-nothing Relays -- Plug setting — Time Setting — Summary — Questions.

## 26.1. INTRODUCTION

'Relay is a device by means of which an electric circuit can be controlled (opened or closed) by the change in the same circuit or other circuit.' An electro-mechnical relay, has one or more coils, movable elements, contact system, etc. The operation of such relay depends on whether the operating torque/force is greater than the restraining torque/force *i.e.*

The relay operates, if the net Force $F$ in Eq. (1) below is positive; or net $T$ in Eq. (2) below is positive.

$$F = F_o - F_r \qquad \text{...(1)}$$

$E$ = Net Force

$F_o$ = Operating Force

$F_r$ = Restraining force

or

$$T = T_o - T_r \qquad \text{...(2)}$$

$T$ = Net torque

$T_o$ = Operating torque

$T_r$ = Restraining torque

Relay operates when Operating force > Restraining force

In electromechanical relays, the operating torque is produced by electromagnetic attraction/electromagnetic induction/thermal effects of electric current. The restraining torque is given by springs. The various terms such a Measuring Relay, All or-nothing relay, trip circuit, time lag relay, instantaneous relay, etc. are covered in section 25.8. They will be studied in this chapter.

The contact circuit of electromechanical relays are quite complex. Simplified diagrams have been given in this section for explaining the principle.

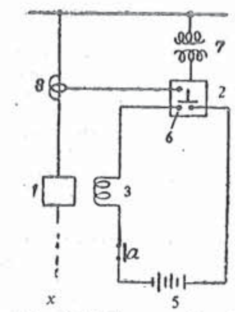
## 26.2. BASIC CONNECTIONS OF TRIP CIRCUIT

Fig. 26.1, given below, illustrates the basic connections of the circuit breaker control for the opening operation. It is rather an over-simplified diagram; for the sake of understanding the principle.

Referring to Fig. 26.1, the protected circuit $X$ is shown by dashed line. When a fault occurs in the protected circuit, the relay (2) connected to the CT and PT actuates and closes its contacts (6).

Current flows from the battery (5) in the trip circuit (4). As the trip coil of the circuit breaker (3) is energized, the circuit breaker operating mechanism is actuated and it operates for the opening operation Auxiliary switch $a$ is an important item in the circuit.






1. Circuit breaker
2. Relay
3. Trip coil of c.b.
4. Trip circuit
5. Battery
6. Relay contacts
7. Potential transformer
8. Current transformer

*a* Auxiliary switch contacts
*x* Protected element/circuit

Fig. 26.1. Simplified diagram of circuit breaker control of opening operation.

## 26.3. AUXILIARY SWITCH, SEALING, AND AUXILIARY RELAYS

Fig. 26.1 is a simplified figure. In actual practice, the measuring relay is assisted by seal-in relay, time-delay relay tripping relay, auxiliary switch, etc. and the resulting contact circuit is quite complex. Further, there are sequential operations within the set of relays. The control circuit is further modified for schemes such as *'Autoreclosure', 'intertripping' 'anti-pumping' trip-free'* Schemes. In this section, the functional details are briefly discussed.

### 26.3.1. Auxiliary Switch

Auxiliary switch is an important device in the trip circuit of the circuit breaker. It is a multi-point switch (4 point, 6 point, 12 point, 24 point) which is mechanically interlocked with the operating mechanism of the circuit breaker such that when the circuit breaker opens, the auxiliary switch also opens, thereby disconnecting trip circuit, certain indicating circuits and control circuits. The terminal blocks are provided in the control cabinet. The various control wiring is done *via* the terminal blocks.

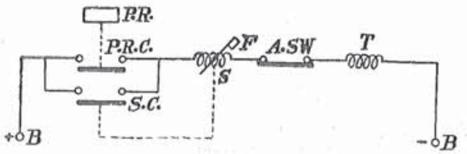
The current in trip circuit is interrupted by Auxiliary Switch and not by the protective relay contacts. The relay contacts are light and delicate so that the weight of moving parts is low and consumption of relay is low. Hence relay contacts are not designed to interrupt the current in trip circuit. The trip coil consumption is of the order 7.5 watts for small oil circuit breakers to about 25 watts for large oil circuit breakers, the voltage ratings being of the order of 30, 125, 250 V.D.C. This voltage for trip current is supplied from battery system. While opening of trip circuit, (an inductive circuit), an inductive circuit is being opened and this needs a robust switching device. Auxiliary switch is designed for such a duty. Auxiliary switch is placed in the switch cubicle or control-cabinet of the circuit-breaker.

Besides the trip circuit connections, the indication circuits (to indicate whether the c.b. is 'open' or close). circuit of interlocking (between breakers, isolators and other devices) and some control circuits are also connected/disconnected by auxiliary switch.

### 26.3.2. 'Sealing', 'Holding', 'Repeat Operation'

As mentioned earlier, the relay contacts are designed for light weight and they are therefore delicate. The protective relay only closes its contacts and it is relieved of other duties such as time lag, tripping, (carring current for longer time, breaking trip circuit), etc. These duties are performed by 'auxiliary relays'. There are various schemes of sealing or holding. Repeat operations are performed by repeat contactors/auxiliary relays. The name 'repeat' means, these relays repeat the operations of protective relay. The repeat contractors close as the protective relay closes and they perform the function of sealing, holding. Fig. 26.2 gives a scheme in which the operations follow the following sequence. (Refer Fig. 26.2).

To begin with the circuit breaker (not shown in the figure) is closed. Therefore auxiliary switch (*ASW*) is closed, (as shown in the figure). If a fault occurs, protective relay operates and closes its



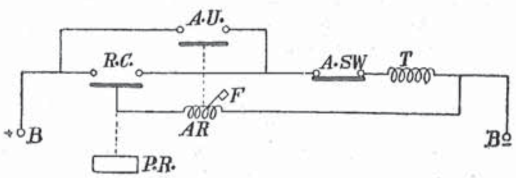

| | |
|---|---|
| $PR$ | Protective Relay |
| $PRC$ | Contacts of Protective Relay |
| $SC$ | Sealing contacts |
| S | Sealing Coil (in series with trip circuit.) |
| $F$ | Flag indicator. |
| $ASW$ | Auxiliary Switch Contacts (operation in conjunction with breaker) |
| $T$ | Trip Coil of CB |
| $B—B$ | Supply from battery, 110 V.D.C. |

Fig. 26.2. *Series Sealing* Circuit, for closed position of C.B. and Auxiliary switch.

contacts ($PRC$). Thereby current flows from battery system ($BB$) through sealing coil ($S$), $ASW$ contacts and trip coil ($T$). Circuit breaker trips. Meanwhile, the contacts ($SC$) operated by sealing relay ($S$) close and thus the contacts ($PRC$) of protective relay are relieved of further duty. Flag ($F$) operates either mechanically or electrically to indicate relay operation.

The auxiliary switch contacts open after a few cycles, as the circuit-breaker opens. The current in the trip circuit is interrupted by auxiliary switch.

There are various methods of sealing such as series sealing (described above), shunt sealing, etc. Fig. 26.3 illustrates the 'shunt Reinforcement' scheme.




| | |
|---|---|
| $RC$ | = Relay contacts |
| $PR$ | = Protective Relay |
| $AR$ | = Auxiliary Relay |
| $AU$ | = Contacts of AR |
| $ASW$ | = Auxiliary switch (shown closed) operator in conjunction with breaker |
| $T$ | = Trip coil |
| $F$ | = Flat |
| $B—B$ | = Battery voltage 110 V.D.C. |

Fig. 26.3. Shunt Reinforcement Scheme for closed position of C.B. and auxiliary switch.

In this scheme, to start with, the auxiliary switch $ASW$ is closed as the breaker (not shown) is closed. As the fault occurs, protective relay ($PR$) closes its contacts $RC$ and current flows through ($ASW$) and trip coil ($T$). Meanwhile the auxiliary relay ($AR$) is energised and its contacts ($AU$) close, thereby, the relay contacts ($RC$) are relieved of further duty. The trip circuit is opened by $ASW$ as the breaker opens.

The auxiliary relays mentioned above are generally attracted armature type instantaneous relays.

The 'Flag' also called 'indicator' or 'target' indicates on the relay that the relay has operated. In some relays, the movement of element of the relay pushes a small shutter to expose the indicator. In some relays the shutter is opened by electrically operated device. The resetting of indicators is usually manual. The operator notes the indication and then resets the indicator. On a relay panel, there are generally several relays. Indicators indicate, which relay has operated. Thereby the attendant knows the cause of circuit-breaker tripping.

The contact systems of static relay are quite different.

## 26.4. MEASUREMENT IN RELAYS

The discrimination involves measurement of actuating quantities (voltage and current) which are present at the relaying point. (Ref. Sec. 25.11) by protective relays. The measurement in majority of protective relays can be grounded as follows :

- Magnitude measurement such as over current, overvoltage, undercurrent.
- Product measurement such as power ($VI \cos \phi$)
- Ratio measurement such as impedance ($V/I$).
- Comparison between similar electrical quantities such as vector difference between currents $I, I$.



### 26.4.1. Magnitude Measurement

The relays under this category respond to magnitude of actuating quantity such as current derived from group of CT's.

Some other relays are energized by magnitude of voltage derived for group of VT's.

Some relays are energized by voltage and respond to parameter such as frequency, waveform, rate of rise. Such relays also can be included in this category.

The actuating quantity fed into the relay is derived from secondaries of CT's or VTs or both. Hence the performance of the protective system depends upon the resultant output of the secondary current/voltages fed into the relay.

The relays can be single actuating quantity type or multi-actuating quantity type.

### 26.4.2. Product Measurement

The double actuating quantity type induction relay have two coils and are actuated by voltage and current. Thereby two fluxes are produced and the torque produced by their interaction is given by,

$$T = kVI \cos \phi$$

k being a constant. Thus, the relay can be arranged to respond to the product of two quantities.

### 26.4.3. Ratio Measurement

The relay can be arranged to operate for a particular setting of the ratio say $V/I$.

One coil of the relay is actuated by voltage $V$ and gives a force $F_1 = k_1 V$.

The other coil is energized by current $I$ and gives a forces $F_2 = k_1 I$ when the relay is on the verge of operation, $F_1$ and $F_2$ are equal,

$$k_1 V = k_2 I$$

Hence $$\frac{V}{I} = \frac{k_1}{k_2} = k$$

### 26.4.4. Vector Difference (or Vector Sum)

The relay element can be connected in the secondary circuit of the CT's in such a way that the vector difference of secondary currents passes through the relay coil. Such arrangement gives a resultant current.

$$\bar{I} = (\bar{I}_1 + \bar{I}_2 + \bar{I}_3)$$

The relay operates when $\bar{I}$ increases above certain value.

## 26.5. TYPE OF RELAYS UNITS

(*a*) Attracted Armature type (Electromagnetic) Relay
(*b*) Balanced Beam (Electromagnetic) Relay
(*c*) Induction Disc (Electromagnetic) Relay
(*d*) Induction Cup (Electromagnetic) Relay
(*e*) Moving Coil and Moving iron (Electromagnetic) Relay
(*f*) Gas operated (Buchholz) Relay (Gas pressure)
(*g*) Rectifier Relays (Rectifier plus moving coil unit)
(*h*) Static Relay (static electronic circuit for measurement)

The electro-magnetic relay operates when operating torque/force exceeds the restraining torque/force.

## 26.6. PICK-UP

When the relay operates, we say, the relay has picked-up. It simply means that the relay with normally open contacts, has closed its contacts.

The pick-up value or pick-up level is the minimum value of operating quantity at which the relay is one the verge of operation, *e.g.*, consider an over current relay. The current injected in the relay coil is very gradually increased. At a current value of 2.51 amperes, the relay has not operated, at a value of 2.52 amperes, the relay begins to operate. Then, 2.52 amperes is the pick-up value.

In some attracted armature type relays, moving iron and moving coil relays, the pick-up value can be changed by changing the spring-tension.

In induction disc relays, the pick-up value corresponds to plug-setting (described later). If plug setting is 2.5 A, the relay starts operating at 2.5 A. If plug setting is 3.5 A, relay starts operating at 3.5 A and so on. However, in such relays the pick-up value is not exact, within about 5% of plug setting. The relay may not pick-up exactly at the plug setting value due to errors introduced by dust, friction, adjustment errors; and because operating torque is minimum at pick-up value.

### 26.7. RESET OR DROP-OFF

Now, we are talking about the relay which has already operated, and the actuating current is still flowing in the relay coil. As the operating quantity is gradually reduced, at some maximum value, the relay value, the relay contacts which have closed, start opening. This condition is called Reset or Drop off.

The value of operating quantity at which the relay (normally open) contacts which were closed due to relay operation, start opening and coming to original state (open).

### 26.8. DROP OFF/PICK-UP RATIO

The ratio of 'drop-off value to pick-up value' is important in self-reset type electromagnetic relays. It is also called 'Holding Ratio'. Since 'pick-up' value is more than 'drop off' value, the holding ratio is always less than 1.

The drop out to cut off ratio is of the order of 0.6 to 0.99 for most electromagnetic relays.

### 26.9. ATTRACTED ARMATURE RELAY (ELECTROMAGNETIC ATTRACTION)

These are simplest type of relays. These relays have coil or an electromagnet energized by coil. The coil is energized by the operating quantity which may be proportional to circuit current or voltage. A plunger or rotating iron vane is subjected to the action of magnetic field produced by the operating quantity. It is basically a single actuating quantity relay.

1. Attracted armature relays respond to both a.c. and d.c. because torque is proportion to $I_2$.

2. The attracted armature relays are fast relays. They have fast operation and fast reset because of small length of travel and light moving parts.

3. They are described as instantaneous. But their operating time does vary with current. Slow operating and resetting times can be obtained by delaying in build up of or decay of flux in the magnetic circuit by fitting copper ring around the magnet, and by means of bellows, dash pots, escapements etc. Operating time as slow as 0.1 sec. and resetting time as slow as 0.5 sec. can be obtained by such means.

4. On the other hand, very high operating speeds are possible. One modern relay has 0.5 millisecond of operating time. The current/time characteristic is hyperbolic (Fig. 26.5).

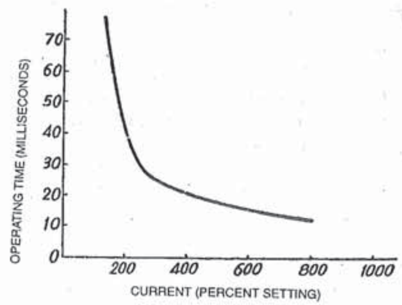



Fig. 26.5. Time current characteristic of a typical attracted armature relay.



5. **Ratio Rest to Pick-up** can be as high as 90-95% for a.c. relays and 60 to 90% for d.c. relays, by means of special design features. But in general the difference between picked-up and reset values is high because once, the relay has picked up the air gap is shortened and smaller magnitude of coil current can hold it in picked up position.

(Refer definitions, section 26.8)

6. These relays do not have directional feature unless they are provided with additional polarized coil.

7. As they are fast and operate on d.c. and a.c., they are affected by transients. The transients contain d.c. component in addition to a.c. wave. Therefore, though the steady state value may be less than relay's pick-up the relay may pick-up during transient state.

8. VA burden depends on construction, setting etc. For a typical relay it is of the order of 0.2 to 0.6 VA for current range 0.1 to 0.4 A.

9. Modern attraction armature relays are compact, robust, reliable.

10. **Operating Principle.** The electromagnetic force exerted on the moving element is proportional to square of the flux in air gap. If saturation is neglected it is proportional to square of operating current. We get

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

where $F$ = net force

$K_1$ = a constant

$I$ = current in operating coil

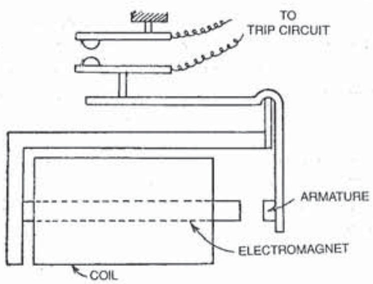
$K_2$ = restraining force including friction.

When relay is on the verge of operation, $F$ is zero

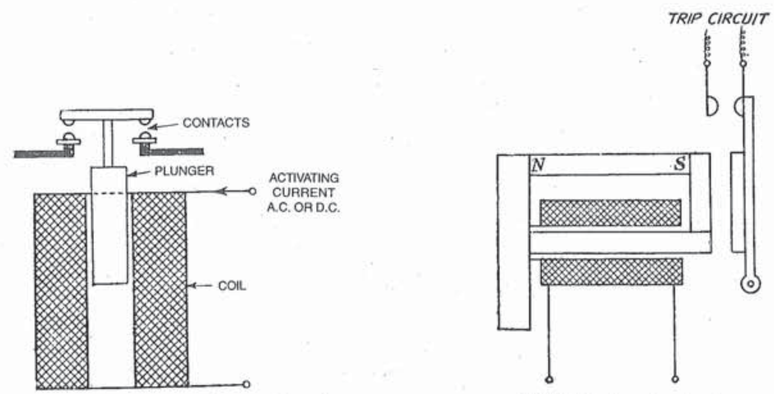
$$K_1 I^2 = K_2$$

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

11. **Types of Constructions.** There is a variety. Fig. 26.6 illustrates a few types of structures of attraction armature type of relay.




(*a*) Hinged armature type relay.




(*b*) Plunger type electromagnetic attraction relay. (*c*) Polarised moving iron type

Fig. 26.6. Attracted armature relay.

**Applications of Attracted Armature type Electromechanical Relay**

Attracted armature relays have many applications in protection of a.c. and d.c. equipment. They are however instantaneous relays and are sensitive to staring currents, load fluctuations and current surges.

Attracted armature relays can be designed to respond to over under current, over/under voltage, for both arc and d.c. applications. They are used as measuring relays or auxiliary relays. Their most usual applications are :

— Overs-current protection, the time lag is obtained by using instantaneous attracted-armature relays in conjunction with a definite time lag relay or inverse time lag relays.

— Definite-time lag over-current and earth fault protection, the attracted armature relay is used in conjunction with definite-time-lag relay for over-current/earth fault protection.

— Differential protection, the instantaneous attracted armature type relay is used for differential protection.

— Auxiliary Relays. Attracted armature relays are used as auxiliary all-or-nothing relays, in the contact systems of protective relaying.

## 26.10. BALANCED BEAM RELAY (ELECTROMAGNETIC ATTRACTION PRINCIPLE)

This type of balanced beam relay (Fig. 26.7) consisted of a horizontal beam pivoted centrally, with one armature attached to either side. There were two coils, one on each side. The beam remained in horizontal position till operating force became more than restraining force. The action being similar to 'see saw' in children park in which a plank is balanced on a support at the middle. Children ride at the ends so that when one end goes up, the other comes down. In a balanced beam relay, coils act like those playing children. The current in one coil gives operating force the current in other coil gives restraining force. The beam is given slight mechanical bias by means of spring or weigh adjustment such that under normal condition the contacts are open. When operating torque increases, the beam tilts and the contacts close. In current balance both coils are energized by current derived from C.T's. In impedance (balance) relay the coils are energized by $V$ and $I$.

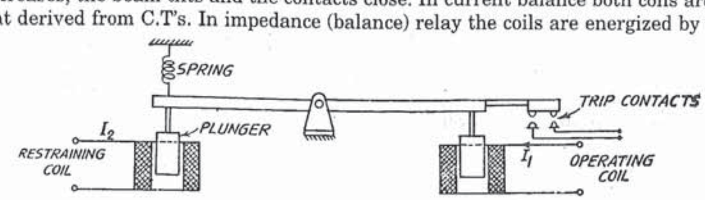



Fig. 26.7. Balance beam relay of early days.

**Operating principle.** Neglecting spring effect, the net torque is given by

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

where $T$ = net torque

$I_1$ = current in operating coil

$I_2$ = current in restraining coil

$K_1, K_2$ = constants.

At the verge of operation, net torque is zero, therefore,

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

$$\frac{I_1}{I_2} = \sqrt{\frac{K_2}{K_1}} = \text{constant.}$$

The operating characteristic is shown in Fig. 26.8 which is an approximate straight line, slightly curved for low currents due to effect of spring. The current which gives operating torque or positive



torque is called operating current. The other one is called restraining current. If one of the coils is actuated by voltage say $V_1$ other by current $I_2$ then the equation is $\frac{V_1}{I_2} = K$ is constant. This principle is used in impedance relays.

1. Balanced beam relay is difficult to be designed over a wide range current because the force is proportional to $I_2$.

2. The relay of this type is fast and instantaneous. In modern relays, electromagnets are provided in place of air-cored coils. Such relays can have time of the order of 1 cycle.

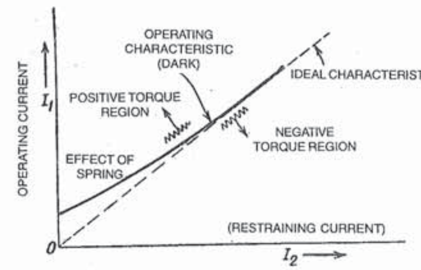



Fig. 26.8. Operating characteristics of balanced beam relay.

3. High ratio of resetting quantity of operating quantity can be obtained.

4. This relay is largely superseded by permanent magnet moving coil relay having better accuracy and lower VA burden.

5. VA burden of balanced beam relay 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 range.

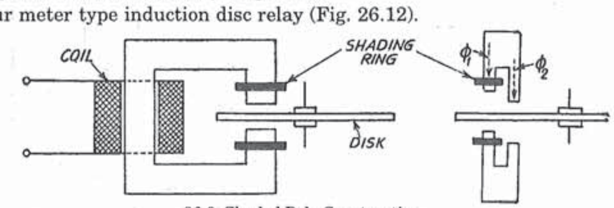
## 26.11. INDUCTION DISC RELAY (ELECTROMAGNETIC)

In this type of relay a metal disc is allowed to rotate between two electromagnets. The electromagnets are energized by alternating currents. The fields produced by the two magnets are displaced in space and phase. The torque is developed by the interaction of the flux of one of the magnets and the eddy currents induced in the disc by the other.

There are two popular constructions :

— Shaded pole induction disc relay (Fig. 26.9)

— Watthour meter type induction disc relay (Fig. 26.12).




26.9. Shaded Pole Construction.

Referring to Fig. 26.9, the shading ring is a copper band or a coil. Effect of shading ring is to produce flux in the shaded portion of the magnet ($\phi_1$) which is displaced in phase and space from the flux in the remaining portion ($\phi_2$). The flux $\phi_1$ induces e.m.f. $E_1$ is the disc at 90° to $\phi_1$. The e.m.f. $E_1$ produces currents $I_1$ lagging behind $E_1$ by small angle. The interaction between $I_1$ and $Q_2$ produces torque, which is proportional to $\phi_2 I_1 \cos \alpha$, where $I_1 \cos \alpha$ is component of $I_1$ in phase with $\phi_2$. Greater the angle $\theta$, greater is the torque.

The torque equation of single quantity induction relay may be expressed as

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

where $T$ = Net torque

$I$ = Current in relay coil

$K_1, K_2$ = Constants.

$\phi_1$ = Flux in shaded portion of magnet
$\phi_2$ = Flux in unshaded portion of magnet
$E_1$ = e.m.f. induced in the disc due to $\phi_1$.
$I_1$ = Current in the disc induced by $E_1$.
Torque $\propto \phi_2 I_1 \cos \alpha$.
$\alpha$ = angle between $\phi_2$ and $I_1$.

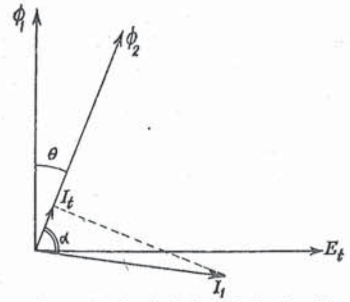



Fig. 26.10. Vector diagram of fluxes and current, for shaded pole induction disc relay.

Similar results are obtained by Watthour meter type induction disc relay (Fig. 26.12). The construction of this relay is similar to the watthour meter commonly used everywhere. It consists of an E-shaped electromagnet and a U-shaped electromagnet with a disc free to rotate in between. The E-shaped magnet produces flux $\phi_1$ and the U-shaped magnet produces flux say $\phi_2$. The phase angle $\theta$ between the fluxes is adjusted by a reactance in parallel with the secondary winding.

Torque is produced by interaction between flux and the eddy currents in the disc (produced by flux $\phi_1$ and $\phi_2$). The relay coil is tapped at several points. The current setting is selected by inserting a knob to take desired number of turns of the coil in the circuit.

1. The operation of induction relay can be controlled by opening secondary coil, as opening of this coil makes relay inoperative.

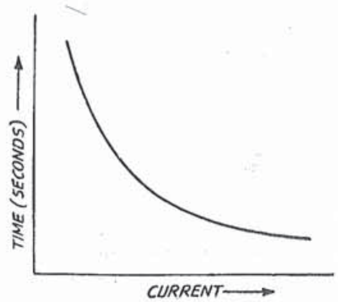



Fig. 26.11. Inverse characteristic.

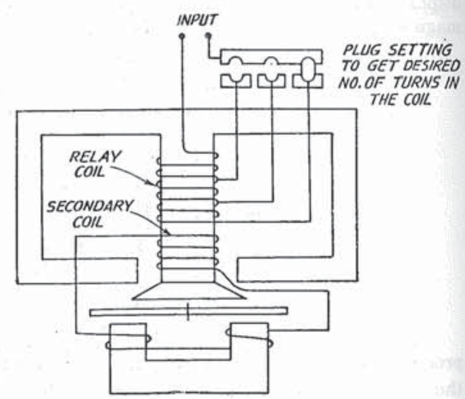



Fig. 26.12. Watthour meter type induction disc relay.

2. The time/current characteristics of induction disc relay is inverse characteristic (Figs. 26.11 and 26.14). The time reduces as current increases.

3. The VA burden depends on rating. It is of the order of 2.5 VA.

4. Modern induction disc relays are robust and reliable.

5. The current setting can be changed by taking the suitable number of turns. The time setting can be obtained by changing

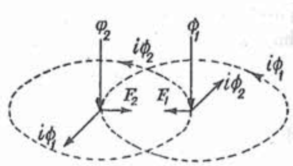



Fig. 26.13. Torque production in an induction relay.



the relative position of contacts by adjusting the length of travel of moving contacts.

6. The effect of d.c. offset may be neglected with inverse time single quantity induction relay, because they are generally slow. The d.c. offset may effect fast relays.

7. Ratio of reset of pick-up is high because operation does not involve any change in air gap. The ratio is above 95%.

8. **Operating time.** Inverse time characteristic is obtained by disc relays (Fig. 26.12). It is 10 to 60 sec.

### Torque Equation of an Induction Disc Relay

Let $\phi_1 = \phi \sin \omega t$

and $\phi_2 = \phi \sin (\omega t + \theta)$

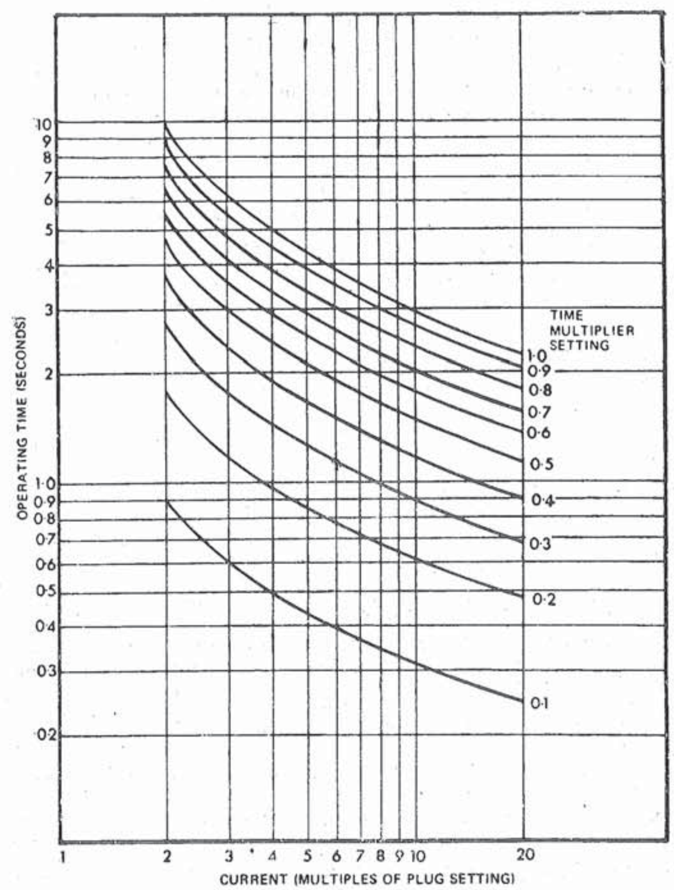



Fig. 26.14. Inverse characteristics of induction disc relays on log scales.

be the two fluxes at a phase difference of $\theta$ and which produce eddy currents $i\phi_1$ and $i\phi_2$ in the disc.

$$i\phi_1 = \frac{d\phi_1}{dt} \propto \phi \cos \omega t$$

$$i\phi_2 = \frac{d\phi_2}{dt} \propto \cos (\omega t + \theta)$$

$$F = (F_2 - F_1) \propto \phi_2 \, i\phi_1 - \phi_1 \, i\phi_2$$

where $F$ is net force due to interaction between $\phi_2$ and $\phi_1$. $F_1$ is force due to interaction between $\phi_1$ and $\phi_2$.

$$F \propto \phi_1 \phi_2 [\sin (\omega t + \theta) \cos \omega t - \sin \omega t \cos (\omega t + \theta)]$$

$$\propto \phi_1 \phi_2 \sin \theta.$$

### 26.11.1. Plug Setting and Time Setting in Induction Disc Relays

In these relays, there is a facility for selecting the plug setting and time setting such that the same relay can be used for a wide range of current, time and characteristics.

Time multiplier setting is generally in the form of an adjustable back-stop which decides the arc-length through which the disc travels, by reducing the length of travel, the time is reduced. The time multiplier setting is marked from about 0.1 to 1, with major divisions marked in between. If relay takes a certain time, say $S$ seconds with time multiplier setting 1, the same relay will take time equal to $T \times S$ seconds for time multiplier setting $T$, other conditions remaining the same.

The arrangement is such that for various plug settings, the ampere-turns (amperes of plug setting $\times$ turns of coil corresponding to the plug setting) are constant for various plug settings. Thereby, the relay characteristics remains the same for various plug settings, for a given time setting. Actually, the relay should start operating at current equal to plug setting. However, due to friction, dust etc. the operations may not take place at exact plug setting value.

The relay characteristic is plotted with multiples of plug setting as an abscissa (log scale) and time in seconds (log scale) as ordinate. Suppose, current injected in relay coil is 10 Amp and plug setting is 2.5 Amp., then plug setting multiplier will be $10/2.5 = 4$.

Fig. 26.14 illustrates typical characteristics of induction disc relays, on log scales.

### 26.11.2. Effect of Time-setting

By reducing the time multiplier, the characteristic is shifted to lower side, indicating that operating time is reduced (Fig. 26.14).

Plug Setting bride is provided with induction disc relays and it provides a wide range of current settings. The plug setting refers to the magnitude of current at which the relay starts to operate. The plug setting bridge comprises connections tapped from relay coil. By inserting the plug, in a particular gap in the bridge, a certain number of turns of the relay coil are brought into circuit.

## 26.12. INDUCTION CUP RELAY (ELECTROMAGNETIC)

This relay has two, four or more electromagnets, in stator. These are energized by the relay coils. A stationary iron core is placed as shown in Fig. 26.15. The rotor consists of a hollow metallic cylindrical cup. The rotor is free to rotate in the gap between the stationary iron and the electromagnets. In this type of relay, the eddy currents are produced in the metallic cup. These currents interact with the flux produced by the other electromagnet and torque is produced. The theory is similar to that of the disc type induction relay.

In Fig. 26.15 structure employing four poles is shown. It has an iron core at the centre and a metal cup between the core and electromagnet.

Fig. 26.15 shows a two pole structure. The two fluxes $\phi_1$ and $\phi_2$ are at right angles and produce eddy current in the cup. Thereby torque is produced.

1. Modern induction cup relays have 4 or more poles. A control spring and moving contacts are carried on an arm attached to the spindle of the cup.



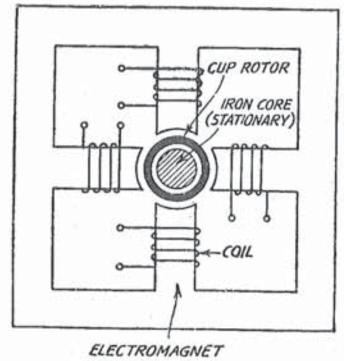



Fig. 26.15. Induction cup structure.

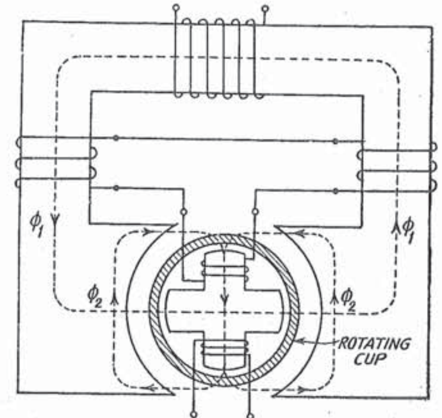



Fig. 26.16. Two pole induction relay.

2. The relay can be responsive to voltage or current. Similar structures are used in either cases.

3. The double actuating quantity relay can be responsive to both voltage and current.

4. The operating time characteristic depends on the type of structure. The relays have inverse time characteristic.

A modern induction cup relay may have an operating time of the order of 0.010 second.

## 26.13. PERMANENT MAGNET MOVING COIL RELAY

In this relay the coil is free to rotate in the magnetic field of a permanent magnet. The actuating current flows through the coil. The torque is produced by the interaction between the filed of the permanent magnet and the field of the coil.

1. **The relay responds to d.c. only.** However it is used in a.c. systems in conjunction with a rectifier.

2. The characteristic is varied by adjusting the control spring. The time setting is obtained by adjusting the position of the contact.

3. The operating torque is proportional to current in the coil. The force on the coil side is given by

$$F \propto NHIL$$

where $F$ = Force

$H$ = Magnetic field vector in the gap

$I$ = Current in the coil

$L$ = Length of the coil.

and torque is given by $T = 2rF$

where $r$ = Radius of coil

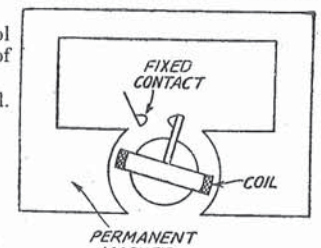



Fig. 26.17. Permanent magnent moving relay.

4. The time/current characteristic of such relays is shown in Fig. 26.18. It is an inverse characteristic.

5. The relay of this kind has uniform torque for the various positions of the coil. Hence it can be accurately set. Theoretically the reset value is equal to operating value.

6. Another popular type of moving coil construction is shown in Fig. 26.19. The coil is supported axially and moves horizontally when current is passed.

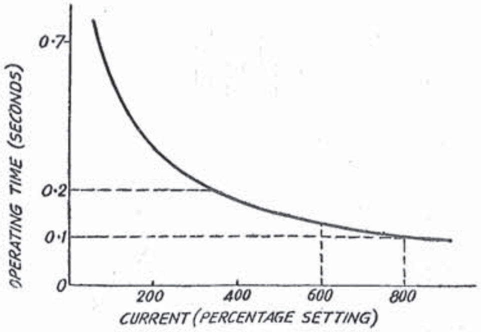



Fig. 25.18. Current-time characteristics of a typical moving coil permanent magnet relay.

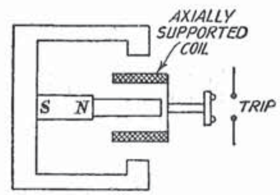



Fig. 25.19. Moving coil relay with axial moving coil.

This relay is faster than the rotating coil type because of the small travel, light parts. Time of the order of 30 m sec. can be obtained. VA burden is small. Sensitivity can be made as low as 0.1 milliwatt. Axial moving coil relays are delicate and should be handled with care.

## 26.14. RECTIFIER RELAY SYSTEMS

(*Courtesy :* Brown Boveri Ltd., Switzerland.)

The moving coil relays are being increasingly used with rectifier relays. In such relays, the quantities to be measured are rectified and then fed to the *moving coil unit.*

The principle and applications of such relays will now be briefly outlined (Fig. 26.20).

In the systems which measure rectified quantities, henceforth referred to as rectifier relays, the measuring element is a polarized moving-coil relay. This ready integrates the arithmetic mean value of the measured quantity. On account of the time taken by integration, it is not possible to gain the high measuring speed of electronic relays. However, the rectifier relays are faster than the mechanical relays since the moving coil has a very small mass.

### 26.14.1. Relays for One Quantity [Fig. 26.20.1]

As Fig. 26.20 shows the design of a relay for one quantity is quite simple. It comprises an input network, the rectifier and the moving-coil measuring system.

In the input network the measured quantity supplied by the main instrument transformer is converted into a form in which it can be processed. The network has setting resistors and an auxiliary transformer which, apart from converting the measured quantity, also serves as an insulating transformer.

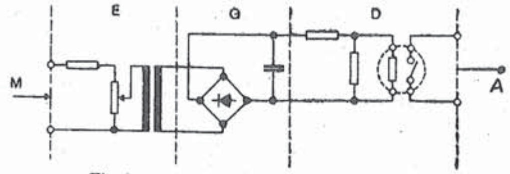



Fig. 26.20.1. Rectifier relay for one quantity.

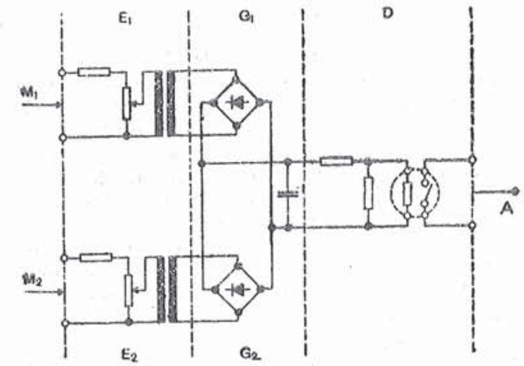
The quantity is rectified in a full wave bridge (full-wave rectifier with centre tap). It may be equipped with smoothing elements.

The rectified quantity is then fed to the moving-coil measuring system, which is usually equipped with series and parallel resistor for adjustment of the pick-up value. The contact of the moving-coil system actuates the tripping relay and signalling device.



### 26.14.2. Relays for Two Quantities

In the relays for two measured quantities (Fig. 26.20.2) the two rectifier bridges are interconnected on the D.C. side in opposition and the moving-coil system is inserted between the two connections.




$D$ = Moving-coil system
$A$ = Relay out
$M, M_1, M_2$ = Measured quantities
$E, E_1, E_2$ = Input networks
$G, G_1, G_2$ = Rectifiers

Fig. 26.20.2. Rectifier relay for two quantities.

The measurement is thus based on the comparison of the two quantities in a bridge circuit according to the electrical balance principle. Since rectification eliminates the influence of frequency and phase angle, this comparison amounts to arithmetical subtraction of one current from the other.

The contacts of the moving-coil system either move in the tripping direction or stay in the blocking position, depending on which current is greater.

By choosing suitable input networks, not only can the measured quantities be compared with one another, their product or quotient can also be determined.

## 26.15. THERMAL RELAYS, BIMETAL RELAYS, THERMOCOUPLES

**Thermal Relays.** These relays operate the thermal effect of electric current. Generally, they do not measure the temperature directly.

Thermal relays sense the current by the temperature rise produced by the current. Thermal relays can also respond to unbalanced three phase currents, which cause rise in temperature due to their negative sequence component.

The simplest thermal relay used in motor starters, overload protection devices employ a bimetallic strip mounted above a resistance wire wound heater coil. The passage of current through the coil causes the bi-metallic strip to deflect and thereby close the relay contacts. A system of levers is arranged to obtain the closure compensation for ambient temperature arranged is usually provided by another bimetal strip, shielded from heater coil and arranged to oppose the bending of main bi-metallic strip.

The bimetal strip consists of two metal strips having different coefficient of (thermal) expansions joined together. As the combined strip is heated, one strip expands more than the other. One support is fixed and uneven expansion causes bending of the strip. This effect can be used to obtain closure of relay contacts.

Temperature Indicators and controllers employing thermocouples are becoming extremely popular in various temperature indicating and controlling devices for higher (above 60°C) temperature range. They are finding their way in protective relaying too. A thermocouple consists of a junction of two selected materials, the junction is connected in electric circuit. The difference in