POWER SYSTEM PROTECTION AND SWITCHGEAR

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Introduction

1.1 Need for Protective Systems

An electrical power system consists of generators, transformers, transmission and distribution lines, etc. Short circuits and other abnormal conditions often occur on a power system. The heavy current associated with short circuits is likely to cause damage to equipment if suitable protective relays and circuit breakers are not provided for the protection of each section of the power system. Short circuits are usually called faults by power engineers. Strictly speaking, the term 'fault' simply means a 'defect'. Some defects, other than short circuits, are also termed as faults. For example, the failure of conducting path due to a break in a conductor is a type of fault.

If a fault occurs in an element of a power system, an automatic protective device is needed to isolate the faulty element as quickly as possible to keep the healthy section of the system in normal operation. The fault must be cleared within a fraction of a second. If a short circuit persists on a system for a longer period, it may cause damage to some important sections of the system. A heavy short circuit current may cause a fire. It may spread in the system and damage a part of it. The system voltage may reduce to a low level and individual generators in a power station or groups of generators in different power stations may lose synchronism. Thus, an uncleared heavy short circuit may cause the total failure of the system.

A protective scheme includes circuit breakers and protective relays to isolate the faulty section of the system from the healthy sections. A circuit breaker can disconnect the faulty element of the system when it is called upon to do so by the protective relay. The function of a protective relay is to detect and locate a fault and issue a command to the circuit breaker to disconnect the faulty element. It is a device which senses abnormal conditions on a power system by constantly monitoring electrical quantities of the system, which differ under normal and abnormal conditions. The basic electrical quantities which are likely to change during abnormal conditions are current, voltage, phase-angle (direction) and frequency. Protective relays utilise one or more of these quantities to detect abnormal conditions on a power system.

Protection is needed not only against short circuits but also against any other abnormal conditions which may arise on a power system. A few examples of other abnormal conditions are overspeed of generators and motors, over-voltage, under-frequency, loss of excitation, overheating of stator and rotor of an alternator, etc. Protective relays are also provided to detect such abnormal conditions and issue alarm signals to alert operators or trip circuit breaker.

A protective relay does not anticipate or prevent the occurrence of a fault, rather it takes action only after a fault has occurred. However, one exception to this is the Buchholz relay, a gas actuated relay, which is used for the protection of power transformers. Sometimes, a slow breakdown of insulation due to a minor arc may take place in a transformer, resulting in the generation of heat and decomposition of the transformer's oil and solid insulation. Such a condition produces a gas which is collected in a gas chamber of the Buchholz relay. When a specified amount of gas is accumulated, the Buchholz relay operates an alarm. This gives an early warning of incipient faults. The transformer is taken out of service for repair before the incipient fault grows into a serious one. Thus, the occurrence of a major fault is prevented. If the gas evolves rapidly, the Buchholz relay trips the circuit breaker instantly.

The cost of the protective equipment generally works out to be about 5% of the total cost of the system.

1.2 Nature and Causes of Faults

Faults are caused either by insulation failures or by conducting path failures. The failure of insulation results in short circuits which are very harmful as they may damage some equipment of the power system. Most of the faults on transmission and distribution lines are caused by overvoltages due to lightning or switching surges, or by external conducting objects falling on overhead lines. Overvoltages due to lighting or switching surges cause flashover on the surface of insulators resulting in short circuits. Sometimes, insulators get punctured or break. Sometimes, certain foreign particles, such as fine cement dust or soot in industrial areas or salt in coastal areas or any dirt in general accumulates on the surface of string and pin insulators. This reduces their insulation strength and causes flashovers. Short circuits are also caused by tree branches or other conducting objects falling on the overhead lines.

Birds also may cause faults on overhead lines if their bodies touch one of the phases and the earth wire (or the metallic supporting structure which is at earth potential). If the conductors are broken, there is a failure of the conducting path and the conductor becomes open-circuited. If the broken conductor falls to the ground, it results in a short circuit. Joint failures on cables or overhead lines are also a cause of failure of the conducting path. The opening of one or two of the three phases makes the system unbalanced. Unbalanced currents flowing in rotating machines set up harmonics, thereby heating the machines in short periods of time. Therefore, unbalancing of the lines is not allowed in the normal operation of a power system. Other causes of faults on overhead lines are: direct lightning strokes, aircraft, snakes, ice and snow loading, abnormal loading, storms, earthquakes, creepers etc. In the case of cables, transformers, generators and other equipment, the causes of faults are: failure of the solid insulation due to aging, heat, moisture or overvoltage, mechanical damage, accidental contact with earth or earthed screens, flashover due to over-voltages, etc.

Sometimes, circuit breakers may trip due to errors in the switching operation, testing or maintenance work, wrong connections, defects in protective devices, etc.

Certain faults occur due to the poor quality of system components or because of a faulty system design. Hence the occurrence of such faults can be reduced by improving the system design, by using components and materials of good quality and by better operation and maintenance.

1.3 Types of Faults

Two broad classifications of faults are:

(i) Symmetrical faults
(ii) Unsymmetrical faults

1.3.1 Symmetrical Faults

A three-phase (3-ϕ) fault is called a symmetrical type of fault. In a 3-ϕ fault, all the three phases are short circuited. There may be two situations—all the three phases may be short circuited to the ground or they may be short-circuited without involving the ground. A 3-ϕ short circuit is generally treated as a standard fault to determine the system fault level.

1.3.2 Unsymmetrical Faults

Single phase to ground, two phase to ground, phase to phase short circuits; single phase open circuit and two phase open circuit are unsymmetrical types of faults.

Single phase to ground (L-G) fault

A short circuit between any one of the phase conductors and earth is called a single phase to ground fault. It may be due to the failure of the insulation between a phase conductor and the earth, or due to a phase conductor breaking and falling to the ground.

Two phase to ground (2L-G) fault

A short circuit between any two phases and the earth is called a double line to ground or a two phase to ground fault.

Phase to phase (L-L) fault

A short circuit between any two phases is called a line to line or phase to phase fault.

Open circuited phases

This type of fault is caused by a break in the conducting path. Such faults occur when one or more phase conductors break or a cable joint or a joint on the overhead lines fails. Such situations may also arise when circuit breakers or isolators open but fail to close one or more phases. Due to the opening of one or two phases, unbalanced currents flow in the system, thereby heating rotating machines. Protective schemes must be provided to deal with such abnormal situations.

Winding faults

All types of faults discussed above also occur on the alternator, motor and transformer windings. In addition to these types of faults, there is one more type of fault, namely the short circuiting of turns which occurs on machine windings.

1.3.3 Simultaneous Faults

Two or more faults occurring simultaneously on a system are known as multiple or simultaneous faults. In simultaneous faults, the same or different types of faults may occur at the same or different points of the system. An example of two different types of faults occurring at the same point is a single line to ground fault on one phase and breaking of the conductor of another phase, both simultaneously present at the same point. The simultaneous presence of an L-G fault at one point and a second L-G fault on another phase at some other point is an example of two faults of the same type at two different points. If these two L-G faults are on the same section of the line, they are treated as a double line to ground fault. If they occur in different line sections, it is known as a *cross-country earth fault*. Cross-country faults are common on systems grounded through high impedance or Peterson coil but they are rare on solidly grounded systems.

1.4 Effects of Faults

The most dangerous type of fault is a short circuit as it may have the following effects on a power system, if it remains uncleared.

(i) Heavy short circuit current may cause damage to equipment or any other element of the system due to overheating and high mechanical forces set up due to heavy current.

(ii) Arcs associated with short circuits may cause fire hazards. Such fires, resulting from arcing, may destroy the faulty element of the system. There is also a possibility of the fire spreading to other parts of the system if the fault is not isolated quickly.

(iii) There may be reduction in the supply voltage of the healthy feeders, resulting in the loss of industrial loads.

(iv) Short circuits may cause the unbalancing of supply voltages and currents, thereby heating rotating machines.

(v) There may be a loss of system stability. Individual generators in a power station may lose synchronism, resulting in a complete shutdown of the system. Loss of stability of interconnected systems may also result. Subsystems may maintain supply for their individual zones but load shedding would have to be resorted in the sub-system which was receiving power from the other subsystem before the occurrence of the fault.

(vi) The above faults may cause an interruption of supply to consumers, thereby causing a loss of revenue.

High grade, high speed, reliable protective devices are the essential requirements of a power system to minimise the effects of faults and other abnormalities.

1.5 Fault Statistics

For the design and application of a protective scheme, it is very useful to have an idea of the frequency of occurrence of faults on various elements of a power system. Usually the power stations are situated far away from the load centres, resulting in hundreds of kilometres' length of overhead lines being exposed to atmospheric conditions. The chances of faults occurring due to storms, falling of external objects on the lines, flashovers resulting from dirt deposits on insulators, etc., are greater for overhead lines than for other parts of the power system. Table 1.1 gives an approximate idea of the fault statistics.

TABLE 1.1 Percentage Distribution of Faults in Various Elements of a Power System

Element	*% of Total Faults*
Overhead Lines	50
Underground Cables	9
Transformers	10
Generators	7
Switchgears	12
CTs, PTs, Relays Control Equipment, etc.	12

From Table 1.1, it is evident that 50% of the total faults occur on overhead lines. Hence it is overhead lines that require more attention while planning and designing protective schemes for a power system.

Table 1.2 shows the frequency of occurrence of different types of faults (mainly the different types of short circuits) on overhead lines. From the table it is evident that the frequency of line to ground faults is more than any other type of fault, and hence the protection against L-G fault requires greater attention in planning and design of protective schemes for overhead lines.

TABLE 1.2 Frequency of Occurrence of Different Types of Faults on Overhead Lines

Types of Faults	*Fault Symbol*	*% of Total Faults*
Line to Ground	L-G	85
Line to Line	L-L	8
Double Line to Ground	2L-G	5
Three Phase	$3\text{-}\phi$	2

In the case of cables, 50% of the faults occur in cables and 50% at end junctions. Cable faults are usually of a permanent nature and hence, automatic reclosures are not recommended for cables.

1.6 Evolution of Protective Relays

In the very early days of the power industry, small generators were used to supply local loads and fuses were the only automatic devices to isolate the faulty equipment. They were effective and their performance was quite satisfactory for small systems.

However, they suffered from the disadvantage of requiring replacement before the supply could be restored. For important lines, frequent interruption in power supply is undesirable. This inconvenience was overcome with the introduction of circuit breakers and protective relays. Attracted armature type electromagnetic relays were first introduced. They were fast, simple and economical. Their use will continue even in future as auxiliary relays due to their simplicity and low cost. Later on, induction disc type inverse time-current relays were developed in the early 1920s to meet the selectivity requirement. They were used for over-current protection. For directional and distance relays, induction cup type units were widely used throughout the world. An induction cup type unit was fast and accurate due to its higher torque/inertia ratio. For greater sensitivity and accuracy, polarised dc relays are being used since 1939.

In 1947, rectifier bridge type comparators were developed in Norway and Germany. Polarised dc relays, energised from rectifier bridge comparators challenged the position of the induction cup type relays. At present they are widely used for the realisation of distance relay characteristics.

Electronic relays using vacuum tubes first appeared in the literature in 1928 and continued up to 1956. They were not accepted because of their complexity, short life of vacuum tubes and incorrect operation under transient conditions. But electronic valves were used in carrier equipment. There was automatic checking of the carrier channel. An alarm was sounded if any tube became defective, and it was replaced immediately.

Magnetic amplifiers were also used in protective relays in the past. A magnetic amplifier consists of a transformer and a separate dc winding. As the transformer action is controlled by the dc winding, the device is also known as transductor. This type of relay is rugged but slow in action. At present such relays are not used.

Hall crystals were also used to construct phase comparators. Because of their low output and high temperature errors, such relays have not been widely adopted except in the USSR.

The first transistorised relay was developed in 1949, soon after the innovation of the transistor. Various kinds of static relays using solid state devices were developed in the fifties. Multi-input comparators giving quadrilateral characteristics were developed in the sixties. Static relays possess the advantages of low burden on the C.T. and P.T., fast operation, absence of mechanical inertia and contact troubles, long life and less maintenance. As static relays proved to be superior to electromagnetic relays, they were used for the protection of important lines, power stations and sub-stations. But they did not replace electromagnetic relays. Static relays were treated as an addition to the family of relays. In most static relays, the output or slave relay is a polarised d.c. relay which is an electromagnetic relay. This can be replaced by a thyristor circuit, but it is used because of its low cost. Electromagnetic relays have continued to be used because of their simplicity and low cost. Their maintenance can be done by less qualified personnel, whereas the maintenance and repair of static relays requires personnel trained in solid state devices. Static relays using digital techniques have also been developed recently.

With the growing size and complexity of modern power networks, fast, accurate and reliable protective schemes will be the demand of the future. Increasing interest is being shown in the use of on-line digital computers for protection. But their cost is 15 to 20 times more than that of conventional protective schemes. The latest fascinating innovation in the field of computer technology is the development of the microprocessor which is making in-roads in every activity of mankind. With the developments in VLSI technology, microprocessors that appeared in the seventies have evolved and have made remarkable progress in recent years. The mass production of inexpensive microprocessors constitutes a major event in electrical as well as computer technology. In the former area, microprocessors are used to replace conventional digital and electromechanical logic systems. In the latter area they are being used as the basis of all types computers. With the recent developments in VLSI technology, sophisticated microprocessors and single-chip microcomputers are being developed. The power industry is also expected to be affected to a great extent by this marvel of technology. Power engineers are presently interested in the application of this powerful tool to the problem of protective relays.

The inherent advantage of microprocessor-based protective schemes, over the existing static relays with one or a very limited range of applications, is their flexibility. The application of microprocessor to protective relays will also result in the availability of faster, more accurate and reliable relaying units. A microprocessor increases the flexibility of a relay due to its programmable approach. It can provide protection at low cost and compete with conventional relays. A number of relaying characteristics can be realised using the same interface. Using a multiplexer, the microprocessor can obtain the required input signals for the realisation of a particular relaying characteristic. Different programs can be used for different characteristics. Individual types and number of relaying units is reduced to a great extent, resulting in a very compact protective scheme. Field tests have demonstrated their feasibility and some schemes are under investigation. A number of schemes have been put into service and their performance is being observed. Microprocessor-based protective schemes are under the active research and development stage.

1.7 Zones of Protection

A power system contains generators, transformers, bus bars, transmission and distribution lines, etc. There is a separate protective scheme for each piece of equipment or element of the power system, such as generator protection, transformer protection, transmission line protection, bus bar protection, etc. Thus, a power system is divided into a number of zones for protection. A protective zone covers one or at the most two elements of a power system. The protective zones are planned in such a way that the entire power system is collectively covered by them, and thus, no part of the system is left unprotected. The various protective zones of a typical power system are shown in Fig. 1.1. Adjacent protective zones must overlap each other, failing which a fault on the boundry of the zones may not lie in any of the zones (this may be due to errors in the measurement of actuating quantities, etc.), and hence no circuit breaker would trip. Thus, the overlapping between the adjacent zones is unavoidable. If a fault occurs in the overlapping zone in a properly protected scheme, more circuit breakers than the minimum necessary to isolate the faulty element of the system would trip. A relatively low extent of overlap reduces the probability of faults in this region and consequently, tripping of too many breakers does not occur frequently.

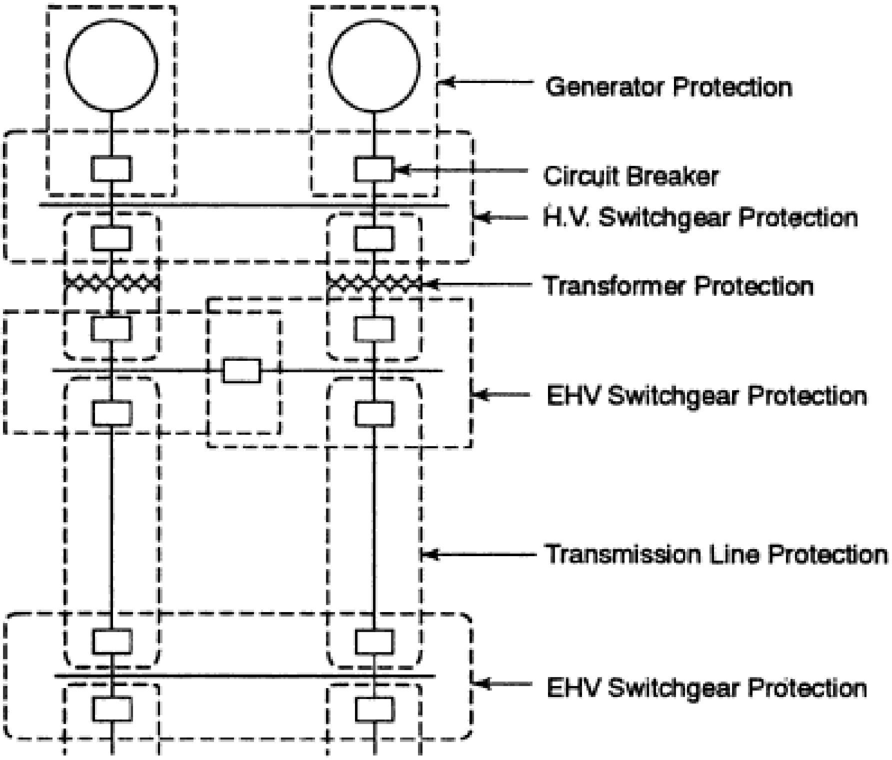


FIGURE 1.1 Zones of protection

1.8 Primary and Back-up Protection

It has already been explained that a power system is divided into various zones for its protection. There is a suitable protective scheme for each zone. If a fault occurs in a particular zone, it is the duty of the primary relays of that zone to isolate the faulty element. The primary relay is the first line of defence. If due to any reason, the primary relay fails to operate, there is a back-up protective scheme to clear the fault as a second line of defence.

The causes of failures of a protective scheme may be due to the failure of various elements, as mentioned in Table 1.3. The probability of failures is shown against each item.

The reliability of a protective scheme should at least be 95%. With proper design, installation and maintenance of the relays, circuit breakers, trip mechanisms, ac and dc wiring, etc. a very high degree of reliability can be achieved.

The back-up relays are made independent of those factors which might cause primary relays to fail. A back-up relay operates after a time delay to give the primary relay sufficient time to operate. When a back-up relay operates, a larger part of the power system is disconnected from the power source, but this is unavoidable. As far as possible, a back-up relay should be placed at a different station. Sometimes, a local back-up is also used. It should be located in such a way that it does not employ components (P.T., C.T., measuring unit,

TABLE 1.3

Name of Equipment	*% of Total Failures*
(a) Relays	44
(b) Circuit breaker interrupters	14
(c) AC wiring	12
(d) Breaker trip mechanisms	8
(e) Current transformers	7
(f) DC wiring	5
(g) P.T.	3
(h) Breaker auxiliary switches	3
(i) Breaker tripcoils	3
(j) DC supply	1

etc.) common with the primary relays which are to be backed up. There are three types of back-up relays:

(a) Remote back-up
(b) Relay back-up
(c) Breaker back-up

1.8.1 Remote Back-up

When back-up relays are located at a neighbouring station,they back-up the entire primary protective scheme which includes the relay, circuit breaker, P.T., C.T. and other elements, in case of a failure of the primary protective scheme. It is the cheapest and the simplest form of back-up protection and is a widely used back-up protection for transmission lines. It is most desirable because of the fact that it will not fail due to the factors causing the failure of the primary protection.

1.8.2 Relay Back-up

This is a kind of a local back-up in which an additional relay is provided for back-up protection. It trips the same circuit breaker if the primary relay fails and this operation takes place without delay. Though such a back-up is costly, it can be recommended where a remote back-up is not possible. For back-up relays, principles of operation that are different from those of the primary protection are desirable. They should be supplied from separate current and potential transformers.

1.8.3 Breaker Back-up

This is also a kind of a local back-up. This type of a back-up is necessary for a bus bar system where a number of circuit breakers are connected to it. When a protective relay operates in response to a fault but the circuit breaker fails to trip, the fault is treated as a bus bar fault. In such a situation, it becomes necessary that all other circuit breakers on that bus bar should trip. After a time-delay, the main relay closes the contact of a back-up relay which trips all other circuit breakers on the bus if the proper breaker does not trip within a specified time after its trip coil is energised.

1.9 Essential Qualities of Protection

The basic requirements of a protective system are as follows:

(i) Selectivity or discrimination
(ii) Reliability
(iii) Sensitivity
(iv) Stability
(v) Fast Operation

1.9.1 *Selectivity or Discrimination*

Selectivity, is the quality of a protective relay by which it is able to discriminate between a fault in the protected section and the normal condition. Also, it should be able to distinguish whether a fault lies within its zone of protection or outside the zone. Sometimes, this quality of the relay is also called discrimination. When a fault occurs on a power system, only the faulty part of the system should be isolated. No healthy part of the system should be deprived of electric supply and hence should be left intact. The relay should also be able to discriminate between a fault and transient conditions like power surges or inrush of a transformer's magnetising current. The magnetising current of a large transformer is comparable to a fault current, which may be 5 to 7 times the full load current. When generators of two interconnected power plants lose synchronism because of disturbances, heavy currents flow through the equipment and lines. This condition is like a short circuit. The flow of heavy currents is known as a power surge. The protective relay should be able to distinguish between a fault or power surge either by its inherent characteristic or with the help of an auxiliary relay. Thus, we see that a protective relay must be able to discriminate between those conditions for which instantaneous tripping is required and those for which no operation or a time-delay operation is required.

1.9.2 *Reliability*

A protective system must operate reliably when a fault occurs in its zone of protection. The failure of a protective system may be due to the failure of any one or more elements of the protective system. Its important elements are the protective relay, circuit breaker, P.T., C.T., wiring, battery, etc. To achieve a high degree of reliability, greater attention should be given to the design, installation, maintenance and testing of the various elements of the protective system. Robustness and simplicity of the relaying equipment also contribute to reliability. The contact pressure, the contact material of the relay, and the prevention of contact contamination are also very important from the reliability point of view. A typical value of reliability of a protective scheme is 95%.

1.9.3 Sensitivity

A protective relay should operate when the magnitude of the current exceeds the preset value. This value is called the pick-up current. The relay should not operate when the current is below its pick-up value. A relay should be sufficiently sensitive to operate when the operating current just exceeds its pick-up value.

1.9.4 Stability

A protective system should remain stable even when a large current is flowing through its protective zone due to an external fault, which does not lie in its zone. The concerned circuit breaker is supposed to clear the fault. But the protective system will not wait indefinitely if the protective scheme of the zone in which fault has occurred fails to operate. After a preset delay the relay will operate to trip the circuit breaker.

1.9.5 Fast Operation

A protective system should be fast enough to isolate the faulty element of the system as quickly as possible to minimise damage to the equipment and to maintain the system stability. For a modern power system, the stability criterion is very important and hence, the operating time of the protective system should not exceed the critical clearing time to avoid the loss of synchronism. Other points under consideration for quick operation are protection of the equipment from burning due to heavy fault currents, interruption of supply to consumers and the fall in system voltage which may result in the loss of industrial loads. The operating time of a protective relay is usually one cycle. Half-cycle relays are also available. For distribution systems the operating time may be more than one cycle.

1.10 Classification of Protective Relays

Protective relays can be classified in various ways depending on their construction, function, etc. and will be discussed in more details in the following chapters.

1.10.1 Classification of Protective Relays Based on Technology

Protective relays can be broadly classified into the following categories, depending on the technology they use for their construction and operation.

(i) Electromagnetic Relays
(ii) Static Relays
(iii) Microprocessor-Based Relays

Electromagnetic relays

Electromagnetic relays include attracted armature, moving coil, induction disc and induction cup type relays. Electromagnetic relays contain an electromagnet (or a permanent magnet) and a moving part. When the actuating quantity exceeds a certain predetermined value, an operating torque is developed which is applied on the moving part. This causes the moving part to travel and to finally close a contact to energise the trip coil of the circuit breaker.

Static relays

Static relays contain electronic circuitry which may include transistors, ICs, diodes and other electronic components. There is a comparator circuit in the relay, which compares two or more currents or voltages and gives an output which is applied to either a slave relay or a thyristor circuit. The slave relay is an electromagnetic relay which finally closes the contact. A static relay containing a slave relay is a semi-static relay. A relay using a thyristor circuit is a wholly static relay. Static relays possess the advantages of having low burden on the C.T. and P.T., fast operation, absence of mechanical inertia and contact trouble, long life and less maintenance. Static relays have proved to be superior to electromagnetic relays and they are being used for the protection of important lines, power stations and sub-stations. Yet they have not completely replaced electromagnetic relays. Static relays are treated as an addition to the family of relays. Electromagnetic relays continue to be in use because of their simplicity and low cost. Their maintenance can be done by less qualified personnel, whereas the maintenance and repair of static relays requires personnel trained in solid state devices.

Microprocessor-based protective relays

Microprocessor-based protective relays are the latest development in this area. With the developments in VLSI technology, sophisticated and fast microprocessors are coming up. Their applications to the problems of protective relaying schemes are of current interest to power engineers. The inherent advantages of microprocessor-based relays over static relays with or a very limited range of applications, are attractive flexibility due to their programmable approach. Microprocessor-based protective relays can provide protection at low cost and compete with conventional relays. The present downward trend in the cost of large scale integrated circuits will encourage wide applications of microprocessor-based relays for the protection of modern complex power networks.

1.10.2 Classification of Protective Relays Based on Their Function

Protective relays can be classified into the following categories, depending on the duty they are required to perform.

(i) Overcurrent relays
(ii) Undervoltage relays
(iii) Impedance relays
(iv) Underfrequency relays
(v) Directional relays, etc.

These are some important relays. Many other relays specifying their duty they perform can be put under this type of classification. The duty which a relay performs is evident from its name. For example, an overcurrent relay operates when the current exceeds a certain limit, an impedance relay measures the line impedance between the relay location and the point of fault and operates if the point of fault lies within the protected section. Directional relays check whether the point of fault lies in the forward or reverse direction.

The above relays may be electromagnetic, static or microprocessor-based relays.

1.11 Classification of Protective Schemes

A protective scheme is used to protect an equipment or a section of the line. It includes one or more relays of the same or different types. The following are the most common protective schemes which are usually used for the protection of a modern power system.

(i) Overcurrent Protection
(ii) Distance Protection
(iii) Carrier-Current Protection
(iv) Differential Protection

1.11.1 Overcurrent Protection

This scheme of protection is used for the protection of distribution lines, large motors, equipment, etc. It includes one or more overcurrent relays. An overcurrent relay operates when the current exceeds its pick-up value.

1.11.2 Distance Protection

Distance protection is used for the protection of transmission or sub-transmission lines; usually 33 kV, 66 kV and 132 kV lines. It includes a number of distance relays of the same or different types. A distance relay measures the distance between the relay location and the point of fault in terms of impedance, reactance, etc. The relay operates if the point of fault lies within the protected section of the line. There are various kinds of distance relays. The important types are impedance, reactance and mho type. An impedance relay measures the line impedance between the fault point and relay location; a reactance relay measures reactance, and a mho relay measures a component of admittance.

1.11.3 Carrier-Current Protection

This scheme of protection is used for the protection of EHV and UHV lines, generally 132 kV and above. A carrier signal in the range of 50–500 kc/s is generated for the purpose. A transmitter and receiver are installed at each end of a transmission line to be protected. Information regarding the direction of the fault current is transmitted from one end of the line section to the other. Depending on the information, relays placed at each end trip if the fault lies within their protected section. Relays do not trip in case of external faults. The relays are of distance type and their tripping operation is controlled by the carrier signal.

1.11.4 Differential Protection

This scheme of protection is used for the protection of generators, transformers, motors of very large size, bus zones, etc. C.T.s are placed on both sides of each winding of a machine. The outputs of their secondaries are applied to the relay coils. The relay compares the current entering a machine winding and leaving the same. Under normal conditions or during any external fault, the current entering the winding is equal to the current leaving the winding. But in the case of an internal fault on the winding, these are not equal. This difference in the current actuates the relay. Thus, the relay operates for internal faults and remains inoperative under normal conditions or during external faults. In case of bus zone protection, C.T.s are placed on the both sides of the bus bar.

1.12 Automatic Reclosing

About 90% of faults on overhead lines are of transient nature. Transient faults are caused by linghtning or external bodies falling on the lines. Such faults are always associated with arcs. If the line is disconnected from the system for a short time, the arc is extinguished and the fault disappears. Immediately after this, the circuit breaker can be reclosed automatically to restore the supply.

Most faults on EHV lines are caused by lightning. Flashover across insulators takes place due to overvoltages caused by lightning and exists for a short time. Hence, only one instantaneous reclosure is used in the case of EHV lines. There is no need for more than one reclosure for such a situation. For EHV lines, one reclosure in 12 cycles is recommended. A fast reclosure is desired from the stability point of view. More details have been given in Ch. 4.

On lines up to 33 kV, most faults are caused by external objects such as tree branches, etc. falling on the overhead lines. This is due to the fact that the support height is less than that of the trees. The external objects may not be burnt clear at the first reclosure and may require additional reclosures. Usually three reclosures at 15-120 seconds' intervals are made to clear the fault. Statistical reports show that over 80% faults are cleared after the first reclosure, 10% require the second reclosure and 2% need the third reclosure, while the remaining 8% are permanent faults. If the fault is not cleared after 3 reclosures, it indicates that the fault is of permanent nature. Automatic reclosures are not used on cables as the breakdown of insulation in cables causes a permanent fault.

1.13 Current Transformers for Protection

Current transformers are used to reduce the heavy current flowing in an element of a power system to low values that are suitable for relay operation. The current rating of a protective relay is usually 5 or 1 ampere. Besides reducing the current level, the C.T. also *isolates* the relay circuit from the primary circuit which is a high voltage power circuit, and allows the use of standardized current rating for relays.

1.13.1 Requirements of C.T.s Used for Protection

The requirements of C.T.s used for protective relays are quite different from those of instrument C.T.s. A C.T. used for instrumentation is required to be accurate over the normal working range of currents, whereas a C.T. used for protection is required to give a correct ratio up to several times the rated primary current. It is due to the fact that the relay has to perform reliably at normal currents as well as at fault currents. Usually fault currents are many times the normal rated currents. For many applications, its accuracy is not important at currents less than the rated value.

1.13.2 Core Material

Figure 1.2 shows the magnetisation characteristics of (a) cold-rolled grain-oriented silicon steel (3%), (b) hot-rolled silicon steel (4%) and (c) nickel-iron (77% Ni, 14% Fe). It is seen that the nickel-iron core has the qualities of highest permeability, low exciting current, low errors and saturation at a relatively low flux density. Instrument C.T.s are required to give a high accuracy for all load currents up to 125% of the rated current. Nickel-iron gives a good accuracy up to 5 times the rated current and hence, it is quite a suitable core material for C.T.s used for meters and instruments. The excessive currents being fed to instruments and meters are prevented during faults on power system due to almost absolute saturation at relatively low flux density.

Cold-rolled grain-oriented silicon steel (3%), which has a high permeability, high saturation level, reasonably small exciting current and low errors is used for the core of the C.T.s used for protective relays. Such core material has reasonably good accuracy up to 10-15 times the rated current, but when we consider currents that are five times under the rated current, the core material made from nickel-iron alloy fares better.

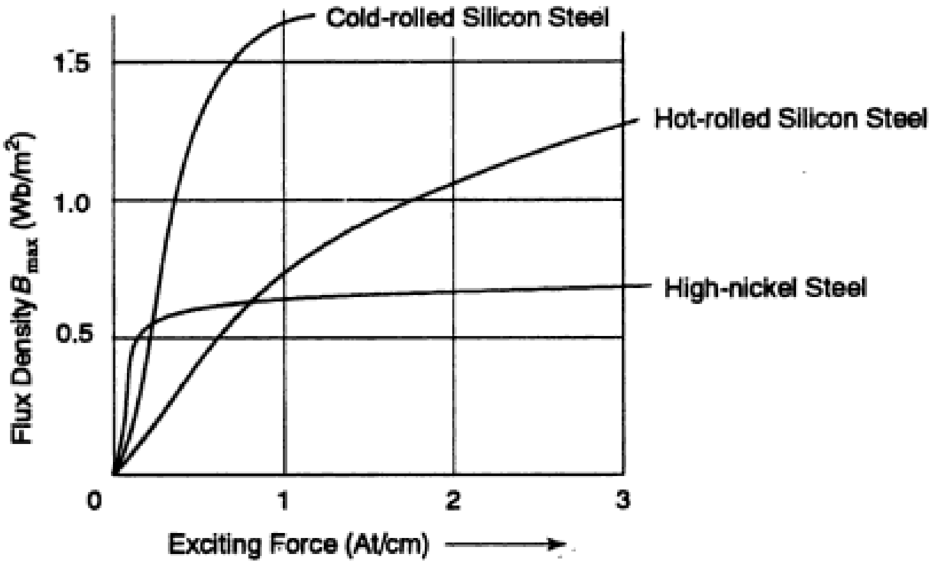


FIGURE 1.2 Magnetisation characteristics of C.T. cores

Hot-rolled silicon steel has the lowest permeability. So it is not suitable for C.T.s. In order to achieve the desired characteristics, composite cores made of laminations of two or more materials are also used in C.T.s.

1.13.3 Accuracy

The accuracy of a current transformer is expressed in terms of the departure of its ratio from its true ratio. This is called the ratio error, and is expressed as:

$$\text{Per cent error} = \left[\frac{NI_s - I_p}{I_p}\right] \times 100$$

$$N = \text{Nominal ratio} = \frac{\text{rated primary current}}{\text{rated secondary current}}$$

I_s = Secondary current

I_p = Primary current

The ratio error of a C.T. depends on its exciting current. When the primary current increases, the C.T. tries to produce the corresponding secondary current, and this needs a greater secondary emf, core flux density and exciting current. A stage comes when any further increase in primary current is almost wholly absorbed in an increased exciting current, and thereby the secondary current hardly increases at all. At this stage, the C.T. becomes saturated. Thus the ratio error depends on saturation.

An accuracy of about 2% to 3% of the C.T. is desirable for distance and differential relays, whereas for many other relays, a higher percentage can be tolerated.

According to standards followed in U.K., protective C.T.s are classified as S, T and U type. The errors of these types of C.T.s are shown in Table 1.4.

TABLE 1.4 C.T.s Errors

Class	*Ratio Error*	I_{ex}/I_{sat}	*Phase Angle Error in Degrees*
S	± 3%	3%	2
T	± 10%	10%	6
U	± 15%	15%	9

I_{ex} = Exciting current.
I_{sat} = Saturating current.

When the primary current increases, at a certain value the core commences to saturate and the error increases. The value of the primary current at which the error reaches a specified limit is known as its *accuracy limit primary current* or *saturation current*. The maximum value of the primary current for a given accuracy limit is specified by the manufacturer. The C.T. will maintain the accuracy at the specified maximum primary current at the rated burden. This current is expressed as a multiple of the rated current. The ratio of accuracy limit primary current and rated primary current is known as the rated *accuracy limit factor* or *saturation factor*, the standard values of which are 5, 10, 15, 20, and 30. The performance of a C.T. is given at certain multiples of the rated current. According to BSS 3938, rated primary currents of C.T.s are up to 75 kA and secondary currents 5 A or 1 A.

1.13.4 C.T. Burden

The C.T. burden is defined as the load connected across its secondary, which is usually expressed in volt amperes (VA). It can also be expressed in terms of impedance at the rated secondary current at a given power factor, usually 0.7 lagging. From the given impedance at rated secondary current, the burden in VA can be calculated. Suppose the burden is 0.5 Ω at 5 A secondary current. Its volt amperes will be equal to $I^2R = 5^2 \times 0.5 = 1.25$ VA. The total burden on the C.T. is that of the relays, meters, connecting leads and the burden due to the resistance of the secondary winding of the C.T. The relay burden is defined as the power required to operate the relay. The burden of relays and meters is given by the manufacturers or it can be calculated from the manufacturer's specifications as the burden depends on their type and design. The burden of leads depends on their resistance and the secondary current. Lead resistance is appreciable if long wires run from the switchyard to the relay panels placed in the control room. Lead burden can also be reduced using low secondary currents. Usually secondary currents of 5 A are used, but current of 2 A or even 1 A can be used to reduce the lead burden. Suppose, the lead resistance is 5 Ω. Then lead burden at 5 A will be $5^2 \times 5 = 125$ VA. The burden at 1 A is only $1^2 \times 5 = 5$ VA. The economy in C.T. cost and space requirement demands shorter lead runs and sensitive relays. The rating of a large C.T. is 15 VA. For a 5 A secondary current, the corresponding burden is 0.6 Ω, and for a 1 A secondary current it is 15 Ω.

1.13.5 Transient Behaviour of C.T.s

For fast relaying (within one or two cycles after the fault inception), it is very essential to know the behaviour of the C.T. during the first few cycles of a fault, when it carries the transient component in addition to the steady-state component of the fault current. For calculation of the fault current, the power system is considered as a lumped R, L series circuit, and the effect of shunt admittance is neglected.

When a fault occurs on a power system, the fault current is given by

$$i_p = \frac{V_{pm}}{Z_p}\sin(\omega t + \alpha - \phi_p) + e^{-(R_p/L_p)t}\cdot\frac{V_{pm}}{Z_p}\sin(\phi_p - \alpha) \tag{1.1}$$

where, the subscript p indicates the primary side of the C.T.

$\phi_p = \tan^{-1}\left(\dfrac{\omega L_p}{R_p}\right)$ is the phase angle of the primary circuit. The fault is assumed to occur at $t = 0$. The parameter α controls the instant on the voltage wave at which the fault occurs.

In Eq. (1.1) for the fault current, the first term is the sinusoidal steady-state current which is called the symmetrical ac component, while the second term is the unidirectional transient component which starts at a maximum and decays exponentially and is called the dc offset current. The dc offset current causes the total fault current to be unsymmetrical till the transient decays. The waveform of the fault current is shown in Fig. 1.3.

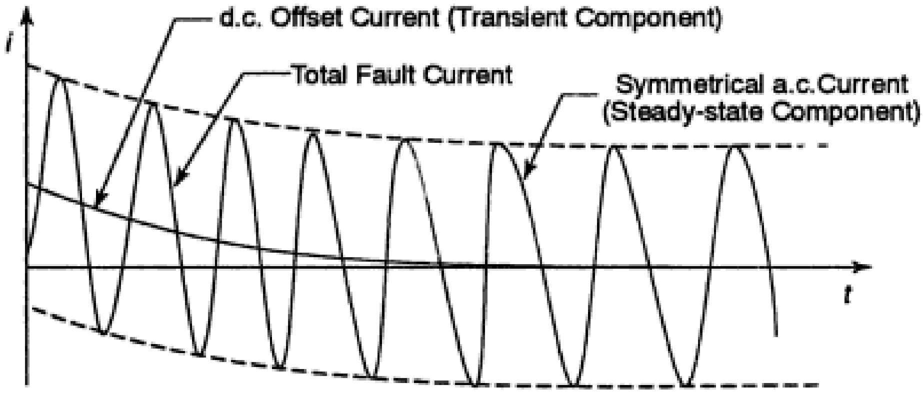


FIGURE 1.3 Waveform of the fault current

The dc offset current (the transient current) will have a maximum value when $\phi_p - \alpha = \pi/2$ radians and Eq. (1.1) reduces to

$$i_p = I_{pm}\left[-\cos\omega t + e^{-(R_p/L_p)t}\right] \tag{1.2}$$

where $I_{pm} = \dfrac{V_{pm}}{Z_p}$, and $Z_p = \sqrt{R_p^2 + (\omega L_p)^2}$

Normally, as the system rated voltage rises above 100 kV, the circuit becomes highly inductive with negligibly small resistance and the phase angle ϕ_p tending to $\pi/2$ rad (or 90°) and α tending to be zero. In the limit where $\phi_p = \pi/2$ rad, fault at zero voltage (for $\alpha = 0$) gives rise to the maximum fault current asymmetry (current doubling).

The primary fault current referred to the secondary side is:

$$i'_p = i_p \left(\frac{N_p}{N_s}\right)$$

and let

$$I'_{pm} = I_{pm} \left(\frac{N_p}{N_s}\right)$$

where N_p and N_s are the number of turns in the primary and secondary, respectively.

In order to estimate the transient flux in the core, the magnetizing current will be neglected as this is one of the worst cases and Eq. (1.2) will be used, i.e. the case of maximum transient primary current.

The secondary voltage is

$$v_s = Z_s i_s = N_s (d\phi/dt) \tag{1.3}$$

where, the subscript s indicates the secondary side of the C.T., and Z_s is the C.T. burden.

From Eq. (1.3), the maximum core flux is given by

$$\phi_m = \left(\frac{1}{N_s}\right) \int v_s \, dt \tag{1.4}$$

Thus, for the steady-state component of i_s, and integrating over a quarter cycle

$$\phi_m = -\left(\frac{1}{N_s}\right) \int_{t=0}^{\pi/2\omega} Z_s I'_{pm} \cos \omega t \, dt$$

$$= -\left(\frac{Z_s I'_{pm}}{N_s \omega}\right) \tag{1.5}$$

For the transient component of i_s, and integrating from $t = 0$ to $t = \infty$

$$\phi_m = \left(\frac{1}{N_s}\right) Z_s I'_{pm} \int_{t=0}^{\infty} e^{-\left(\frac{R_p}{L_p}\right)t} dt$$

$$= \left(\frac{Z_s I'_{pm}}{N_s \omega}\right) \left(\frac{\omega L_p}{R_p}\right)$$

$$= \left(\frac{Z_s I'_{pm}}{N_s \omega}\right)\left(\frac{X_p}{R_p}\right) \tag{1.6}$$

Therefore, the component of the core flux due to the transient component of the fault current is X_p / R_p times the component of the core flux due to the steady-state component of the fault current. Considering the worst case of a fault near a large power station, X_p / R_p could be as high as 30, corresponding to a primary-circuit time constant of $L_p / R_p = 0.1$s, or about 5 cycles.

Assuming that the two fluxes can be added numerically (the worst case), the total core flux is equal to the steady-state component multiplied by the factor

$$1 + \left(\frac{X_p}{R_p}\right) = 1 + \frac{2\pi f L_p}{R_p} = 1 + 2\pi T_p$$

where T_p is the primary circuit time-constant in cycles. The flux waveforms are shown in Fig. 1.4.

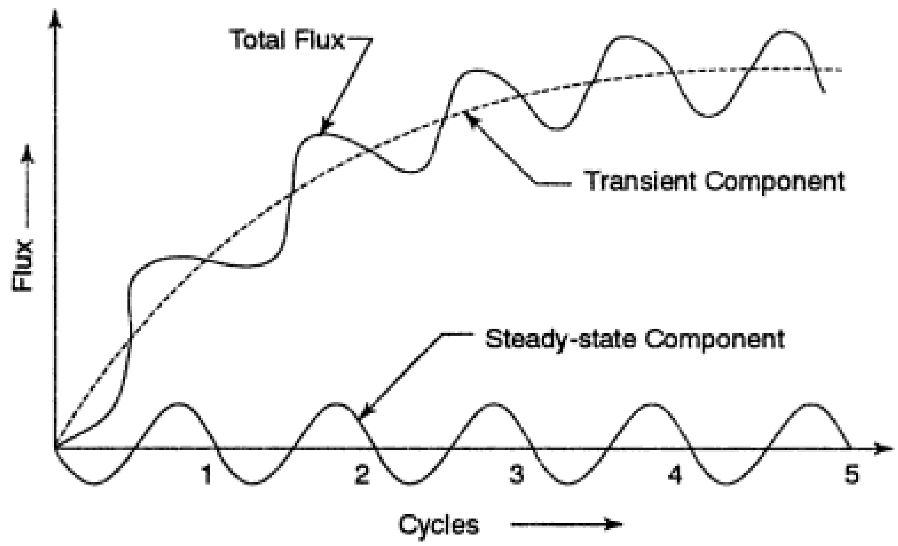


FIGURE 1.4 C.T. core fluxes during transient period

The value of X_p/R_p increases with the system voltage because of the increased spacing of the conductors. The component of the core flux due to transient dc offset current increases X_p/R_p times the flux due to the symmetrical (steady-state) ac current. Therefore, it is clear that there is a large transient flux swing in the magnetic core of the C.T. With this large flux-swing during the transient period, the magnetic core of the C.T. of conventional design will get saturated causing undesirable effects on the performance of the protective relays connected to the secondary of the C.T.

In current transformers of conventional design, saturation of the cores due to the transient dc component of the fault current is possible within a few milliseconds, after which their secondary current is fully distorted, resulting in an inaccurate measurement of the fault current by the relay. In order to prevent an adverse effect upon the performance of the relays, the current transformer cores must be greatly enlarged or air-gaps should be provided in the cores.

The choice of the appropriate current transformer design depends upon the protective system requirement. Where the operation of the protective system is not affected by the C.T. core saturation, as in the case of a plain overcurrent relay, the conventional type of C.T. may be used. But where a saturation-free current transformation is essential for correct and rapid working of the system protection, the dimension of the C.T. core must be greatly increased. The increase of core section in such cases leads us to unreasonable core sizes with the use of iron-enclosed cores in high-power systems. Therefore, for such cases, cores having air-gaps, called linear cores have been developed. By providing such air gaps, the time constant of the C.T. is reduced to a great extent since the current main flux density is diminished. Generally, the flux due to the dc component assumes smaller values, if the C.T. time constant is reduced. Therefore, C.T. cores with air gaps are almost free from the problem of saturation and consequent distortion of the secondary current.

The linear cores provide an entirely new solution to a wide range of protective systems providing saturation free transformation of transient phenomena with dc offset components of great time constants.

1.13.6 Linear Couplers

The C.T. core may be of iron or non-ferrous material, usually air or plastic. An iron-cored C.T. has substantial power output which is adequate for electromagnetic relays. A C.T. having non-ferrous material as core has low power output which is suitable for static relays but is inadequate for electromagnetic relays. An air or plastic-cored C.T. has a linear characteristic and is called a linear coupler. Such C.T.s have no saturation limit and hence show no transient errors, i.e. ratio and phase angle errors which arise due to saturation. Problems caused by dc transients are also reduced to a great extent. Such C.T.s do not have lead resistance problem. A C.T. with a small air gap in its iron core has also linear characteristic, and has no transient errors. Such C.T.s are called *transactors*.

1.13.7 C.T. Construction

Current transformers can be classified into two categories: bar primary C.T.s and wound primary C.T.s. In a bar primary type C.T., the primary is a straight conductor which is a part of the power system. In this type of C.T., the primary does not necessarily form a part of the C.T. The secondary has a ring type iron core on which the winding is wound uniformly over the entire periphery. Figure 1.5 shows a C.T. of this type. This type of construction has a negligible leakage flux of both primary and secondary and hence, possesses low reactance. As there is only one primary turn, the primary current should be high enough (about 400 A) to produce sufficient exciting ampere-turns to give a reasonable output. A bushing C.T. is a sub-class of the bar primary type C.T. It is placed over an insulator bushing enclosing a straight conductor. The

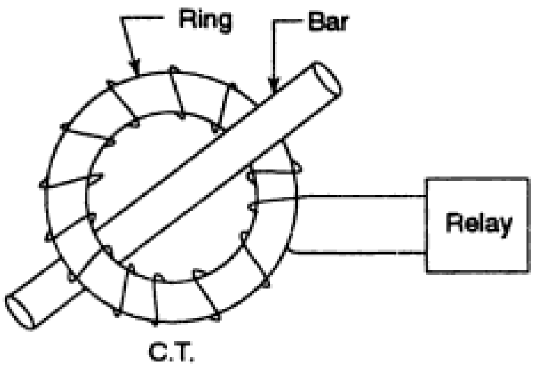


FIGURE 1.5 C.T. : Primary-bar and secondary-ring

bushing C.T. has comparatively more exciting current and a large magnetic path owing to the large diameter of the bushing.

Wound type C.T.s have E, I, T or L type cores. The primary winding is wound on the iron core. As the primary turns are fewer, they cannot be distributed uniformly over the iron core. Such C.T.s have high leakage flux and hence possess a high reactance.

1.13.8 Modern Trends in C.T. Design

High voltage C.T.s are the oil-filled type. At a system voltage of 400 kV and above there is a severe insulation problem. C.T.s for this range of system voltage become extremely expensive. Their performance is also limited due to the large dimensional separation of the secondary winding from the primary winding. These problems are overcome using SF_6 (gas) and clophen (liquid) as insulation, thus reducing the size and cost of C.T.s.

A new trend is to use electronic sensors to tackle this problem occurring in extra high voltage (EHV) and ultra high voltage (UHV) systems. A linear coupler encircles the EHV conductor. A signal proportional to the secondary current is generated and transmitted via the communication channel. Light beam, laser beam and radio frequency are being used to transmit this signal.

It is seen that the secondary potential supply seldom creates any problem but problems with secondary current supply arise frequently.

1.14 Potential Transformer

Potential transformers are used to reduce the system voltage to levels low enough to suit the ratings of protective relays. The voltage rating of a protective relay is usually 110 V. The percentage ratio error is given by

$$\text{Per cent ratio error} = \frac{KV_s - V_p}{V_p} \times 100$$

where K = Nominal voltage ratio, V_s = Secondary voltage and V_p = Primary voltage.

The accuracy of P.T.s used for meters and instruments is only important at normal system voltages, whereas P.T.s used for protection require errors to be limited over a wide range of voltages under fault conditions. This may be about 5% to 150% of the nominal voltage. The ratio error and phase angle error for potential transformers required for protection according to ISS:3156 (Part III) 1966 are given in Table 1.5.

TABLE 1.5 Limits of Voltages and Phase Angle Errors for P.T.s

	0.05 to 0.9 times rated primary voltage 0.25 to 1.0 times rated output at unity p.f.	
Class	*Ratio Error*	*Phase Angle Error (in Degrees)*
3.0	± 3%	2
5.0	± 5%	5

1.14.1 Types of Construction

The following two types of construction are used for P.T.s.

(i) Electromagnetic type

(ii) Capacitor type

Electromagnetic type

This type of a P.T.s is conveniently used up to 132 kV. It is similar to a conventional wound type transformer with additional features to minimise errors. As its output is low, it differs from power transformers in physical size and cooling techniques. In the UK, a 3-phase construction with 5 limbs is used. While in the USA single phase construction is more common. The voltage rating of a P.T. governs its construction. For lower voltages, up to 3.3 kV, dry type transformers with varnish impregnated and taped windings are quite satisfactory. For higher voltages, oil immersed P.T.s are used. Recently P.T.s with windings impregnated and encapsulated in synthetic resins have been developed for higher voltages. This technique has made it possible to use dry type P.T.s for system voltages up to 66 kV. For voltages above 132 kV, if electromagnetic type P.T.s are to be used, several P.T.s are connected in cascade. In cascade connection, the primary windings of CTs are connected in series, though each primary is on a separate core. Coupling coils are provided alongwith each primary to keep the effective leakage inductance to a low value. They also distribute the voltage equally. Such an arrangement is conveniently placed in a porcelain enclosure. However, capacitor type P.T.s are more economical at higher system voltages.

As the voltage decreases, the accuracy of electromagnetic type P.T.s decreases but is acceptble down to 1% of normal voltage.

Capacitor type

At a higher voltages, electromagnetic type P.T.s become very expensive and hence it is a common practice to use a capacitance voltage divider as shown in Fig. 1.6. V_2 may be only about 10% or less of the system voltage. This arrangement, called a capacitor P.T. is used at 132 kV and above. The reactor L is included to tune the capacitor P.T. to reduce the ratio and phase angle errors with the variation of VA burden, frequency, etc. The reactor is adjusted to such a value that at system frequency it resonates with the capacitors. Capacitor P.T.s are more economical than electromagnetic type in this range of system voltage, particularly where high voltage capacitors are used for carrier-current coupling. The transient performance of a capacitor type P.T. is inferior to that of an electromagnetic type. A capacitor type P.T. has the tendency of introducing harmonics in the secondary voltage. High voltage capacitors are enclosed in a porcelain housing. The performance of the voltage divider type capacitor P.T. is not as good as that of the electromagnetic type.

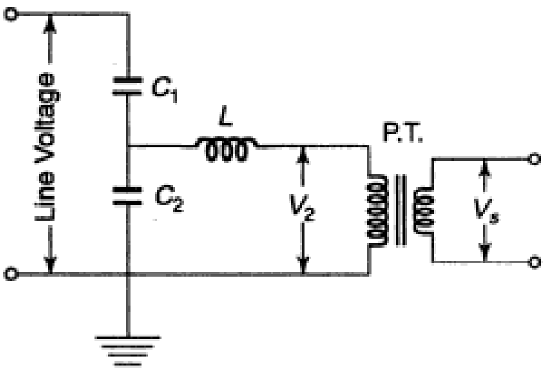


FIGURE 1.6 Capcitor P.T.

The performance of high speed distance relays is less reliable with capacitor type P.T.s. Hence, the decision regarding the choice of a P.T. will depend whether economy in P.T. cost or relay performance is more important for a particular power line. Errors of capacitor type P.T.s can be reduced by reducing its burden. It is due to the fact that the series connected capacitors perform the function of a potential divider if the current drawn by the burden is negligible compared to the current flowing through the capacitors connected in series.

An electronic amplifier having high input impedance and VA output high enough to supply the VA burden can be included in the capacitor type P.T. arrangement. Such an arrangement gives a good transient response.

Finally, it can be concluded that the secondary potential supply seldom creates any problem but problems with secondary current supply arise frequently.

1.15 Summation Transformer

On many occasions the need to derive a single-phase quantity from three-phase quantities may arise. A summation transformer and sequence filters, etc. are used for the purpose. Figure 1.7 (a) shows a schematic diagram of a summation transformer where the primary windings are connected to the output terminals of the line C.T.s. Figures 1.7 (b) and (c) show corresponding phase diagrams. The number of turns between R and Y phases is equal to those between Y and B. But more turns are provided between B and neutral. Table 1.6 shows the output current in terms of the C.T. rated current for a given fault current in each type of fault.

The output of a summation C.T. is given by

$$I_{\text{output}} = (N+2)\, I_R + (N+1)\, I_Y + N I_B$$

This can be converted to their symmetrical components. Taking R phase as reference we get,

$$\begin{aligned} I_{\text{output}} &= (N+2)(I_1 + I_2 + I_0) + (N+1)(a^2 I_1 + a I_2 + I_0) \\ &\quad + N(a I_1 + a^2 I_2 + I_0) \\ &= 3I_0 (N+1) + I_1 (2 + a^2 + a^2 N + aN + N) \\ &\quad + I_2 (2 + a + a^2 N + aN + N) \\ &= 3I_0 (N+1) + I_1 (2 + a^2) + I_2 (2 + a) \\ &= K_0 I_0 + K_1 I_1 + K_2 I_2 \end{aligned}$$

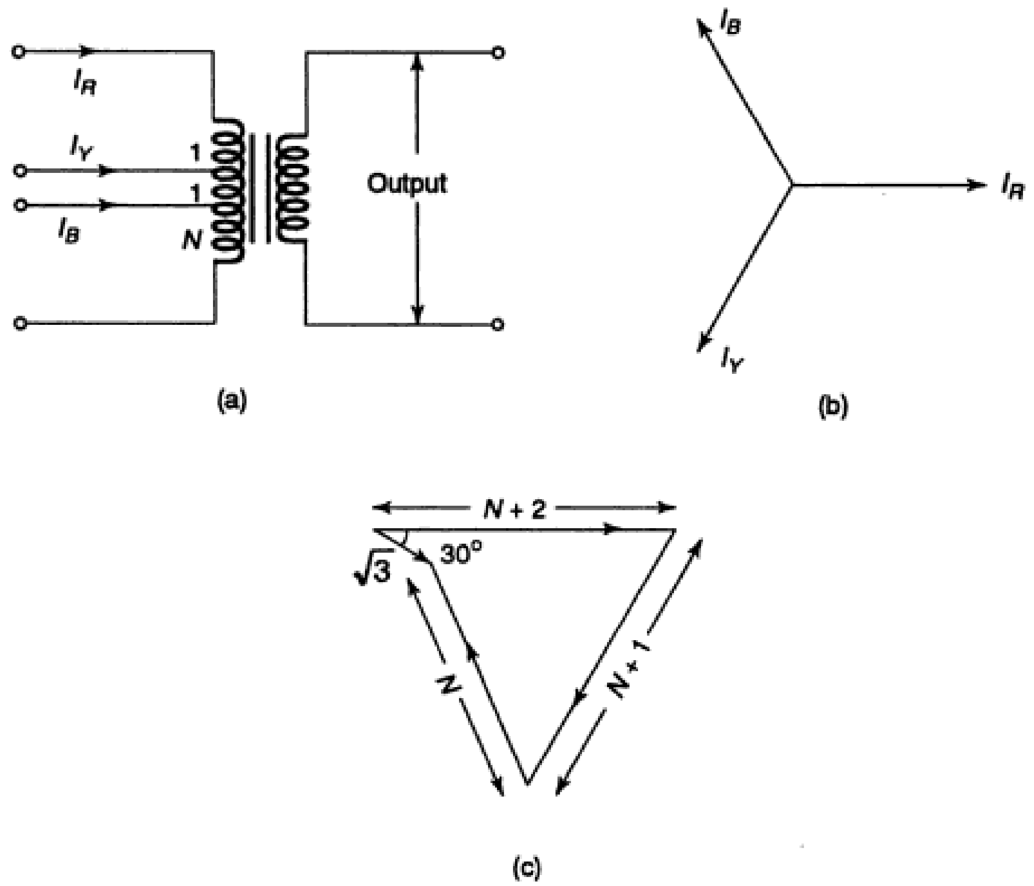


FIGURE 1.7 (a) Summation transformer (b) Phasor diagram of 3-phase input current (c) Phasor diagram of summated output for 3-phase balanced input current

TABLE 1.6 Output of Summation Transformer

Type of Fault	R-G	Y-G	B-G	R-Y	Y-B	B-R	R-Y-B
Summation C.T. turns	$N+2$	$N+1$	N	1	1	2	3
Output current	14%	16.5%	20%	90%	90%	45%	52%

Using the derived equation, I_{output} can be calculated for different types of faults. Table 1.7 shows the constants K_1, K_2 and K_0 for various types of faults for a summation transformer.

TABLE 1.7 Constants for Different Types of Faults for Summation Transformer

Type of Fault	K_0	K_1	K_2
R-G, Y-B, Y-B-G	$3(N+1)$	$2+a^2$	$2+a$
Y-G, B-R, B-R-G	$3(N+1)$	$a(2+a^2)$	$a^2(2+a)$
B-G, R-Y, R-Y-G	$3(N+1)$	$a^2(2+a^2)$	$a(2+a)$

Under certain fault conditions, I_{output} of a summation transformer is negligibly small or is zero. This is the serious drawback of a summation transformer. To overcome this difficulty, a special kind of sequence filter which gives an output of the form $5I_2 - I_1$, is used now-a-days.

1.16 Phase-sequence Current-segregating Network

A general type of phase-sequence filter network can be developed as shown in Fig. 1.8 (a). The output of the network or any other kind of summation device can be written in the form given below.

$$I_{output} = K_0I_0 + K_1I_1 + K_2I_2$$

The constants K_0, K_1 and K_2 depend on the device which is used to derive a single-phase quantity from the 3-phase quantities.

The phase-sequence filter giving an output in the form of $I_1 - KI_2$ gives the most uniform response for any type of fault. The value of K may be 5 or 6. Figure 1.8 (b) shows a phase sequence filter of this type. Table 1.8 shows the values of constants for general type phase sequence network and $I_1 - KI_2$ type phase-sequence filter.

1.17 Basic Relay Terminology

Relay A relay is an automatic device by means of which an electrical circuit is indirectly controlled (opened or closed) and is governed by a change in the same or another electical circuit.

Protective relay A protective relay is an automatic device which detects an abnormal condition in an electrical circuit and causes a circuit breaker to isolate the faulty element of the system. In some cases it may give an alarm or visible indication to alert operator.

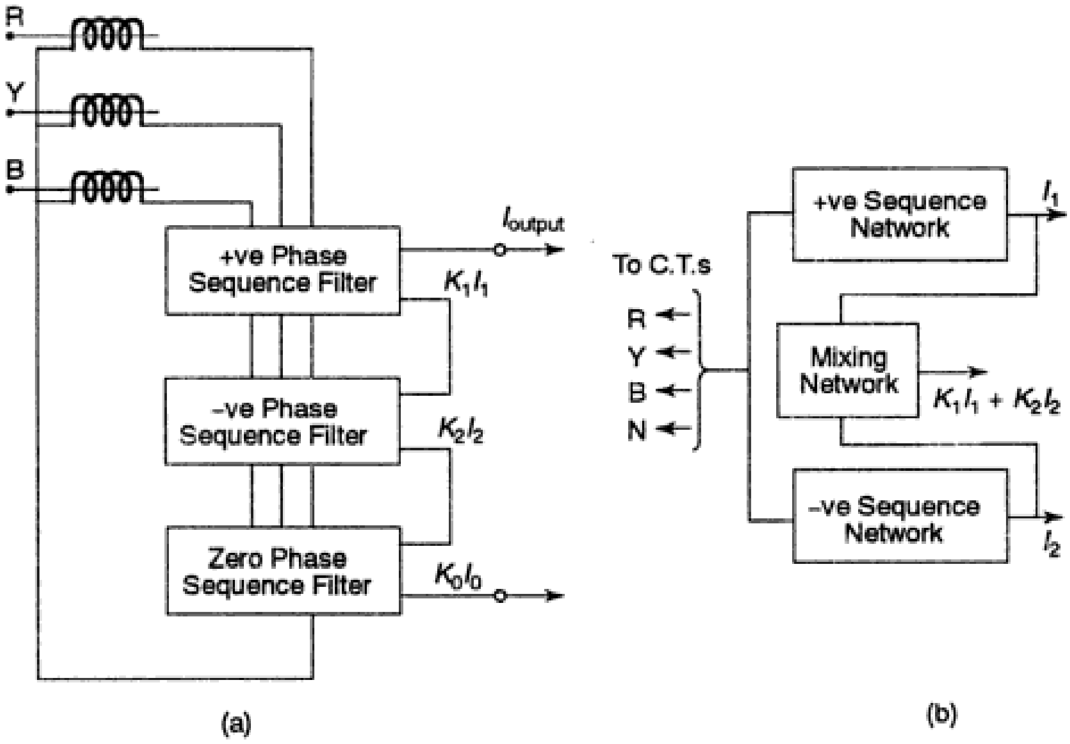


FIGURE 1.8 (a) Phase sequence filter network (b) ($K_1I_1 + K_2I_2$) type phase sequence filter network

TABLE 1.8 Value of Constants K_0, K_1 and K_2, Outpur of Phase-sequence Filter

Type of Faults	*Any Summation Device*			*$(K_1 - KI_2)$ Type Device*
	K_0	K_1	K_2	*Output*
R-G, Y-B, Y-B-G	K_Z	K_P	K_N	$I_1 - KI_2$
Y-G, B-R, B-R-G	K_Z	aK_P	a^2K_N	$aI_1 - a^2KI_2$
B-G, R-Y, R-Y-G	K_Z	a^2K_P	aK_N	$a^2I_1 - aKI_2$

K = 5 or 6
K_Z = Constant for zero-sequence component
K_P = Constant for +ve sequence component
K_N = Constant for –ve sequence component

Operating force or torque A force or torque which tends to close the contacts of the relay.

Restraining force or torque A force or torque which opposes the operating force/torque.

Pick-up (level) The threshold value of the actuating quantity (current, voltage, etc.) above which the relay operates.

Reset or drop-out (level)	The threshold value of the actuating quantity (current, voltage, etc.) below which the relay is de-energised and returns to its normal position or state. Consider a situation where a relay has closed its contacts and the actuating current is still flowing. Now, due to some reason, the abnormal condition is over and the current starts decreasing. At some maximum value of the current the contacts will start opening. This condition is called reset or drop-out. The maximum value of the actuating quantity below which contacts are opened is called the reset or drop-out value.
Operating time	It is the time which elapses from the instant at which the actuating quantity exceeds the relays pick-up value to the instant at which the relay closes its contacts.
Reset time	It is the time which elapses from the moment the actuating quantity falls below its reset value to the instant when the relay comes back to its normal (initial) position.
Setting	The value of the actuating quantity at which the relay is set to operate.
Seal-in relay	This is a kind of an auxiliary relay. It is energised by the contacts of the main relay. Its contacts are placed in parallel with those of the main relay and is designed to relieve the contacts of the main relay from their current carrying duty. It remains in the circuit until the circuit breaker trips. The seal-in contacts are usually heavier than those of the main relay.
Reinforcing relay	This is a kind of an auxiliary relay. It is energised from the contacts of the main relay. Its contacts are placed in parallel with those of the main relay and it is also designed to relieve the main relay contacts from their current carrying duty. The difference between a reinforcing relay and a seal-in relay is that the latter is designed to remain in the circuit till the circuit breaker operates. But this is not so with the reinforcing relay. The reinforcing relay is used to hold a signal from the initiating relay (main relay) for a longer period. As the contacts of the main relay are not robust, they are closed for a short time.
Back-up relay	A back-up relay operates after a slight delay, if the main relay fails to operate.
Back-up protection	The back-up protection is designed to clear the fault if the primary protection fails. It acts as a second line of defence.
Primary protection	If a fault occurs, it is the duty of the primary protective scheme to clear the fault. It acts as a first line of defence. If it fails, the back-up protection clears the fault.

Measuring relay	It is the main protective relay of the protective scheme, to which energising quantities are applied. It performs measurements to detect abnormal conditions in the system to be protected.
Auxiliary relays	Auxiliary relays assist protective relays. They repeat the operations of protective realys, control switches, etc. They relieve the protective relays of duties like tripping, time lag, sounding an alarm, etc. They may be instantaneous or may have a time delay.
Electromagnetic relays	Such relays operate on the electromagnetic principle i.e. an electromagnet attracts magnetic moving part or a force is exerted on a current carrying conductor when placed in the magnetic field or a force is produced by the principle of induction, etc. Moving iron, moving coil, attracted armature, induction disc and induction cup type relays come under this group of relays.
Static relays	These are solid state relays and employ semiconductor diodes, transistors, thyristors, logic gates, ICs, etc. The measuring circuit is a static circuit and there are no moving parts. In some static relays, a slave relay which is a d.c. polarised relay is used as the tripping device.
Microprocessor-based relay	A microprocessor can be used to perform all functions of a relay. It can measure electrical quantities, make comparisons, perform computations, and send tripping signals. It can realise all sorts of relaying characteristics, even irregular curves which cannot be realised by electromagnetic or static relays easily.
Overcurrent relay	A relay which operates when the actuating current exceeds a certain preset value (its pick-up value).
Undervoltage relay	A relay which operates when the system voltage falls below a certain preset value.
Directional or reverse power relay	A directional relay is able to detect whether the point of fault lies in the forward or reverse direction with respect to the relay location. It is able to sense the direction of power flow, i.e. whether the power is flowing in the normal direction or the reverse direction.
Polarised relay	A relay whose operation depends on the direction of current or voltage.
Flag or target	Flag is a device which gives visual indication whether a relay has operated or not.

Time-lag relay	A time-lag relay operates after a certain preset time lag. The time lag may be due to its inherent design feature or may be due to the presence of a time-delay component. Such relays are used in protection schemes as a means of time discrimination. They are frequently used in control and alarm schemes.
Instantaneous relay	An instantaneous relay has no intentional time delay in its operation. It operates in 0.1 second. Sometimes the terms high set or high speed relays are also used for the relays which have operating times less than 0.1 second.
Inverse time relay	A relay in which the operating time is inversely proportional to the magnitude of the operating current.
Definite time relay	A relay in which the operating time is independent of the magnitude of the actuating current.
Inverse definite minimum time(IDMT) relay	A relay which gives an inverse time characteristic at lower values of the operating current and definite time characteristic at higher values of the operating current.
Induction relay	A relay which operates on the principle of induction. Examples are induction disc relays, induction cup relays etc.
Moving coil relay	This type of a relay has a permanent magnet and a moving coil. It is also called a permanent magnet d.c. moving coil relay. The actuating current flows in the moving coil.
Moving iron relay	This is a dc polarised, moving iron type relay. There is an electromagnet, permanent magnet and a moving armature in its construction.
Printed disc relay	This relay operates on the principle of a dynamometer. There is a permanent magnet or an electromagnet and a printed disc. Direct current is fed to the printed circuit of the disc.
Thermal relay	This relay utilises the electrothermal effect of the actuating current for its operation.
Distance relay	A relay which measures impedance or a component of the impedance at the relay location is known as a distance relay. It is used for the protection of a transmission line. As the impedance of a line is proportional to the length of the line, a relay which measures impedance or its component is called a distance relay.
Impedance relay	A relay which measures impedance at the relay location is called an impedance relay. It is a kind of a distance relay.
Modified impedance relay	It is an impedance relay having shifted characteristics. The voltage coil includes some current biasing.

Reactance relay	A ralay which measures reactance at the relay location is called a reactance relay. It is a kind of a distance relay.
MHO relay (admittance or angle admittance)	This is a kind of a distance relay. It measures a particular component of the impedance, i.e. $\frac{Z}{\cos(\phi - \theta)}$, where ϕ is the power factor angle and θ is the design angle to shift MHO characteristic on the R-X diagram. Its characteristic on the R-X diagram is a circle passing through the origin. It is a directional relay. It is also known as an admittance or angle admittance relay.
Conduction relay	This is a MHO relay whose diameter (passing through the origin) lies on the R-axis.
Offset MHO characteristic	In an offset MHO relay, the MHO characteristic is shifted on the R-X diagram to include the origin.
Angle impedance relay (ohm relay)	The characteristic of this relay on the R-X diagram is a straight line passing at an angle and cutting both the axes. It is a kind of a distance relay and is also called an Ohm relay.
Elliptical relay	The characteristic of an elliptical relay on the R-X diagram is an ellipse. This is also a kind of a distance relay.
Quadrilateral relay	The characteristic of a quadrilateral relay on the R-X diagram is a quadrilateral. This too is a kind of a distance relay.
Frequency sensitive relay	This is a relay which operates at a predetermined value of the system frequency. It may be an under-frequency relay or an over-frequency relay. An under-frequency relay operates when the system frequency falls below a certain value. An over-frequency relay will operate when the system frequency exceeds a certain preset value of the frequency.
Differential relay	A relay which operates in response to the difference of two actuating quantities.
Earth fault relay	A relay used for the protection of an element of a power system against earth faults is known as an earth fault relay.
Phase fault relay	A relay used for the protection of an element of a power system against phase faults is called a phase fault relay.
Negative sequence relay	A relay for which the actuating quantity is the negative sequence current. When the negative sequence current exceeds a certain value, the relay operates. This type of a relay is used to protect electrical machines against overheating due to unbalanced currents.
Zero sequence relay	A relay for which the actuating quantity is the zero sequence current. This type of a relay is used for earth fault protection.

Starting relay or fault detector	This is a relay which detects abnormal conditions and initiates the operation of other elements of the protective scheme.
Notching relay	A relay which switches in response to a specific number of applied impulses is called a notching relay.
Protective zone	A power system is divided into a number of zones from the protection point of view. Each element of the power system has a separate protective scheme for its protection. The elements which come under a protective scheme are said to be in the zone of protection of that particular scheme. Similarly, a protective relay has its own zone of protection.
Reach	This term is mostly used in connection with distance relays. A distance relay operates when the impedance (or a component of the impedance) as seen by the relay is less than a preset value. This preset impedance (or a component of impedance) or corresponding distance is called the reach of the relay. In other words, it is the maximum length of the line up to which the relay can protect.
Overreach	Sometimes a relay may operate even when a fault point is beyond its present reach (i.e. its protected length).
Underreach	Sometimes a relay may fail to operate even when the fault point is within its reach, but it is at the far end of the protected line. This phenomenon is called underreach.
Selectivity or discrimination	It is the ability of a relay to discriminate between faulty conditions and normal conditions (or between a fault within the protected section and outside the protected section). In other words, it is the quality of the protective system by which it distinguishes between those conditions for which it should operate and those for which it should not.
Reliability	A protective relay must operate reliably when a fault occurs. The reliability of a protective relay should be very high, a typical value being 95%.
Sensitivity	A protective relay should be sensitive enough to operate when the magnitude of the actuating quantity exceeds its pick-up value.
Stability	This is the ability of the protective system to remain inoperative under all load conditions, and also in case of external faults. The relay should remain stable when a heavy current due to an external fault is flowing through it.
Fast operation	A protective relay should be fast enough to cause the isolation of the faulty section as quickly as possible to minimise the

damage and to maintain the stability.

Burden	The power consumed by the relay circuitry at the rated current is known as its burden.
Blocking	The prevention of tripping of the relay is called blocking. It may be due to the operation of an additional relay or due to its own characteristic.
Unit system of protection	A unit system of protection is one which is able to detect and respond to faults occurring only within its own zone of protection. It is said to have absolute discrimination. Its zone of protection is well defined. It does not respond to the faults occurring beyond its own zone of protection. Examples of unit protection are differential protection of alternators, transformers or bus bars, frame leakage protection, pilot wire and carrier current protection.
Non-unit system of protection	A non-unit system of protection does not have absolute discrimination (selectivity). It has dependent or relative discrimi nation. The discrimination is obtained by time grading, current grading or a combination of current and time grading of the relays of several zones. In this situation, all relays may respond to a given fault. Examples of non-unit system of protection are distance protection and time graded, current graded or both time and current graded protection.
Restricted earth fault protection	This is an English term which may be misunderstood in other countries. It is used in the context of transformer or alternator. It refers to the differential protection of transformers or alternators against ground faults. It is called restricted because its zone of protection is restricted only to the winding of the alternator or transformer. The scheme responds to the faults occurring within its zone of protection. It does not respond to faults beyond its zone of protection.
Protective gear or equipment	It includes protective relays, P.T.s, C.T.s and ancillary equipment to be used in a protective system.
Protective system	It is a combination of protective gear equipment to secure isolation of the faulty element under predetermined conditions, usually abnormal or to give an alarm signal or both.
Protective scheme	A protective scheme may consist of several protective systems. It is designed to protect one or more elements of a power system.
Residual current	It is the algebraic sum of all currents in a multiphase system. It is denoted by I_{res}. In a 3-phase system $I_{res} = I_A + I_B + I_C$

Exercises

1. Explain the nature and causes of faults. Discuss the consequences of faults on a power system.
2. What are the different types of faults? Which type of fault is most dangerous?
3. Discuss briefly the role of protective relays in a modern power system.
4. What do you understand by a zone of protection? Discuss various zones of protection for a modern power system.
5. Explain what you understand by primary and back-up protection. What is the role of back-up protection? What are the various methods of providing back-up protection?
6. Explain what you understand by pick-up and reset value of the actuating quantity.
7. Discuss what you understand by selectivity and stability of a protective relay.
8. Discuss the essential qualities of a protective relay.
9. Explain the basic difference between a C.T. used for instrumentation and a C.T. used for protection.
10. Explain C.T. burden. How is it specified?
11. Discuss how saturation affects the accuracy of C.T.s. Explain the accuracy limit factor or saturation factor.
12. What is a linear coupler? Where is it used?
13. Discuss the different types of P.T.s with their areas of applications.
14. What is a summation transformer? Where is it used?

Two

Operating Principles and Relay Construction

Protective relays are classified into the following three categories, depending on the technologies they use for their construction and operation.

1. Electromagnetic and electrothermal
2. Static—using semiconductor devices like ICs, transistor, diodes, logic gates, etc.
3. Microprocessor based

There are various types of protective relays in each category, depending on the operating principle and application.

2.1 Electromagnetic Relays

The following are the important types of construction of electromagnetic relays.

(i) Attracted armature
(ii) Induction disc
(iii) Printed disc dynamometer
(iv) Permanent magnet
(v) Moving-coil
(vi) Polarised moving-iron

2.1.1 Attracted Armature Relay

Hinged armature and plunger type construction comes under this group of relays. Figure 2.1 (a) shows a hinged armature type construction. The coil is energised by an operating quantity proportional to the system current or voltage. The operating quantity produces a magnetic flux which in turn produces an electromagnetic force. The electromagnetic force is proportional to the square of the flux in the air gap or the square of the current. The attractive force increases as the armature approaches the pole of the electromagnet. This type of a relay is used for the protection of small machines, equipment, etc. It is also used for auxiliary relays, such as indicating flags, slave relays, alarm relays, annunciators, semaphores, etc.

The actuating quantity of the relay may be either ac or dc. In dc relays, the electromagnetic force of attraction is constant. In the case of ac relays, sinusoidal current flows through the coil and hence the force of attraction is given by

$$F = KI^2 = K(I_{max} \sin \omega t)^2 = \frac{1}{2}K(I_{max}^2 - I_{max}^2 \cos 2\omega t)$$

From the above expression, it is evident that the electromagnetic force consists of two components. One component is constant and is equal to $\frac{1}{2}KI_{max}^2$. The other component is time dependent and pulsates at double the frequency of the applied ac quantity. Its magnitude is $\frac{1}{2}KI_{max}^2 \cos 2\omega t$. The total force is a double frequency pulsating force. This may cause the armature to vibrate at double the frequency. Consequently, the relay produces a humming sound and becomes noisy. This difficulty can be overcome by making the pole of the electromagnet of shaded construction. Alternatively, the electromagnet may be provided with two coils. One coil is energised with the actuating quantity. The other coil gets its supply through a phase shifting circuit.

The restraining force is provided by a spring. The reset to pick-up ratio for attracted armature type relays is 0.5 to 0.9. For this type of a relay, the ratio for ac relays is higher as compared to dc relays. The VA burden is low, which is 0.08 W at pick-up for the relay with one contact, 0.2 W for the relay with four contacts. The relay is an instantaneous relay. The operating speed is very high. For a modern relay, the operating time is about 5 ms. It is faster than the induction disc and cup type relays. Attracted armature relays are compact, robust and reliable. They are affected by transients as they are fast and operate on both dc and ac. The fault current contains a dc component in the beginning for a few cycles. Due to the presence of dc transient, the relay may operate though the steady state value of the fault current may be less than its pick-up. A modified construction as shown in Fig. 2.1(b) reduces the effect of dc transients.

Plunger type relay

In this type of a relay, there is a solenoid and an iron plunger which moves in and out of the solenoid to make and break the contact. This type of construction has however become obsolete as it draws more current.

2.1.2 *Induction Disc Relay*

There are two types of construction of induction disc relays, namely the shaded pole type, as shown in Fig. 2.2; and watt hour meter type, as shown in Fig. 2.3.

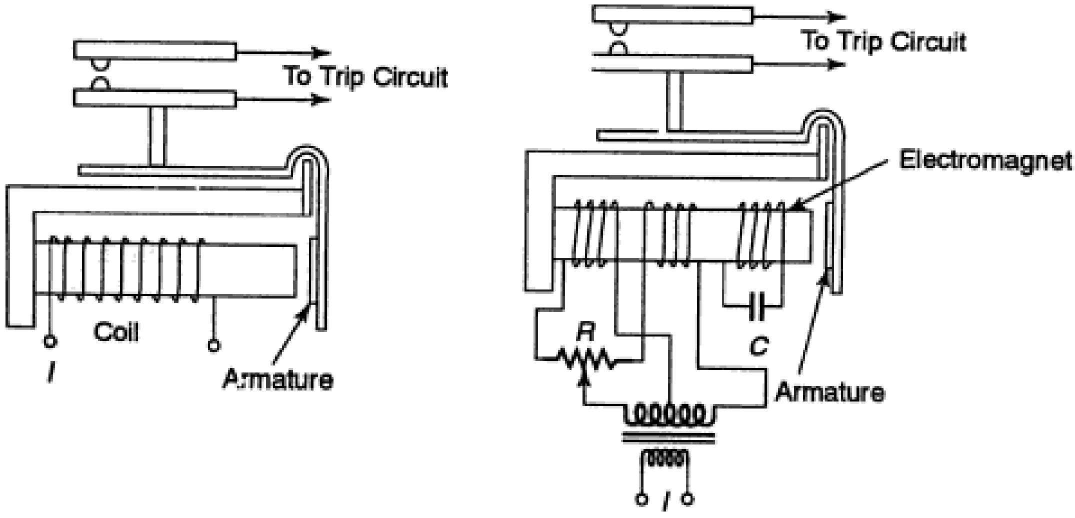


FIGURE 2.1 (a) Hinged armature type relay (b) Modified hinged armature type relay

Figure 2.2 (a) shows a simple theoretical figure, whereas Fig. 2.2 (b) shows the construction which is actually used in practice. The rotating disc is made of aluminium. In the shaded pole type construction, a C-shaped electromagnet is used. One half of each pole of the electromagnet is surrounded by a copper

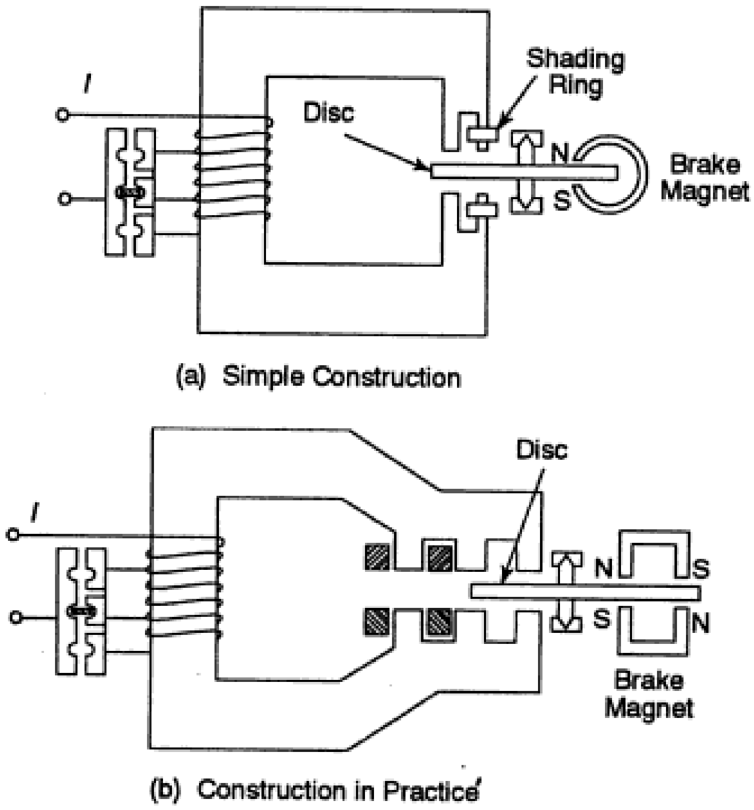


FIGURE 2.2 Shaded pole type induction disc relay

band known as the shading ring. The shaded portion of the pole produces a flux which is displaced in space and time with respect to the flux produced by the unshaded portion of the pole. Thus two alternating fluxes displaced in space and time cut the disc and produce eddy currents in it. Torques are produced by the interaction of each flux with the eddy current produced by the other flux. The resultant torque causes the disc to rotate.

In wattmetric type of construction, two electromagnets are used: upper and lower one. Each magnet produces an alternating flux which cuts the disc. To obtain a phase displacement between two fluxes produced by upper and lower electromagnets, their coils may be energised by two different sources. If they are energised by the same source, the resistances and reactances of the two circuits are made different so that there will be sufficient phase difference between the two fluxes.

Induction disc type construction is robust and reliable. It is used for overcurrent protection. Disc type units give an inverse time current characteristic and are slow compared to the induction cup and attracted armature type relays. The induction disc type is used for slow-speed relays. Its operating time is adjustable and is employed where a time-delay is required. Its reset/pick-up ratio is high, above 95% because its operation does not involve any change in the air gap. The VA burden depends on its application, and is generally of the order of 2.5 VA. The torque is proportional to the square of the actuating current if single actuating quantity is used.

A spring is used to supply the resetting torque. A permanent magnet is employed to produce eddy current braking to the disc. The magnets should remain stable with age so that its accuracy will not be affected. Magnets of high coercive force are used for the purpose. The braking torque is proportional to the speed of the disc. When the operating current exceeds pick-up value, driving torque is produced and the disc accelerates to a speed where the braking torque balances the driving torque. The disc rotates at a speed proportional to the driving torque.

It rotates at a constant speed for a given current. The disc inertia should be as small as possible, so that it should stop rotating as soon as the fault current disappears when circuit breaker operates at any other location or fault current is for a short moment (i.e. transient in nature). After the cessation of the fault current, the disc will travel to some distance due to inertia. This distance should be minimum. It is called the over-run of the disc. A brake magnet is used to minimise over-run. The over-run is usually not more than 2 cycles on the interruption of a current which is 20 times the current setting.

At a current below pick-up value, the disc remains stationary by the tension of the control spring acting against the normal direction of disc rotation. The disc rests against a backstop. The position of the backstop is adjustable and therefore, the distance by which the moving contact of the relay travels before it closes contacts, can be varied. The distance of travel is adjusted for the time setting of the relay.

The rotor (disc) carries an arm which is attached to its spindle. The spindle is supported by jewelled bearings. The arm bridges the relay contacts. In earlier constructions, there were two contacts which were bridged when the relay operated. In modern units however, there is a single contact with a flexible lead-in.

Current setting

In disc type units, there are a number of tappings provided on coil to select the desired pick-up value of the current. These tapings are shown in Fig. 2.3. This will be discussed in more detail in the next chapter.

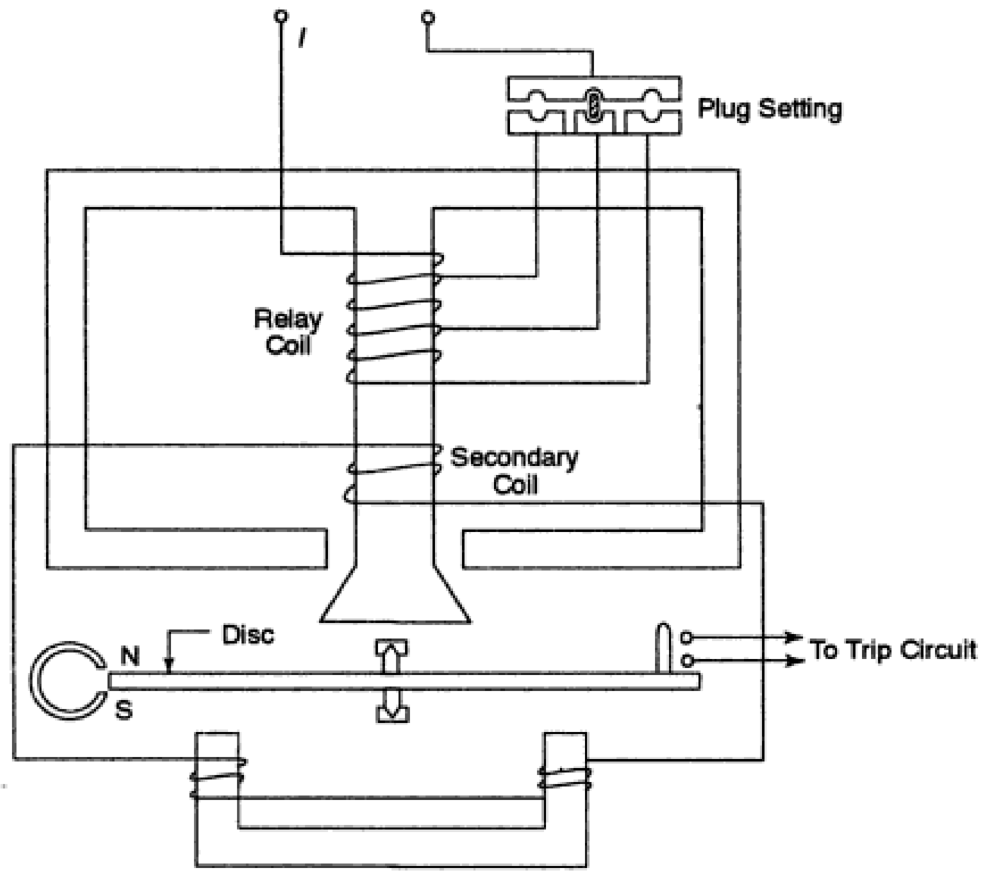


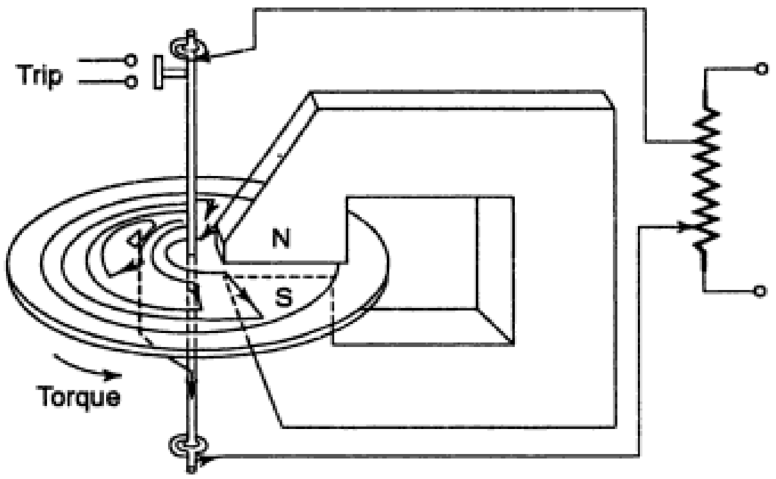
FIGURE 2.3 Wattmetric type induction-disc relay

Time setting

The distance which the disc travels before it closes the relay contact can be adjusted by adjusting the position of the backstop. If the backstop is advanced in the normal direction of rotation, the distance of travel is reduced, resulting in a shorter operating time of the relay. More details on time-setting will be discussed in the next chapter.

2.1.3 Printed Disc Relay

Figure 2.4 shows the construction of a printed disc inverse time relay. Its operating principle is the same as that of a dynamometer type instrument.



FIGUR 2.4 Printed disc inverse time relay

There is a permanent magnet to produce a magnetic field. The current from the C.T. is fed to the printed disc through a rectifier. When a current carrying conductor is placed in a magnetic field, a force is developed, thereby a torque is exerted on it. On this very principle, torque is produced in a printed disc relay.

Figure 2.5 shows the construction of a printed disc extremely inverse time relay ($I^2t = K$ relay). To obtain $I^2t = K$ characteristic, an electromagnet and a printed disc are used. The electromagnet is energised from the C.T. through a rectifier.

Printed disc relays give a much more accurate time characteristic. They are also very efficient. A printed disc relay is 50 to 100 times more efficient than the induction disc type. The maximum efficiency that an induction disc relay can have is only about 0.05%, which is extremely poor. Characteristics other than inverse time-current characteristic can be obtained by including a non-linear network in between the printed circuit of the disc and the rectified current input.

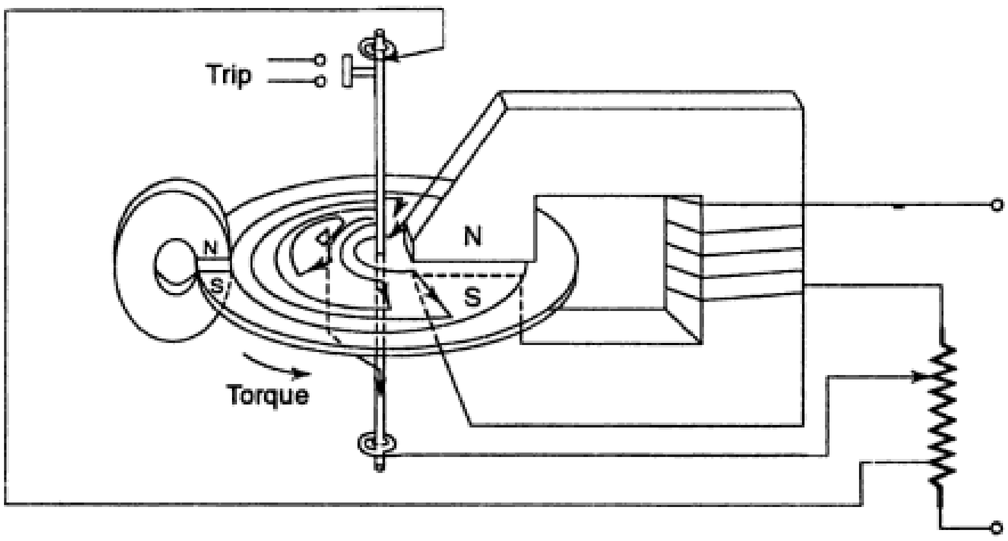


FIGURE 2.5 Printed disc extremely inverse time relay

2.1.4 Induction Cup Relay

Figure 2.6 shows an induction cup relay. A stationary iron core is placed inside the rotating cup to decrease the air gap without increasing inertia. The spindle of the cup carries an arm which closes contacts. A spring is employed to provide a resetting torque. When two actuating quantities are applied, one may produce an operating torque while the other may produce restraining torque. Brake magnets are not used with induction cup type relays. It operates on the same principle as that of an induction motor. It employs a 4 or 8-pole structure. The rotor is a hollow cylinder (inverted cup). Two pairs of coils, as shown in the figure, produce a rotating field which induces current in the rotor. A torque is produced due to the interaction between the rotating flux and the induced current, which causes rotation. The inertia of the cup is much less than that of a disc. The magnetic system is more efficient and hence the magnetic leakage in the magnetic circuit is minimum. This type of a magnetic system also reduces the resistance of the induced current path in the rotor. Due to the low weight of the rotor and efficient magnetic system its torque per VA is about three times that of an induction disc type construction. Thus, its VA burden is greatly reduced. It possesses high sensitivity, high speed and produces a steady non-vibrating torque. Its parasitic torques due to current or voltage alone are small. Its operating time is to the order of 0.01 second. Thus with its high torque/inertia ratio, it is quite suitable for higher speeds of operation.

Magnetic saturation can be avoided by proper design and the relay can be made to have its characteristics linear and accurate over a wide range with very high reset to pick-up ratio. The pick-up and reset values are close together. Thus this type is best suited where normal and abnormal conditions are very close together. It is inherently self compensating for dc transients. In other words, it is less sensitive to dc transients. The other system transients as well as transients associated with C.T.s and relay circuits can also be minimised by proper design. However, the magnitude of the torque is affected by the variation in the system frequency. Induction cup type relays were widely used

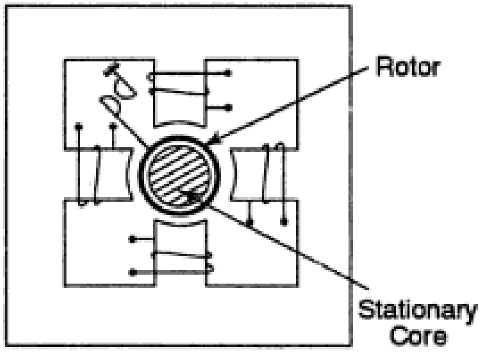


FIGURE 2.6 Induction cup relay

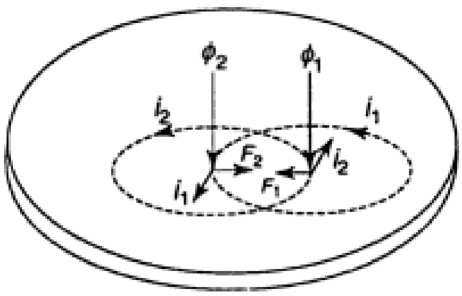


FIGURE 2.7 Torque produced in an induction relay

for distance and directional relays. Later, however, they were replaced by bridge rectifier type static relays.

2.1.5 Theory of Induction Relay Torque

Flux ϕ_1 and ϕ_2 are produced in a disc type construction by shading technique. In wattmetric type construction, ϕ_1 is produced by the upper magnet and ϕ_2 by the lower magnet. A voltage is induced in a coil wound on the lower magnet by transformer action. The current flowing in this coil produces flux ϕ_2. In case of the cup type construction, ϕ_1 and ϕ_2 are produced by pairs of coils, as shown in Fig. 2.6. The theory given below is true for both disc type and cup type induction relays. Figure 2.7 shows how force is produced in a rotor which is cut by ϕ_1 and ϕ_2. These fluxes are alternating quantities and can be expressed as follows.

$$\phi_1 = \phi_{1m} \sin \omega t \qquad \phi_2 = \phi_{2m} \sin (\omega t + \theta)$$

where θ is the phase difference between ϕ_1 and ϕ_2. The flux ϕ_2 leads ϕ_1 by θ.

Voltages induced in the rotor are:

$$\begin{aligned} e_1 &\propto \frac{d\phi_1}{dt} \\ &\propto \phi_{1m} \cos \omega t \\ e_2 &\propto \frac{d\phi_2}{dt} \\ &\propto \phi_{2m} \cos (\omega t + \theta) \end{aligned}$$

As the path of eddy currents in the rotor has negligible self-inductance, with negligible error it may be assumed that the induced eddy currents in the rotor are in phase with their voltages.

$$\begin{aligned} i_1 &\propto \phi_{1m} \cos \omega t \\ i_2 &\propto \phi_{2m} \cos (\omega t + \theta) \end{aligned}$$

The current produced by the flux interacts with the other flux and vice versa. The forces produced are:

$$\begin{aligned} F_1 &\propto \phi_1 i_2 \\ &\propto \phi_{1m} \sin \omega t \cdot \phi_{2m} \cos (\omega t + \theta) \\ &\propto \phi_{1m} \phi_{2m} \cos (\omega t + \theta) \cdot \sin \omega t \\ F_2 &\propto \phi_2 i_1 \\ &\propto \phi_{2m} \sin (\omega t + \theta) \cdot \phi_{1m} \cos \omega t \\ &\propto \phi_{1m} \phi_{2m} \sin (\omega t + \theta) \cdot \cos \omega t \end{aligned}$$

As these forces are in opposition, the resultant force is

$$
\begin{aligned}
F &= (F_2 - F_1) \\
&\propto \phi_{1m}\,\phi_{2m}\,[\sin(\omega t + \theta)\cos\omega t - \cos(\omega t + \theta)\cdot\sin\omega t] \\
&\propto \phi_{1m}\,\phi_{2m}\sin\theta
\end{aligned}
$$

The suffix m is usually dropped and the expression is written in the form of $F = K\phi_1\phi_2 \sin\theta$. In this expression, ϕ_1 and ϕ_2 are rms values.

If the same current produces ϕ_1 and ϕ_2, the force produced is given by

$$F = K I^2 \sin\theta$$

where θ is the angle between ϕ_1 and ϕ_2. If two actuating currents M and N produce ϕ_1 and ϕ_2, the force produced is

$$F = KMN \sin\theta$$

2.1.6 Moving Coil Relays

Figure 2.8 shows a permanent magnet moving coil relay. It is also called a polarised dc moving coil relay. It responds to only dc actuating quantities. It can be used with ac actuating quantities in conjuction with rectifiers. Moving coil relays are most sensitive type electromagnetic relays. Modern relays have a sensitivity of 0.1 mW. These relays are costlier than induction cup or moving iron type relays. The VA burden of moving coil relays is very small. These are used as slave relays with rectifier bridge comparators.

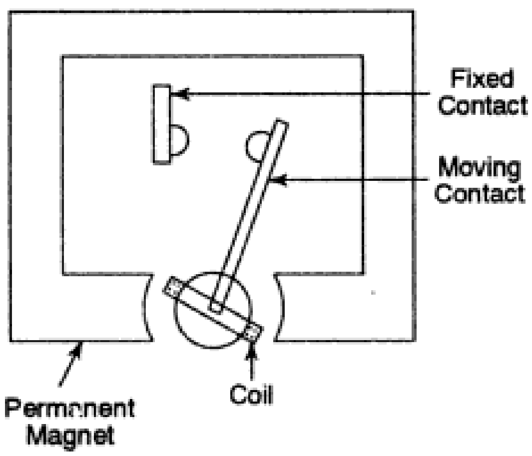


FIGURE 2.8 Rotating moving coil relay

There are two types of moving-coil relays: rotary moving coil and axially moving coil type. The rotary moving coil type is similar to a moving-coil indicating instrument. Figure 2.8 shows a rotary moving coil type construction. The components are: a permanent magnet, a coil wound on a non-magnetic former, an iron core, a phosphor bronze spiral spring to provide resetting torque, jewelled bearing, spindle, etc. The moving coil assembly carries an arm which closes the contact. Damping is provided by an aluminium former. The operating time is about 2 cycles. A copper former can be used for heavier damping and slower operation. The operating torque is produced owing to the interaction between the field of the permanent magnet and that of the coil. The operating torque is proportional to the current carried by the coil. The torque exerted by the spring is proportional to deflection. The relay has an inverse operating time/current characteristic.

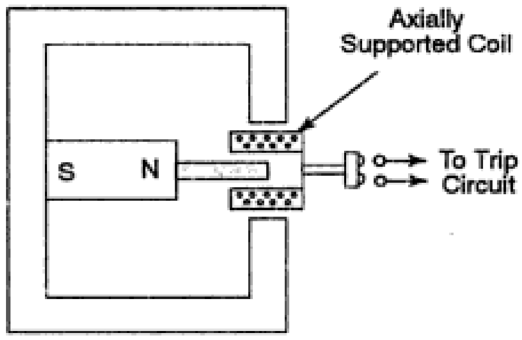


FIGURE 2.9 Axial moving coil relay

Figure 2.9 shows an axially moving coil type construction. As this type has only one air gap, it is more sensitive than the rotary moving coil relay. It is faster than the rotary moving coil relay because of light parts. An operating time of the order of 30 msec can be obtained. Sensitivities as low as 0.1 mW can be obtained. Its coils are wound on a cylindrical former which is suspended horizontally. The coil has only axial movement. The relay has an inverse operating time/current characteristic. The axially moving coil relay is a delicate relay and since the contact gap is small, it has to be handled carefully.

2.1.7 Polarised Moving Iron Relays

Figure 2.10 shows a typical polarised moving iron relay. There are different types of constructions of this type (see Ref. 1). The construction shown in the figure is a flux shifting attracted armature type construction. Polarisation increases the sensitivity of the relay. A permanent magnet is used for polarisation. The permanent magnet produces flux in addition to the main flux. It is a dc polarised relay, meant to be used with dc only. However, it can be used with ac with rectifiers. Modern relays have sensitivities in the range of 0.03 to 1 mW, depending on their construction. Using transistor amplifiers, a relay's sensitivity can be increased to 1 μW for pick-up. It is used as a slave relay with rectifier bridge comparators. As its current carrying coil is stationary, it is more robust than the moving coil type dc polarised relay. Its operating time is 2 msec to 15 msec depending upon the type of construction. An ordinary attracted armature type relay is not sensitive to the polarity of the actuating quantity whereas a dc polarised relay will only operate when the input is of the currect polarity.

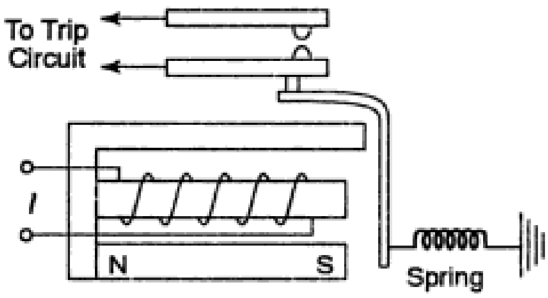


FIGURE 2.10 Polarised moving iron relay

2.1.8 Balanced Beam Relay

A balanced beam relay is also a kind of attracted armature type relay, but is usually discussed under its own separate heading. As its name indicates, it consists of a beam carrying two electromagnets at its ends. One gives operating torque while the other restraining torque. The beam is supported at the middle and it remains horizontal under normal conditions. When the operating torque exceeds the restraining torque, an armature fitted at one end of the beam is pulled and its contacts are closed. Though now obsolete, this type of a relay was popular in the past for constructing impedance and differential relays. It has been superseded by rectifier bridge comparators and permanent magnet moving coil relays. The beam type relay is robust and fast in operation, usually requiring only 1 cycle, but is not accurate as it is affected by dc transients.

2.1.9 Auxiliary Relay, Auxiliary Switch and Flag

A protective relay is assisted by auxiliary relays for a number of important operations. A protective relay performs the task of measurement and under the required condition, it closes its contacts. It is relieved of other duties such as tripping, time lag, breaking of trip circuit current, giving alarm, showing flags, etc. These duties are performed by auxiliary relays. Auxiliary relays repeat the operations of protective relays, control switches, etc. Repeat contact and auxiliary switches are also used to assist protective relays. The reasons for employing auxiliary relays, repeat contactors and auxiliary switches are:

(i) Protective relay contacts are delicate and light in weight. They are not capable of carrying large amount of current for a long period.

(ii) The protective relays do not have enough contacts to perform all duties required in a protective scheme.

The commonly used auxiliary relays have been described below.

Seal-in relay

A seal-in relay is an auxiliary relay which is employed to protect the contacts of a protective relay. Once the protective relay closes its contacts, the seal-in relay is energized. Its contacts bypass the contacts of the protective relay, close and seal the circuit while the tripping current flows. It may also give an indication by showing a flag (target). It is an instantaneous relay, and operates on attracted armature principle.

Time-lag relays

Time-lag relays operate after a preset time-lag. They are used in protection schemes as a means of time discrimination, for example, time graded schemes which will be discussed in the next chapter. They are also used in control and alarm circuits to allow time for the required sequence of operations to take place. The principle of producing time delays will be discussed later (see Sec. 2.1.11).

Alarm relays

An alarm relay gives both an audible and a visual indication. At a substation, it is sufficient to provide a trip alarm and one non-trip alarm, which is common to the whole substation. In the control room of a generating station, the trip alarm and non-trip alarm should be separate for each primary circuit. There is an arrangement for alarm cancellation by pressing a button. The alarm circuit is interrupted on pushing this button. When the relay is de-energised, the initiating contact of the cancellation mechanism is reset so that it can receive another alarm.

Repeat contactors

A repeat contactor repeats the operation of a protective relay. It is sometimes needed because a protective relay may not have a sufficient number of contacts. It may also be required to take over the operation from the initiating relay if the contacts of the latter are not designed for carrying current for long periods. Its most important requirements are that it should be fast and absolutely reliable. It should also be robust and compact. It is usually mounted in the same case as the relay for which it is required to repeat the operation.

Repeat contactors operate on the attracted armature principle. It may be connected either in series or in parallel with the relay. It contains a number of contacts which are placed in parallel. However, having more than three contacts in parallel is usually not pratical.

Flag or target

When a relay operates, a flag is indicated to show its operation. When on a relay panel there are several relays, it is the flag that indicates, the relay that has operated. This helps the operator to know the cause of the tripping of the circuit breaker. It is also called the target or indicator. Its coil is connected in series with the trip coil of the circuit breaker, as shown in Fig. 2.11. The resetting of a flag indicator is usually manual. There is a button or knob outside the relay case to reset the flag indicator. A flag indicator may either be electrical or mechanical. In a mechanical flag indicator, the movement of the armature of the relay pushes a small shutter to expose the flag. In an electrically operated flag indicator there is a solenoid which is energised when relay contacts are closed. Electrical flags being more reliable are preferred.

Auxiliary switch

An auxiliary switch is connected in series with the trip-coil circuit, as shown in Fig. 2.11. It is mechanically interlocked with the operating mechanism of the circuit breaker so that the auxiliary switch opens when the circuit breaker opens. The opening of the auxiliary switch prevents unnecessary drainage of the battery.

When the trip-coil of the circuit breaker is energised, it actuates a mechanism of the circuit breaker, which causes the operating force to come into action to open the circuit breaker.

2.1.10 Connections for Seal-in Relay, Auxiliary Switch and Circuit Breaker Trip-Coil

Figure 2.11 (a) shows the connection for a seal-in relay, circuit breaker trip-coil and auxiliary switch. In order to protect the contacts of the protective relay, a seal-in relay is employed. Its contacts bypass the contacts of the protective relay and seal the circuit closed, while the tripping current flows. Some relays employ a simple holding coil in series with the relay contacts, as shown in Fig. 2.11(b). The holding coil is wound on a small soft iron core which acts on a small armature on the moving-contacts assembly to hold the contacts tightly closed, once they have established the flow of current through the trip coil. The holding coils are used to protect the relay contacts against damage which may be caused due to the make and break action of the contacts.

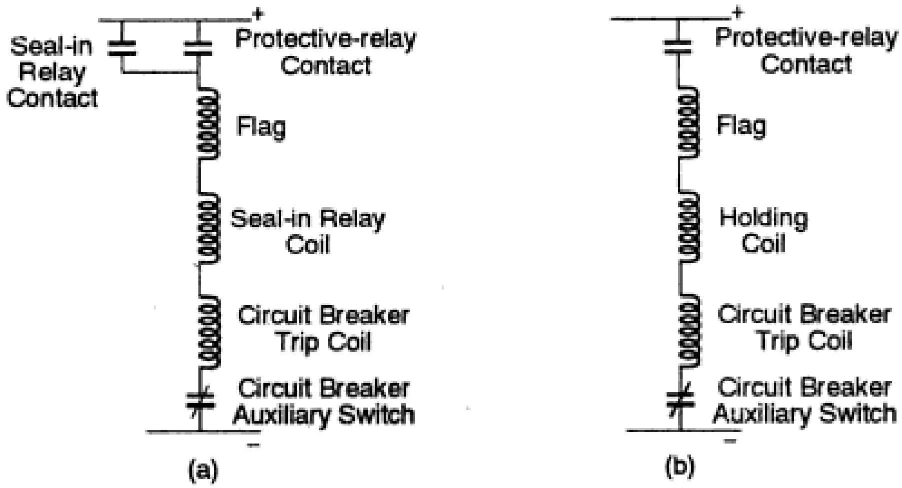


FIGURE 2.11 Circuit breaker trip coil circuit (a) With seal-in relay (b) With holding coil

2.1.11 *Techniques to Produce Time-delays*

Sometimes, a protective relay is required to operate after a preset time delay. Intentional time delays are necessary for such relays. The intentional time-delay may be caused by inherent design features of the relay or by a delay producing component of the relay. Sometimes, a starting relay or instantaneous relay is used in conjunction with a timing relay to perform certain operations after a preset time. A time-lag relay (timing relay) is an auxiliary relay designed to operate after a preset time-delay.

Mechanical time-delay

The time delay may be produced by mechanical, electrical or electronic components. Oil dashpots, pneumatic damping, toothed gears, cams, mercury switches, etc. are some examples of mechanical devices which are used to produce a time delay. In an oil dashpot, there is a magnetically operated plunger. Oil flowing through an orifice in the cylinder retards the relay movement. The pneumatic timer contains a metal chamber, a diaphragm and solenoid. These mechanical devices are crude devices and do not produce accurate delays. The mercury switch, however, gives an accurate delay. The mercury tube has two sections. One section contains mercury and the other section contains contacts. The tube is tilted so that mercury flows from one section to the other and bridges the contacts. The flow of mercury is impeded by a construction between the two sections of the tube. The time setting is fixed by the design of the tube. It is not possible to have a range of time settings on a particular mercury switch. Toothed gears or cams are also used to produce time delay.

Thermal time-delay

Thermal devices employing expansion of bimetal strip or spiral, unimetal (brass) strips, etc. are also used to produce time-delay.

Electrical time-delay

Time delay can be produced by employing a short-circuiting ring around a solenoid pole; a circuit containing reactance, capacitance or non-linear resistance; a resonent circuit, etc.

Short-circuiting ring

A short-circuiting copper band is fitted around the pole piece of an attracted armature hinged-type relay. This arrangement provides eddy current path for damping. To obtain a time-delay on pick-up, the band is placed at the armature end of the core. By this technique, a delay of about 0.1 s can be produced in pick-up with a large armature gap and a stiff restraining spring. To obtain a delayed reset, the band is placed at the frame end of the solenoid. A delay up to 0.5 s in drop out can be obtained with a short lever arm and a light spring load. Time-delay can also be produced by employing a copper tube inside the coil.

Capacitance

A capacitor which is connected in parallel with the relay coil is charged through a resistor, as shown in Fig. 2.12 (a). A longer time-delay is obtained

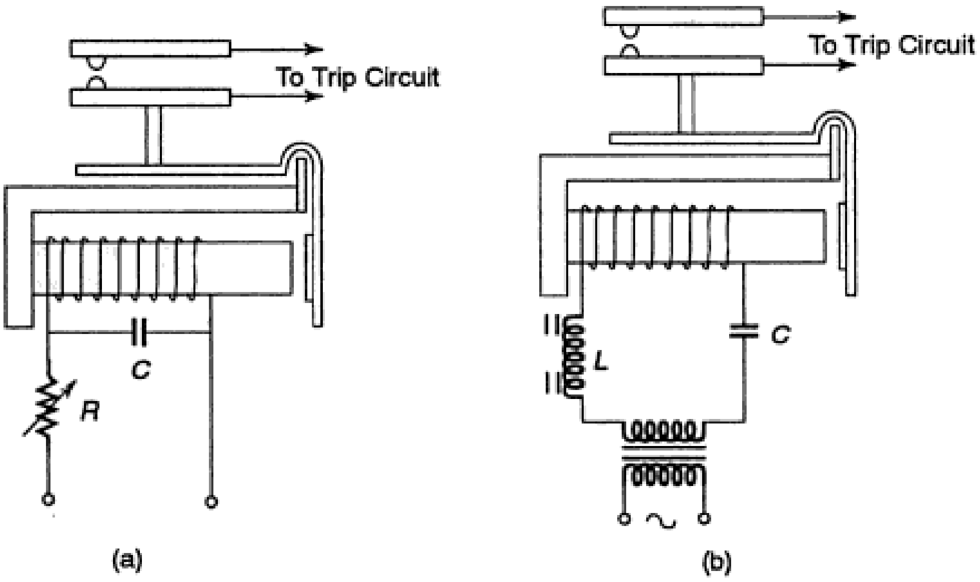


FIGURE 2.12 (a) Capacitor charge delay (b) Resonance build-up delay

by this technique. A delay of up to 0.5 s can be obtained on pick-up with a capacitor of reasonable size. For ac applications, a rectifier should be included.

Resonant circuit

A resonant circuit, as shown in Fig. 2.12 (b) can be employed to produce a delay of up to 3 cycles.

Ballistic resistance

This technique is based on the principle of delaying the build-up of operating voltage. This includes thermistors or filament lamps. Figure 2.12 (c) shows a metal filament lamp connected across the relay coil. A resistance is also placed in the circuit as shown in the figure. The hot resistance of the lamp filament is 10 times its cold resistance. The relay coil is short-circuited by the lamp, thereby keeping the magnetic flux to zero for a short time until the filament becomes incandescent.

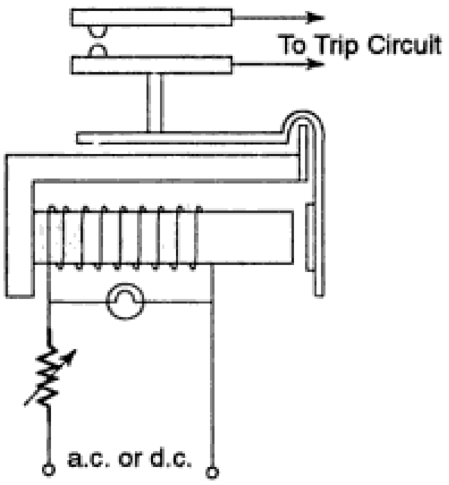


FIGURE 2.12(c) Lamp filament heating delay

Alternatively, a thermistor or a carbon filament can be placed in series with the relay coil. The thermistor resistance being high at room temperature limits the coil current. As the current drawn by the relay coil heats the thermistor, its resistance decreases until the relay current becomes sufficient for pick-up.

Synchronous motor

A synchronous motor, geared to a reduced speed can be also used on ac to produce more precise, long time delays.

Electronic time delay

Longer time delays are obtained with *R-C* circuits. *R-C* circuits are also used with electromagnetic relays, as shown in Fig. 2.12 (a). Longer time delays can be obtained with *R-C* circuits when used with electronic relays rather than with electromagnetic relays. This is due to the fact that a smaller current is needed with electronic relays, which in turn takes longer time to charge the capacitor.

Figure 2.13 shows a time-delay circuit employing a transistor. A constant dc voltage is applied to an *R-C* network to charge the capacitor *C* through resistor *R*. When the voltage of capacitor *C* reaches a suitable value, the transistor starts conducting. A realy is placed in the collector circuit. This relay operates when the transistor starts conducting. The time delay depends on the value of the capacitor and the magnitude of the charging current. As the charging current is small in a transistor circuit, a delay of several minutes can

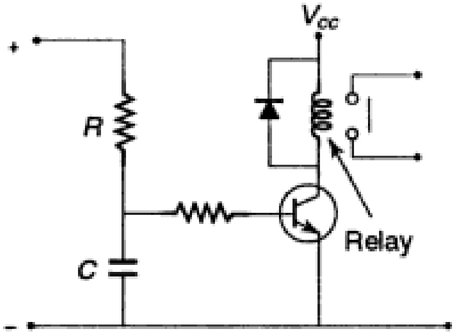


FIGURE 2.13 Static time delay circuit

be obtained with a capacitor of only few microfarads. Delays of several hours can be obtained with tantalum capacitors of a few hundred microfarads.

Counter

For obtaining even more accurate time-delays, electronic counters are used. A crystal oscillator or some suitable electronic circuitry is employed to generate a train of high frequency pulses. Counters are used as frequency dividers. A number of counters may be connected in cascade and different time-lags may be obtained from different stages of the cascaded counters.

2.1.12 Bearings

The pivot and jewel bearing is commonly used for precision relays. Spring-mounted jewels are used in modern relays. The design is such that shocks are taken on a shoulder and not on a jewel.

For high sensitivity and low friction, a single ball bearing between two cup-shaped sapphire jewels is used.

Multi-ball bearings provide friction as low as the jewel bearings and have greater resistance to shock. They are also capable of combining side-thrust and end-thrust in a single bearing. Miniature bearings less than 1.6 mm in diameter are now available.

Knife-edge bearings, pin bearings or resilient strips are used in hinged armature relays.

2.1.13 Backstops

When the moving part of the relay is stationary, it rests against a backstop. The material of a backstop should be chosen carefully so that it should not be sticky. To avoid magnetic adherence, the material should be non-metallic. The molecular adherence can be overcome using a hard surface rounded to a large radius. Smooth backstops made of agate or nylon are used.

2.1.14 Contacts

The reliability of protective relays depends on their contact performance. The following are the requirements of good contacts.

(i) Low contact resistance
(ii) High contact pressure
(iii) Freedom form corrosion
(iv) Bounce free

(v) Self clearing action
(vi) Freedom from sparking
(vii) Dust proof

Silver is the most commonly used material for relay contacts. It has the lowest resistance. Copper is not used because of its higher resistance. Silver cadmium oxide is used where high currents are to be handled. It has low resistance like silver but does not weld or become sticky. An alloy consisting of 67% gold, 26% silver and 7% platinum is used for small currents and very light contact pressure. Non-corroding materials like gold, palladium or rhodium can be used for sensitive relays where the contact pressure needs to be very low. These materials are not recommended for protective relays where high contact pressure is required.

The most reliable relay contacts are cylindrical contacts at right angles, as they give the optimum high pressure. The high contact pressure, bounce-proof contacts, hard smooth contact surfaces and dust proof relay cases minimise the maintenance of protective relays.

On silver contacts silver oxide does not form readily. Even when formed, its thickness does not exceed 10 Å and hence can easily be moved aside by high pressure or wiping action. Humid sulphurous and high temperature atmosphere causes corrosion. In polluted atmospheres where coal fires are used, silver sulphide is formed readily, especially in the presence of heat and humidity. It is not breakable like oxides but it is soft and thus can be squeezed aside by high pressure. A thin petrolatum coating can reduce corrosion of contacts without increasing their resistance. It is helpful in polluted atmospheres.

A dust-proof casing is usually used for modern relays. A filter is provided at the back to trap any dust and to allow the relay to breathe. A relay with such a casing is quite suitbale for a dusty or otherwise dirty atmosphere. In a relay with poor ventilation, particularly in a sealed relay, high resistance polymers may appear on contacts. This is due to organic emanations from the coil insulation material. All insulating materials, except teflon give off organic vapour to a certain degree. Phenolic resin gives off organic vapours more than others. Polyester and epoxide varnishes now available have good performance and are quite satisfactory for coil insulation. Relay casings with good ventilation and having dust filters minimise the collection of high resistance polymers on the contacts. Encapsulated contacts as in the case of reed relays provide the best solution to the problem. Alternatively, the relay coil can also be encapsulated.

An electromagnetic relay used with comparators is usually of a small rating. When such relays control auxiliary relays and timing units, they are to be protected with spark quenching circuits. A series resistor and capacitor connected across the contacts is a simple spark quenching circuit.

2.1.15 Reed Relay

A reed relay consists of a coil and nickel-iron strips (reeds) sealed in a closed glass capsule, as shown in Fig. 2.14. The coil surrounds the reed contact. When the coil is energised, a magnetic field is produced which causes the reeds to come together and close the contact. Reed relays are very reliable and are maintenance free. As far as their construction is concerned, they are electromagnetic relays. But from the service point of view, they serve as static relays. They are used for control and other purposes.

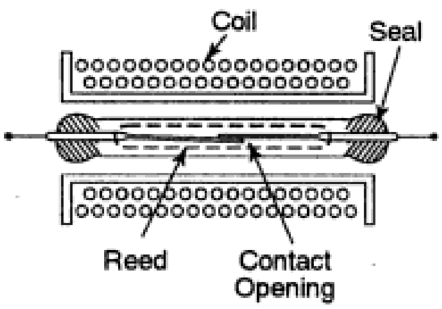


FIGURE 2.14 Reed relay

They can also be used as a protective relays. They are quite suitable to be used as slave relays. Their input requirement is 1 W to 3 W and they have speed of 1 or 2 msec. They are completely bounce free and are more suitable for normally-closed applications. Heavy duty reed relays can close contacts carrying 2kW at 30 A maximum current or at a maximum of 300 V dc supply. The voltage withstand capacity for the insulation between the coil and contacts is about 2kV. The open contacts can withstand 500 V to 1 kV.

2.2 Thermal Relays

These relays utilise the electro-thermal effect of the actuating current for their operation. They are widely used for the protection of small motors against overloading and unbalanced currents. The thermal element is a bimetallic strip, usually wound into a spiral to obtain a greater length, resulting in a greater sensitivity. A bimetallic element consists of two metal strips of different coefficients of thermal expansion, joined together. When it heats up one strip expands more than the other. This results in the bending of the bimetallic strip. The thermal element can be heated directly by passing the actuating current through the strip, but usually a heater coil is employed. When the bimetallic element heats up, it bends and deflects, thereby closing the relay contacts. For the ambient temperature compensation, a dummy bimetallic element *shielded* from the heater coil and designed to oppose the bending of the main bimetallic strip is employed. When the strip is in a spiral form, the unequal expansions of the two metals causes the unwinding of the spiral, which results in the closure of the contacts. Figure 2.15 (a) shows a simple arrangement to indicate the operating principle. Figure 2.15 (b) shows a spiral form. Unimetallic strips are also used as thermal elements in a hair-pin like shape, as shown in Fig. 2.15 (c). When the strip gets heated, it expands and closes the contacts.

For the protection of 3-phase motors, three bimetallic strips are used. They

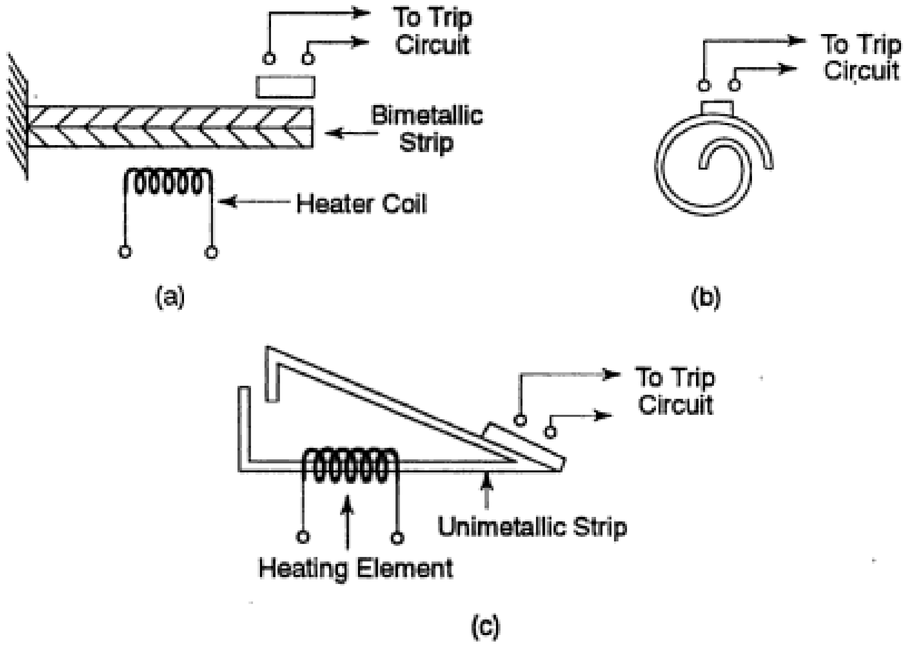


FIGURE 2.15 (a) Bimetallic thermal relay (b) Bimetallic spiral type thermal relay (c) Unimetallic thermal relay

are energised by currents from the three phases. Their contacts are arranged in such a way that if any one of the spirals moves differently from the others, due to an unbalance exceeding 12%, their contacts meet and cause the circuit breakers to trip. These spirals also protect the motor against overloading.

Thermocouples and resistance temperature detectors are also used in protection. In the protection of a large generator, such elements are placed in the stator slots. The element forms an arm of a balancing bridge. In normal condition, the bridge is balanced. When the temperature exceeds a certain limit, the bridge becomes unbalanced. The out-of-balance current energises a relay which trips a circuit breaker. This will be discussed in detail in the chapter dealing with protection of machines.

2.3 Static Relays

In a static relay, the comparison or measurement of electrical quantities is performed by a static circuit which gives an output signal for the tripping of a circuit breaker. Most of the present day static relays include a dc polarised relay as a slave relay. The slave relay is an output device and does not perform the function of comparison or measurement. It simply closes contacts. It is used because of its low cost. In a fully static relay, a thyristor is used in place of the electromagnetic slave relay. The electromagnetic relay used as a slave relay provides a number of output contacts at low cost. Electromagnetic multicontact tripping arrangements are much simpler than an equivalent group of thyristor circuits.

A static relay (or solid state relay) employs semiconductor diodes, transistors, zener diodes, thyristors, logic gates, etc. as its components. Now-a-days, integrated circuits are being used in place of transistors. They are more reliable and compact.

Earlier, induction cup units were widely used for distance and directional relays. Later these were replaced by rectifier bridge type static relays which employed dc polarised relays as slave relays. Where overcurrent relays are needed, induction disc relays are in universal use throughout the world. But ultimately static relays will supersede all electromagnetic relays, except the attracted armature relays and dc polarised relays as these relays can control many circuits at low costs.

2.3.1 Merits and Demerits of Static Relays

The advantages of static relays over electromagnetic relays are as follows.

(i) Low burden on C.T.s and P.T.s. The static relays consume less power and in most of the cases they draw power from the auxiliary dc supply.
(ii) Fast response.
(iii) Long life.
(iv) High resistance to shock and vibration.
(v) Less maintenance due to the absence of moving parts and bearings.
(vi) Frequent operations cause no deterioration.
(vii) Quick resetting and absence of overshoot.
(viii) Compact size.
(ix) Greater sensitivity as amplification can be provided easily.
(x) Complex relaying characteristics can easily be obtained.
(xi) Logic circuits can be used for complex protective schemes.

The logic ciruit may take decisions to operate under certain conditions and not to operate under other conditions.

The demerits of static relays are as follows:

(i) Static relays are temperature sensitive. Their characteristics may vary with the variation of temperature. Temperature compensation can be made by using thermistors and by using digital techniques for measurements, etc.
(ii) Static relays are sensitive to voltage transients. The semiconductor components may get damaged due to voltage spikes. Filters and shielding can be used for their protection against voltage spikes.
(iii) Static relays need an auxiliary power supply. This can however be easily supplied by a battery or a stabilized power supply.

2.3.2 Comparators

When faults occur on a system, the magnitude of voltage and current, and phase angle between voltage and current may change. These quantities during faulty conditions are different from those under healthy conditions. The static relay circuitry is designed to recognise the changes and to distinguish between healthy and faulty conditions. Either magnitudes of voltage/current (or corresponding derived quantities) are compared or phase angle between voltage and current (or corresponding derived quantities) are measured by the static relay circuitry and a trip signal is sent to the circuit breaker when a fault occurs. The part of the circuitry which compares the two actuating quantities either in amplitude or phase is known as the *comparator*. There are two types of comparators—amplitude comparator and phase comparator.

Amplitude comparator

An amplitude comparator compares the magnitudes of two input quantities, irrespective of the angle between them. One of the input quantities is an operating quantity and the other a restraining quantity. When the amplitude of the operating quantity exceeds the amplitude of the restraining quantity, the relay sends a tripping signal. The actual circuits for comparators will be discussed in subsequent chapters.

Phase comparator

A phase comparator compares two input quantities in phase angle, irrespective of their magnitudes and operates if the phase angle between them is $\leq 90°$.

2.3.3 Duality between Amplitude and Phase Comparators

An amplitude comparator can be converted to a phase comparator and vice-versa if the input quantities to the comparator are modified. The modified input quantities are the sum and difference of the original two input quantities. To understand this fact, consider the operation of an amplitude comparator which has two input signals M and N as shown in Fig. 2.16 (a). It operates when $|M| > |N|$. Now change the input quantities to $(M + N)$ and $(M - N)$ as shown in Fig. 2.16(b). As its circuit is designed for amplitude comparison, now with the changed input, it will operate when $|M + N| > |M - N|$. This condition will be satisfied only when the phase angle between M and N is less than 90°. This has been illustrated with the vector diagram shown in Fig. 2.17. It means that the comparator with the modified inputs has now become a phase comparator for the original input signals M and N.

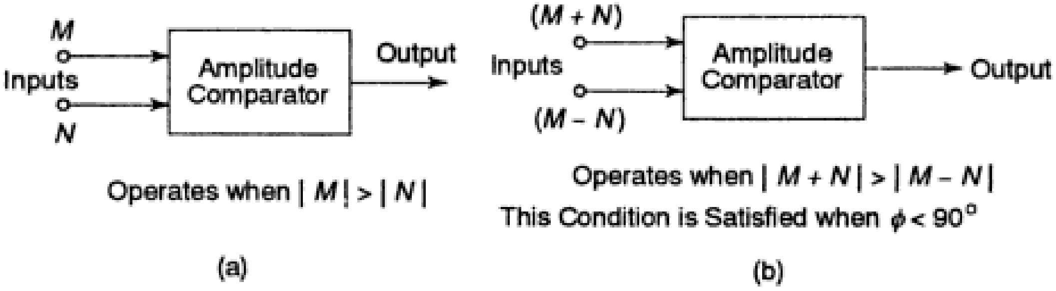


FIGURE 2.16 (a) Amplitude comparator (b) Amplitude comparator used for phase comparison

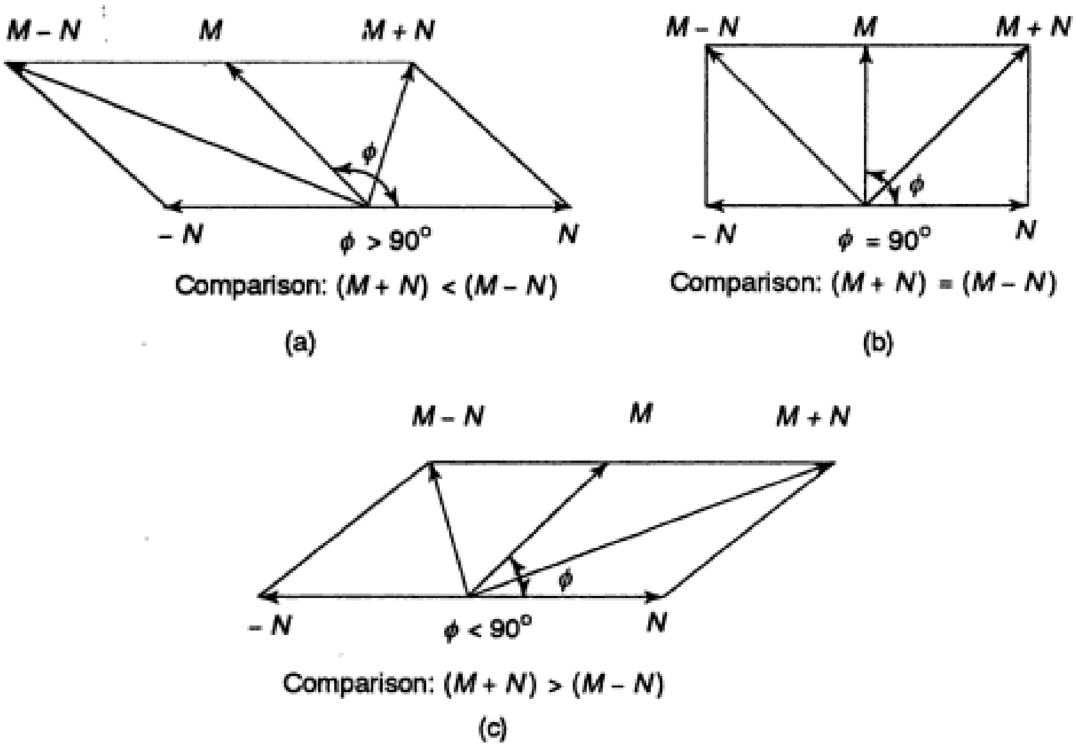


FIGURE 2.17 Vector diagram for amplitude comparator used for phase comparision

Similarly, consider a phase comparator shown in Fig. 2.18 (a). It compares the phases of input signals M and N. If the phase angle between M and N, i.e. angle ϕ is less than 90°, the comparator operates. Now change the input signals to $(M + N)$ and $(M - N)$, as in Fig. 2.18 (b). With these changed inputs, the comparator will operate when phase angle between $(M + N)$ and $(M - N)$, i.e. angle λ is less than 90°. This condition will be satisfied only when $|M| > |N|$. In other words, the phase comparator with changed inputs has now become an

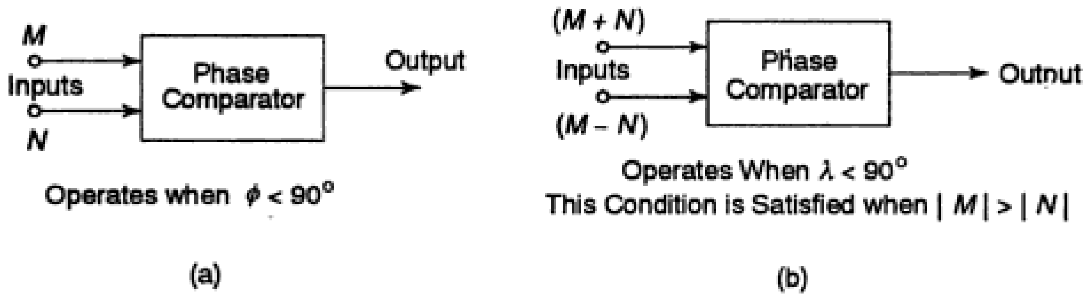


FIGURE 2.18 (a) Phase comparator (b) Phase comparator used for amplitude comparison

amplitude comparator for the original input signals M and N. This has been illustrated with vector diagrams as shown in Fig. 2.19.

Figure (2.17) shows three vector diagrams for an amplitude comparator. The phase angle between the original inputs M and N is ϕ. Now the inputs to the amplitude comparator are changed to $(M + N)$ and $(M - N)$ and its behaviour is examined with the help of three vector diagrams. The three vector diagrams are with phase angel ϕ (*i*) greater than 90°, (ii) equal to 90° and (iii) less than 90°, respectively. When ϕ is less than 90°, $|M + N|$ becomes greater than $|M - N|$ and the relay operates with the modified inputs. When ϕ is equal to 90° or greater than 90°, the relay does not operate.

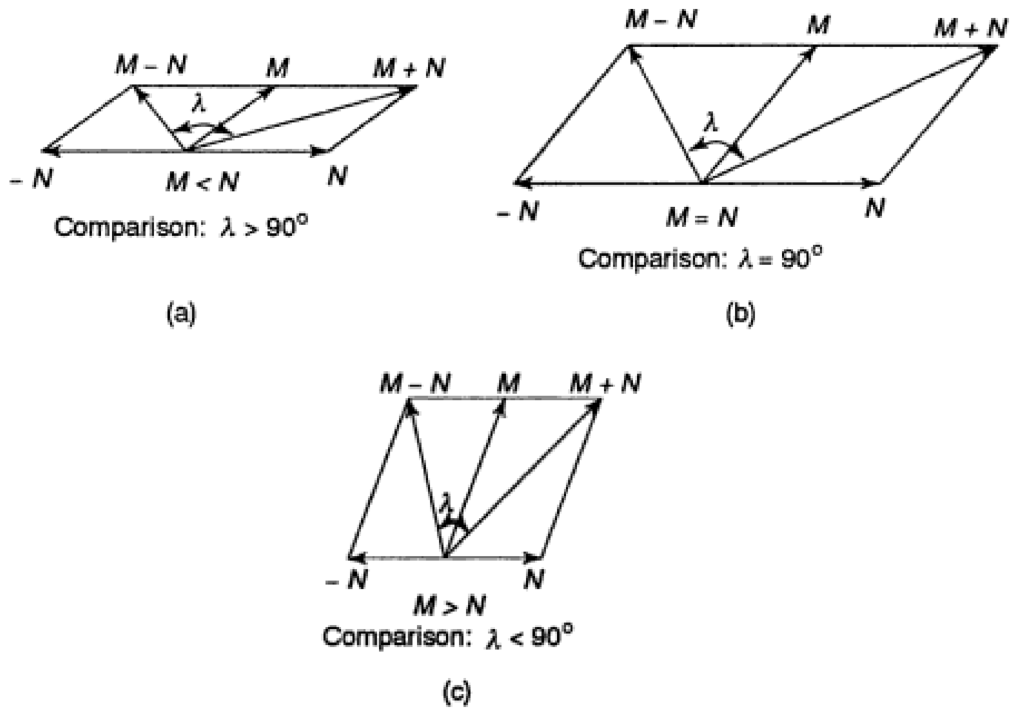


FIGURE 2.19 Phase comparator used for amplitude comparison

The vector diagrams show that $|M + N|$ becomes greater than $|M - N|$ only when ϕ is less than 90°. This will be true irrespective of the magnitude of M and N. In other words, this will be true whether $|M| = |N|$ or $|M| > |N|$ or $|M| < |N|$. The figures have been drawn with $|M| = |N|$. The reader can draw vector diagrams with $|M| < |N|$ or $|M| > |N|$. The results will remain the same. This shows that with changed inputs, the amplitude comparator is converted to a phase comparator for the original inputs.

Figure 2.19 shows three vector diagrams for a phase comparator. The original inputs are M and N. Now the inputs of the phase comparators are changed to $(M + N)$ and $(M - N)$, and its behaviour is examined with the help of three vector diagrams drawn for (i) $|M| < |N|$, (ii) $|M| = |N|$ and (iii) $|M| > |N|$. The angle between $(M + N)$ and $(M - N)$ is λ. The angle λ becomes less than 90° only when $|M| > |N|$. As the comparator under consideration is a phase comparator, the relay will trip. But for the original inputs M and N, the comparator behaves as an amplitude comparator. This will be true irrespective of the phase angle ϕ between M and N. The figure has been drawn with ϕ less than 90°. The reader can check it by drawing vectors with $\phi = 90°$ or $\phi > 90°$. The result will remain the same.

2.3.4 Types of Amplitude Comparators

As the ratio of the instantaneous values of sinusoidal inputs varies during the cycle, instantaneous comparison of two inputs is not possible unless at least one of the signals is rectified. There are various techniques to achieve instantaneous comparison. In some techniques both inputs are rectified, while in some methods, only one of the inputs is rectified. When only one input signal is rectified, the rectified quantity is compared with the value of the other input at a particular moment of the cycle. Besides instantaneous (or direct) comparison, the integrating technique is also used.

The amplitude comparison can be done in a number of different ways. The following are some important methods which will be described to illustrate the principle.

(i) Circulating current type rectifier bridge comparators
(ii) Phase splitting type comparators
(iii) Sampling comparators.

Rectifier bridge type amplitude comparator

The rectifier bridge type comparators are widely used for the realisation of overcurrent and distance relay characteristics. The operating and restraining quantities are rectified and then applied to a slave relay or thyristor circuit. Figure 2.20 (a) shows a rectifier bridge type amplitude comparator. There are two full wave rectifiers, one for the operating quantity and the other for the restraining quantity. The outputs of these bridges are applied to a dc polarised relay. When the operating quantity exceeds the restraining quantity, the relay operates. Figure 2.20 (b) shows a rectifier bridge type amplitude comparator with the thyristor circuit as an output device.

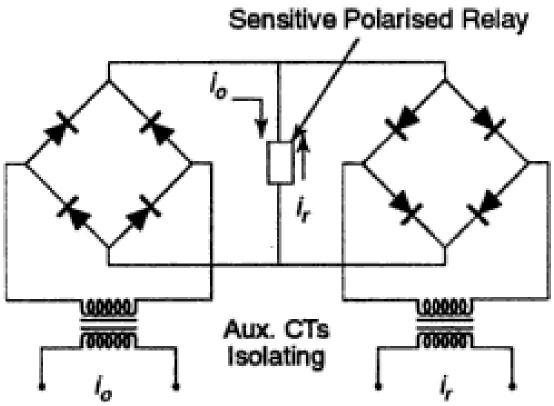
To get more accurate results the bridge rectifier can be replaced by a precision rectifier employing an operational amplifier. The circuit for the precision rectifier has been discussed while describing microprocessor based relays.

Phase-splitting type amplitude comparators

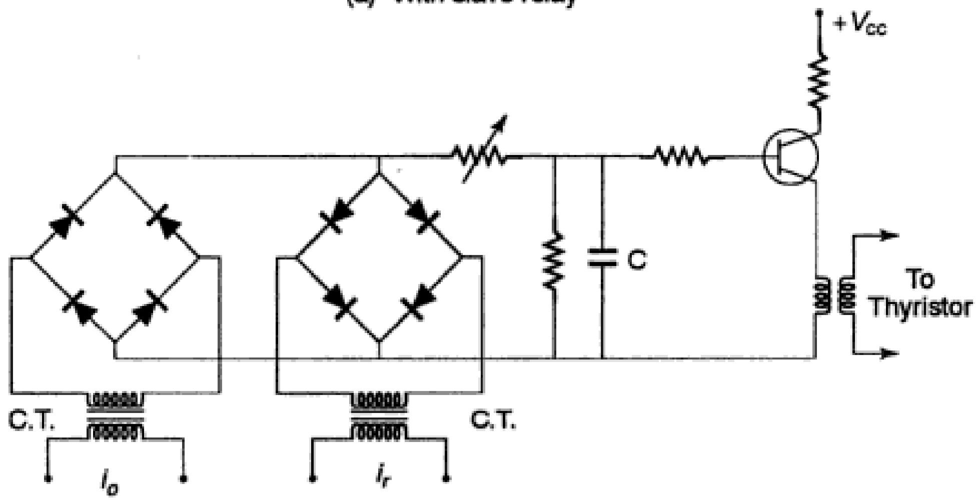
Figure 2.21 shows a phase splitting of inputs before rectification. The input is split into six components 60° apart, so that the output after rectification is smoothed within 5%. As both input signals to the relay are smoothed out before they are compared, a continuous output signal is obtained. The operating time depends on the time constant of the slowest arm of the phase-splitting circuit and the speed of the output device.

Sampling Comparators

In sampling comparators, one of the inputs is rectified and it is compared with the other input at a particular moment. The instantaneous value of the other input is sampled at a particular desired moment. Such comparators are used to realise reactance and MHO relay characteristics as discussed in Chapter 4, Section 4.6.1 and 4.6.2.



(a) With slave relay



(b) With thyristor circuit

FIGURE 2.20 Rectifier bridge type amplitude comparator

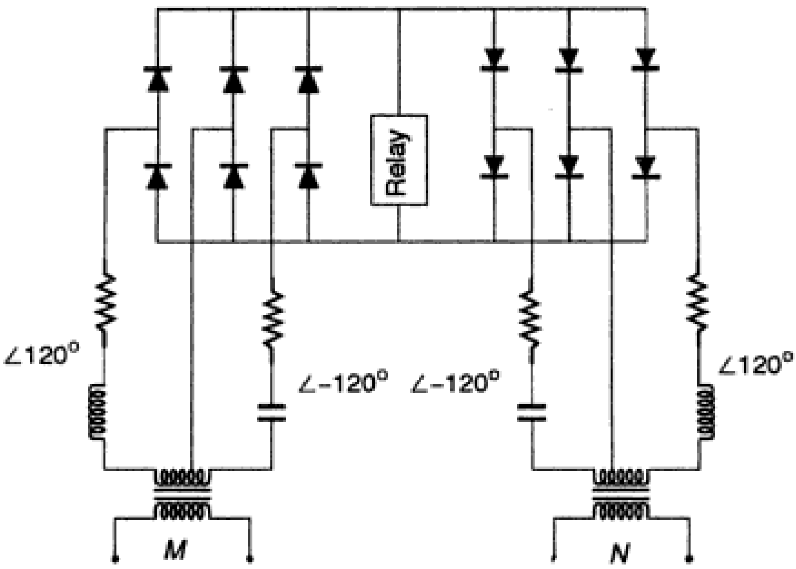


FIGURE 2.21 Phase splitting type amplitude comparator

2.3.5 Types of Phase Comparators

Phase comparison can be made in a number of different ways. Some important techniques are described below.

(i) Vector product phase comparators
(ii) Coincidence type phase comparators.

(i) Vector product phase comparators

In these comparators, the output is proportional to the vector product of the ac input signals. The Hall effect phase comparator and magneto-resistivity phase comparator come under this category of phase comparators.

Hall effect phase comparator

Hall effect is utilised to realise this phase comparator. Indium antimonide (InSb) and indium arsenide (InAs) have been found suitable semiconductors for this purpose. Of which indium arsenide is considered better. Protective relays based on Hall effect have been used mainly in the USSR only. These devices have low output, high cost and they can cause errors due to rising temperatures.

Magneto-resistivity

Some semiconductors exhibit a resistance variation property when subjected to a magnetic field. Suppose two input signals are V_1 and V_2. V_1 is applied to produce a magnetic field through a semiconductor disc. V_2 sends a current through the disc at a right angle to the magnetic field. The current flowing through the disc is proportional to $V_1 V_2 \cos \phi$, where ϕ is the phase angle between the two voltages. Therefore, this can be used as a phase comparator. This device is considered to be better than the Hall effect type comparator because it gives a higher output, its construction and circuitry are simpler and no polarising current is required. This device is also used only in the USSR.

(ii) Coincidence circuit type phase comparators

In a coincidence circuit type phase comparator, the period of coincidence of positive polarity of two input signals is measured and compared with a predetermined angle, usually 90°. Figure 2.22 shows the period of coincidence represented by an angle ψ. If the two input signals have a phase difference of ϕ, the period of coincidence $\psi = 180 - \phi$. If ϕ is less than 90°, ψ will be greater than 90°. The relay is required to trip when ϕ is less than 90°, i.e. $\psi > 90°$. Thus, the phase comparator circuit is designed to send a trip signal when ψ exceeds 90°.

Various techniques have been developed to measure the period of coincidence. The following are some important ones which will be described to illustrate the principle.

(a) Phase-splitting type phase comparator
(b) Integrating type phase comparator

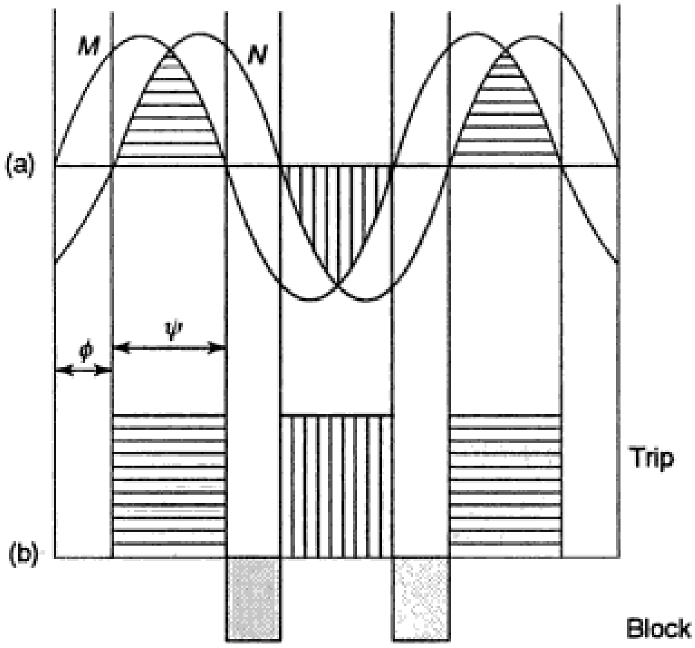


FIGURE 2.22 Period of coincidence of sine wave inputs

(c) Rectifier bridge type phase comparator
(d) Time-bias type phase comparator.

Phase-splitting type phase comparator

In this technique, both inputs are split into two components shifted ± 45° from the original wave, as shown in Fig. 2.23 (a). All the four components, which are now available, are fed into an AND gate as shown in Fig. 2.23 (b). The tripping occurs when all the four signals become simultaneously positive at any time during the cycle. An AND gate is used as a coincidence detector. The coincidence of all the four signals occurs only when ϕ is less than 90°. The full range of operation is

$$-90° < \phi < 90°$$

It is a technique of direct comparison.

Integrating type phase comparator

In this technique, the coincidence time is measured for each cycle by integrating the output of an AND gate (coincidence detector) to which input signals are applied. Figure 2.22 (a) shows two sinusoidal input signals. The hatched area shows the time of overlap (time of coincidence) of the two inputs. During this period, both inputs are positive. This period is represented by ψ. The phase difference between the two inputs is ϕ. The angle $\psi = 180 - \phi$. If ϕ is less than 90°, ψ is greater than 90°. If these two inputs are applied to an AND gate, the output of the gate is a series of square pulses. We get a square wave output during the period of coincidence and no output for the rest of the period of a cycle,. as shown in Fig. 2.22 (b).

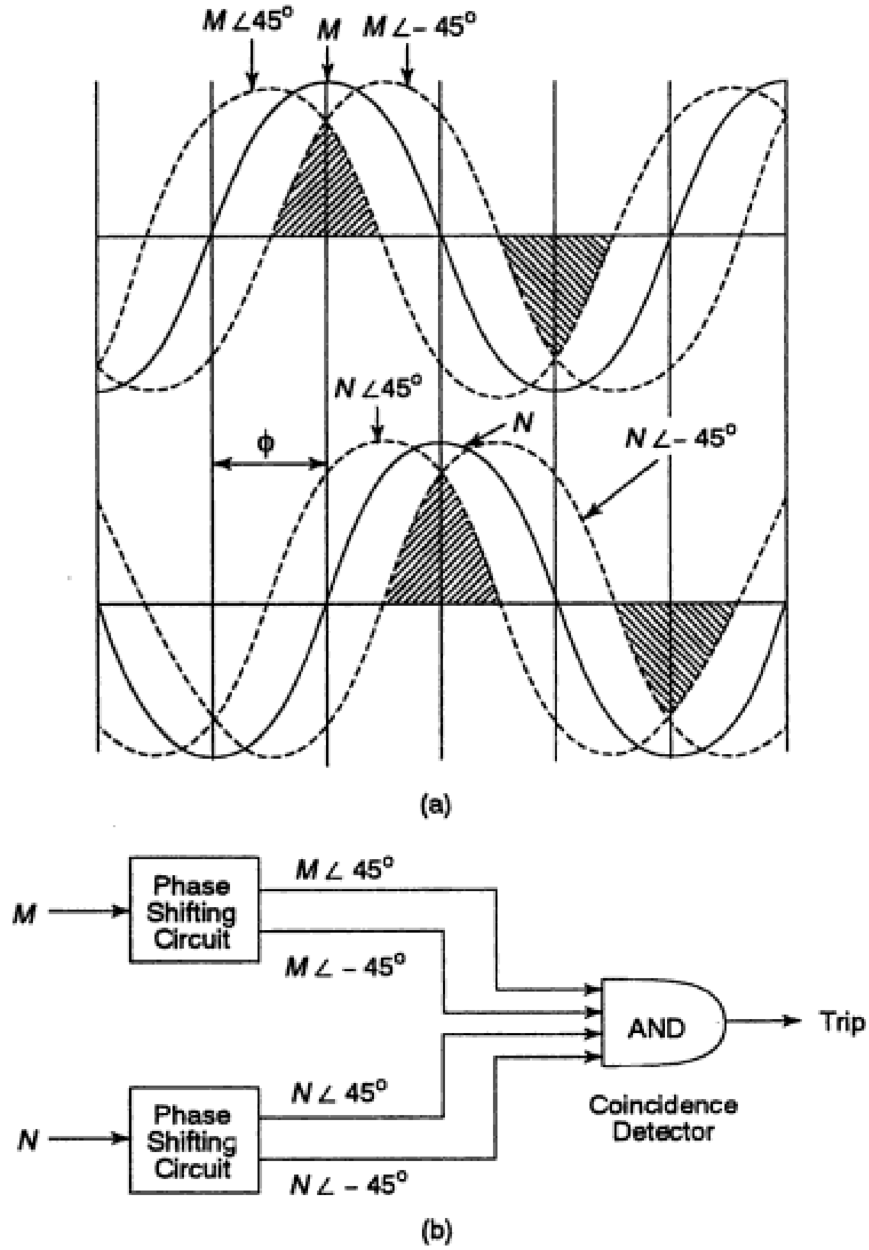


FIGURE 2.23 Phase-comparator with phase-split inputs

Figure 2.24 (a) shows the block diagram of a phase comparator. The sinusoidal inputs are first converted into square waves and then are applied to an AND gate. The output of the AND gate is a chain of pulses as shown in Fig. 2.24 (b). This is for $\phi < 90°$, i.e. $\psi > 90°$. The relay will provide a trip output. The output of the AND gate is applied to an integrator. The output of the integrator is shown in Fig. 2.24 (c). This output is applied to a level detector which finally gives a TRIP signal. The integrating circuit may be employed as shown in Fig. 2.25. The level detector may be a thyristor circuit.

Figure 2.24 (d) & (e) show the outputs of the AND gate and the integrator, respectively. This situation is for $\psi = 90°$ and is the limiting condition. The relay may be set to operate at $\psi = 90°$.

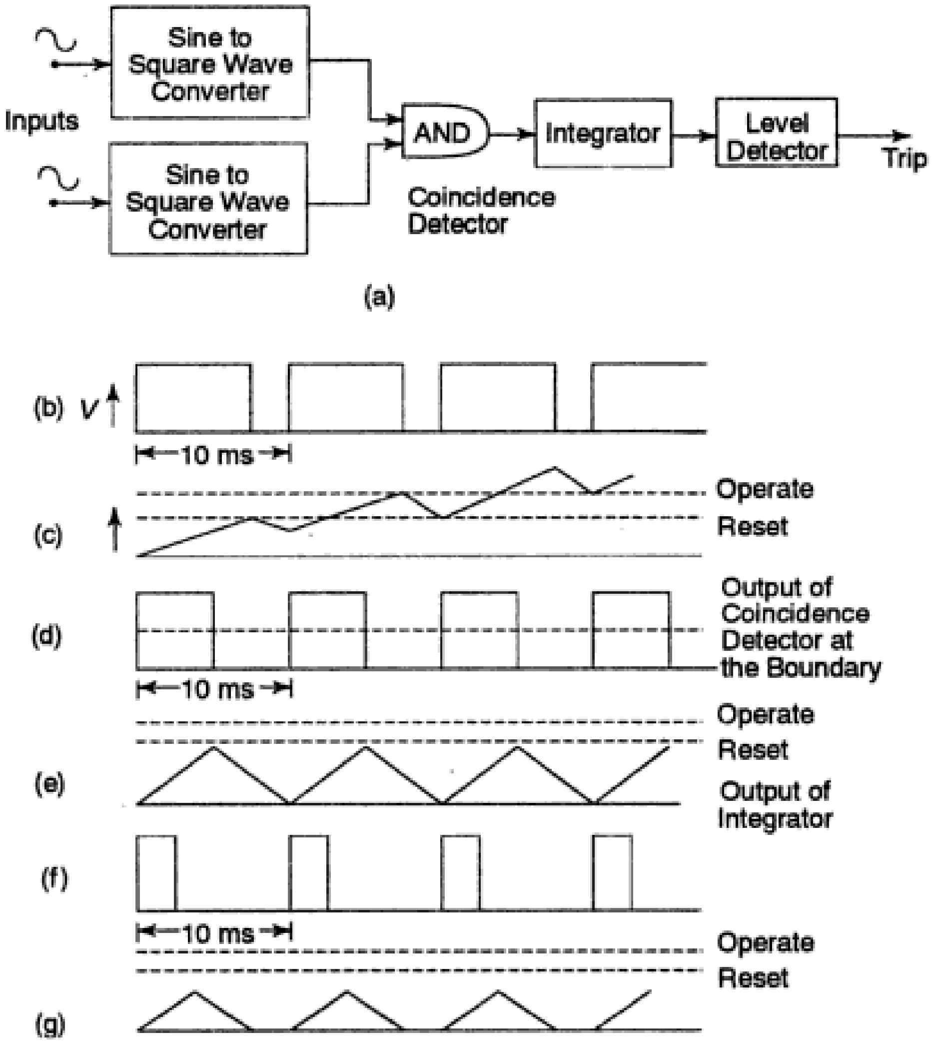


FIGURE 2.24 Integrating type phase comparator

Figure 2.24 (f) & (g) show the outputs of the AND gate and the integrator, respectively, for $\psi < 90°$. For this condition, the relay does not operate.

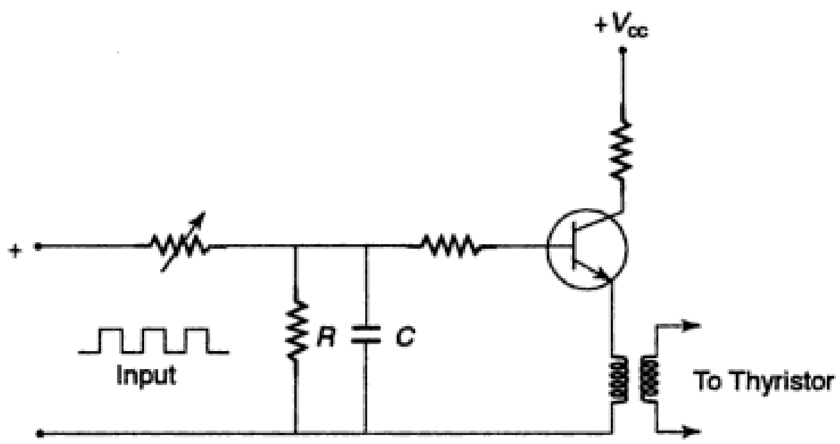


FIGURE 2.25 Integrating circuit

Rectifier bridge type phase comparator

Rectifier bridge type comparators are widely used for the realisation of distance relay characteristics. For more accurate results the bridge rectifier can be replaced by a precision rectifier employing operational amplifiers as shown in Fig. 7.22. Figure 2.26 (a) shows a rectifier bridge phase comparator. There are two signals M and N. To compare the phases of M and N, the bridge compares the amplitudes of $(M + N)$ and $(M - N)$. This circuit gives two tripping signals per cycle. Figure 2.26 (b) is the alternative way of drawing the same circuit. Figure 2.26 (c) shows a half-wave phase comparator with the directions of currents to illustrate how phase comparison is made by amplitude comparison. This circuit gives one tripping signal per cycle. The direction shown is true for a particular moment during the whole cycle when $M > N$ and both have a positive polarity. At other moments, the direction may change but every time the amplitudes of $(M + N)$ and $(M - N)$ are compared. The current flowing in the polarised relay is $I_R = [|M + N| - |M - N|]$. Therefore, the phase of M and N is compared. The output device shown in these figures is a polarised dc relay. It can be replaced by an integrator circuit and thyristor.

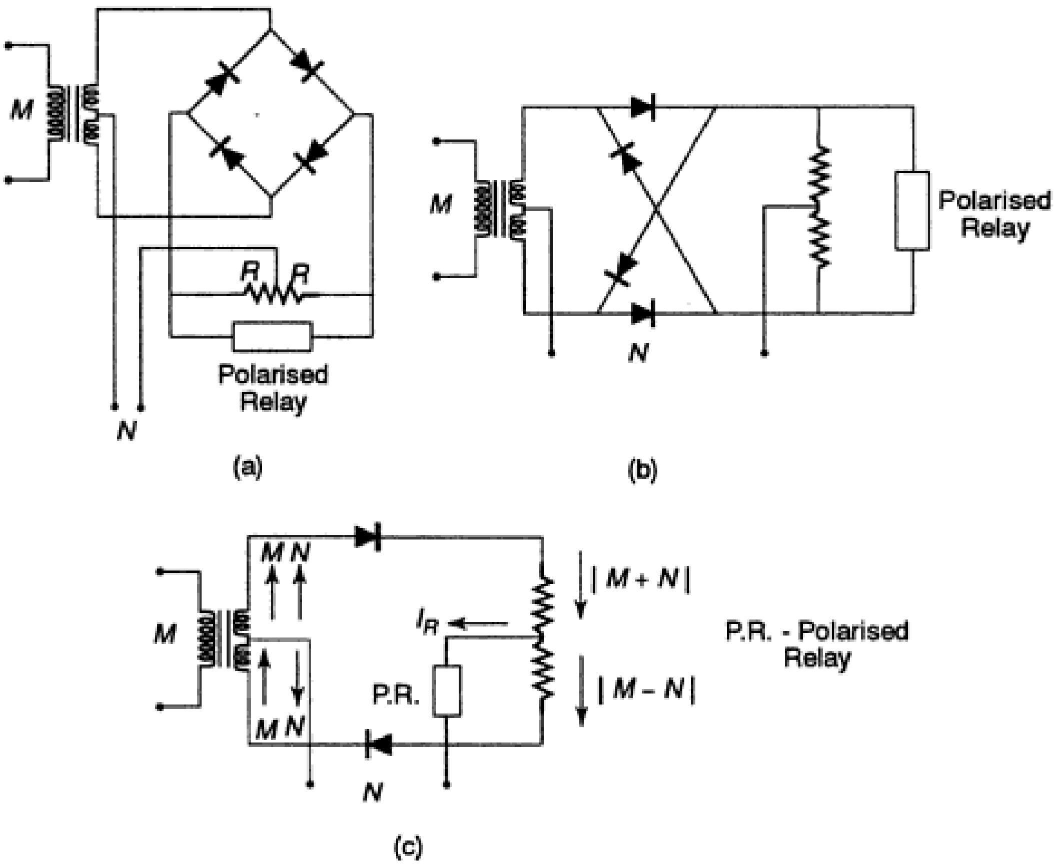


FIGURE 2.26 Rectifier bridge type phase comparator

Time-bias type phase comparator

A time-bias type phase comparator has been shown in Fig. 2.27 (a). In this technique, the inputs are applied to an AND gate which gives a square block output during the coincidence period of the two sinusoidal inputs. The output from the AND gate is fed to another AND gate through two different channels:

one directly and the other through a delay circuit. The delay circuit gives a delayed output. The output is delayed by an angle δ from the starting point of the block as shown in Fig. 2.27 (b) and (c). The delay δ is kept 90°. If the block and pulse (output of the delay circuit) still coincide, the second AND gate will give an output, as shown in Fig. 2.27 (b). If the block and pulse do not coincide, the second AND gate does not give any output as shown in Fig. 2.27(c). This means that the output of the first gate has to persist for a period δ so that the second gate may operate and send a tripping signal. This technique is more suitable for multi-input comparators. However, it is subject to false tripping by a false transient signal whereas phase comparators discussed earlier are not.

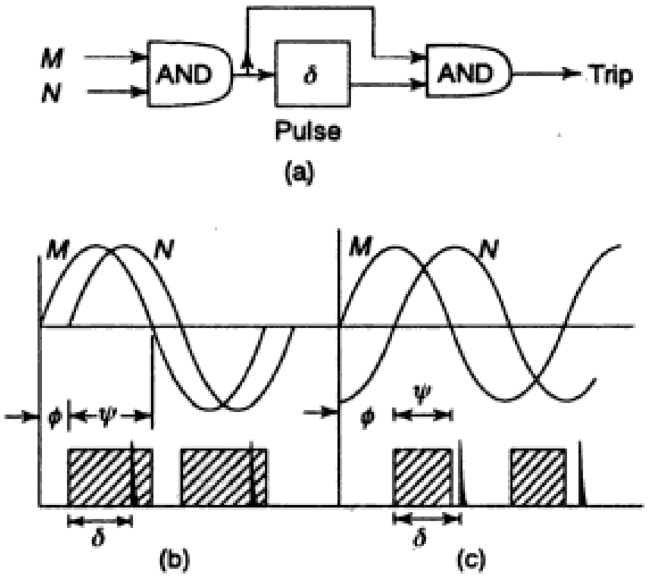


FIGURE 2.27 Time bias type phase comparator

2.4 Microprocessor-based Protective Relays

With the developments in LSI technology, microprocessors appeared in 1970s and have made remarkable progress in recent years. Fast and sophisticated microprocessors at low price are now available. Their application to power system protection will result in the availability of faster, more accurate and reliable relays than the existing ones. Though digital techniques have already been adopted for static relays, hardwired circuitry has very limited flexibility. The addition of microprocessors increases the flexibility of relays due to its programmable approach. A number of characteristics as required can be obtained using the same interface. With the help of multiplexer, the microprocessor can obtain the desired signals for a particular characteristic. Different programs can be used for different characteristics. Microprocessor-based protective schemes have attractive compactness in addition to flexibility. They can provide protection at low cost and compete with conventional relays.

Microprocessor-based relays are being used in distance and differential protection. Detailed description of microprocessor-based protective relays is given in Chapter 8.

Exercises

1. Draw a neat sketch of an induction disc relay and discuss its operating principle.
2. For what type of protective relay will you recommend (i) an induction disc type (ii) induction cup type construction? What measures are taken to minimise the over-run of the disc?
3. What are the merits of induction cup construction over the induction disc construction?
4. Derive an expression for torque produced by an induction relay.
5. Discuss the working principle of a permanent magnet moving coil relay with a neat sketch. State the area of its applications.
6. Describe the operating principle of a moving iron type dc polarised relay. Suggest some suitable area of its applications.
7. What are the different types of electromagnetic relays? Discuss their field of applications.
8. Explain why attracted armature type relays are noisy. What measures are taken to minimise the noise?
9. Discuss why the ratio of reset to pick up should be high.
10. Discuss the working principle, types and applications of thermal relays.
11. What are the advantages of static relays over electromagnetic relays?
12. Explain what are amplitude and phase comparators.
13. Discuss how an amplitude comparator can be converted to a phase comparator, and vice versa.
14. Discuss the operating principle of a rectifier bridge phase comparator.
15. Discuss the principle of a coincidence circuit for phase comparator.
16. With a neat sketch, describe the principle of a reed relay. Where is it used?

THREE

Overcurrent Protection

A protective relay which operates when the load current exceeds a preset value, is called an overcurrent relay. The value of the preset current above which the relay operates is known as its pick-up value. An overcurrent relay is used for the protection of distribution lines, large motors, power equipment, etc. A scheme which incorporates overcurrent relays for the protection of an element of a power system, is known as an overcurrent scheme or overcurrent protection. An overcurrent scheme may include one or more overcurrent relays.

At present electromagnetic relays are widely used for overcurrent protection. The induction disc type construction, as shown in Fig. 2.2(b) is commonly used.

3.1 Time-current Characteristics

A wide variety of time-current characteristics is available for overcurrent relays. The name assigned to an overcurrent relay indicates its time-current characteristic as described below.

3.1.1 Definite-time Overcurrent Relay

A definite-time overcurrent relay operates after a predetermined time when the current exceeds its pick-up value. Curve (a) of Fig. 3.1 shows the time-current characteristic for this type of relay. The operating time is constant, irrespective of the magnitude of the current above the pick-up value. The desired definite operating time can be set with the help of an intentional time-delay mechanism provided in the relaying unit.

3.1.2 Instantaneous Overcurrent Relay

An instantaneous relay operates in a definite time when the current exceeds its pick-up value. The operating time is constant, irrespective of the magnitude of the current, as shown by the curve (a) of Fig. 3.1. There is no intentional time-

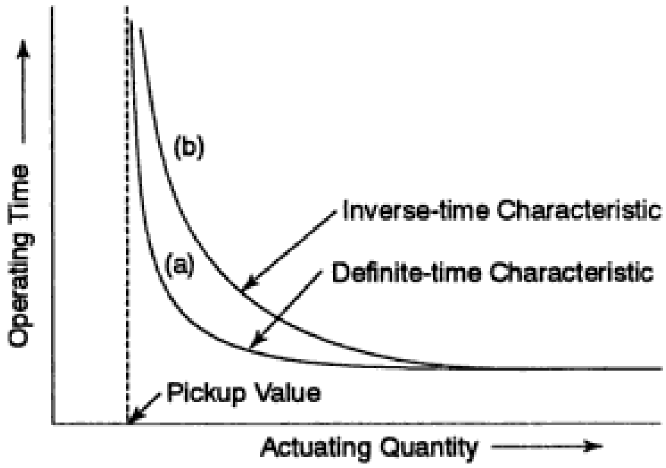


FIGURE 3.1 Definite-time and inverse-time characteristics of overcurrent relays

delay. It operates in 0.1s or less. Sometimes the term like "high set" or "high speed" is used for very fast relays having operating times less than 0.1s.

3.1.3 Inverse-time Overcurrent Relay

An inverse-time overcurrent relay operates when the current exceeds its pick-up value. The operating time depends on the magnitude of the operating current. The operating time decreases as the current increases. Curve (b) of Fig. 3.1 shows the inverse time-current characteristic of this type of relays.

3.1.4 Inverse Definite Minimum Time Overcurrent (I.D.M.T.) Relay

This type of a relay gives an inverse-time current characteristic at lower values of the fault current and definite-time characteristic at higher values of the fault current. Generally, an inverse-time characteristic is obtained if the value of the plug setting multiplier is below 10. For values of plug setting multiplier between 10 and 20, the characteristic tends to become a straight line, i.e. towards the definite time characteristic. Figure 3.2 shows the characteristic of an I.D.M.T. relay along with other characteristics. I.D.M.T. relays are widely used for the protection of distribution lines. Such relays have a provision for current and time settings which will be discussed later on.

3.1.5 Very Inverse-time Overcurrent Relay

A very inverse-time overcurrent relay gives more inverse characteristic than that of a plain inverse relay or the I.D.M.T. relay. Its time-current characteristic lies between an I.D.M.T. characteristic and extremely inverse characteristic, as shown in Fig. 3.2. The very inverse characteristic gives better selectivity than the I.D.M.T. characteristic. Hence, it can be used where an I.D.M.T. relay fails to achieve good selectivity. Its recommended standard time-current characteristic is given by

$$t = \frac{13.5}{I - 1}$$

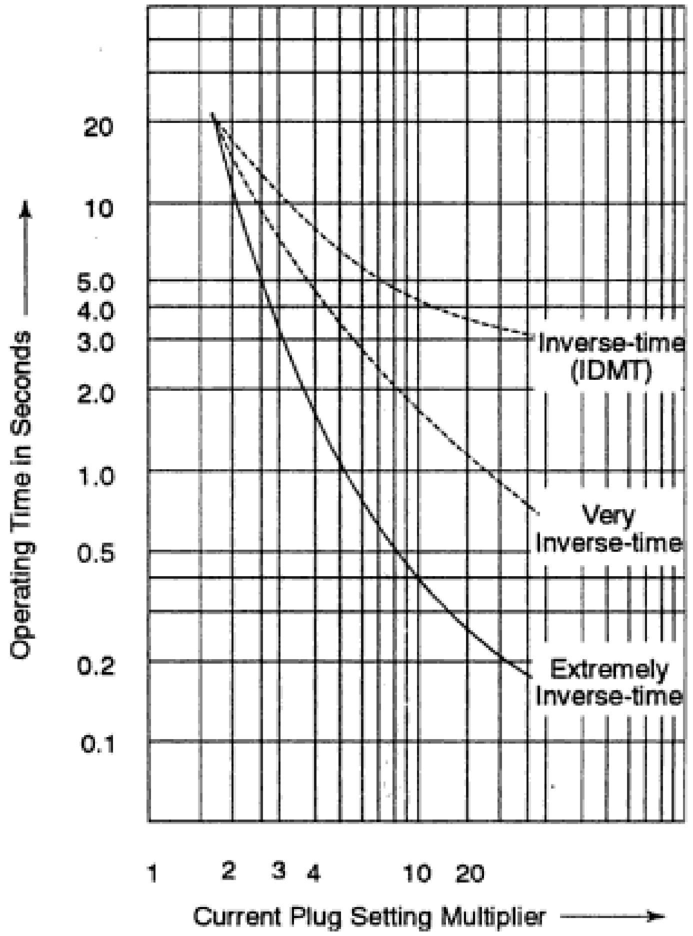


FIGURE 3.2 IDMT, very inverse-time and extremely inverse-time characteristics

The general expression for time-current characteristic of overcurrent relays is given by

$$t = \frac{K}{I^n - 1}$$

The value of n for very inverse characteristic may lie between 1.02 and 2.

Very inverse time-current relays are recommended for the cases where there is a substantial reduction of fault current as the distance from the power source increases. They are particularly effective with ground faults because of their steep characteristic.

3.1.6 Extremely Inverse-time Overcurrent Relay

An extremely inverse time overcurrent relay gives a time-current characteristic more inverse than that of the very inverse and I.D.M.T. relays, as shown in Fig. 3.2. When I.D.M.T. and very inverse relays fail in selectivity, extremely inverse relays are employed. I.D.M.T. relays are not suitable to be graded with fuses. Enclosed fuses have time-current characteristics according to the law

$$I^{3.5} t = K$$

The electromagnetic relay which gives the steepest time-current characteristic is an extremely inverse relay. The time-current characteristic of an extremely inverse relay is $I^2t = K$. Its characteristic is not good enough to be graded with fuses. But the best that can be done with electromagnetic relay is to use extremely inverse relays to grade with fuses.

An extremely inverse relay is very suitable for the protection of machines against overheating. The heating characteristics of machines and other apparatus is also governed by the law $I^2t = K$. Hence, this type of relays are used for the protection of alternators, power transformers, earthing transformers, expensive cables, railways trolley wires, etc. The rotors of large alternators may be overheated if an unbalanced load or fault remains for a longer period on the system. In such a case, an extremely inverse relay, in conjunction with a negative sequence network is used. By adjusting the time and current settings, a suitable characteristic of the relay is obtained for a particular machine to be protected.

A relay should not operate on momentary overloads. But it must operate on sustained short circuit current. For such a situation, it is difficult to set I.D.M.T. relays. An extremely inverse relay is quite suitable for such a situation. This relay is used for the protection of alternators against overloads and internal faults. It is also used for reclosing distribution circuits after a long outage. After long outages, when the circuit breaker is reclosed there is a heavy inrush current which is comparable to a fault current. An I.D.M.T. relay is not able to distinguish between the rapidly decaying inrush current of the load and the persistent high current of a fault. Hence, an I.D.M.T. relay trips again after reclosing. But an extremely inverse relay is able to distinguish between a fault current and inrush current due to its steep time-current characteristic. Therefore an extremely inverse relay is quite suitable for the load restoration purpose.

3.1.7 Special Characteristics

Overcurrent relays, having their time-current characteristics steeper than those of extremely inverse relays are required for certain industrial applications. These relays have time-current characteristic $I^n = K$ with $n = 2$. To protect rectifier transformers, a highly inverse characteristic of $I^8 t = K$ is required. The characteristics having $n = 2$ are realised by static relays or microprocessor-based overcurrent relays. Enclosed fuses have a time-current characteristic of $I^{3.5}t = K$. A static relay or microprocessor-based relay can be designed to give $I^{3.5}t = K$ characteristic, suitable to be graded with fuses.

3.1.8 Method of Defining Shape of Time-current Characteristics

The general expression for time-current characteristics is given by

$$t = \frac{K}{I^n - 1}$$

The approximate expression is

$$t = \frac{K}{I^n}$$

For definite-time characteristic, the value of n is equal to 0. According to the British Standard, the following are the important characteristics of overcurrent relays.

(i) I.D.M.T.: $$t = \frac{0.14}{I^{0.02} - 1}$$

(ii) Very inverse: $$t = \frac{13.5}{I - 1}$$

(iii) Extremely inverse: $$t = \frac{80}{I^2 - 1}$$

The inverse time-current characteristics obtained from the above expressions are not straight line characteristics. A microprocessor-based relay can easily give straight line characteristics of the form $t = K/I^n$ with any value of n. These characteristics are straight line characteristics on log t/log I graph. The advantage of such simplified time-current curves is the saving in time in calculating relay time settings.

3.1.9 Technique to Realise Various Time-current Characteristics Using Electromagnetic Relays

The magnetic circuit of an overcurrent relay can be designed to saturate above a certain value of the actuating current. Below this value of the actuating current, the relay gives an inverse characteristic. Above the saturation value of the current, the relay gives a straight line characteristic, parallel to the current-axis. It means that whatever may be the value of the current above saturation value the operating time remains constant.

If the core is designed to saturate at the pick-up value of the current, the relay gives a definite time-characteristic. If the core is designed to saturate at a later stage, an I.D.M.T. characteristic is obtained. If the core saturates at a still later stage, a very inverse characteristic is obtained. If the saturation occurs at a very late stage, the relay gives an extremely inverse characteristic.

3.2 Current Setting

The current above which an overcurrent relay should operate can be set. Suppose that a relay is set at 5 A. It will then operate if the current exceeds 5 A. Below 5A, the relay will not operate. There are a number of tappings on the current coil, available for current setting, as shown in Fig. 2.2. and Fig. 2.3. An overcurrent relay which is used for phase to phase fault protection, can be set at 50% to 200% of the rated current in steps of 25%. The usual current rating of this relay is 5A. So it can be set at 2.5 A, 3.75 A, 5 A,..., 10 A. When a relay is set at 2.5 A, it will operate when current exceeds 2.5 A. When the relay is set at 10 A, it will operate when current exceeds 10 A. The relay which is used for protection against ground faults (earth-fault relay) has settings 20% to 80% of the rated current in steps of 10%. The current rating of an earth-fault relay is usually 1A.

If time-current curves are drawn, taking current in amperes on the *X*-axis, there will be one graph for each setting of the relay. To avoid this complex situation, the plug setting multipliers are taken on the *X*-axis. The actual r.m.s. current flowing in the relay expressed as a multiple of the setting current (pick-up current) is known as the plug setting multiplier (PSM). Suppose, the rating of a relay is 5A and it is set at 200%, i.e. at 10 A. If the current flowing through the relay is 100 A, then the plug setting multiplier will be 10. The PSM = 4 means 40 A of current is flowing, PSM = 6 means 60 A of current is flowing and so on.

If the same relay is set at 50% , i.e. at 2.5 A, the PSM = 4 means 10 A; PSM = 6 means 15 A; PSM = 10 means 25A and so on.

Hence, PSM can be expressed as

$$\text{PSM} = \frac{\text{Secondary current}}{\text{Relay current setting}}$$

$$= \frac{\text{Primary current during fault, i.e. fault current}}{\text{Relay current setting} \times \text{C.T. ratio}}$$

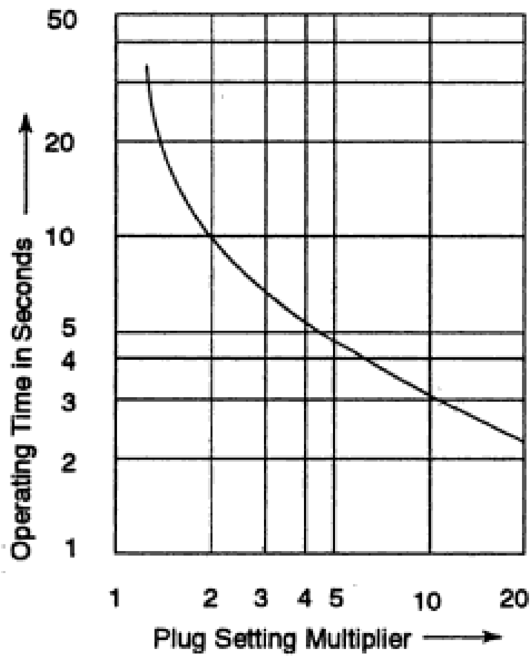


FIGURE 3.3 Standard I.D.M.T. characteristic

While plotting the time-current characteristic, if PSM is taken on the *X*-axis, there will be only one curve for all the settings of the relay. Figure 3.3 shows a time-current characteristic with PSM on the *X*-axis. The curve is generally plotted on log/log graph. Only this curve will give the operating time for different settings of the relay. Suppose the relay is set at 5 A. The operating times for different currents are shown in Table 3.1.

If the same relay is set at 10 A, the corresponding operating times for different currents are shown in Table 3.2, using the same curve of Fig. 3.3.

TABLE 3.1

Current in Amperes	5	10	20	50
PSM	1	2	4	10
Operating time in seconds	No operation	10	5	3

TABLE 3.2

Current in Amperes	5	10	20	40	100
PSM	less than 1	1	2	4	10
Operating time in seconds	Relay will not operate	No operation	10	5	3

3.3 Time Setting

The operating time of the relay can be set at a desired value. In induction disc type relay, the angular distance by which the moving part of the relay travels for closing the contacts can be adjusted to get different operating time. There are 10 steps in which time can be set. The term time multiplier setting (TMS) is used for these steps of time settings. The values of TMS are 0.1, 0.2,..., 0.9, 1. Suppose that at a particular value of the current or plug setting multiplier (PSM), the operating time is 4 s with TMS = 1. The operating time for the same current with TMS = 0.5 will be $4 \times 0.5 = 2$ s. The operating time with TMS = 0.2 will be $4 \times 0.2 = 0.8$ s.

Figure 3.4 (a) shows time-current characteristics for different values of TMS. The characteristic at TMS = 1 can also be presented in the form shown in Fig. 3.4(b).

Example The current rating of a relay is 5 A. PSM = 1.5, TMS = 0.4, C.T. ratio = 400/5, fault current = 6000 A. Determine the operating time of the relay. At TMS = 1, operating time at various PSM are:

PSM	2	4	5	8	10	20
Operating time in seconds	10	5	4	3	2.8	2.4

Solution C.T. ratio = 400/5 = 80

Relay current setting = $5 \times 1.5 = 7.5$ A

$$\text{PSM} = \frac{\text{Secondary current}}{\text{Relay current setting}}$$

$$= \frac{\text{Primary current (fault current)}}{\text{Relay current setting} \times \text{C.T. ratio}}$$

$$= \frac{6000}{7.5 \times 80} = 10$$

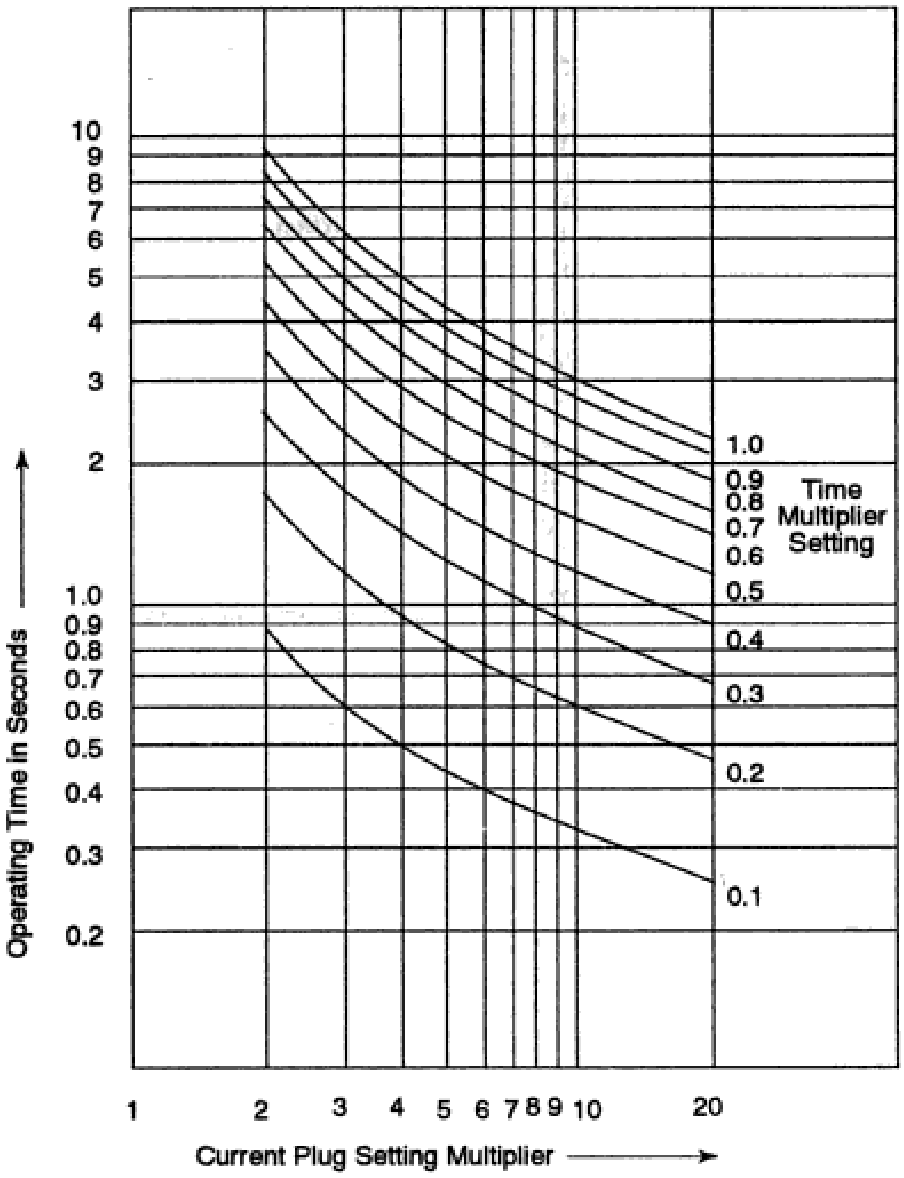


FIGURE 3.4(a) Time-current characteristics for different values of TMS

Operating time from the given table at PSM = 10 is 2.8s. This time is for TMS = 1. The operating time for TMS = 0.4 will be equal to $2.8 \times 0.4 = 1.12$ s.

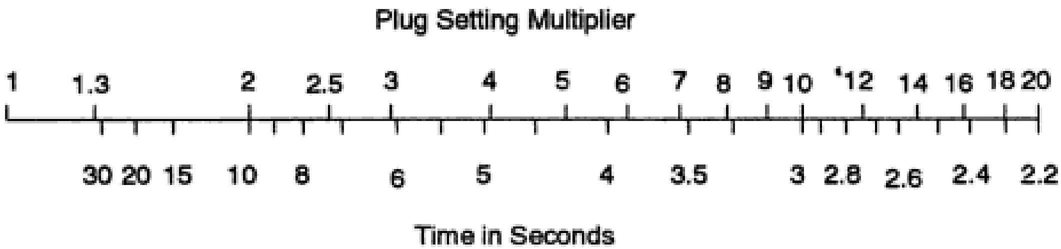


FIGURE 3.4(b) Logarithmic scale for IDMT relay at TMS = 1

3.4 Overcurrent Protective Schemes

Overcurrent protective schemes are widely used for the protection of distribution lines. A radial feeder may be sectionalised and two or more overcurrent relays may be used, one relay for the protection of each section of the feeder, as shown in Fig. 3.5 If a fault occurs beyond *C*, the circuit breaker at substation *C* should trip. The circuit breakers at *A* and *B* should not trip as far as the normal operation is concerned. If the relay at *C* fails to operate, the circuit breaker at *B* should trip as a back-up protection. Similarly, if a fault occurs between *B* and *C*, the circuit breaker at *B* should trip; the circuit breaker at *A* should not trip. But in the case of failure of a relay and /or the circuit breaker at *B*, the circuit breaker at *A* should trip. Thus, it is seen that the relays must be selective with each other. For proper selectivity of the relays, one of the following schemes can be employed, depending on the system conditions.

(i) Time-graded system
(ii) Current-graded system
(iii) A combination of time and current grading.

3.4.1 Time-graded System

In this scheme, definite-time overcurrent relays are used. When a definite-time relay operates for a fault current, it starts a timing unit which trips the circuit breaker after a preset time, which is independent of the fault current. The operating time of the relays is adjusted in increasing order from the far end of the feeder, as shown in Fig. 3.5. The difference in the time setting of two adjacent relays is usually kept at 0.5 s. This difference is to cover the operating time of the circuit breaker and errors in the relay and C.T. With fast circuit breakers and modern accurate relays, it may be possible to reduce this time further to 0.4s or 0.3s.

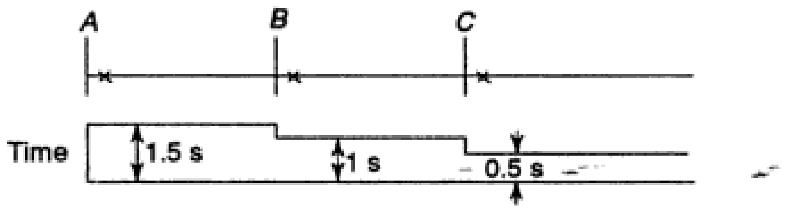


FIGURE 3.5 Time-graded overcurrent protection of a feeder

When a fault occurs beyond *C*, all relays come into action as the fault current flows through all of them. The least time setting is for the relay placed at *C*. So it operates after 0.5 s and the fault is cleared. Now the relays at *A* and *B* are reset. If the relay or circuit breaker at *C* fails, the fault remains uncleared. In this situation, after 1s, the relay at *B* will operate and the circuit breaker at *B* will trip. If the circuit breaker at *B* also fails to operate after 1.5 s circuit breaker at *A* will trip.

The drawback of this scheme is that for faults near the power source, the operating time is more. If a fault occurs near the power source, it involves a large current and hence it should be cleared quickly. But this scheme takes the longest time in clearing the heaviest fault, which is undesirable because the heaviest fault is the most destructive.

This scheme is suitable for a system where the impedance (distance) between substations is low. It means that the fault current is practically the same if a fault occurs on any section of the feeder. This is true for a system in which the source impedance Z_s is more than the impedance of the protected section, Z_1. If the neutral of the system is grounded through a resistance or an impedance, Z_s is high and $Z_s/(Z_s + Z_1)$ is not sufficiently lower than unity. In this situation, the advantage of inverse-time characteristic cannot be obtained. So definite relays can be employed, which are cheaper than I.D.M.T. relays. Definite-time relays are popular in Central Europe.

3.4.2 Current-graded System

In a current-graded scheme, the relays are set to pick-up at progressively higher values of current towards the source. The relays employed in this scheme are high set (high speed) instantaneous overcurrent relays. The operating time is kept the same for all relays used to protect different sections of the feeder, as shown in Fig. 3.6. The current setting for a relay corresponds to the fault current level for the feeder section to be protected.

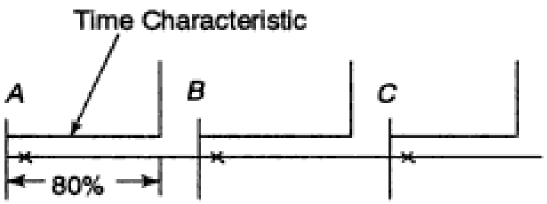


FIGURE 3.6 Instantaneous overcurrent protection of a feeder

Ideally, the relay at *B* should trip for faults any where between *B* and *C*. But it should not operate for faults beyond *C*. Similarly, the relay at *A* should trip for faults between *A* and *B*. The relay at *C* should trip for faults beyond *C*. This ideal operation is not achieved due to the following reasons.

(i) The relay at *A* is not able to differentiate between faults very close to *B* which may be on either side of *B*. If a fault in the section *BC* is very close to the station *B*, the relay at *A* 'understands' that is in section *AB*. This happens due to the fact that there is very little difference in fault currents if a fault occurs at the end of the section *AB* or in the beginning of the section *BC*.

(ii) The magnitude of the fault current cannot be accurately determined as all the circuit parameters may not be known.

(iii) During a fault, there is a transient condition and the performance of the relays is not accurate.

Consequently, to obtain proper discrimination, relays are set to protect only a part of the feeder, usually about 80%. Since this scheme cannot protect the entire feeder, this system is not used alone. It may be used in conjunction with I.D.M.T. relays, as shown in Fig. 3.7.

The performance of instantaneous relays is affected by the dc component of transients. The error introduced by the dc offset component causes the relay to

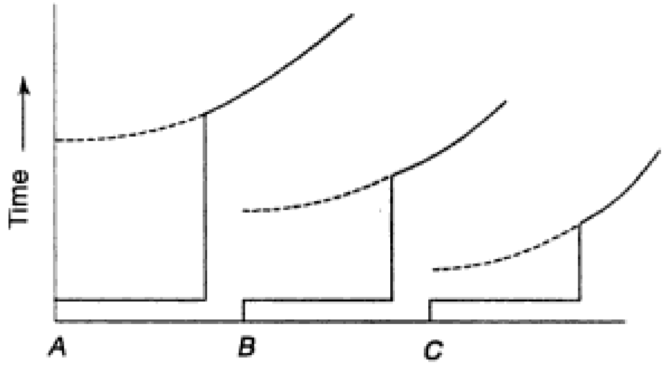


FIGURE 3.7 Combined instantaneous and I.D.M.T. protection

overreach. Higher the X/R ratio of the system, greater is the problem. A dc filter is used to overcome this problem. In the USA an instantaneous relay, employing induction cup type construction is used for this purpose as it is less sensitive to the d.c. offset component. A less expensive solution is to employ a relay as shown in Fig. 2.1 (b). This arrangement also provides a high reset to pick-up ratio, more than 90%.

The current-graded scheme is used where the impedance between substations is sufficient to create a margin of difference in fault currents. For such a system Z_s is smaller compared to Z_1. The advantage of this system as compared to the time-graded scheme is that the operating time is less near the power source.

3.4.3 Combination of Current and Time-grading

This scheme is widely used for the protection of distribution lines. I.D.M.T. relays are employed in this scheme. They have the combined features of current and time-grading. I.D.M.T. relays have current as well as time setting arrangements. The current setting of the relay is made according to the fault current level of the particular section to be protected. The relays are set to pick-up progressively at higher current levels, towards the source. Time setting is also done in a progressively increasing order towards the source. The difference in operating times of two adjacent relays is kept 0.5 s.

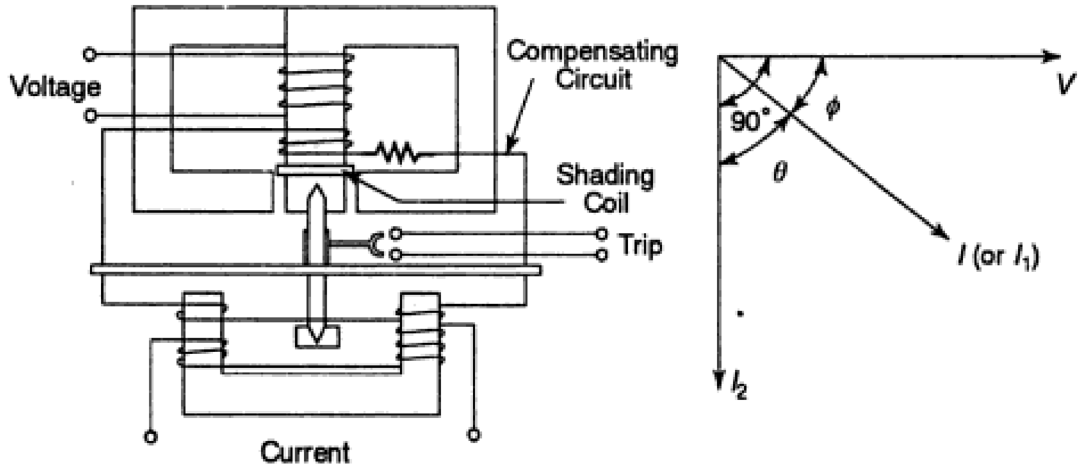
An inverse time-current characteristic is desirable where Z_s is small compared with Z_1. If a fault occurs near the substation, the fault current is $I = E/Z_s$. If a fault occurs at the far end of the protected section, the fault current $I = E/(Z_s + Z_1)$. If Z_1 is high compared to Z_s, there is an appreciable difference in the fault current for a fault at the near end and for a fault at the far end of the protected section of the feeder. For such a situation, a relay with inverse-time characteristic would trip faster for a fault near the substation , which is a very desirable feature. Inverse time relays on solidly grounded systems have an advantage. Definite-time characteristic is desirable where Z_s is large compared to Z_1. An I.D.M.T. characteristic is a compromise. At lower values of fault current, its characteristic is an inverse-time characteristic. At higher values of fault current, it gives a definite-time characteristic.

Though I.D.M.T. relays are widely used for the protection of distribution systems and some other applications, in certain situations very inverse and extremely inverse relays are used instead of I.D.M.T. relays. This has already been discussed in section 3.1.5 and 3.1.6.

3.5 Reverse Power or Directional Relay

Figure 3.8(a) shows an electromagnetic directional relay. A directional relay is energised by two quantities, namely voltage and current. Fluxes ϕ_1 and ϕ_2 are set up by voltage and current, respectively. Eddy currents induced in the disc by ϕ_1 interact with ϕ_2 and produce a torque. Similarly, ϕ_2 also induces eddy currents in the disc, which interact with ϕ_1 and produce a torque. The resultant torque rotates the disc. The torque is proportional to $VI \cos \phi$, where ϕ is the phase angle between V and I. The torque is maximum when voltage and current are in phase. To produce maximum torque during the fault condition, when the power factor is very poor, a compensating winding and shading are provided, as shown in Fig. 3.8 (a).

Earlier it has been mentioned that the torque produced by an induction relay is given by $T = \phi_1 \phi_2 \sin \theta \propto I_1 I_2 \sin \theta$, where ϕ_1 and ϕ_2 are fluxes produced by I_1 and I_2, respectively. The angle between ϕ_1 and ϕ_2 or I_1 and I_2 is θ. If one of the actuating quantities is voltage, the current flowing in the voltage coil lags behind voltage by approximately 90°. Assume this current to be I_2. The load current I (say I_1) lags V by ϕ. Then the angle θ between I_1 and I_2 is equal to $(90 - \phi)$, as shown in Fig. 3.8(b).



(a) Construction (b) Phasor diagram

FIGURE 3.8 Induction disc type directional relay

$$T = I_1 I_2 \sin(90 - \phi) \propto I_1 I_2 \cos\phi \propto VI \cos\phi$$

An induction cup construction can also be used to produce a torque proportional to $VI \cos\phi$. The arrangement is shown in Fig. 3.9. Two opposite poles are energised by voltage and the other two poles by current. Here voltage is a polarising quantity. The polarising quantity is one which produces one of the two fluxes. The polarising quantity is taken as a reference with respect to the other quantity which is current in this case.

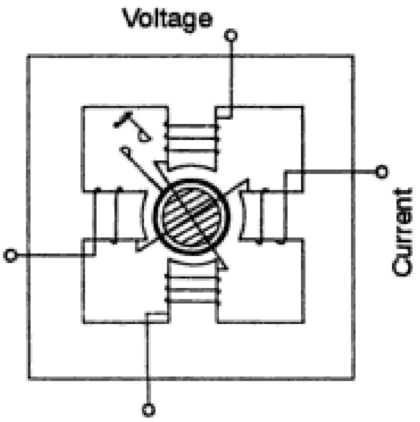


FIGURE 3.9 Induction cup type directional relay

Torque produced is positive when $\cos\phi$ is positive, i.e. ϕ is less than 90°. When ϕ is more than 90° (between 90° and 180°), the torque is negative. At a particular relay location, when power flows in the normal direction, the relay is connected to produce negative torque. The angle between the actuating quantities supplied to the relays is kept (180° $- \phi$) to produce negative torque. If due to any reason, the power flows in the reverse direction, the relay produces a positive torque and it operates. In this condition, the angle between the actuating quantities ϕ is kept less than 90° to produce a positive torque. This is shown in Fig. 3.10 (a). For normal flow of power, the relay is supplied with V and $-I$. For reverse flow, the actuating quantities become V and I. Torque becomes $VI \cos\phi$, i.e. positive. This can be achieved easily by reversing the current coil, as shown in Fig. 3.10 (b).

Relaying units supplied with single actuating quantity discussed earlier are non-directional overcurrent relays. Non-directional relays are simple and less expensive than directional relays.

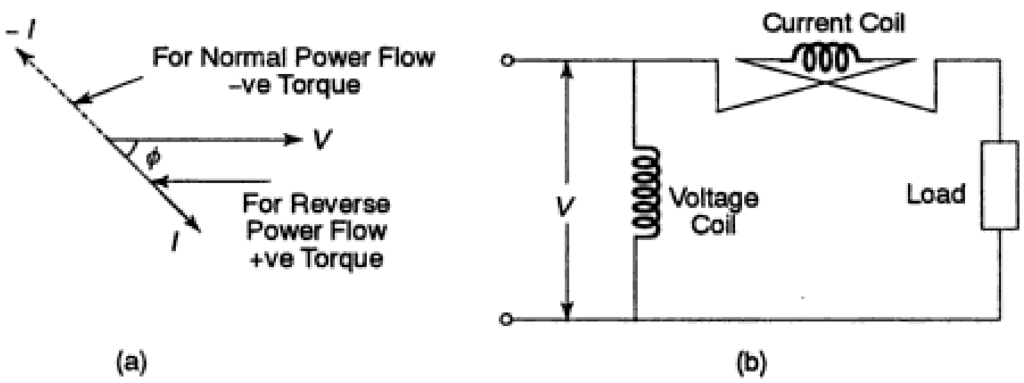


FIGURE 3.10 (a) Phasor diagram for directional relay
(b) Connection of current coil for reverse power relay

3.5.1 Directional Relay Connections

When a close-up fault occurs, the voltage becomes low and the directional relay may not develop sufficient torque for its operation. Under certain fault conditions the power factor may be very low due to which insufficient torque is developed. If the relay is connected in the normal way to develop a torque proportional to $VI \cos \phi$, these types of problems cannot be overcome. To get sufficient torque during all types of faults, irrespective of their locations with respect to the relays, the relay connections are to be modified. Each relay is energised by current from its respective phase and voltage from the other two phases.

There are two methods of connections, one of them is known as the 30° connection and the other the 90° connection. In the 30° connection the current coil of the relay of phase *A* is energised by phase current I_A and line voltage $V_{A\text{-}C}$. Similarly, the relay in phase *B* is energised by I_B and $V_{B\text{-}A}$, the relay in phase *C* with I_C and $V_{C\text{-}B}$, as shown by the vector diagram, Fig. 3.11 (a). The relay is designed to develop maximum torque when its current and voltage are in phase. This condition with present connection is satisfied when the system power factor is 0.866 lagging. See Ref. 2 for details.

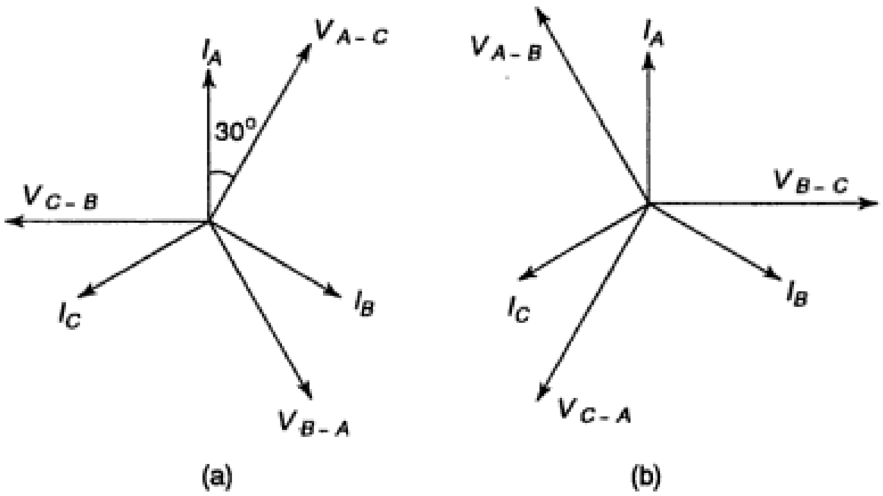


FIGURE 3.11 Phasor diagram for directional relay connections
(a) For 30° connection (b) For 90° connection

The 90° connection gives better performance under most circumstances. In this connection, the relay in phase *A* is energised by I_A and $V_{B\text{-}C}$, *B* phase relay by I_B and $V_{C\text{-}A}$ and *C* phase relay by I_C and $V_{A\text{-}B}$, as shown in Fig. 3.11 (b). The relays are designed to develop maximum torque when the relay current leads voltage by 45° and have internal compensation. For all types of faults, L-L, L-G, 2L-G, 3-ϕ, the phase angle seen by the relay is well below 90°. This connection also ensures adequate voltage polarisation, except for a three-phase close-up fault when the voltages on all phases become very small. For three-phase symmetrical faults the 90° connection is better than the 30° connection, (see Ref. 2 for more details).

3.5.2 Directional Overcurrent Relay

A directional overcurrent relay operates when the current exceeds a specified value in a specified direction. Figure 3.12 shows a directional overcurrent relay. It contains two relaying units, one overcurrent unit and the other a directional unit. For directional control, the secondary winding of the overcurrent unit is kept open. When the directional unit operates, it closes the open contacts of the secondary winding of the overcurrent unit. Thus, a directional feature is attributed to the overcurrent relay. The overcurrent unit may be of either a wattmeter or shaded pole type. In shaded pole type, the opening is made in the shading coil which is in this case a wound coil instead of an ordinary copper strip.

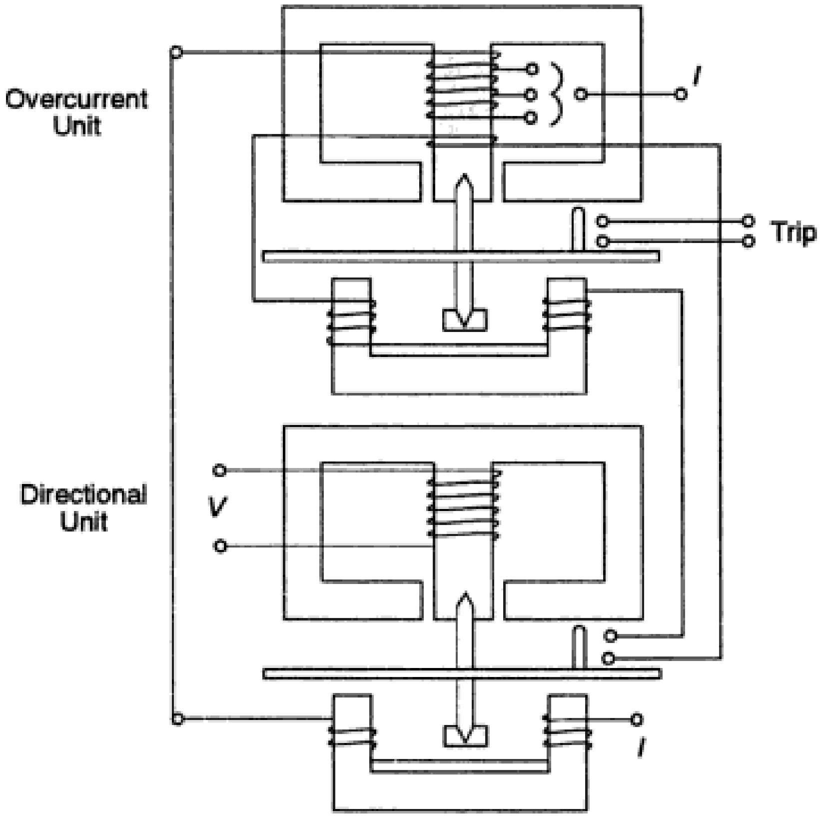


FIGURE 3.12 Directional overcurrent relay

3.6 Protection of Parallel Feeders

Figure 3.13 shows an overcurrent protective scheme for parallel feeders. At the sending end of the feeders (at *A* and *B*), non-directional relays are required. The symbol ↔ indicates a non-directional relay. At the other end of feeders (at *C* and *D*), directional overcurrent relays are required. The arrow mark for directional relays placed at *C* and *D* indicate that the relay will operate if current flows in the direction shown by the arrow. If a fault occurs at *F*, the directional relay at *D* trips, as the direction of the current is reversed. The relay at C does not trip, as the current flows in the normal direction. The relay at B trips for a fault at F. Thus, the faulty feeder is isolated and the supply of the healthy feeder is maintained.

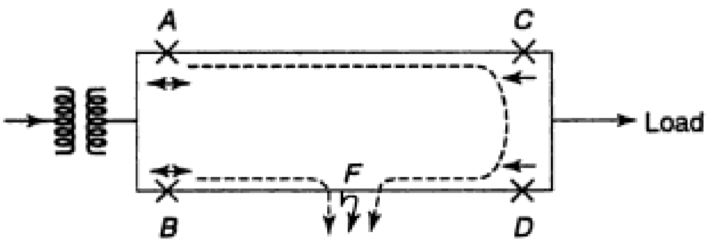


FIGURE 3.13 Protective scheme for parallel feeder

If non-directional relays are used at C and D, both relays placed at C and D will trip for a fault at F. This is not desired as the healthy feeder is also tripped. Due to this very reason relays at C and D are directional overcurrent relays. For faults at feeders, the direction of current at A and B does not change and hence relays used at A and B are non-directional.

3.7 Protection of Ring Mains

Figure 3.14 (a) shows an overcurrent scheme for the protection of a ring feeder. Figure 3.14 (b) is another way of drawing the same scheme. Compared with radial feeders, the protection of ring feeders is costly and complex. Each

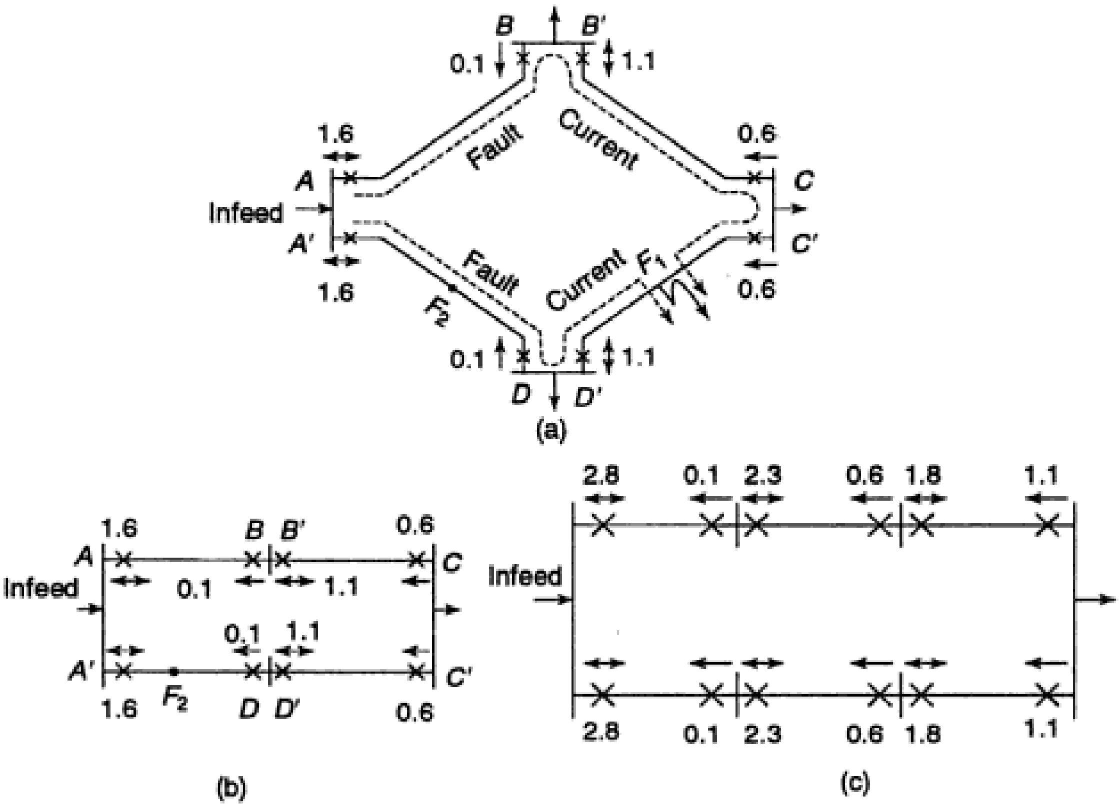


FIGURE 3.14 Protection of ring feeder

feeder requires two relays. A non-directional relay is required at one end and a directional relay at the other end. The operating times for relays are determined by considering the grading, first in one direction and then in the other direction, as shown in Fig. 3.14.

If a fault occurs at F_1 as shown in Fig. 3.14 (a), the relays at C' and D' will trip to isolate the faulty feeder. The relay at C will not trip as the fault current is not flowing in its tripping direction though its operating time is the same as that of C'. Similarly, the relays at B and D will not trip as the fault currents are not in their tripping direction, though their operating time is less than the operating time of B' and D' respectively. Figure 3.14 (b) is an alternative way of drawing the same scheme. In this figure, loads, though present are not shown on buses A, B and D so as to make the figure simple to understand. If a fault occurs at F_2, the relays at A' and D will trip.

Figure 3.14 (c) shows a scheme involving an even greater number of feeders.

3.8 Earth Fault and Phase Fault Protection

A fault which involves ground is called an *earth fault*. Examples are—single line to ground (L-G) fault and double line to ground (2L-G) fault. Faults which do not involve ground are called *phase faults*. The protective scheme used for the protection of an element of a power system against earth faults is known as earth fault protection. Similarly, the scheme used for the protection against phase faults is known as phase fault protection.

3.8.1 Earth Fault Relay and Overcurrent Relay

Relays which are used for the protection of a section (or an element) of the power system against earth faults are called earth fault relays. Similarly, relays used for the protection of a section of the power system against phase faults are called phase fault relays or overcurrent relays. The operating principles and constructional features of earth fault relays and phase fault relays are the same. They differ only in the current levels of their operation. The plug setting for earth fault relays varies from 20% to 80% of the C.T. secondary rating in steps of 10%. Earth fault relays are more sensitive than the relays used for phase faults. The plug setting for phase fault relays varies from 50% to 200% of the C.T. secondary rating in steps of 25%. The name phase fault relay or phase relays is not common. The common name for such relays is overcurrent relay. One should not confuse this term with the general meaning of overcurrent relay. In a general sense, a relay which operates when the current exceeds its pick-up value is called an overcurrent relay. But in the context under consideration, i.e. phase fault protection and earth fault protection, the relays which are used for the protection of the system against phase faults are called overcurrent relays.

3.8.2 Earth Fault Protective Schemes

An earth fault relay may be energised by a residual current as shown in Fig. 3.15 (a) i_a, i_b and i_c are currents in the secondary of C.T.s of different phases. The sum ($i_a + i_b + i_c$) is called residual current. Under normal conditions the residual current is zero . When an earth fault occurs, the residual current is non-zero. When it exceeds pick-up value, the earth fault relay operates. In this scheme, the relay operates only for earth faults. During balanced load conditions, the earth fault relay carries no current; hence theoretically its current setting may be any value greater than zero. But in practice, it is not true as ideal conditions do not exist in the system. Usual!y, the minimum plug setting is made at 20% or 30%. The manufacturer provides a range of plug settings for earth fault relay from 20% to 80% of the C.T. secondary rating in steps of 10%.

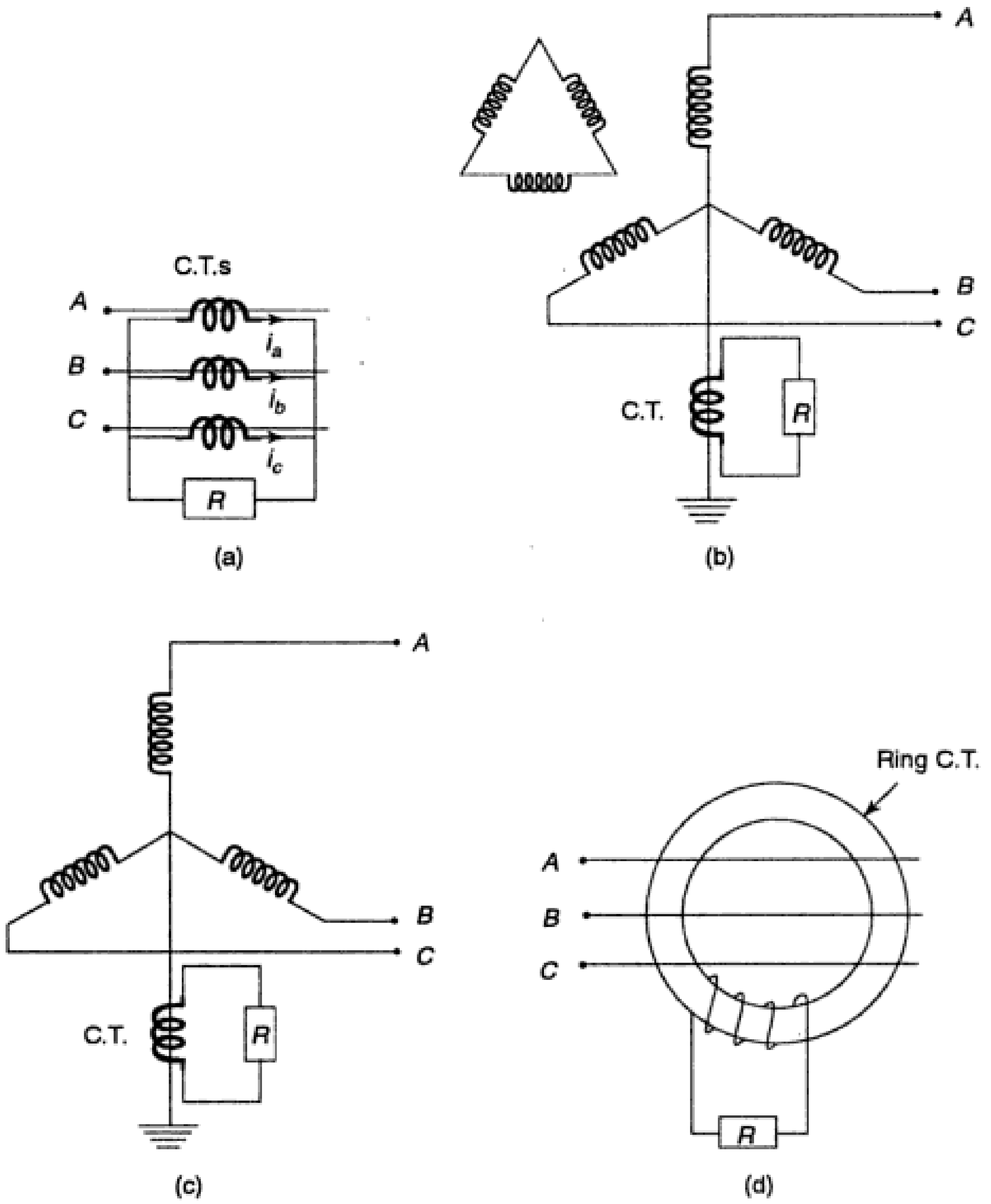


FIGURE 3.15 Various earth fault protective schemes

The magnitude of the earth fault current depends on the fault impedance. In case of an earth fault, the fault impedance depends on the system parameter and also on the type of neutral earthing. The neutral may be solidly grounded, grounded through resistance or reactance. The fault impedance for earth faults is much higher than that for phase faults. Hence, the earth fault current is low compared to the phase fault currents. An earth fault relay is set independent of load current. Its setting is below normal load current. When an earth fault relay is set at lower values, its ohmic impedance is high, resulting in a high C.T. burden.

Figure 3.15 (b) and 3.15 (c) show an earth fault relay used for the protection of transformer and an alternator, respectively. When an earth fault occurs, zero sequence current flows through the neutral. It actuates earth fault relay.

Figure 3.15 (d) shows the connection of an earth fault relay using a special type of C.T. known as a core-balance C.T., which encircles the three-phase conductors.

3.9 Combined Earth Fault and Phase Fault Protective Scheme

Figure 3.16 shows two overcurrent relays (phase to phase fault relays) and one earth fault relay. When an earth fault occurs, the burden on the active C.T. is that of an overcurrent relay (phase fault relay) and the earth fault relay in series. Thus, the C.T. burden becomes high and may cause saturation.

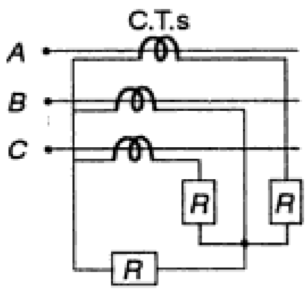


FIGURE 3.16 Two overcurrent and one earth fault relays

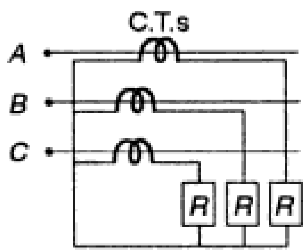


FIGURE 3.17 Three overcurrent relays

3.10 Phase Fault Protective Scheme

Figure 3.17 shows three overcurrent relays for the protection of a three-phase system. This scheme is mainly for the protection of the system against phase faults. If there is no separate scheme for earth fault protection, the overcurrent relays used in this scheme will also sense earth faults but they will be less sensitive.

3.11 Directional Earth Fault Relay

For the protection against ground faults, only one directional overcurrent relay is required. Its operating principle and construction is similar to the directional overcurrent relays discussed earlier. It contains two elements, a directional element and an I.D.M.T. element. The directional element has two coils. One coil is energised by current and the other by voltage. The current coil of the directional element is energised by residual current and the potential coil by residual voltage, as shown in Fig. 3.18 (a). This connection is suitable for a place where the neutral point is not available. If the neutral of an alternator or transformer is grounded, connections are made as shown in Fig. 3.18(b). If the neutral point is grounded through a P.T. the potential coil of the directional earth fault relay may be connected to the secondary of the P.T. The I.D.M.T. element has a plug setting of 20% to 80%.

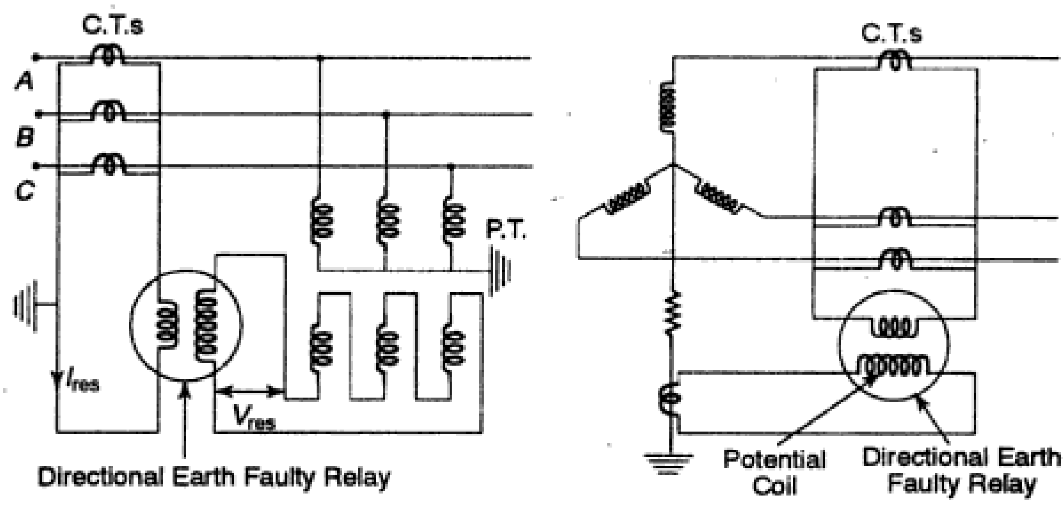


FIGURE 3.18 Connection of a directional earth fault relay

A special five limbs P.T. which can energise both the earth fault relay as well as the phase fault relays, as shown in Fig. 3.19, may be used.

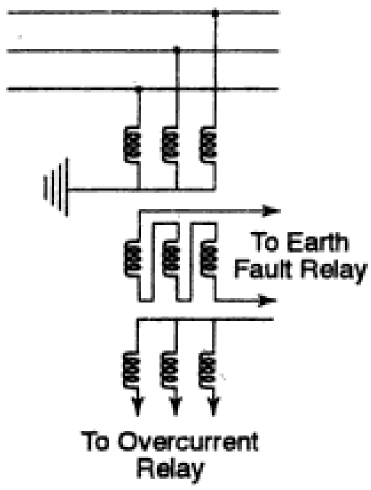


FIGURE 3.19 Five limb P.T.

3.12 Static Overcurrent Relays

The general expression for the operating time of a time-current relay is

$$t = \frac{K}{I^n - 1}$$

Inverse time electromagnetic relays produce time-current curves according to this law only up to a few times the C.T. rating because of magnetic saturation. The time-current characteristic does not follow a simple mathematical equation and it is very difficult to obtain consistency between the characteristics of individual relays. The time-current characteristic of static relays depends on the *R-C* circuit which can be precisely controlled. In the static relays circuit, components are linear, thereby it becomes easier to produce characteristics according to the above law. With an electromagnetic unit, the maximum value of n which is the index of I may be only up to 2. With static relay time-current characteristic with higher values of n can easily be realised. The characteristic of the form $t = K/I^n$ can be realised which will give straight line characteristic on log t/log I graph. Since the time-current characteristics, given by $t = K/I^n$ are not asymptotic to the pick-up value of the current, a separate device to control pick-up is required. Similarly, for an I.D.M.T. relay, a separate unit will provide the definite time portion of the characteristic. With straight line curves there is a great saving in computing relay time settings.

At present most overcurrent relays are of electromagnetic type. So static relays with time-current characteristics to match those of existing induction disc relays can be used. But for new lines it would be better to employ static relays with straight line characteristics.

With static relays it is possible to realise any one of the three most common time-current characteristics, i.e. inverse, very inverse or extremely inverse characteristic using three different plug-in R-C timing circuits or by a switching device.

3.12.1 Advantages of Static Relays

The main advantages of static relays over electromagnetic relays are:

(i) C.T. burden is about one tenth, thereby a smaller C.T. can be employed.

(ii) The space required for a single-phase relay is half and that for a three-phase relay is about one third. Consequently, the panel space and overall cost of installation are reduced. This helps in miniaturization of control equipment.

(iii) Instantaneous reset can easily be achieved . This allows the application of automatic reclosing of circuit breaker.

(iv) Accuracy in time-current characteristics.

(v) Fast operation, absence of mechanical inertia and bouncing of contacts.

(vi) Long life and less maintenance, immunity to vibration, dust and polluted atmosphere.

3.12.2 Instantaneous Overcurrent Relay

The block schematic diagram of the static instantaneous overcurrent relay is shown in Fig. 3.20. The current derived from the main C.T. is fed to the input transformer which gives a proportional output voltage. The input transformer has an air gap in the iron core to give linearity in the current /voltage relationship up to the highest value of current expected, and is provided with tappings on its secondary winding to obtain different current settings. The output voltage of the transformer is rectified through a rectifier and then filtered at a single stage to avoid undesirable time delay in filtering so as to

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