High Voltage Engineering & Power System Protection – 21EE71

Module- 3

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Course Module Details

Module-3

- **Introduction to Power System Protection**: Need for protective schemes, Types of Fault and it's Effects, Essential Qualities of Protection, Primary and Backup Protection. Relay Construction and Operating Principles: Introduction, Electromechanical Relays, Static Relays – Merits and Demerits of Static Relays, Numerical Relays, Comparison between Electromechanical Relays and Numerical Relays.
- **Overcurrent Protection**: Introduction, Time–current Characteristics, Current Setting, Time Setting, Directional Relay, Protection of Parallel Feeders and Ring Mains, Earth Fault, Phase Fault Protection and Combined Earth and Phase Fault Protective Scheme, Static Overcurrent Relays, Numerical Overcurrent Relays

Learning Resources prescribed by University:

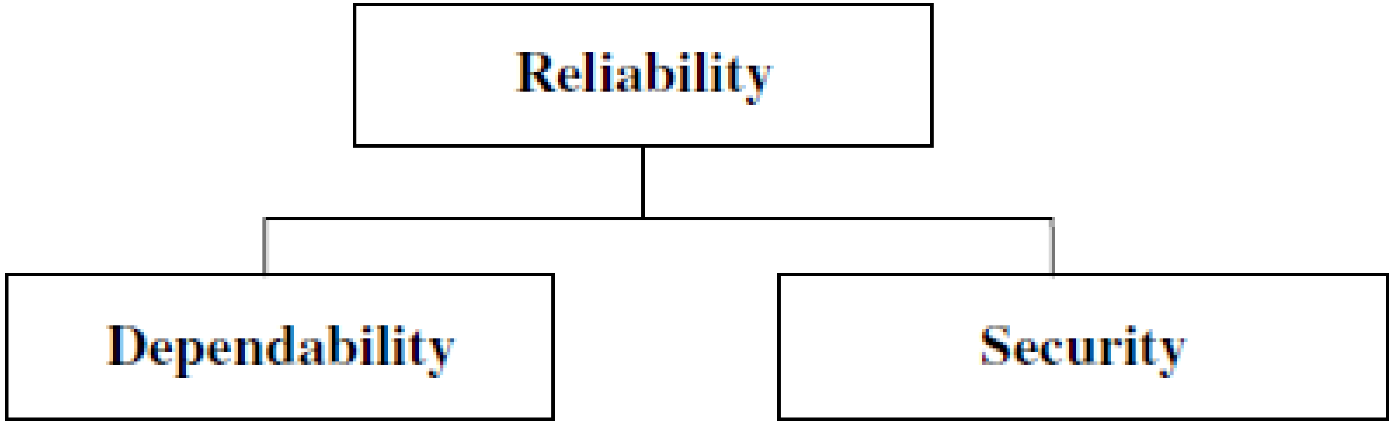
Textbook			
Power System Protection and Switchgear	**Badri Ram, D.N. Vishwakarma**	**McGraw Hill**	**2nd Edition**
Power System Protection and Switchgear	Bhuvanesh Oza et al	McGraw Hill	1st Edition, 2010
Reference Books			
Protection and Switchgear	Bhavesh et al	Oxford	1st Edition, 2011
Power System Switchgear and Protection	N. Veerappan S.R. Krishnamurthy	S. Chand	1st Edition, 2009
Fundamentals of Power System Protection	Y.G.Paithankar S.R. Bhide	PHI	1st Edition, 2009

Power System Protection – Main Functions
1. To safeguard the entire system to maintain continuity of supply. 2. To minimize damage and repair costs. 3. To ensure safety of personnel.

Essential Qualities of Protection

1. *Selectivity*: To detect and isolate the faulty item only.
2. *Stability*: To leave all healthy circuits intact to ensure continuity of supply.
3. *Speed*: To operate as fast as possible when called upon, to minimize damage, production downtime and ensure safety to personnel.
4. *Sensitivity*: To detect even the smallest fault, current or system abnormalities and operate correctly at its setting.

Power System Protection – Qualities



1. *Dependability*: It MUST trip when called upon.
2. *Security*: It must NOT trip when not supposed to.

Power System Protection – Basic Components

1. *Voltage transformers and current transformers*: To monitor and give accurate feedback about the healthiness of a system.
2. *Relays*: To convert the signals from the monitoring devices, and give instructions to open a circuit under faulty conditions or to give alarms when the equipment being protected, is approaching towards possible destruction.
3. *Fuses*: Self-destructing to save the downstream equipment being protected.
4. *Circuit breakers*: These are used to make circuits carrying enormous currents, and also to break the circuit carrying the fault currents for a few cycles based on feedback from the relays.
5. *DC batteries*: These give uninterrupted power source to the relays and breakers that is independent of the main power source being protected.

Fault types and their effects

1. Active Fault

The ‘active’ fault is when actual current flows from one phase conductor to another (phase-to-phase), or alternatively from one phase conductor to earth (phase-to-earth).

This type of fault can also be further classified into two areas, namely the ‘solid’ fault and the ‘incipient’ fault.

a) **Solid fault** occurs as a result of an immediate complete breakdown of insulation as would happen if, say, a struck in an underground cable, bridging conductors, etc. or the cable was dug up by a bulldozer.

In mining, a rockfall could crush a cable, as would a shuttle car. In these circumstances the fault current would be very high resulting in an electrical explosion

b) Incipient Fault

The ‘incipient’ fault, on the other hand, is a fault that starts as a small thing and gets developed into catastrophic failure. Like for example some partial discharge (excessive discharge activity often referred to as Corona) in a void in the insulation over an extended period can burn away adjacent insulation, eventually spreading further and developing into a ‘solid’ fault.

Other causes can typically be a high-resistance joint or contact, alternatively pollution of insulators causing tracking across their surface. Once tracking occurs, any surrounding air will ionize which then behaves like a solid conductor consequently creating a ‘solid’ fault.

2. Passive Faults

Passive faults are not real faults in the true sense of the word, but are rather conditions that are stressing the system beyond its design capacity, so that ultimately active faults will occur.

Typical examples are:

- **Overloading** leading to over heating of insulation (deteriorating quality, reduced life and ultimate failure).
- **Overvoltage**: Stressing the insulation beyond its withstand capacities.
- **Under frequency:** Causing system to behave incorrectly.
- **Power swings:** Generators going out-of-step or out-of-synchronism with each other. It is therefore very necessary to monitor these conditions to protect the system against

these conditions.

3. Transient and permanent faults

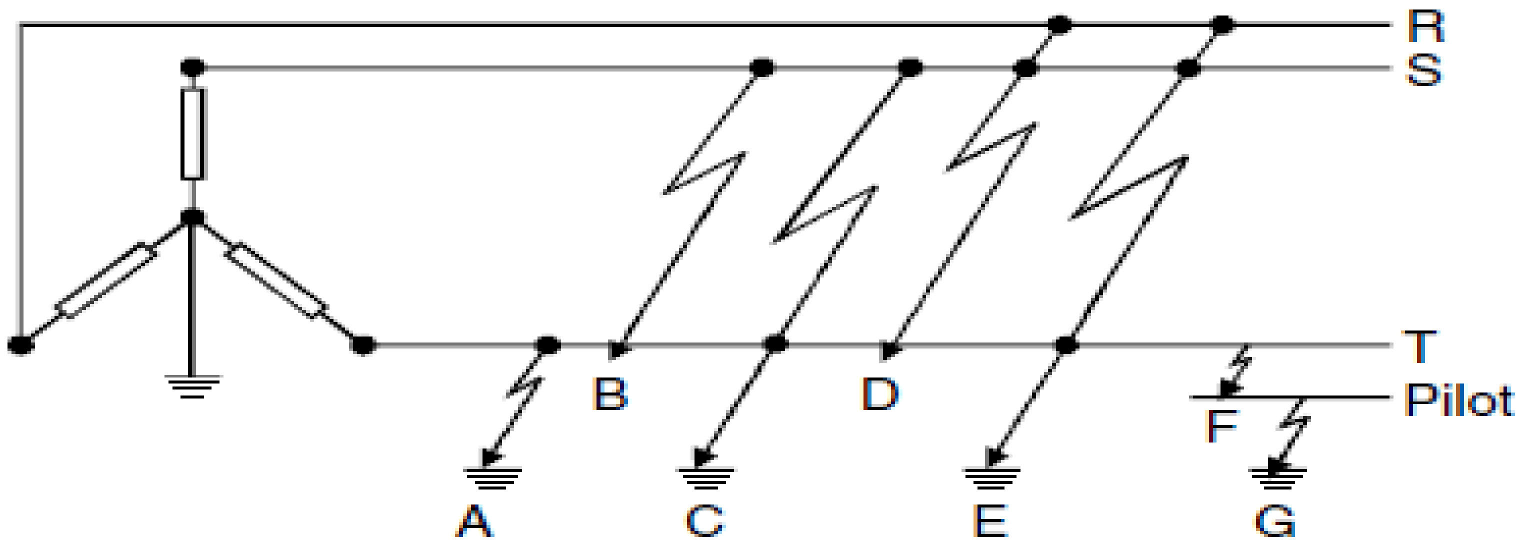
Transient faults are faults, which do not damage the insulation permanently and allow the circuit to be safely re-energized after a short period.

A typical example would be an insulator flashover following a lightning strike, which would be successfully cleared on opening of the circuit breaker, which could then be automatically closed. Transient faults occur mainly on outdoor equipment where air is the main insulating medium.

Permanent faults, as the name implies, are the result of permanent damage to the insulation. In this case, the equipment has to be repaired and recharging must not be entertained before repair/restoration.

Types of faults on a three-phase system

Largely, the power distribution is globally a three-phase distribution especially from power sources. The types of faults that can occur on a three-phase AC system are shown in Figure



Types of faults on a three-phase system: (A) Phase-to-earth fault; (B) Phase-to-phase fault; (C) Phase-to-phase-to-earth fault; (D) Three-phase fault; (E) Three-phase-to-earth fault; (F) Phase-to-pilot fault; (G) Pilot-to-earth fault**

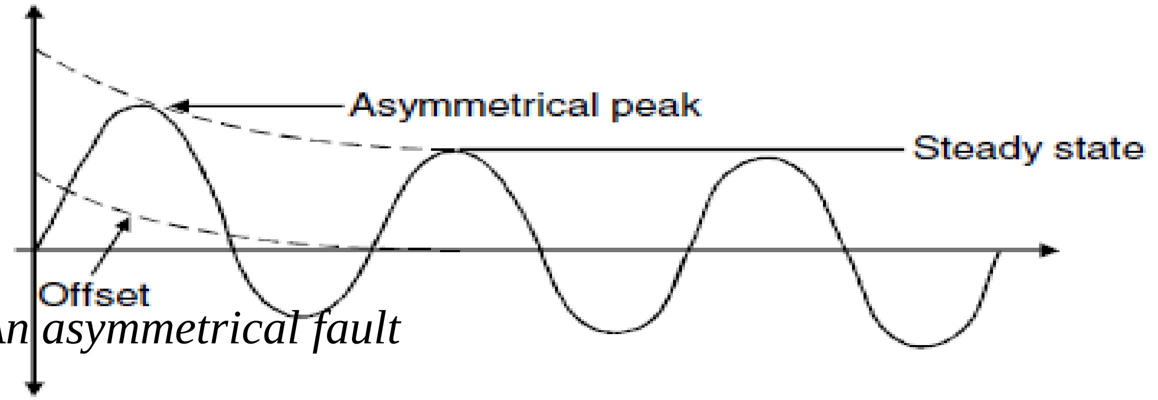
**In underground mining applications only*

Symmetrical and Asymmetrical Faults

	Types of fault	% of occurrence
asymmetrical faults	Single Line to ground faults	70%
	Double line faults	15%
	Double line to ground faults	10%
symmetrical faults	Triple line faults (Balanced three phase faults)	5%

Symmetrical fault is a balanced fault with the sinusoidal waves being equal about their axes, and represents a steady-state condition.

An asymmetrical fault displays a DC offset, transient in nature and decaying to the steady state of the symmetrical fault after a period of time, as shown in Figure



An asymmetrical fault

Symmetrical and Asymmetrical faults

Symmetrical faults: Fault current is same in all the Three Phases and hence system remains balanced even after fault occurrence, Three Phase Short Circuit is generally treated as a standard fault to determine the system fault level

symmetrical fault conditions are analyzed on a single phase basis using thevenin's theorem or using bus matrix impedance matrix. these faults are relatively rare, but are the easiest to analyze so we'll consider them first

Unsymmetrical faults: Fault current is not same in all the Three Phases , System is no longer balanced; these faults are very common, but more difficult to analyze. Analyzed using symmetrical components

Causes of Faults

Equipment	Cause of fault	% of Total Faults
Overhead lines	Lightning strokes, Storms, earthquakes, icing Birds, falling trees, kites aero planes, snakes, etc. Internal over-voltages.	30—40
Underground cables	Damage during digging Insulation failure due to temperature rise Failure of joints	8—10
Alternators (Generator)	Stator faults, Rotor faults, Abnormal conditions, Faults in associated equipment Faults in protective system	6—8
Transformers	Insulation failure, Faults in tap-changer, Faults in bushing, Faults in protection circuit, Inadequate protection, Overloading, over voltage.	10—12
CT, PT	Over-voltages, Insulation failures, Breaking of conductors, Wrong connections	15-20
Switchgear	Insulation failure, Mechanical defect, Leakage of air/oil/gas, Inadequate rating Lack of maintenance.	10-12

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.

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

EFFECTS OF FAULTS

- Short circuits may cause the unbalancing of supply voltages and currents, thereby heating rotating machines.
- 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.
- These 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

Faults analysis

- Fault currents cause equipment damage due to both thermal and mechanical processes.
- The main goal of fault analysis is to determine the magnitudes of the currents present during the fault:
- For proper choice of circuit breakers and protective relaying, we must estimate the magnitude of currents that would flow under short circuit conditions-this is the scope of fault analysis (study)

The Reason to analyze faults are:

- ➢ We need to determine the maximum current to ensure devices can survive the fault.
- ➢ We need to determine the maximum current the circuit breakers (CBs) need to interrupt to correctly choose the size of the CBs.
- ➢ To set the relays so that can detect it.
- ➢ To make sure that the circuit breakers ratings are such that they are capable of interrupting the fault current

In a power system, the most severe fault is three phase fault and less severe fault is open conductor fault. **The various faults in the order of decreasing severity are,**

1) Three phase fault
2) Double line-to-ground fault
3) Line-to-line fault
4) Single line-to-ground fault
5) Open conductor fault

Fault calculations

The fault condition of a power system can be divided into subtransient, transient, and steady state periods. The currents in the various parts of the system and in the fault locations are different in these periods. The estimation of these currents for various types of faults at various locations in the system is commonly referred to as fault calculations

ZONES OF PROTECTION

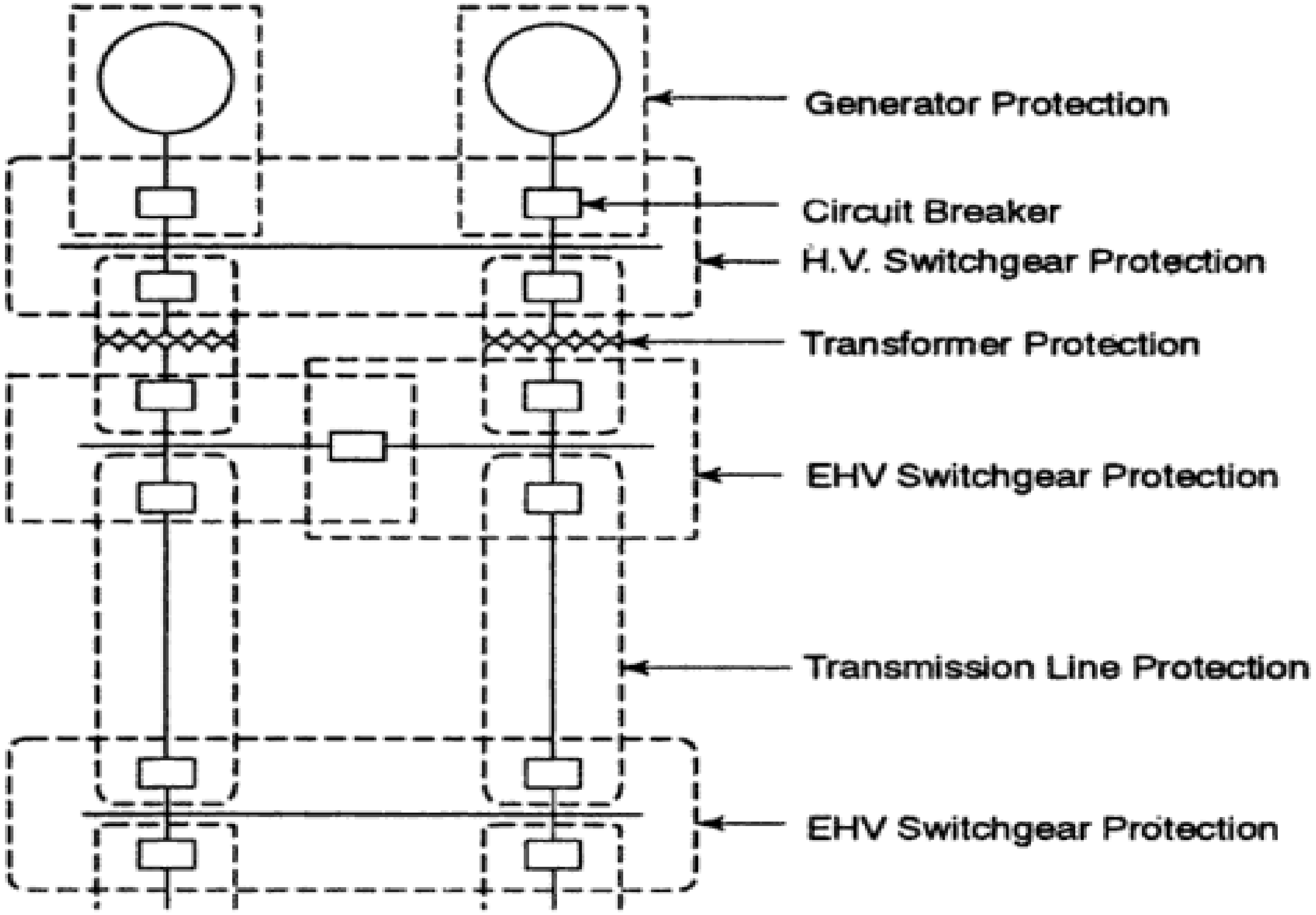
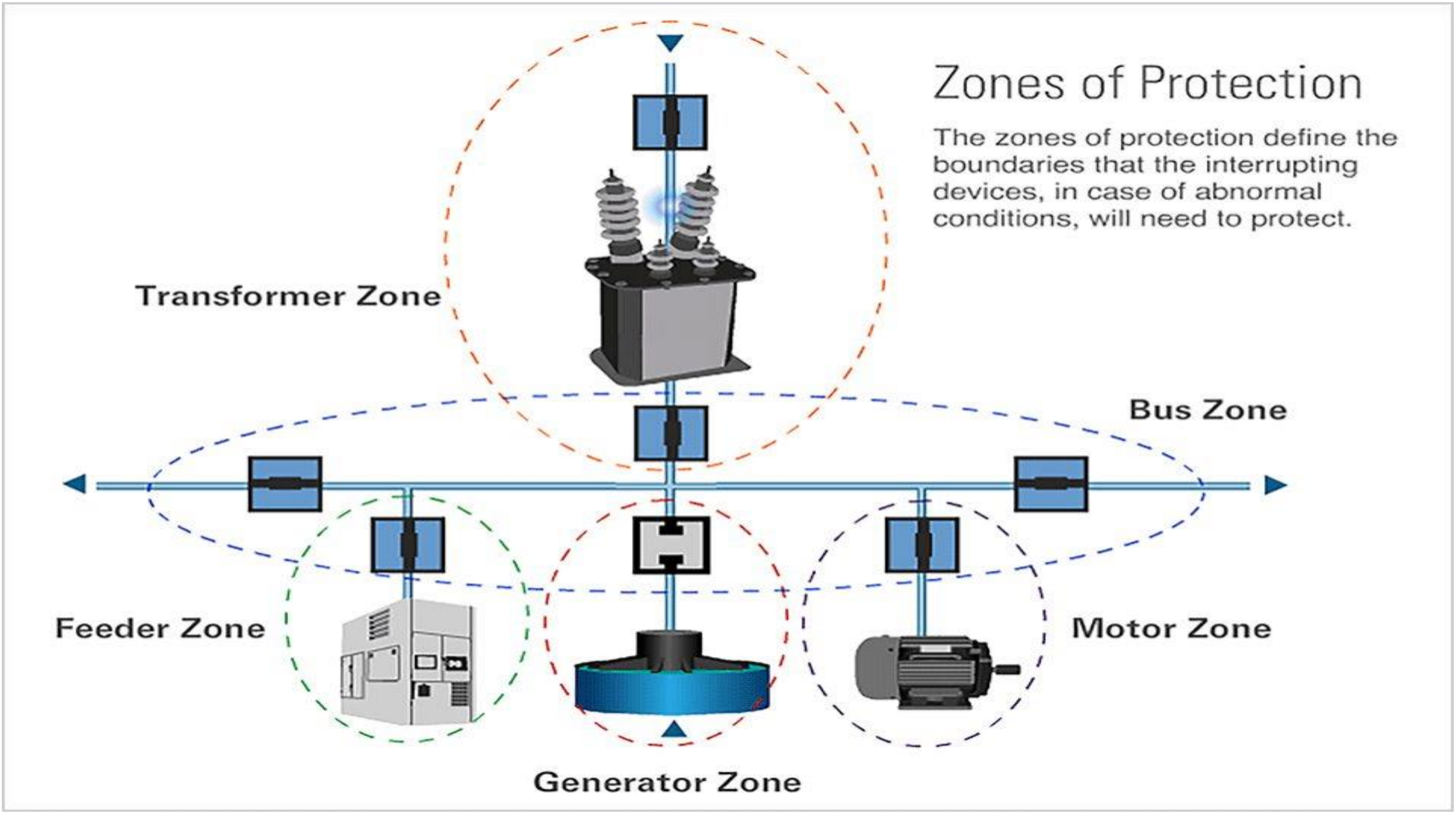


FIGURE 1.1 Zones of protection

Neighboring zones overlap so that no 'dead spot' are left in the protected system

ZONES OF PROTECTION



ZONES OF PROTECTION

It is common for zones of protection to overlap so that multiple layers of protection are afforded to each piece of equipment. This points to the idea of primary and secondary (backup) protection

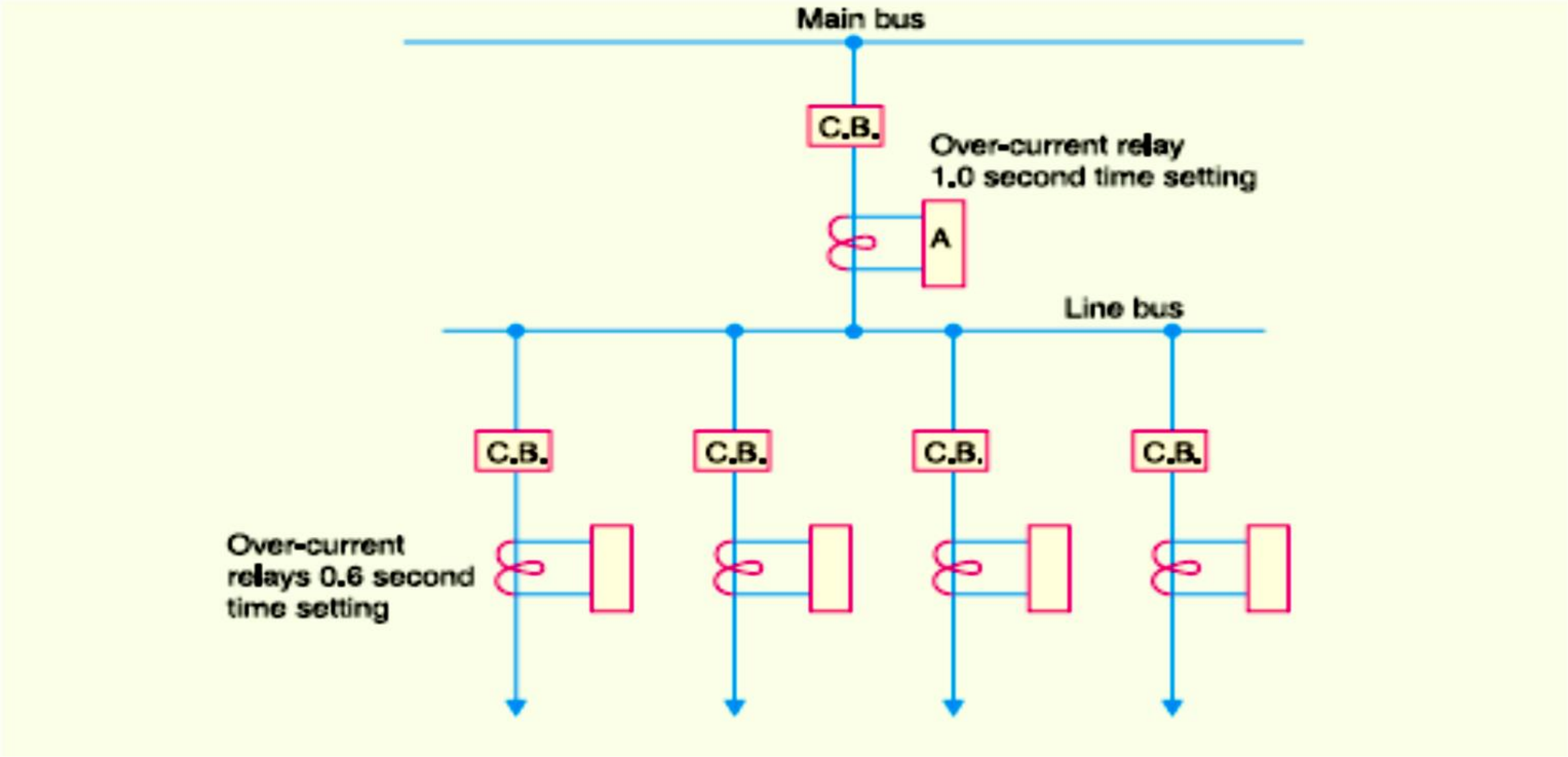
Overlapping and backup protection is implemented to avoid the possibility of unprotected areas, especially for critical equipment. This is accomplished by the strategic placement of the instrument transformers (current transformers or potential transformers)

The power system is divided into protective zones

- Generators
- Transformers
- Buses and distribution feeders
- Transmission lines
- Motors

Neighboring zones overlap so that no 'dead spot' are left in the protected system

PRIMARY AND BACK-UP PROTECTION



PRIMARY AND BACK-UP PROTECTION

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

Relay Back-up.

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

Breaker Back-up

Breaker Back-up. Different breakers are provided for main and back-up protection, both the breakers being in the same station

Remote back-up

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

Relay Construction and Operating Principles

- Electromechanical Relays
- Static Relays – Merits and Demerits of Static Relays
- Numerical Relays
- Comparison between: Electromechanical Relays and Numerical Relays

CLASSIFICATION OF PROTECTIVE RELAYS

Protective relays can be classified in various ways depending on the technology used for their construction, their speed of operation, their generation of development, function, etc

Classification of Protective Relays Based on Technology

Protective relays can be broadly classified into the following three categories

- Electromechanical relays – were developed in earlier 1920s
- Static relays - were developed in earlier 1960s
- Numerical relays - were developed in earlier 1980s
    - Microprocessor-based relay
    - Microcontroller-based relay

Electromechanical Relays

- Electromechanical relays operate by mechanical forces generated on moving parts due to electromagnetic or electrothermic forces created by the input quantities.
- The mechanical force results in physical movement of the moving part which closes the contacts of the relay for its operation.
- Since the mechanical force is generated due to the flow of an electric current, the term 'electromechanical relay' is used.
- Most electromechanical relays use either electromagnetic attraction or electro-magnetic induction principle for their operation. Such relays are called **electromagnetic relays**.

Some electromechanical relays also use electrothermic principle for their operation and are based upon the forces created by expansion of metals caused by temperature rise due to flow of current. Such relays are called thermal relays.

Depending on the principle of operation, Electromechanical relays are classified as

1. The electromagnetic relays are of two types, i.e
   - **(i) Attracted armature relays**
     - **a. Solenoid type relay**
     - **b. Balanced beam type relay**
   - **i. Induction relays**
     - **a. Shaded-pole type induction disc relay**
     - **b. Wattmetric type induction disc relay**
     - **c. Induction cup Relay**
2. Thermal Relay

Electromechanical_Relays

(i) Electromagnetic attraction

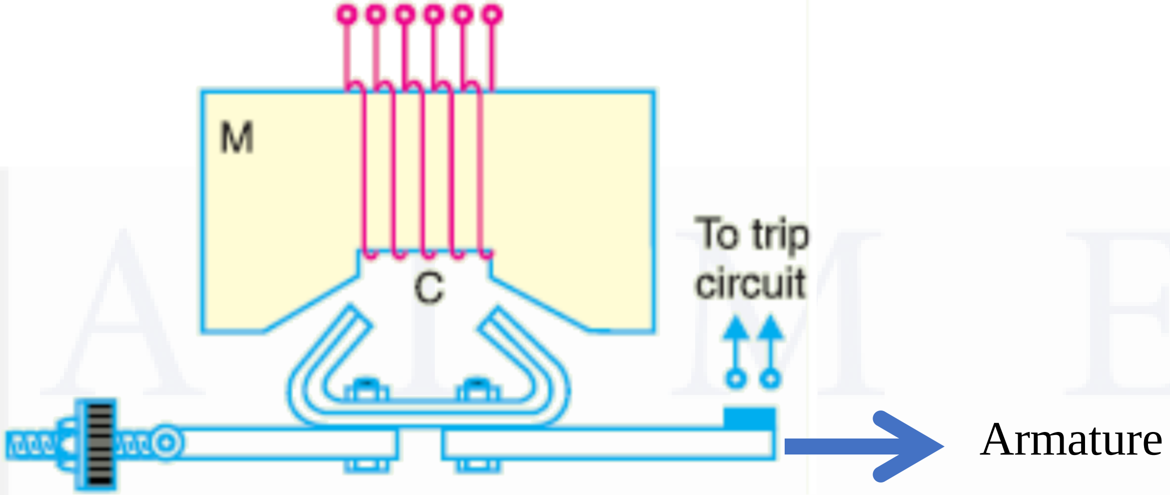
Electromagnetic attraction relays operate by virtue of an armature being attracted to the poles of an electromagnet or a plunger being drawn into a solenoid.

The electromagnetic force exerted on the moving element is proportional to the square of the current flow through the coil

Such relays may be actuated by D.C. or A.C. quantities.

Electromagnetic attraction type relay

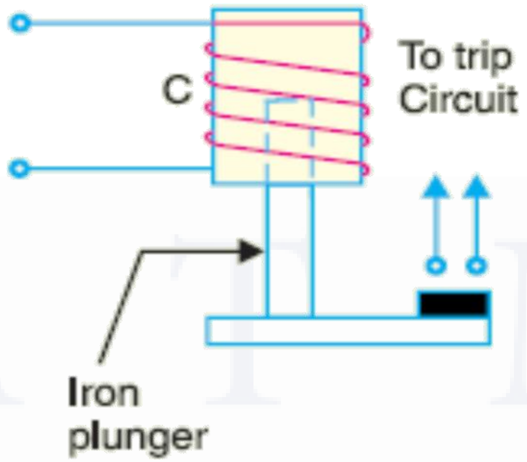
Attracted armature type relay



when a short-circuit occurs, the current through the relay coil increases sufficiently and the relay armature is attracted upwards. The contacts on the relay armature bridge a pair of stationary contacts attached to the relay frame. This completes the trip circuit which results in the opening of the circuit breaker and, therefore, in the disconnection of the faulty circuit

Electromagnetic attraction type relay

1. Solenoid type relay



It consists of a solenoid and movable iron plunger arranged as shown. Under normal operating conditions, the current through the relay coil C is such that it holds the plunger by gravity or spring in the position shown.

on the occurrence of a fault, the current through the relay coil becomes more than the pickup value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, thus opening the circuit breaker and disconnecting the faulty circuit

Electromagnetic attraction type relay

2. Balanced beam type relay

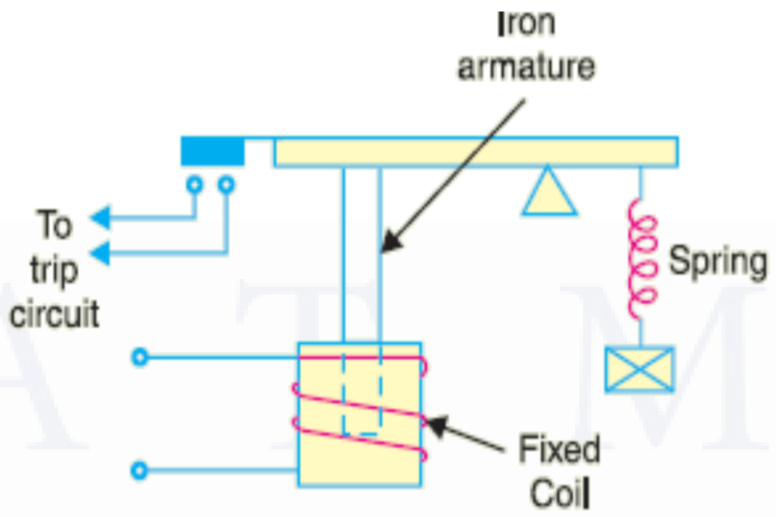


Fig. shows the schematic arrangement of a balanced beam type relay. It consists of an iron armature fastened to a balance beam.

Under normal operating conditions, the current through the relay coil is such that the beam is held in the horizontal position by the spring.

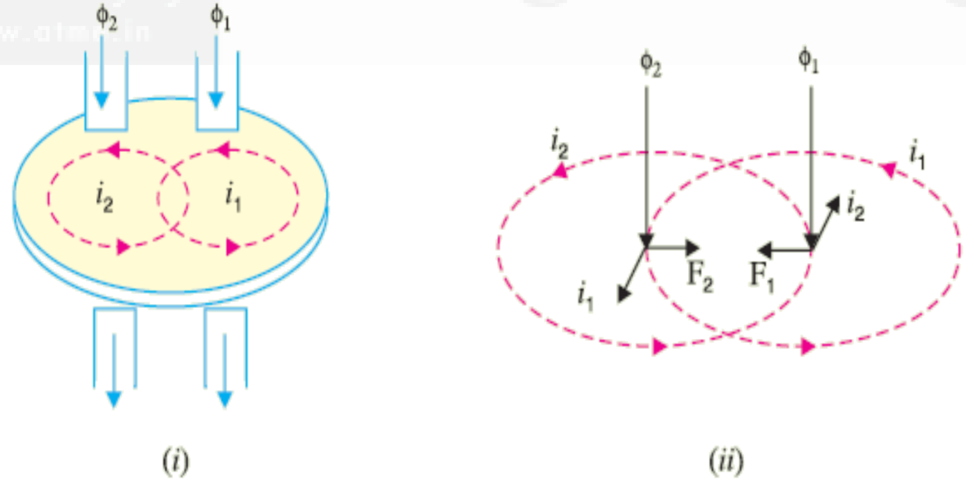
when a fault occurs, the current through the relay coil becomes greater than the pickup value and the beam is attracted to close the trip circuit. This causes the opening of the circuit breaker to isolate the faulty circuit

(ii) Electromagnetic induction

Electromagnetic induction relays operate on the principle of induction motor and are widely used for protective relaying purposes involving A.C. quantities.

They are not used with d.c. quantities owing to the principle of operation.

An induction relay essentially consists of a pivoted aluminium disc (form of the rotor of the non-magnetic moving element) placed in two alternating magnetic fields of the same frequency but displaced in time and space. The torque is is developed by the interaction of electromagnetic fluxes with eddy current, that is induced in the rotor by these fluxes..



$$F \propto \varphi_1\, \varphi_2 \sin \alpha$$

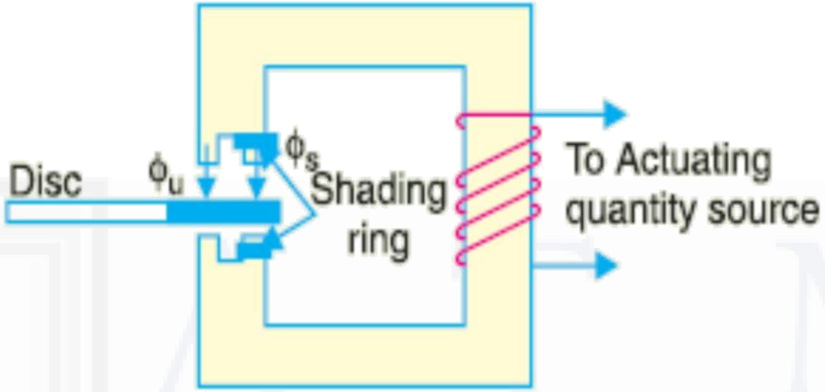
The different type of structure has been used for obtaining the phase difference in the fluxes. These structures are

a. Shaded pole structure

b. Watt-hour meter or double winding structure

c. Induction cup structure

1. Shaded-pole type induction disc relay



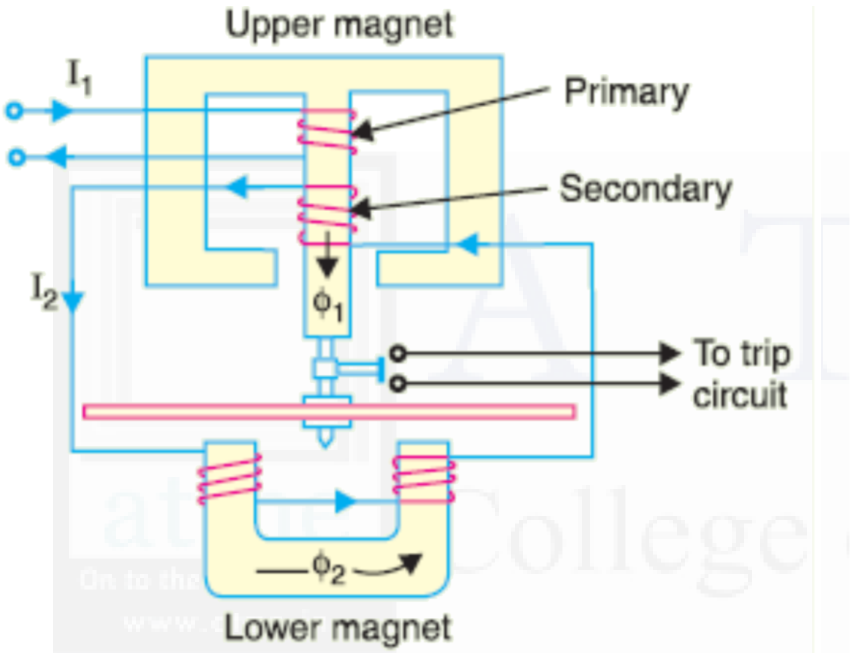
- It consists of a pivoted aluminium disc free to rotate in the air-gap of an electromagnet.
- One half of each pole of the magnet is surrounded by a copper band known as shading ring.

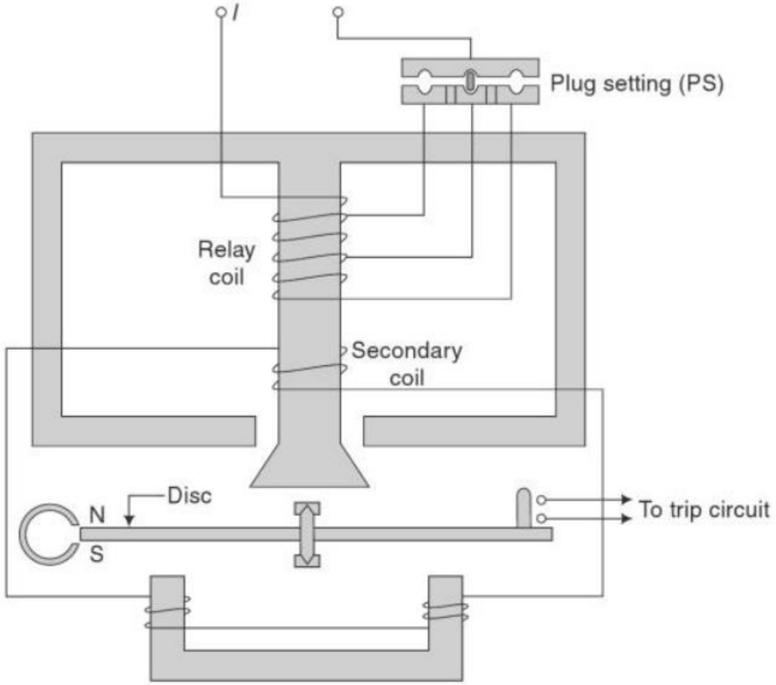
The alternating flux φs in the shaded protion of the poles will, owing to the reaction of the current induced in the ring, lag behind the flux φu in the unshaded portion by an angle α.

These two a.c. fluxes differing in phase will produce the necessary torque to rotate the disc. As proved earlier, the driving torque T is $T \propto \varphi s\ \varphi u \sin \alpha$

Assuming the fluxes φs and φu to be proportional to the current I in the relay coil, $T \propto I^2 \sin \alpha$

2. Wattmetric type induction disc relay.



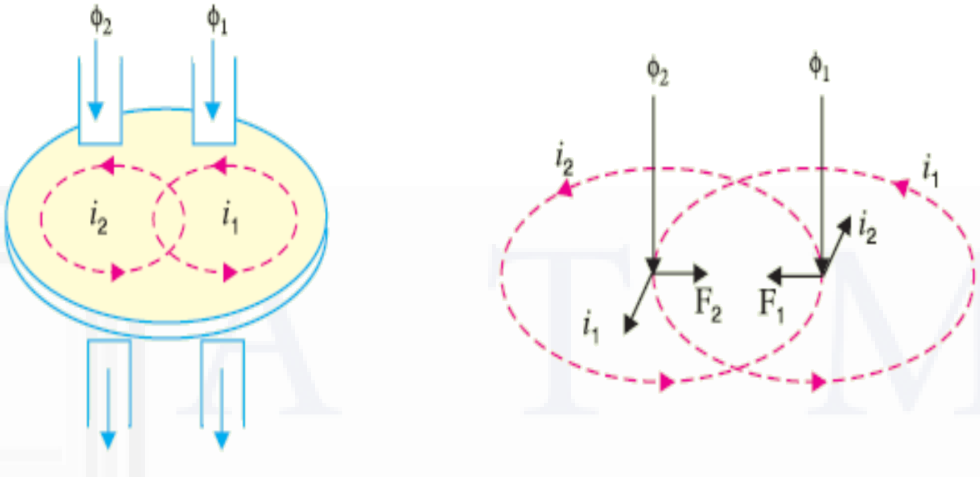


It consists of a pivoted aluminium disc arranged to rotate freely between the poles of two electromagnets.

The primary current induces e.m.f. in the secondary and so circulates a current I2 in it. The flux φ2 induced in the lower magnet by the current in the secondary winding of the upper magnet will lag behind φ1 by an angle α.

The two fluxes φ1and φ2 differing in phase by α will produce a driving torque on the disc proportional to φ1φ2 sin α.

Production of torque in an induction relay



(i) (ii)

$$F \propto \varphi_1 \varphi_2 \sin \alpha$$

The two A.C. fluxes Ø2 and Ø1 differing in phase by an angle α induce e.m.f.s' in the disc and cause the circulation of eddy currents i2 and i1 respectively. These currents lag behind their respective fluxes by 90º. Referring to Fig.(ii) Where the two A.C. fluxes and induced currents are shown separately for clarity

$$\text{let } \varphi_1 = \varphi_1 max \sin \omega t$$

$$\varphi_2 = \varphi_2 max \sin (\omega t + \alpha)$$

where φ1 and φ2 are the instantaneous values of fluxes and φ2 leads φ1 by an angle α.

Production of torque in an induction relay

Assuming that the paths in which the rotor currents flow have negligible self-inductance, the rotor currents will be in phase with their voltages.

$$\therefore\ i_1 \propto d(\varphi_{1max} \sin \omega t)/dt \quad \propto \ \varphi_{1max} \cos \omega t$$

$$\text{And} \quad i_2 \propto d\varphi_2/dt \quad \propto \quad \varphi_{2max} \cos(\omega t + \alpha)$$

Now, $F_1 \propto \varphi_1 i_2$ and $F_2 \propto \varphi_2 i_1$

Fig. (*ii*) shows that the two forces are in opposition.

$\therefore$ Net force F at the instant considered is

$$\begin{aligned} F &\propto F_2 - F_1 \\ &\propto \varphi_2 i_1 - \varphi_1 i_2 \\ &\propto \varphi_{2max} \sin(\omega t + \alpha)\, \varphi_{1max} \cos \omega t - \varphi_{1max} \sin \omega t\, \varphi_{2max} \cos(\omega t + \alpha) \\ &\propto \varphi_{1max} \varphi_{2max} [\sin(\omega t + \alpha) \cos \omega t - \sin \omega t \cos(\omega t + \alpha)] \\ &\propto \varphi_{1max} \varphi_{2max} \sin \alpha \\ &\propto \varphi_1 \varphi_2 \sin \alpha \qquad \ldots (i) \end{aligned}$$

$$F \propto \varphi_1 \varphi_2 \sin \alpha$$

The following points may be noted from exp. (*i*):

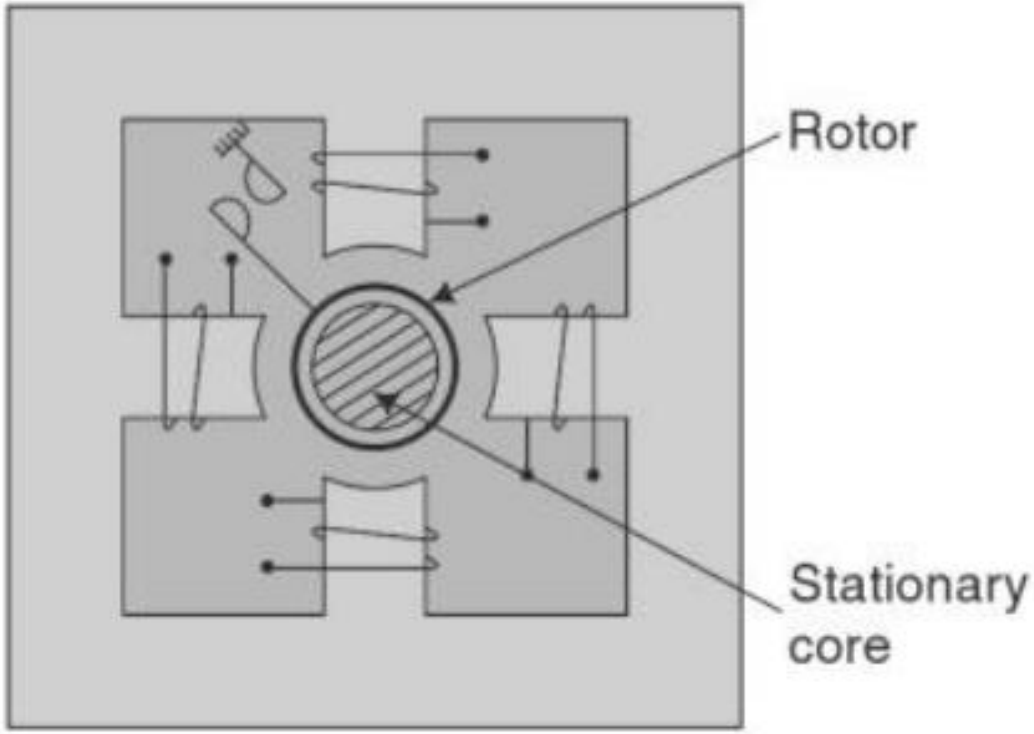
where $\varphi 1$ and $\varphi 2$ are the r.m.s. values of the fluxes

(a) The greater the phase angle α between the fluxes, the greater is the net force applied to the Disc. Obviously, the maximum force will be produced when the two fluxes are 90° out of phase.

(b) The net force is the same at every instant. This fact does not depend upon the assumptions made in arriving at exp. (i).

(c) The direction of net force and hence the direction of motion of the disc depends upon which flux is leading.

3. Induction cup Relay.



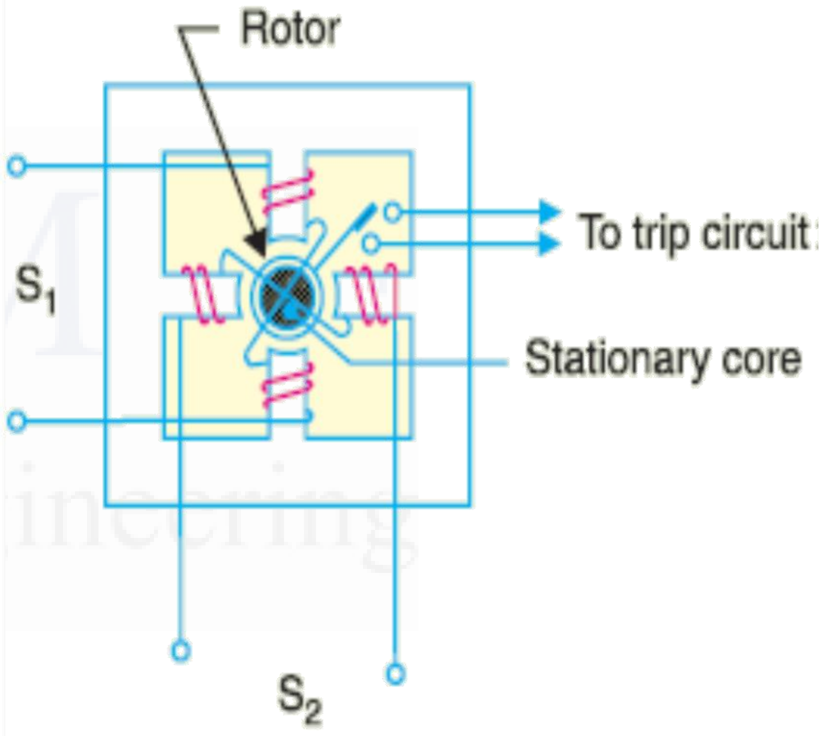
3. Induction cup Relay

- It closely resembles an induction motor, except that the rotor iron is stationary, only the rotor conductor portion being free to rotate. The moving element is a hollow cylindrical rotor which turns on its axis. The rotating field is produced by two pairs of coils wound on four poles as shown.

- The rotating field induces currents in the cup to provide the necessary driving torque. If φ1 and φ2 represent the fluxes produced by the respective pairs of poles, then torque produced is proportional to φ1φ2 sin α where α is the phase difference between the two fluxes.

- Induction cup structures are more efficient torque producers than either the shaded-pole or the watthour meter structures.

- This type of relay has very high speed and may have an operating time less then 0·1 second



Static Relays

These relays contain electronic circuits which may include transistors, IC, 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 electromagnetic relay which finally closes the contact.

Merits and Demerits of Static Relays

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

(i) Low burden on CTs and VTs. 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 circuit 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.

Numerical Relays

- A numerical relay is that in which the measured ac quantities are sequentially sampled and converted into numerical (digital) data form.
- A microprocessor or a microcontroller processes the data numerically (i.e., performs mathematical and/or logical operations on the data) using an algorithm to calculate the fault discriminants and make trip decisions
- The main features of numerical relays are their economy, compactness, flexibility reliability, self-monitoring and self-checking capability, multiple functions, low burden on instruments transformers and improved performance over conventional relays of electromechanical and static types.

1. Microprocessor-based relay:

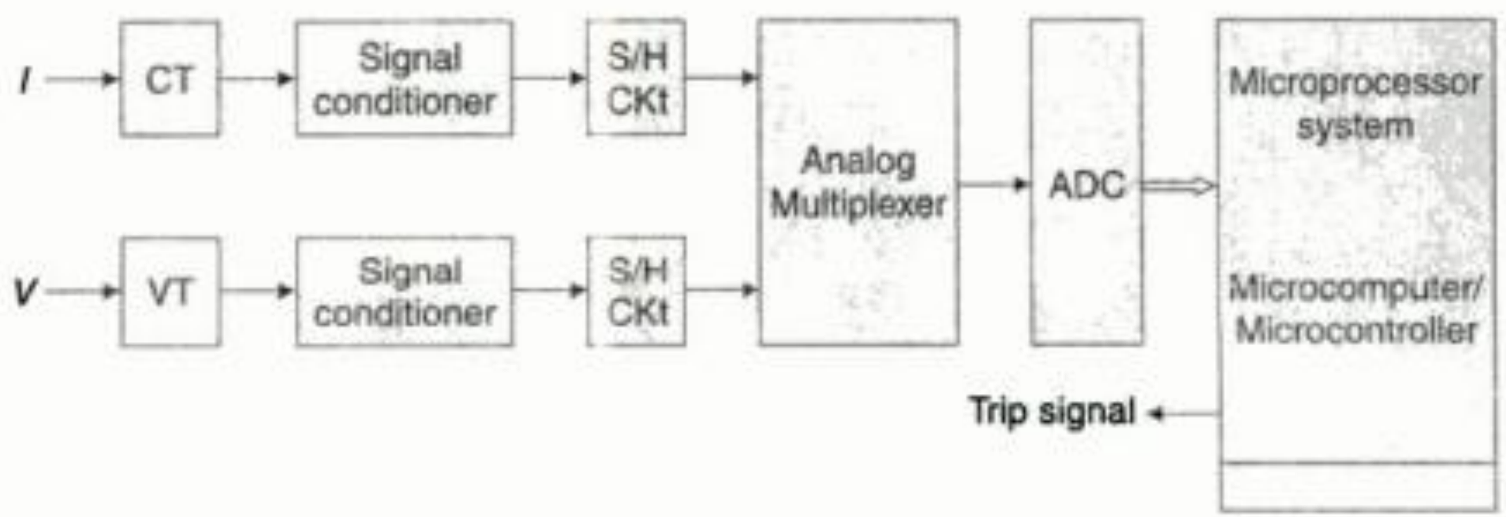
A microprocessor is used to perform all functions of a relay. It measures electrical quantities, makes comparisons, performs computations, and sends tripping signals.

It can realize all sorts of relaying characteristics, even irregular curves which cannot be realised by electromechanical or static relays easily.

2. Microcontroller-based relay:

A microcontroller is used for performing all the function of the relay. It measures the electrical quantities by acquiring them in digital form through a data acquisition system, makes comparisons, processes the digital data to calculate the fault discriminants and make trip decisions. It can realized all sorts of relaying characteristics

The Schematic Diagram of a typical numerical relay



- The levels of voltage and current signals of the power system are reduced by voltage and current transformers (VT and CT). The outputs of the CT and VT (transducers) are applied to the signal conditioner which brings real-World signals into digitizer.
- The signal conditioner electrically isolates the relay from the power system reduces the level of the input voltage, converts current to equivalent voltage and remove high frequency components from the signals using analog filters.

- The output of the signal conditioner are applied to the analog interface, which includes sample and hold (S/H) circuits, analog multiplexer and analog-to-digital (A/D) converters
- These components sample the reduced level signals and convert their analog levels to equivalent numbers the are stored in memory for processing.
- The signal conditioner, and the analog interlace (i.e., S/H CKt, analog multiplexer and A/D converter) constitute the data acquisition system (DAS).
- The acquired signals in the form of discrete numbers are processed by a numerical relaying algorithm to calculate the fault discriminants and make trip decisions.
- If there is a fault within the defined protective zone, a trip signal is issued to the circuit breaker

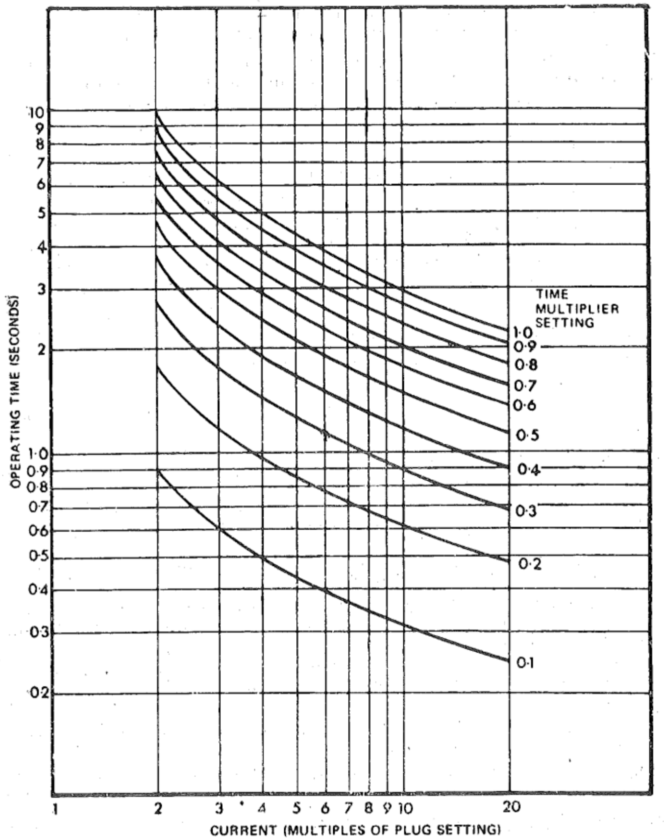
RELAYS AND NUMERICAL RELAYS

Sr. No.	Feature	Electromechanical Relay	Numerical Relay
1.	Size	Bigger	Compact
2.	Characteristics	Fixed	Selectable
3.	Flexibility	No flexibility	Flexibility due to programmability.
4.	Communication feature	Not available	Available
5.	Blocking feature	Not available	Available
6.	Self-supervision	Not available	Available
7.	Adaptability	Not adaptable	Adaptable to changing system condition.
8.	Multiple-functions	Not possible	Possible
9.	Accuracy	± 5% or more	± 2%
10.	Speed of operation	Slow	Fast
11.	Burden on Transducers (CTs and VTs)	Very high	Extremely low
12.	Consistancy of calibration	Deteriorate with time	No effect on calibration even after use of 20-25 years
13.	Setting	Through plug setting in fix steps.	Software based settings.
14.	Memory feature	No memory of any type is available.	Several memory features are available.
15.	Maintenance	Cumbersome and frequent maintenance required.	Maintenance free relays
16.	Output relay programming	Not available	Available
17.	Accessibility of relay from remote place	Not possible	Remote accessibility is available
18.	Status of service values	Not available	Available
19.	Safety of personnel	Not adequate due to non-accessibility at remote location.	Adequate safety is provided.
20.	Spares requirement	There is need to stock several items as spare.	Universal designs minimise the spares requirement.

Time–current Characteristics, Current Setting, Time Setting

Plug-setting multiplier and represents the number of times the relay current is in excess of the current setting

PSM= Current injected in relay coil (secondary current of (CT)) / plug setting
Or
PSM=Primary fault current / (Relay Setting Current* C.T ratio)

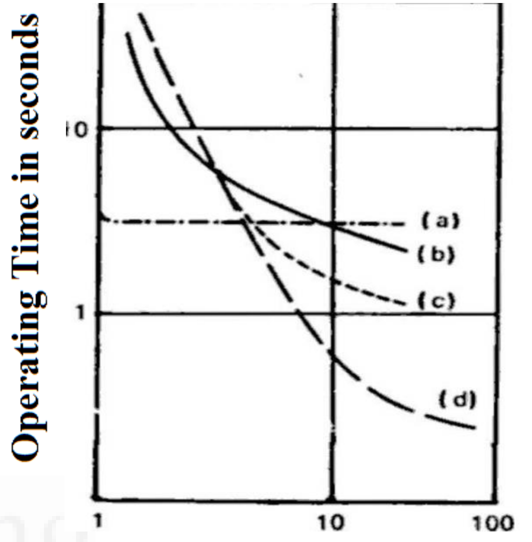


Inverse Characteristics of induction disc relay on log scale Effect of Time-setting

By reducing the time multiplier, the characteristic is shifted to lower side, indicating that operating time is reduced

The operating time of all over current relays tends to become asymptotic (Straight Line) to a definite minimum value with increase in the value of current. This is inherent in electromagnetic relays due to saturation of the magnetic circuit. So by varying the point of saturation different characteristics are obtained; these are:

- Definite time.
- Inverse characteristics
- Inverse definite minimum time (IDMT)
- Very inverse
- Extremely inverse



Multiples of plug setting

Fig shows the Characteristics of various overcurrent relays: (a) definite time ;(b) IDMT; (c) Very inverse; (d) extremely inverse

THANK YOU

High Voltage Engineering & Power System Protection – 21EE71

Module- 3B

Prepared By,

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Course Module Details

Module-3b

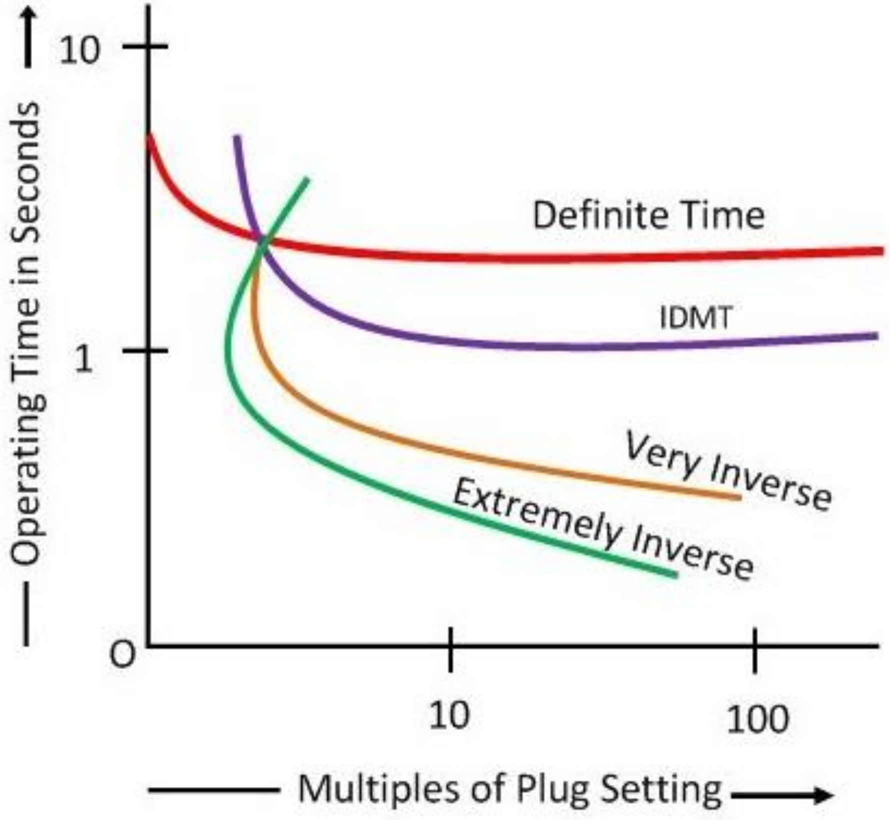
Overcurrent Protection: Introduction, Time–current Characteristics, Current Setting, Time Setting, Directional Relay, Protection of Parallel Feeders and Ring Mains, Earth Fault, Phase Fault Protection and Combined Earth and Phase Fault Protective Scheme, Static Overcurrent Relays, Numerical Overcurrent Relays

Learning Resources prescribed by University:

Textbook			
Power System Protection and Switchgear	**Badri Ram, D.N. Vishwakarma**	**McGraw Hill**	**2nd Edition**
Power System Protection and Switchgear	Bhuvanesh Oza et al	McGraw Hill	1st Edition, 2010
Reference Books			
Protection and Switchgear	Bhavesh et al	Oxford	1st Edition, 2011
Power System Switchgear and Protection	N. Veerappan S.R. Krishnamurthy	S. Chand	1st Edition, 2009
Fundamentals of Power System Protection	Y.G.Paithankar S.R. Bhide	PHI	1st Edition, 2009

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



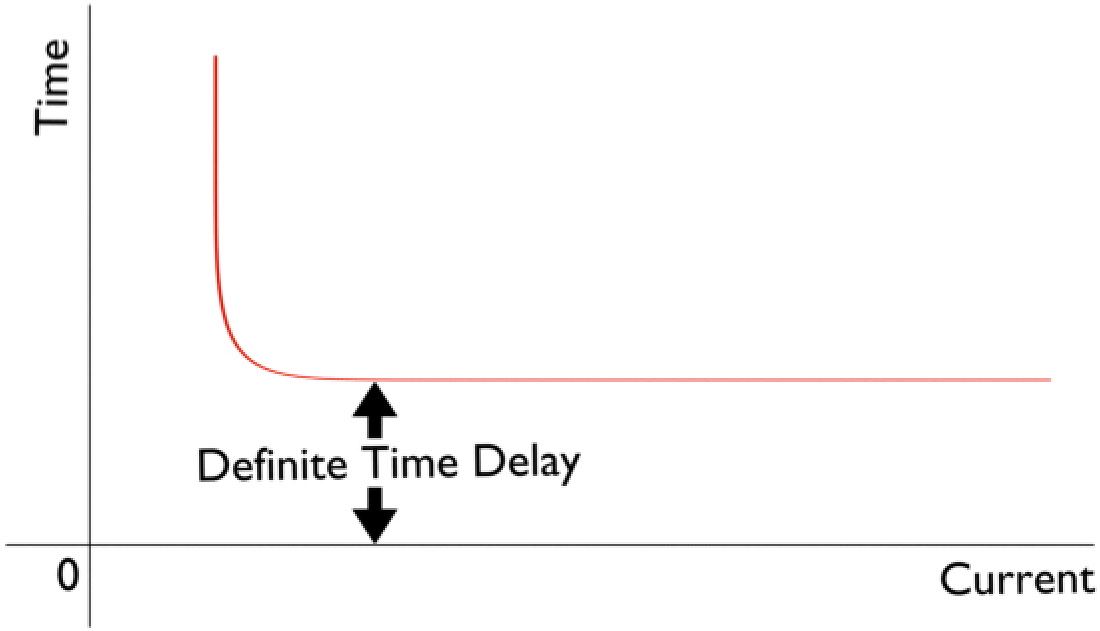
Characteristic of Various Overcurrent Relay

Instantaneous Overcurrent Relay

- An instantaneous relay operates instantly without any intentional time delay when the current exceeds it s pick-up value.
- As the name suggests, this relay operates instantaneously, that is, without an intentional time delay. However, in practice, no relay can operate instantaneously, that is, in zero time. Therefore, a relay that operates within 20 to 40 ms is known as instantaneous relay
- The operating time is constant, irrespective of the magnitude of the current
- There is no intentional time-delay
- It operates in 0.1s or less

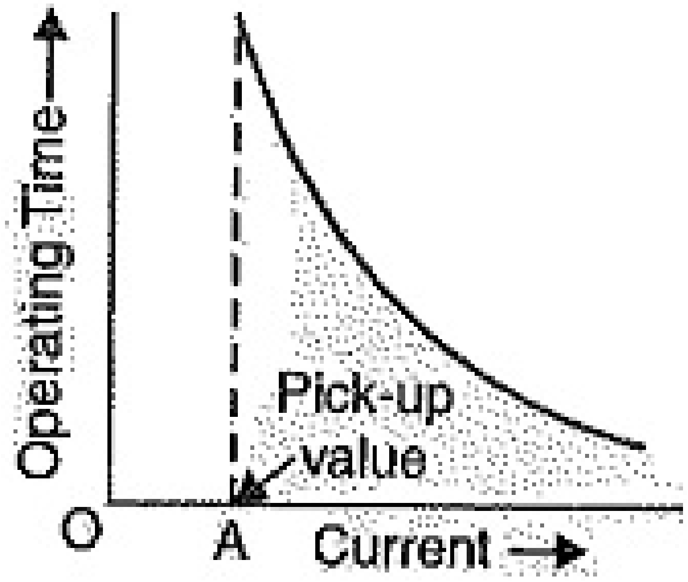
Definite-time delay Overcurrent Relay

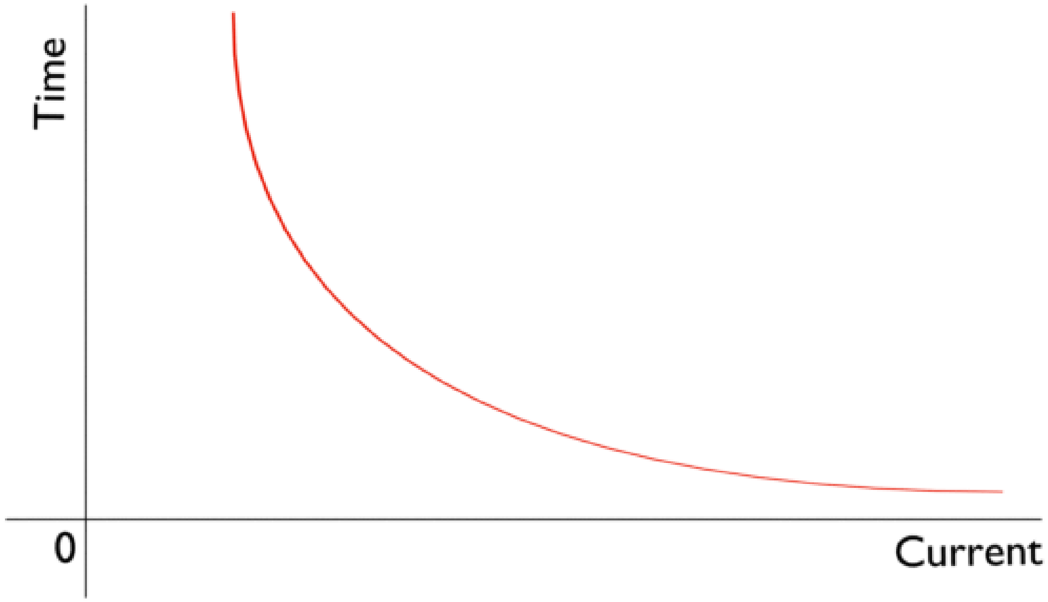
- A definite-time overcurrent relay operates after a after a definite period of time when the current exceeds its pick-up value
- The operating time is constant, irrespective of the magnitude of the current above the pick-up value.
- The desired definite operating time can be set with the help of an intentional time-delay mechanism provided in the relaying unit.



Normal 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





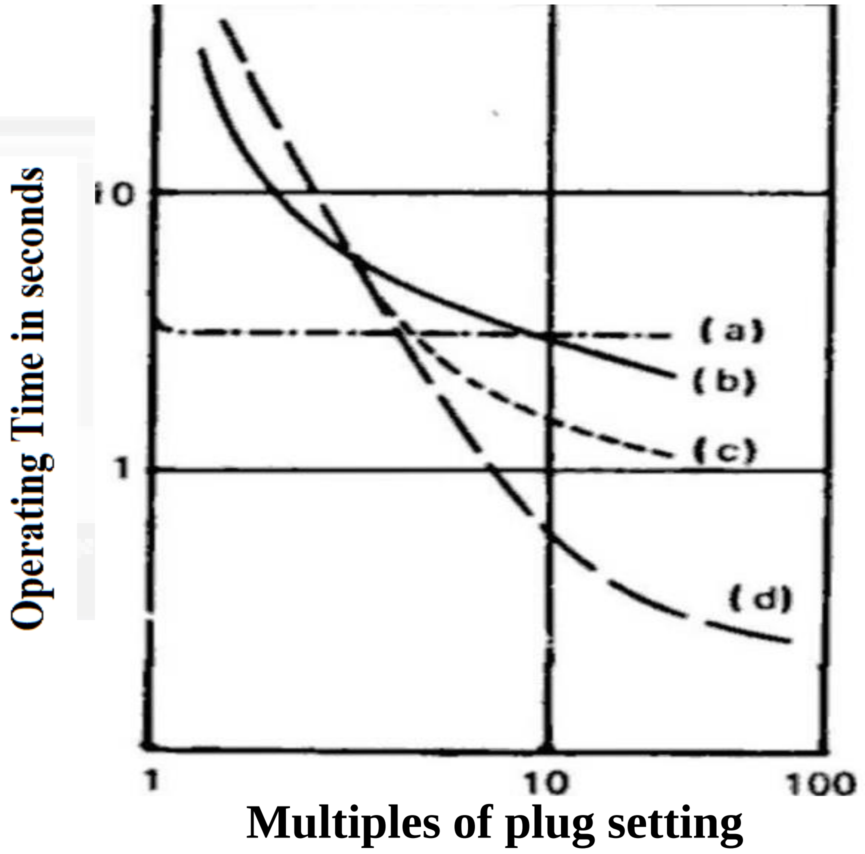
Inverse Definite Minimum Time Overcurrent (I.D.M.T.) Relay

- 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 define time characteristic

- ID.M.T. relays are widely used for protection of distribution lines. Such relays have a provision for current and time settings

Figure shows the characteristic of IDMT relay along with other characteristics



Characteristics of various overcurrent relays:

(a) Definite time delay ; (b) IDMT; (c) Very inverse; (d) extremely inverse

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

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

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.

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 Transformer a highly inverse characteristic of I8.t = K is required

The characteristic having n = 2 are realized by static relays or microprocessor-based overcurrent relays.

Enclosed fuses have time-current characteristics according to the law $I^{3.5} * t = K$

A static or microprocessor based overcurrent relay can be designed to give $I^{3.5} * t = K$ characteristics, suitable to be graded with fuses

Inverse Time Over Current (TOC/IDMT) relay trip time Calculation

Inverse Time Over Current is also referred to as Time Over Current (TOC), or Inverse Definite Minimum Time (IDMT). It means that the trip time is inversely proportional to the fault current.

The trip time is calculated from the following parameters:

- **Trip curve**. Select from the standard set of IEC and IEEE curves.
- **Relay pickup current (A)**. The electrical current pickup set point $\mathbf{I_s}$ in the relay.
- **Fault current (A).** The expected short circuit fault current **I**.
- **TMS or TD setting.**
- IEC time multiplier setting (TMS).
- IEEE time dial (TD). In some relays and literature, a TDM (Time Dial Multiplier) is used, instead of a **TD** (Time Dial). The relationship is as follows: TDM= TD / 7

Calculation of Tripping Time:

IEC 60255 Tripping Curves

The IEC 60255 standard defines four standard current time characteristics – standard inverse (SI), very inverse (VI), extremely inverse (EI) and long-time inverse.

Each characteristic can be calculated from

Equation for trip time: $$t = \frac{K}{\left(\frac{I}{I_s}\right)^{\alpha} - 1} \times TMS$$

t = tripping time in (S)
I_s is the relay pick-up current setting.
I is the actual current i.e fault (actual) secondary CT current (A)
TMS = time multiplier setting
k and **α** are the curve type constants.

See the table below

Equation constants

Curve type	α	K
Standard Inverse(Normal Inverse(3.0))	0.02	0.14
Normal Inverse(1.3)	0.02	0.061
Normal Inverse(0.6)	0.02	0.028
Very Inverse	1.0	13.5
Extremely Inverse	2.0	80
Long-time Inverse	1.0	120

For definite-time characteristic, the value of α = 0

Calculation of Tripping Time:

IEC 60255 Tripping Curves

Relay Characteristics	Equations (IEC 60255)
Standard inverse (SI)	$t = TMS * \frac{0.14}{(I_r)^{0.02} - 1}$
Very inverse (VI)	$t = TMS * \frac{13.5}{I_r - 1}$
Extremely inverse (EI)	$t = TMS * \frac{80}{I_r^2 - 1}$
Long time stand by earth fault	$t = TMS * \frac{120}{I_r - 1}$

Where: Ir = I/Is, I= Measured current, Is=Relay setting current, TMS=Time Multiplier Setting

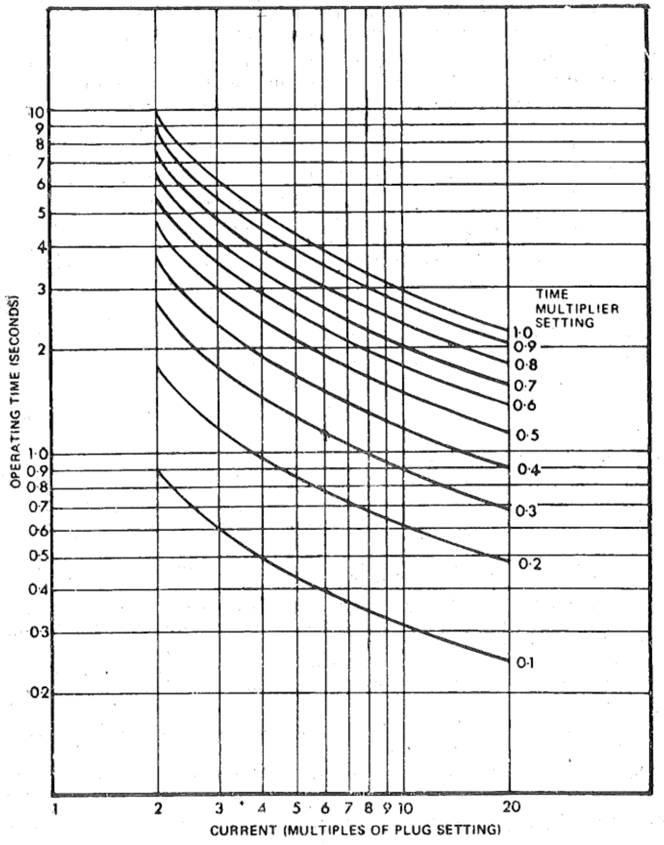
Time–current Characteristics, Current Setting, Time Setting

Plug-setting multiplier and represents the number of times the relay current is in excess of the current setting

PSM= Current injected in relay coil (secondary current of (CT)) / plug setting

Or

PSM=Primary fault current / (Relay Setting Current* C.T ratio)



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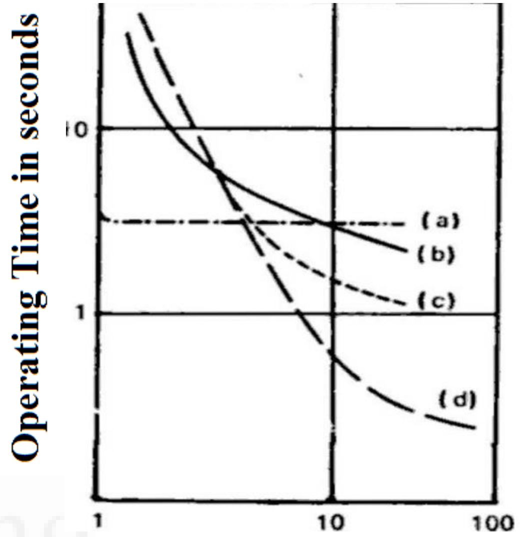
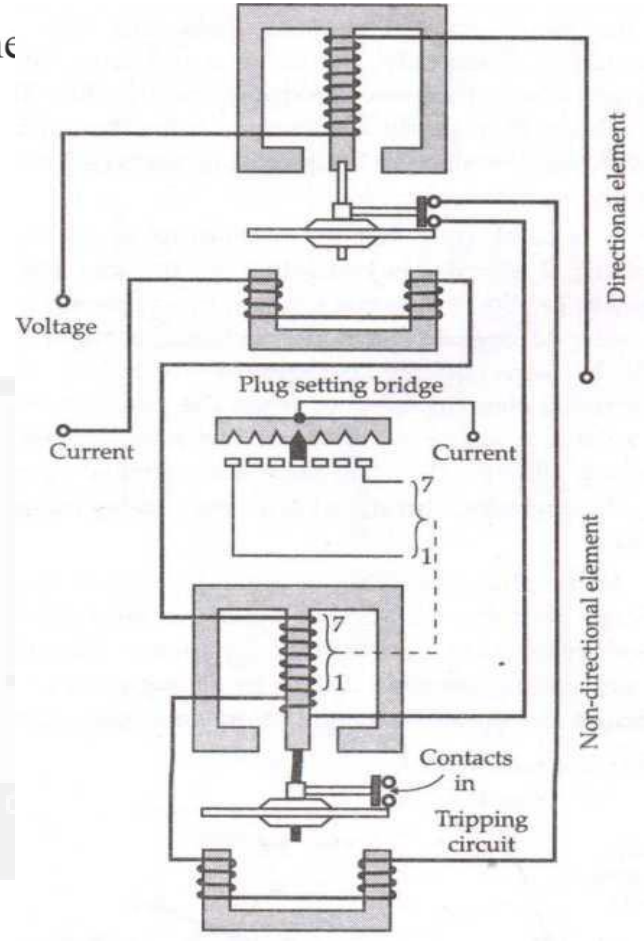
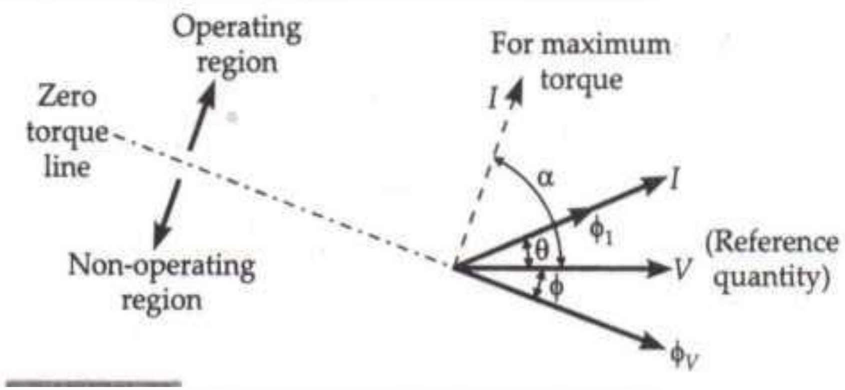


Multiples of plug setting

Fig shows the Characteristics of various overcurrent relays: (a) definite time ;(b) IDMT; (c) Very inverse; (d) extremely inverse

DIRECTIONAL RELAY (OVERCURRENT RELAY)





T α V*I***Sin (Φ+θ),**

Maximum torque occurs when **Sin(θ+Φ)** is a maximum i.e., when (θ+Φ) =90°, the condition shown by the dotted line in above Fig.

Zero torque will occur when sin(θ+Φ)= 0 i.e., (θ+Φ)= 0 or 180° this being satisfied when the relay current phasor lies along the chain dotted line which is at right angles to the maximum torque line

- A Directional Relay consists of two main units mounted in a common case:

1. Directional Unit: This unit includes an induction cup relay with two opposite poles fed by voltage and current.
2. Non-Directional or Overcurrent Unit: This unit can be of either a shaded pole type or wattmeter type.

i. Directional Unit:

- Potential Coil: Connected to the system voltage through a potential transformer.
- Current Coil: Energized by the circuit current through a current transformer.
- Flux Production: The potential coil produces flux in the upper electromagnet, while the current coil produces flux in the lower electromagnet.

i. Non-Directional Unit:

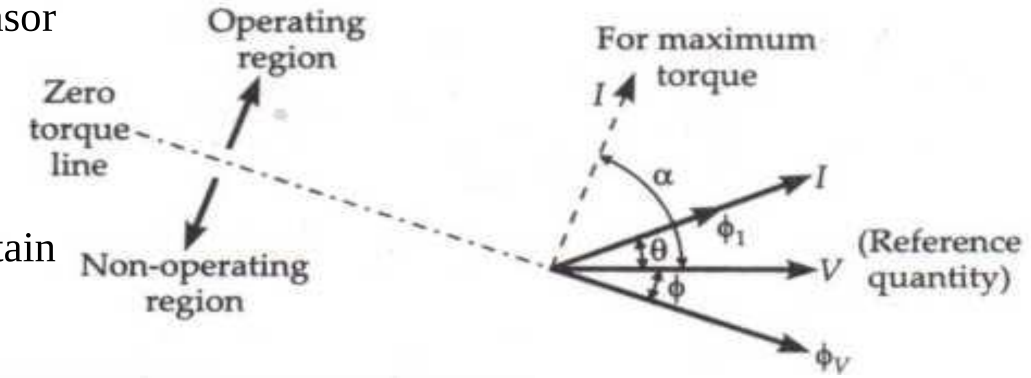
- Coil Winding: Wound on the upper electromagnet and connected to the circuit current through a current transformer.
- Plug Setting Bridge: Adjusts the current setting.
- Aluminum Disc: Placed between the two magnets, with a moving contact that closes the fixed contact (trip circuit contacts) after the operation of the directional unit.

- **Working of Directional Relay**
- Normal Operation: During normal conditions, the relay measures the angle between the voltage and current. The torque produced by the relay coils is due to the interaction of flux produced by one coil with the current of the second coil2.
- Fault Condition: When a fault occurs, the fault current flows through the current coil, producing flux in the lower magnet of the directional unit. The current in the voltage coil produces another flux in the upper magnet1.
- Torque Production: The interaction of the two fluxes produces a driving torque on the aluminum disc. The direction of the torque depends on the direction of power flow in the circuit3.
- Relay Operation: If the power flows in the normal direction, the driving torque and restraining torque (due to the spring) help each other to turn away the moving contact from the fixed contacts, keeping the relay inoperative. If the power flows in the reverse direction due to a fault, the driving torque becomes large enough to rotate the disc and close the trip circuit, causing the circuit breaker to disconnect the faulty section

DIRECTIONAL RELAY (OVERCURRENT RELAY)

•**Reference Quantity (Voltage)**: The voltage V is often considered the reference phasor. Its phase is used as a reference to determine the relative position of the current phasor I.

•**Current Phasor I**: The current phasor I can shift in phase depending on the direction of power flow or the nature of the fault. Its angle with respect to the voltage phasor determines whether the relay will operate.



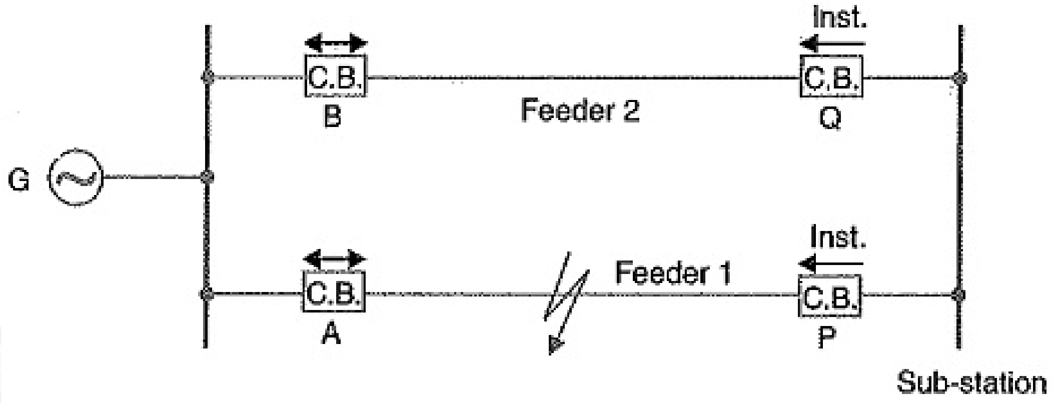
•**Operating Region and Non-Operating Region**:

•The relay is designed to operate (trip) when the current phasor III lies within a certain angular region relative to the reference voltage.

•**Zero Torque Line** separates the operating and non-operating regions. When I is in the operating region, the relay produces positive torque and can trip. In the non-operating region, the torque is zero or negative, and the relay will not trip.

•**Maximum Torque Angle α\alphaα**: The angle α\alphaα between I and V corresponds to the angle where the relay generates maximum torque. This angle is pre-set in the relay and typically aligns with the expected fault current angle for forward faults. When I is at this angle, the relay is most sensitive and produces the highest torque, leading to quicker operation

Protection of Parallel feeders



Suppose an earth fault occurs on feeder 1 as shown in Fig. It is desired that only circuit breakers at A and P should open to clear the fault, whereas feeder-2 should remain intact to maintain the continuity of supply.

The above arrangement accomplishes this job. The shown fault is fed via two routes, viz.

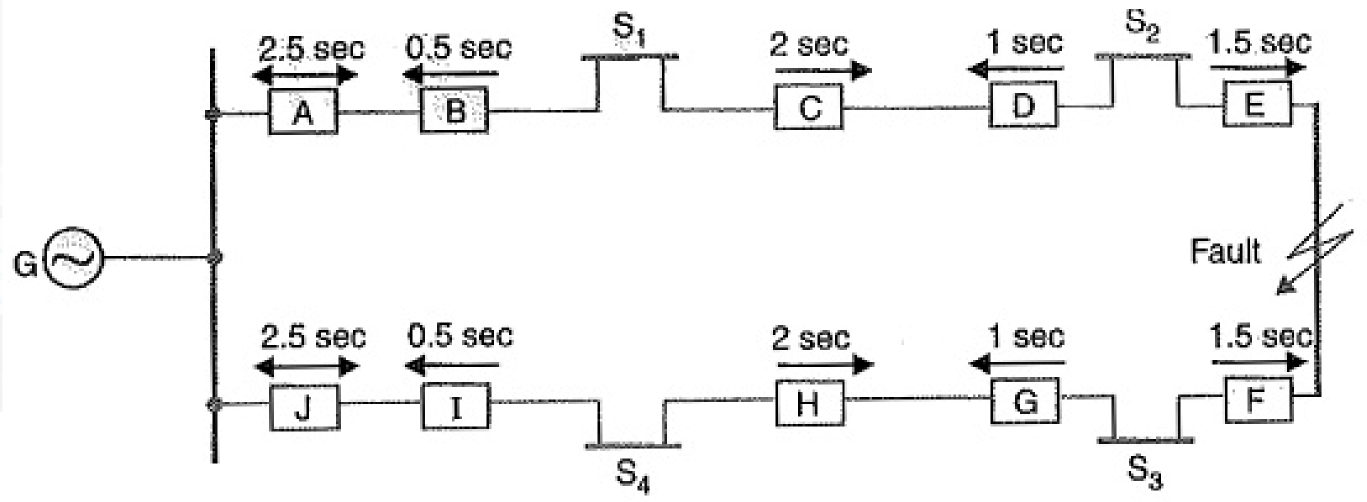
(a) Directly from feeder 1 via the relay A

(b) From feeder 2 via B, Q, sub-station and P

Therefore, power flow in relay Q will be in normal direction but is reversed in the relay P. This causes the opening of circuit breaker at P. Also the relay A will operate while relay B remains inoperative. It is because these relays have inverse-time characteristics and current flowing in relay A is in excess of that flowing in relay B. In this way only the faulty feeder is isolated.

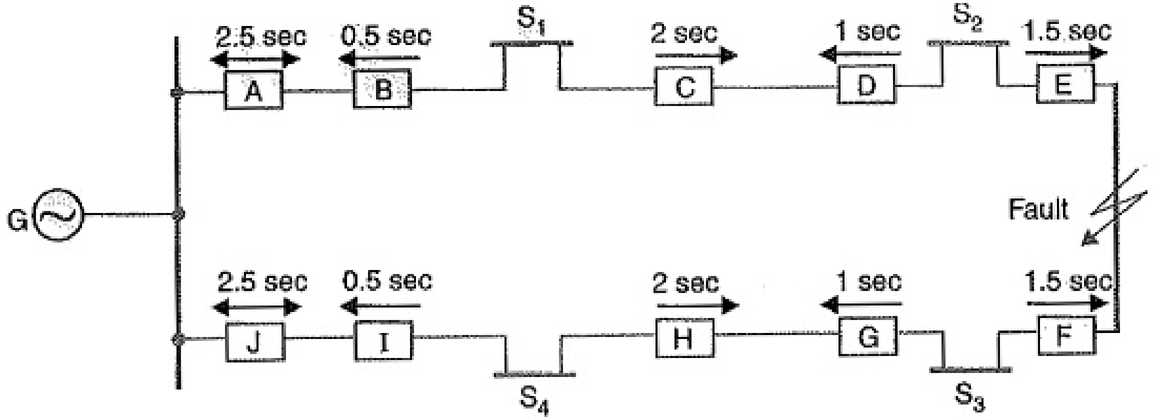
Protection of Ring main system

In this system, various power stations or sub-stations are interconnected by alternate routes, thus forming a closed ring. In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the ring, thereby maintaining continuity of supply



Above Fig. shows the single line diagram of a typical ring main system consisting of one generator G supplying four sub-stations S1, S2, S3 and S4. In this arrangement, power can flow in both directions under fault conditions. Therefore, it is necessary to grade in both directions round the ring and also to use directional relays.

Protection of Ring main system



In order that only faulty section of the ring is isolated under fault conditions, the types of relays and their time settings should be as follows :

(i) The two lines leaving the generating station should be equipped with non-directional overcurrent relays (relays at A and J in this case).

(ii) At each sub-station, reverse power or directional relays should be placed in both incoming and outgoing lines (relays at B, C, D, E, F, G, H and I in this case).

There should be proper relative time-setting of the relays. As an example, going round the loop GS1 S2 S3 S4G ; the outgoing relays (viz at A, C, E, G and I) are set with decreasing time limits e.g. A = 2·5 sec, C = 2 sec, E = 1·5 sec G = 1 sec and I = 0·5 sec

Similarly, going round the loop in the opposite direction (i.e. along G S4 S3 S2 S1 G), the outgoing relays (J, H, F, D and B) are also set with a decreasing time limit e.g.

J = 2·5 sec, H = 2 sec, F = 1·5 sec, D = 1 sec, B = 0·5 sec.

Earth Fault Protection

1. **Residual Current Devices (RCDs)**: These devices detect imbalance between live and neutral currents, indicating a leakage to earth. They are highly sensitive and can detect leakage currents as low as 5 mA.
2. **Zero Sequence Current Transformers (ZSCTs)**: Used to detect earth faults by measuring the sum of the currents in all three phases. Any imbalance indicates a fault.
3. **Directional Earth Fault Relays**: These relays determine the direction of the fault current, which is crucial in complex networks to identify the fault location accurately.
4. **High Impedance Restricted Earth Fault (REF) Protection**: This method uses a high impedance relay connected across the secondary of a current transformer to detect earth faults within a specific zone, providing high sensitivity and stability

Phase Fault Protection

1. **Differential Protection**: This method compares the current entering and leaving a protected zone. Any difference indicates a fault. It is highly sensitive and fast-acting, making it ideal for protecting transformers and generators.
2. **Distance Protection**: Measures the impedance between the relay location and the fault. It is effective for protecting transmission lines as it can determine the fault location based on the impedance measurement.
3. **Overcurrent Relays**: These relays operate when the current exceeds a preset value. They are simple and cost-effective, used widely in distribution networks.
4. **Directional Overcurrent Relays**: Similar to overcurrent relays but with the added capability of determining the direction of the fault current, which is essential in interconnected networks.

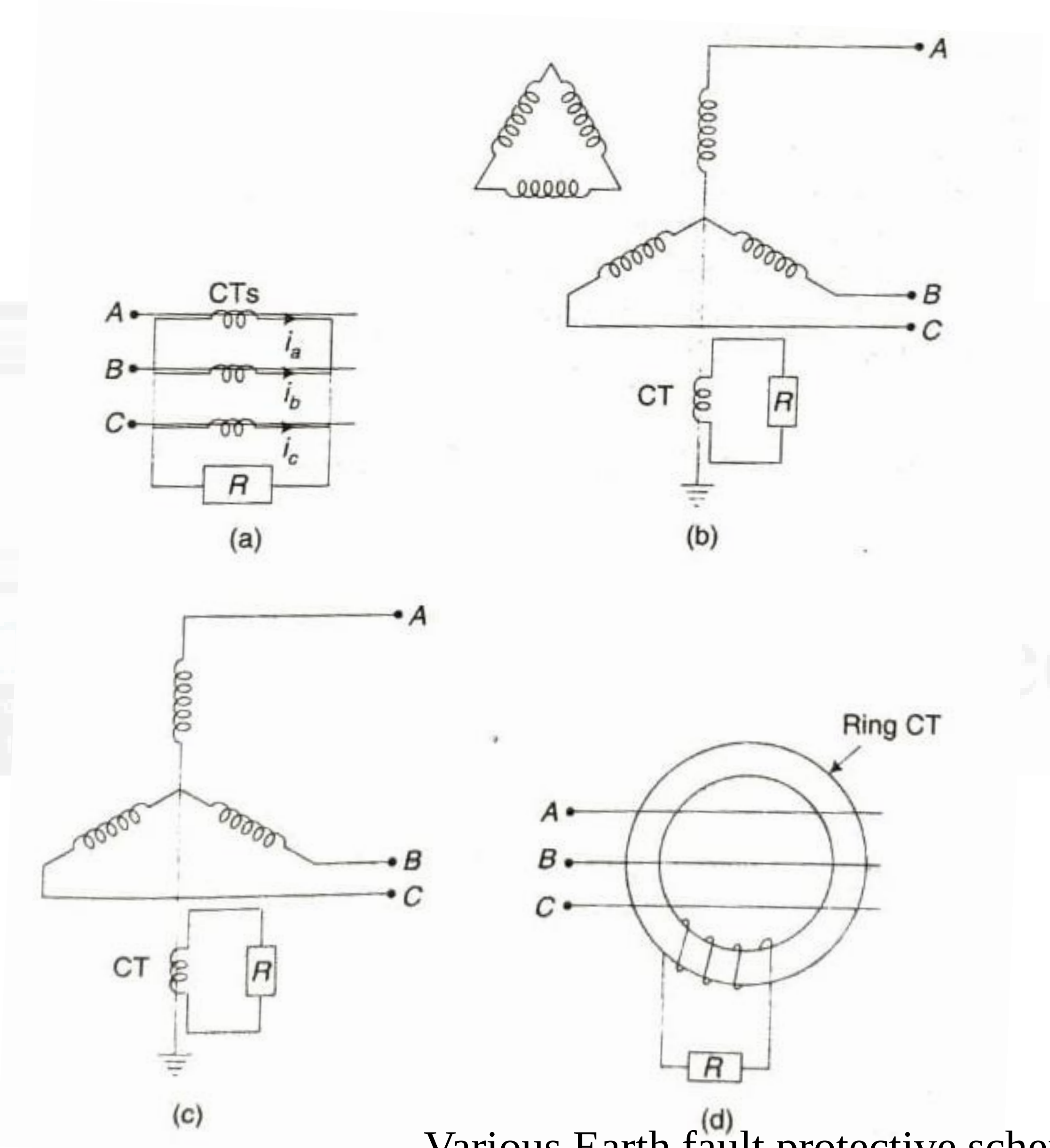
EARTH-FAULT PROTECTION
(Called Ground protection in USA)

Earth Fault

Earth Fault is an unintended fault between the live conductor and the earth. When earth fault occurs, the electrical system gets short-circuited and the short-circuited current flows through the system. The fault current returns through the earth or any electrical equipment, which damages the equipment. It also interrupts the continuity of the supply and may shock the user. To protect the equipment and for the safety of people, fault protection devices are used in the installation.

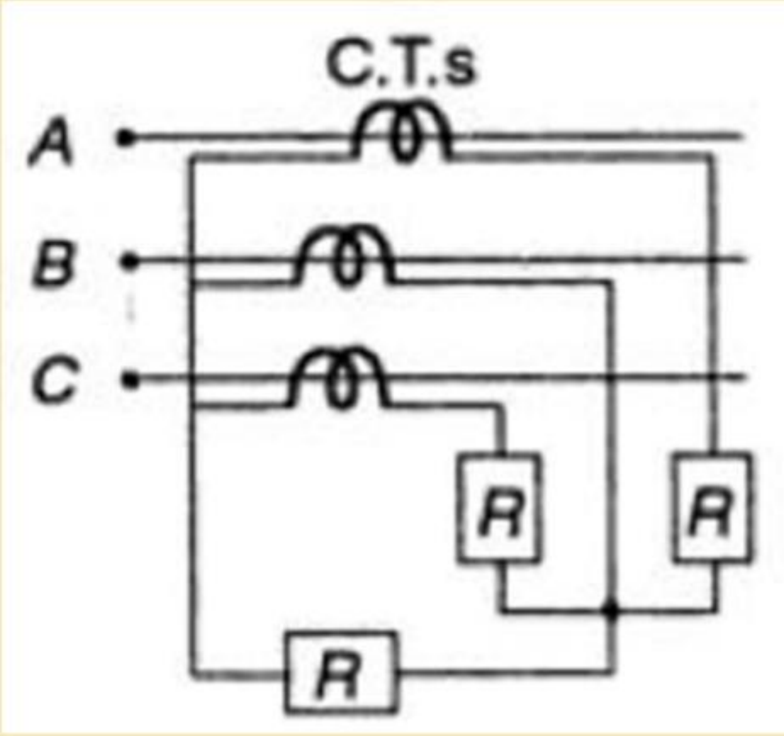
When the fault current flows through earth return path, the fault is called Earth Fault. Other faults which do not involve earth are called phase faults. Since earth faults are relatively frequent, earth fault protection is necessary in most cases. When separate earth fault protection is not economical, the phase relays sense the earth fault currents. However such protection lacks sensitivity. Hence separate earth fault protection is generally provided. Earth fault protection senses earth fault current: Following are the method of earth fault protection.

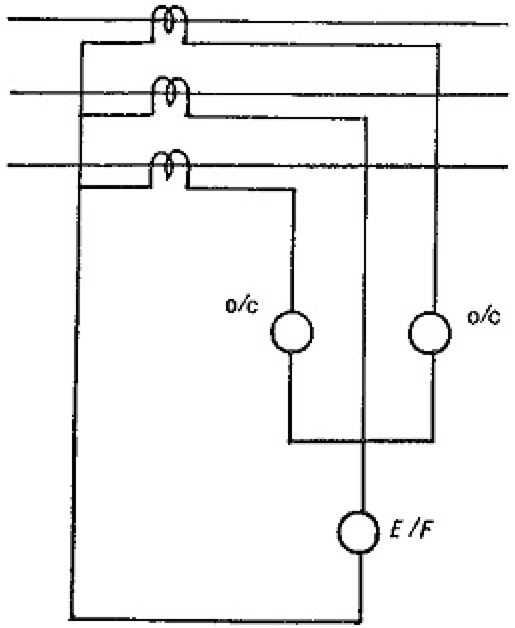
Earth Fault and Phase Fault Protection



Various Earth fault protective schemes

Combined Earth Fault and Phase Fault Protective Scheme

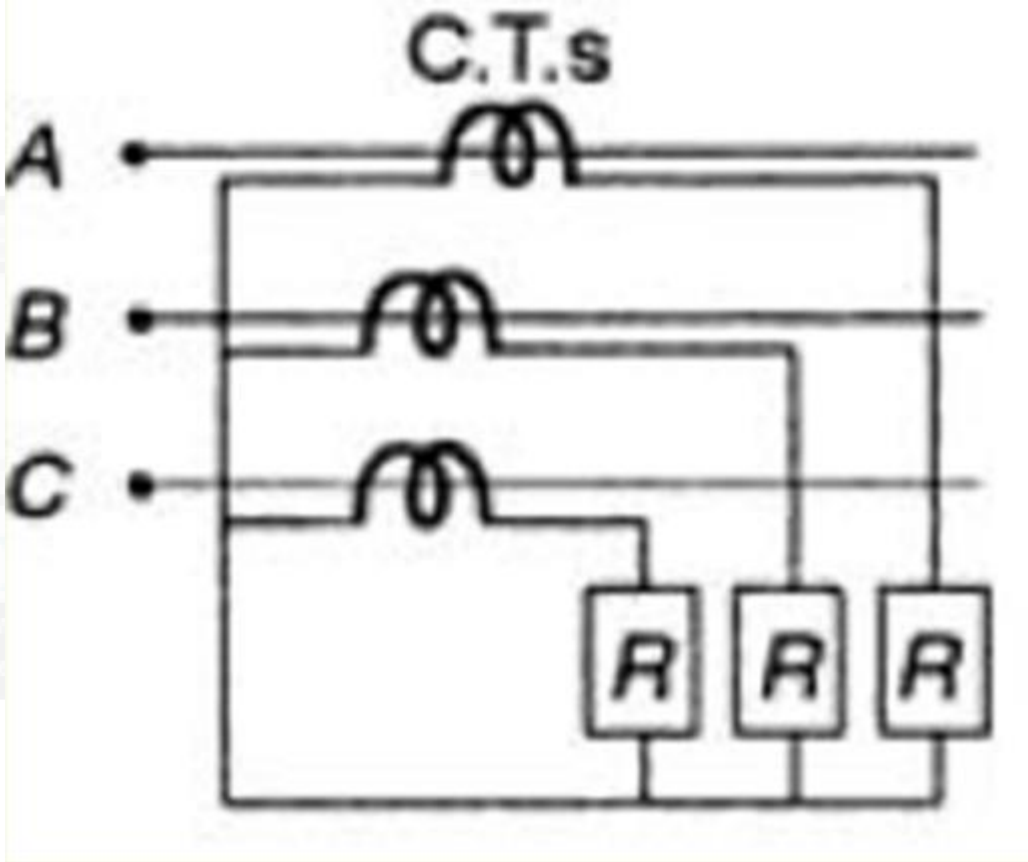




Two overcurrent relay and one earth fault relay

Residual current (protective relaying) The sum of the three phase currents on a three-phase circuit. The current that flows in the neutral return circuit of three wye-connected current transformers is residual current Residual

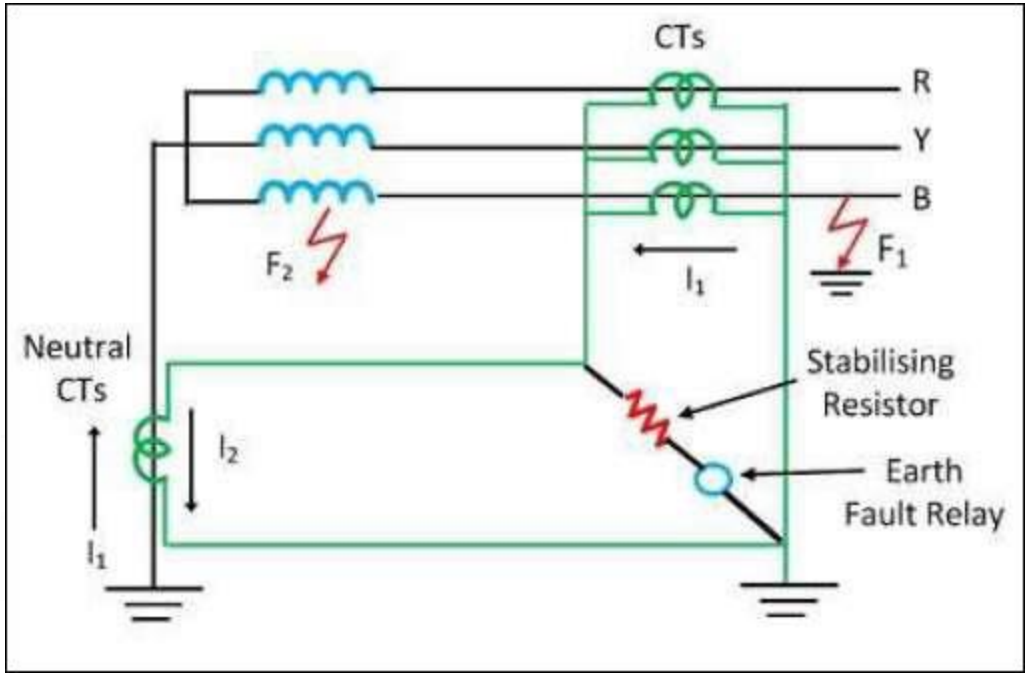
Phase Fault Protection



Three overcurrent relays

Restricted Earth Fault Protection Scheme

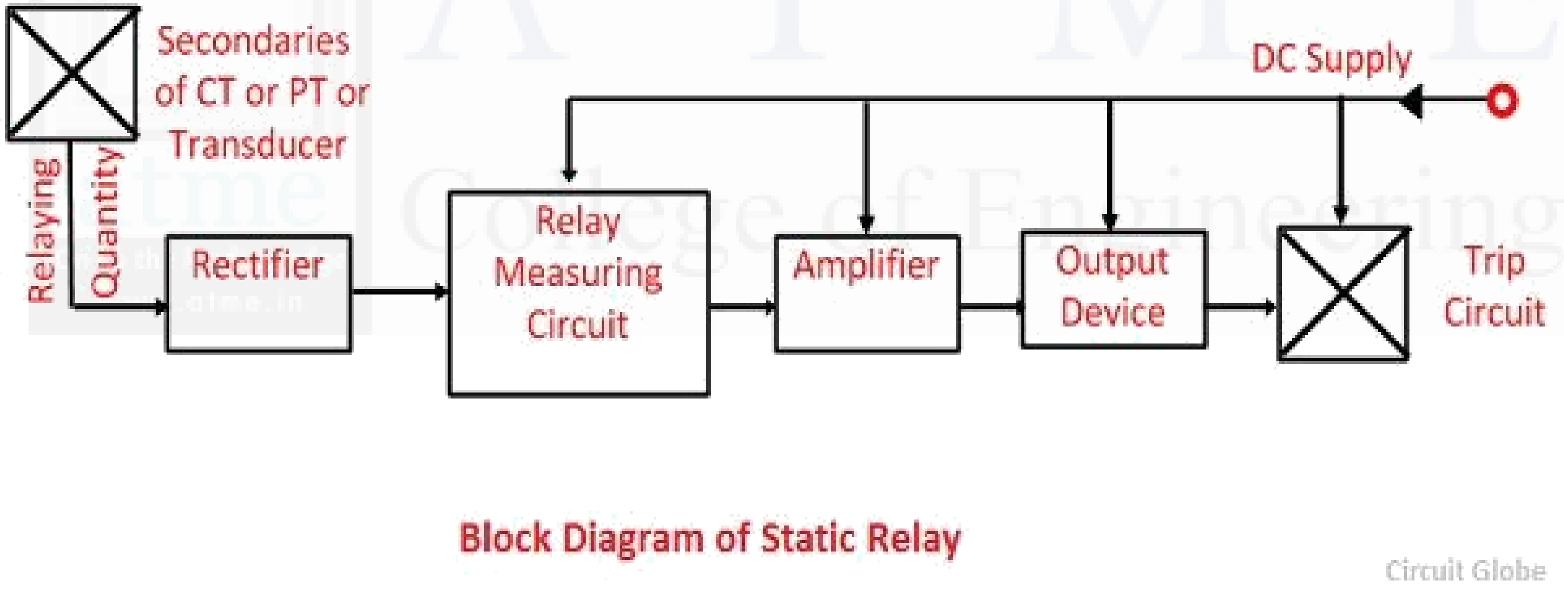
Let us consider a star winding transformer, which is protected by a **Restricted Earth Fault** (EFR) **Protection** with the Earth Fault Protection protecting device as shown in the figure below. The following image shows the Earth Fault Protection with EFR.



When an external fault F1 occurs in the network, I1 and I2 flow through the secondary side of the CTs. The resultant of I1 and I2 will be zero. However, if an internal fault F2 occurs inside the protective zone, only I2 flows and I1 is neglected. The resultant current I2 passes through the earth fault relay, which senses the fault current and protects the restricted portion of winding. The fault current is approximately 15% more than the rated winding current. To avoid the magnetizing inrush current, the stabilizing current must be in series with the relay.

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



Block Diagram of Static Relay

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Numerical Relays

- A numerical relay is that in which the measured ac quantities are sequentially sampled and converted into numerical (digital) data form. A microprocessor or a microcontroller processes the data numerically (i.e., performs mathematical and/or logical operations on the data) using an algorithm to calculate the fault discriminants and make trip decisions.
- The main features of numerical relays are their economy, compactness, flexibility reliability, self-monitoring and self-checking capability, multiple functions, low burden on instruments transformers and improved performance over conventional relays of electromechanical and static types.

Microprocessor-based over current relay

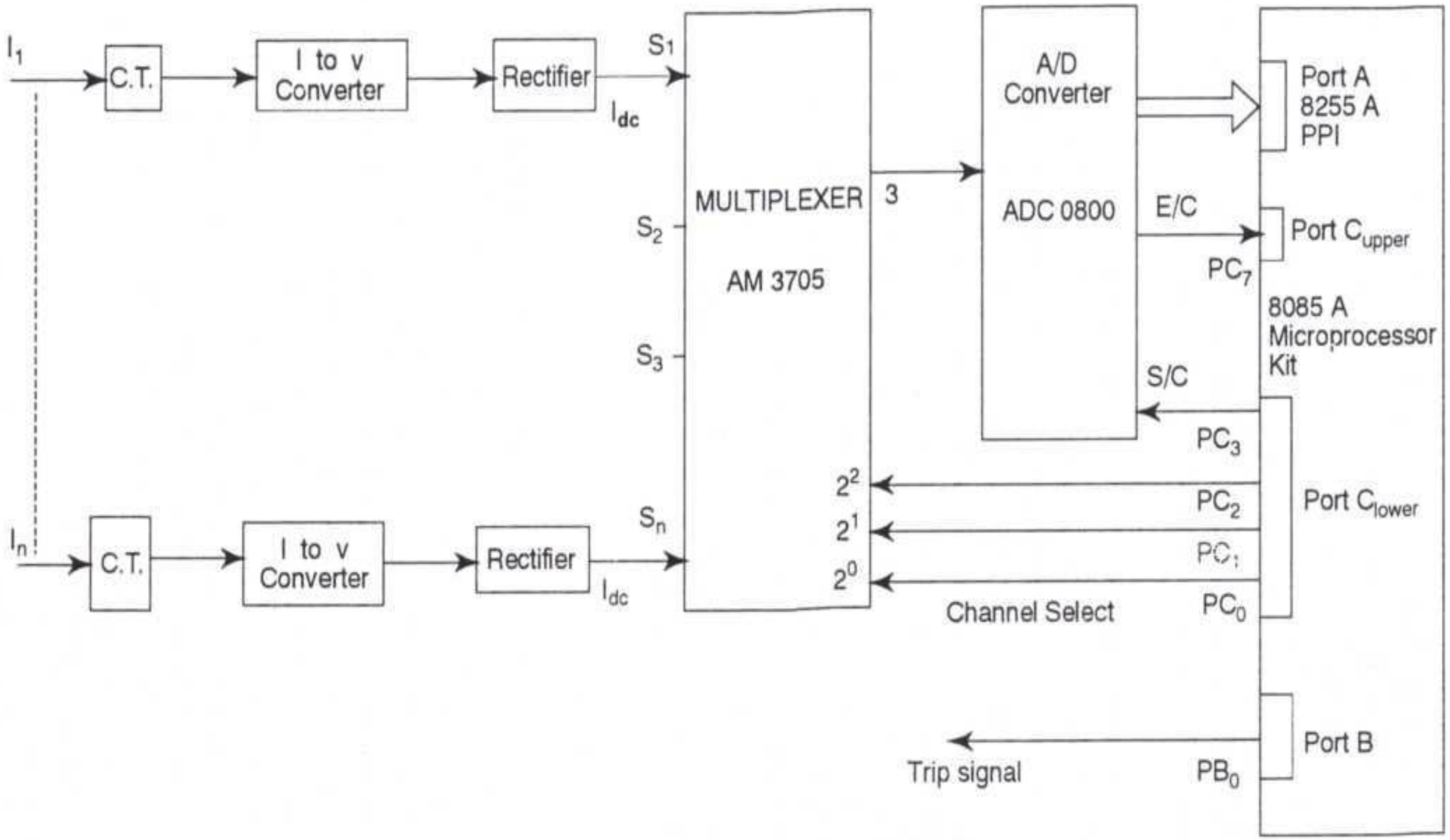
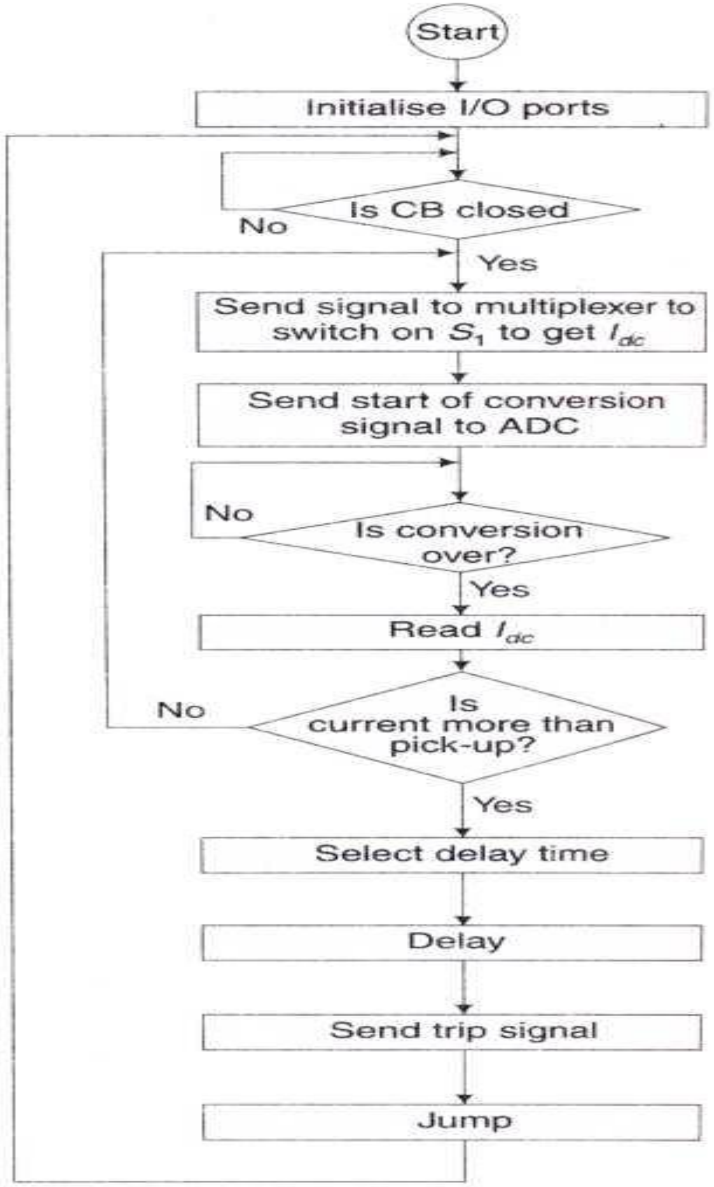


FIGURE (a) Block schematic diagram of overcurrent relay



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