

POWER SYSTEM PROTECTION

(R22A0214)

LECTURE NOTES B.TECH

(III YEAR–II SEM)

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By

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MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY**III Year B. TECH - II- SEM****L/T/P/C****3 /0 /0/3****(R22A0214)POWER SYSTEM PROTECTION****Pre-requisites:** Power Systems-I, Power Systems-II**Course Objectives:**

- To introduce all kinds of circuit breakers and relays for protection of Generators, Transformers and feeder bus bars from Over voltages and other hazards.
- To describe neutral grounding for overall protection.
- To understand the phenomenon of Over Voltages and its classification.

Course Outcomes:

At the end of the course the student will be able to:

- Compare and contrast electromagnetic, static and microprocessor-based relays
- Apply technology to protect power system components.
- Analyze quenching mechanisms used in air, oil and vacuum circuit breakers

UNTI-I:**Protective Relays:**

Introduction, Need for power system protection, effects of faults, evolution of protective relays, zones of protection, primary and backup protection, essential qualities of protection, classification of protective relays and schemes, current transformers, potential transformers, basic relay terminology.

Operating Principles and Relay Construction:

Electromagnetic relays, thermal relays, static relays, microprocessor based protective relays

UNTI-II:**Over-Current Protection:**

Time-current characteristics, current setting, over current protective schemes, directional relay, protection of parallel feeders, protection of ring mains, Phase fault and earth fault protection, Combined earth fault and phase fault protective scheme, Directional earth fault relay.

Distance Protection:

Impedance relay, reactance relay, MHO relay, input quantities for various types of distance relays, Effect of arc resistance, Effect of power swings, effect of line length and source impedance on the performance of distance relays, selection of distance relays, MHO relay with blinders, Reduction of measuring units, switched distance schemes, auto re-closing.

UNTI-III:**Pilot Relaying Schemes:**

Wire Pilot protection, Carrier current protection.

AC Machines and Bus Zone Protection:

Protection of Generators, Protection of transformers, Bus zone protection, frame leakage protection.

UNTI-IV:**Static Relays:**

Amplitude and Phase comparators, Duality between AC and PC, Static amplitude comparator, integrating and instantaneous comparators, static phase comparators, coincidence type of phase comparator, static over current relays, static directional relay, static differential relay, static distance

relays, Multi input comparators, concept of Quadrilateral and Elliptical relay characteristics.

Microprocessor Based Relays:

Advantages, over current relays, directional relays, distance relays.

UNTI-V:

Circuit Breakers:

Introduction, arcing in circuit breakers, arc interruption theories, re-striking and recovery voltage, resistance switching, current chopping, interruption of capacitive current, oil circuit breaker, air blast circuit breakers, SF6 circuit breaker, operating mechanism, selection of circuit breakers, high voltage DC breakers, ratings of circuit breakers, testing of circuit breakers.

Fuses:

Introduction, fuse characteristics, types of fuses, application of HRC fuses, discrimination.

TEXT BOOKS:

1. Badriram and D.N. Vishwakarma, Power System Protection and Switchgear, TMH 2001.
2. U. A. Bakshi, M. V. Bakshi: Switchgear and Protection, Technical Publications, 2009.

REFERENCE BOOKS:

1. C. Russel Mason – “The art and science of protective relaying, Wiley Eastern, 1995
2. L. P. Singh “Protective relaying from Electromechanical to Microprocessors”, New Age International

Chapter 1: INTRODUCTION

The purpose of an Electric Power System is to generate and supply electrical energy to consumers. The power system should be designed and managed to deliver this energy to the utilization points with both reliability and economically. The capital investment involved in power system for the generation, transmission and distribution is so great that the proper precautions must be taken to ensure that the equipment not only operates as nearly as possible to peak efficiency, but also must be protected from accidents. The normal path of the electric current is from the power source through copper (or aluminium) conductors in generators, transformers and transmission lines to the load and it is confined to this path by insulation. The insulation, however, may break down, either by the effect of temperature and age or by a physical accident, so that the current then follows an abnormal path generally known as Short Circuit or Fault. Any abnormal operating state of a power system is known as FAULT. Faults in general consist of short circuits as well as open circuits. Open circuit faults are less frequent than short circuit faults, and often they are transformed in to short circuits by subsequent events.

Switchgear and protection

Switchgear and protection are essential components of electrical power systems, ensuring the safe and reliable operation of electrical networks and equipment. Let's start with an introduction to both switchgear and protection:

Switchgear:

Switchgear refers to a combination of electrical disconnect switches, circuit breakers, fuses, and other protective devices used to control, protect, and isolate electrical equipment in a power system. Its primary functions include:

Switching Operations: Switchgear allows operators to control the flow of electrical power by enabling the opening and closing of electrical circuits. This is essential for normal system operation and maintenance.

Protection: Switchgear plays a crucial role in safeguarding electrical equipment and preventing damage due to overcurrents, short circuits, and other electrical faults. When a fault occurs, switchgear isolates the faulty section to prevent further damage.

Isolation: In case of maintenance, repair, or when electrical equipment needs to be disconnected from the power supply, switchgear provides a means to safely isolate the equipment, ensuring the safety of maintenance personnel.

Fault Clearing: Switchgear devices like circuit breakers and fuses are designed to interrupt the flow of current during faults, thus protecting the equipment and preventing electrical fires or explosions.

Switchgear can be classified into several types based on its application and voltage level:

Low Voltage (LV) Switchgear: Used in distribution networks with voltages typically up to 1 kV.

Medium Voltage (MV) Switchgear: Designed for voltages from 1 kV to 33 kV, typically used for regional distribution.

High Voltage (HV) Switchgear: Used in transmission networks for voltages exceeding 33 kV.

Protection:

Protection in the context of electrical power systems involves measures and equipment designed to detect and respond to abnormal operating conditions, faults, and disturbances. Its main objectives are:

1. Need for power system protection:

Power system protection is essential for maintaining the reliability, safety, and stability of electrical power systems. It involves a set of strategies, devices, and practices designed to detect and mitigate faults, abnormalities, and disturbances within a power system. Here's why power system protection is crucial:

Ensure personal safety: faults in power systems can lead to hazardous conditions, fires, explosions, and electric shocks. Protection schemes detect these faults quickly and isolate the faulty section to prevent accidents and protect personnel working on the system and the public.

Protect equipment: Electrical power systems consist of various components such as generators, transformers, circuit breakers, transmission lines, and distribution equipment. These components are costly and critical for the functioning of the system. Power system protection ensures that these components are safeguarded from various types of faults, such as short circuits, overloads, and insulation failures

Maintain system stability: Faults can lead to voltage instability, frequency deviations, and even cascading failures that affect larger portions of the power system. Protection mechanisms help prevent such instabilities by isolating faulty areas before they can spread and cause broader disruption.

System Reliability: Power outages can have severe economic and social consequences. Power system protection minimizes downtime by isolating faulty sections and allowing the rest of the system to continue operating. This enhances the overall reliability of the power supply.

Optimal System Performance: By preventing prolonged system disturbances and minimizing equipment damage, power system protection contributes to maintaining optimal system performance and reducing maintenance and repair costs.

Mitigation of Natural Disasters: Power system protection can also include measures to mitigate the impact of natural disasters like lightning strikes, storms, and earthquakes, which can disrupt the power infrastructure.

Integration of Renewable Energy: Modern power systems are incorporating a significant amount of renewable energy sources, which can have variable and intermittent outputs. Proper protection mechanisms ensure the smooth integration of these sources while maintaining system stability and reliability.

Remote Monitoring and Control: Power system protection often involves sophisticated technologies that allow for remote monitoring, control, and diagnostics. This enables faster response times and the ability to assess the health of the system components.

2. Effects of faults:

In the context of electrical engineering and power systems, a "fault" refers to an abnormal condition or malfunction in an electrical circuit or system. Faults can take various forms and can occur for a wide range of reasons. When a fault occurs, it typically involves a deviation from the normal operation of the electrical system, potentially leading to electrical disturbances, equipment damage, safety hazards, or service interruptions.

Common types of electrical faults include:

Short Circuit Fault: A short circuit occurs when there is an unintended and direct electrical connection between two or more conductors with different voltages or phases. This results in a sudden surge of current, potentially causing damage to equipment and posing safety risks.

Symmetrical and unsymmetrical (or symmetrical and asymmetrical) faults refer to different types of electrical faults in a three-phase power system. These terms describe whether the fault conditions affect all three phases of the system equally (symmetrical) or result in imbalances between the phases (unsymmetrical or asymmetrical). Here's a more detailed explanation of these two types of faults:

Open circuit faults:

An "open circuit fault" refers to a type of electrical fault that occurs when a part of an electrical circuit becomes interrupted, resulting in a loss of electrical continuity. There are two types of open circuit faults: single conductor open and double conductor open. . In an open circuit fault, the electrical path is broken or disconnected, preventing the flow of current through that part of the circuit. This can lead to various consequences depending on the location and significance of the open circuit.

Effects of faults :

Voltage and Frequency Instability: Faults can cause sudden drops in voltage levels and frequency deviations. These disturbances can affect the stability of the power system and disrupt the operation of sensitive equipment.

Power Interruptions: Faults often result in the interruption of electrical power to consumers. This can lead to downtime, inconvenience, and financial losses for businesses and individuals

Equipment Damage: Electrical faults can cause damage to power system equipment, including transformers, circuit breakers, and other components. The severity of the damage depends on the fault type and how quickly it is cleared.

Fire Hazards: Electrical faults, particularly those involving short circuits, can generate high temperatures and sparks. In some cases, this can lead to electrical fires, which can cause extensive damage and pose a safety risk.

Voltage Sag and Swell: Depending on the nature of the fault, voltage levels can temporarily drop (voltage sag) or rise (voltage swell) in parts of the power system. These voltage variations can affect the operation of sensitive equipment and may require voltage regulation measures.

Transient Overvoltages: Faults can result in transient overvoltages, also known as voltage transients or surges. These high-voltage spikes can damage equipment and lead to insulation breakdowns.

Cascading failure: If not properly managed, this process can continue to cascade through the power system, with each new fault or protective device operation triggering further disturbances. This can lead to a domino effect, causing more and more sections of the grid to go offline.

Electromagnetic Interference (EMI): Faults can generate electromagnetic interference, which can affect nearby electronic devices and communication systems. EMI can disrupt data transmission, radio signals, and other sensitive equipment.

System Reconfiguration: In some cases, power system operators may need to reconfigure the network to restore power after a fault. This involves switching to alternate paths and reestablishing connections to minimize the impact of the fault.

System Restoration: After clearing a fault, power system operators must safely restore power to affected areas. This process involves coordination and may require manual intervention.

Safety Concerns: Faults can create safety hazards for workers and the public. Electrical faults can generate sparks, arcs, and other dangerous conditions that require proper safety precautions.

Data Analysis and Investigation: Power system operators and engineers often conduct post-fault analysis and investigations to determine the cause of the fault, assess the extent of damage, and implement preventive measures.

To mitigate the effects of faults in power systems, utilities and operators implement various protective measures, including circuit breakers, fuses, relays, and automated fault detection and isolation systems. These measures help reduce downtime, protect equipment, and ensure the safe and reliable operation of electrical power systems.

3. Zones of protection

"Zones of protection" in the context of power systems refer to predefined areas or sections within an electrical network that are covered by specific protective devices and relays. These zones are strategically designed to ensure the reliable and safe operation of the power system by

promptly detecting and isolating faults or abnormal conditions. Here's a more detailed explanation of zones of protection:

Purpose: The primary purpose of establishing zones of protection is to minimize the spreading of faults and disturbances within the electrical grid. When a fault occurs, such as a short circuit or an equipment failure, the goal is to isolate the affected area while keeping the rest of the power system operational. This helps prevent widespread blackouts and ensures that power is available to as many customers as possible.

Protective Devices: Zones of protection are defined by the placement of protective devices, such as circuit breakers, relays, and fuses, throughout the power system. Each protective device is responsible for monitoring the electrical parameters (e.g., current, voltage, frequency) within its designated zone.

Coordination: Coordination between protective devices is crucial in zones of protection. The settings and response times of these devices are carefully coordinated to ensure that the device closest to the fault operates first. This coordination prevents unnecessary disconnections and ensures that only the faulty section is isolated.

Types of Zones: Zones of protection can be categorized into various types based on the area they cover and the equipment they protect. Some common types of zones of protection include:

- 1. Primary/main/unit Protection Zone:** This is the innermost zone and typically covers the immediate vicinity of equipment, such as transformers, generators, and circuit breakers. It responds to faults that occur very close to the protected equipment.
- 2. Backup/secondary/nonunit Protection Zone:** Located outside the primary protection zone, this zone provides a secondary layer of protection. It acts as a backup in case the primary protection devices fail to clear the fault.

Reliability and Selectivity: Zones of protection are designed for reliability and selectivity. Reliability ensures that protective devices operate when needed, and selectivity ensures that only the minimum necessary portion of the system is disconnected during a fault.

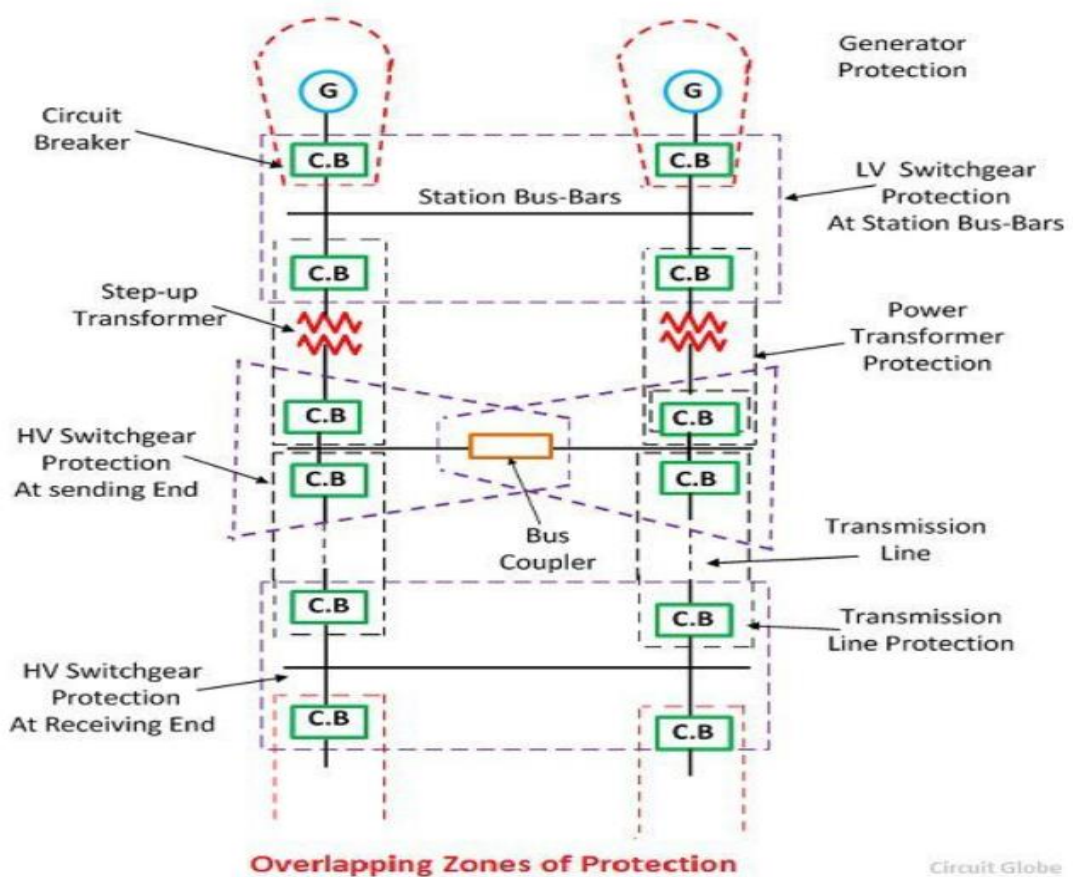
Automation: In modern power systems, zones of protection often incorporate automation and advanced technologies, such as digital relays and communication systems. These technologies enable faster fault detection, better coordination, and remote monitoring and control of protective devices.

Testing and Maintenance: Regular testing and maintenance of protective devices within each zone are essential to ensure their proper functioning. This helps identify and address issues before they become critical.

In summary, zones of protection are a fundamental concept in power system engineering and operation. They are designed to safeguard the electrical grid by isolating faults while maintaining power supply to unaffected areas. The careful coordination and placement of protective devices within these zones are crucial for the reliable and safe operation of power systems.

The protection zone cover the entire power system, and no part of the equipment is left unprotected. It usually consists one or more element of the power system. The protection zone of the power system mainly depends upon the rating of the machine, its location, the probability of faults and abnormal condition of the equipment.

Overlapping Zone of Power System

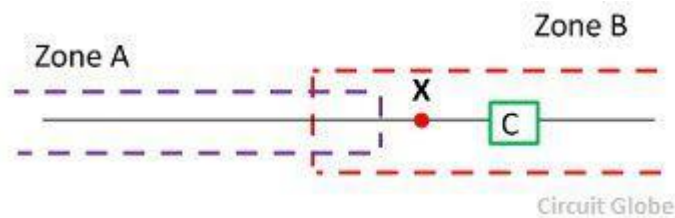


If there were no overlapping in the protective zone, then the failure occurs in the equipment will not lie in any one of the zones and hence no circuit breaker would be tripped. The fault

occurs in the unprotective system will damage the equipment and hence disturb the continuity of the supply. The figure below shows a certain amount of overlapping between the protective zones.

The probability of failure in the overlap region is very small. Because when the fault occurs in any one of the two overlapping regions than the breaker of both the region will be opened, and the systems are isolated.

Consider the two protective zone A and B which will overlap each other. The X is the fault occurs in the zone B, and due to this fault, the circuit breakers of zone B tripped along with the C (circuit breaker). The relay of the zone B will also trip the circuit breaker of zone A for other faults in the zone B which occurs to the right of the C (circuit breaker). Hence the unnecessary tripping of the breaker can be tolerated only in the particular region.



The scheme which senses the fault of any of the certain unit will have a high degree of sensitivity and it also has the adaptability of the fast speed of operation.

4. Primary and Backup protection:

Primary protection :

Primary protection relays are critical components in power systems, designed to quickly and directly respond to faults within their designated zones to prevent damage to equipment and ensure the safety and reliability of the system. Here are some examples of primary protection relays:

Differential Protection Relay: This relay is commonly used to protect transformers, motors, and generators. It compares the current entering and leaving the protected equipment. If there's a mismatch, indicating a fault within the zone, the relay operates to trip the circuit and isolate the fault.

Overcurrent Protection Relay: Overcurrent relays are widely used in power systems to protect against overloads and short circuits. They operate when the current exceeds a preset

threshold, signaling a fault. These relays are employed for feeder and motor protection, among other applications.

Distance Protection Relay: Distance relays are used for transmission line protection. They measure the impedance or reactance of the line and operate if a fault occurs within a predefined distance. Distance protection is effective for detecting faults on long transmission lines.

Generator Differential Protection Relay: This relay safeguards generators by comparing the currents entering and leaving the generator stator winding. Any imbalance indicating a fault within the generator triggers the relay to disconnect the generator from the system.

Transformer Differential Protection Relay: Transformer differential protection relays protect transformers by monitoring the current imbalance between the primary and secondary windings. They are crucial for detecting internal faults in transformers.

Busbar Protection Relay: Busbar protection relays monitor the health of electrical busbars in substations. They detect faults such as short circuits and phase-to-phase faults on the busbars.

Feeder Differential Protection Relay: Used for distribution feeders, these relays compare the current entering and leaving the feeder. If there's a mismatch, the relay operates to isolate the faulted section of the feeder.

Motor Differential Protection Relay: Motor protection relays detect faults within motors by comparing the current entering and leaving the motor windings. They protect motors from issues like phase imbalance and locked rotor conditions.

Generator Loss of Excitation (LOE) Relay: LOE relays monitor the excitation level of generators. If the generator loses excitation, which can lead to instability, the relay operates to trip the generator.

Directional Overcurrent Protection Relay: These relays not only detect overcurrent conditions but also determine the direction of fault current flow. This is particularly useful for protecting transmission lines, ensuring that faults are cleared in the right direction.

These are just a few examples of primary protection relays, and many more specialized relays exist to address specific protection needs in power systems. Each relay plays a critical role in safeguarding electrical equipment and maintaining system reliability.

Backup protection:

Backup protection relays provide secondary protection in case primary protection relays fail to operate or if there's a delay in their operation. They help ensure the reliability and safety of power systems. Here are some examples of backup protection relays

Backup Overcurrent Protection Relay: If the primary overcurrent relay fails to operate or if its settings are inadequate, a backup overcurrent relay can provide an additional layer of protection. It operates based on current levels and trip times.

Backup Distance Protection Relay: Similar to backup overcurrent protection, a backup distance relay ensures that faults on transmission lines are cleared if the primary distance relay fails to operate or if there's a fault outside the zone of protection.

5. Essential qualities of protection /characterstics or properties of relays :

The essential qualities of protection systems, particularly in the context of electrical power systems, include:

Reliability: Protection systems must be highly reliable to promptly detect and respond to faults or abnormalities in the power system. Reliability ensures the safety of both the equipment and personnel.

Selectivity: Protection devices should accurately discriminate between different types of faults and isolate only the affected portion of the power system while keeping the rest operational. This minimizes disruptions and maintains service continuity.

Speed: Fast detection and response are critical to prevent equipment damage, minimize downtime, and maintain the stability of the power system. Protection systems must operate within milliseconds or even microseconds.

Sensitivity: Protection systems must be sensitive enough to detect even minor deviations from normal operating conditions. This ensures that incipient faults are detected before they escalate into major issues.

The power consumed by the relay coil must be minimum. lower the power consumption higher sensitivity and lower burden to the current transformer.

Security: Protection systems should be resistant to tampering or external interference. They should be able to operate reliably under various environmental conditions, including extreme weather or electromagnetic interference.

Coordination: Protection devices should be coordinated to operate in a sequential and coordinated manner. This ensures that the closest device to the fault operates first, preventing unnecessary tripping of healthy parts of the system.

Economy: The cost of protective equipment should not exceed 5% of the cost of the equipment it is designed to safeguard.

Adequateness : The space occupied by relay is to minimum and simple in operation.

Stable : relay should operate as many times until the fault is present.

Adaptability: Protection systems should be adaptable to changing system conditions, such as load variations or network reconfigurations. They should also accommodate different fault types and fault locations.

Remote Monitoring and Control: Modern protection systems often include remote monitoring and control capabilities, allowing operators to assess and control the system's status from a central location.

Scalability: Protection systems should be scalable to accommodate expansions or modifications in the power system. They should also be able to integrate with new technologies and equipment.

These qualities collectively ensure that protection systems effectively safeguard power systems, preventing faults and disturbances from causing damage, outages, or safety hazards.

6. classification of protective relays and schemes:

Protective relays and schemes are essential components of electrical power systems, designed to detect and respond to abnormal conditions to protect equipment and ensure system reliability. Here's a classification of protective relays and some common relay schemes:

1. Based on Operating Principles:

- **Electromagnetic Relays:** under this electromagnetic attraction and Induction are two types. Operate based on electromagnetic induction principles and are commonly used for overcurrent, under-voltage, and distance protection.
- **Static Relays:** Use solid-state components like transistors and diodes for operation, offering greater flexibility and accuracy.

- **Digital or Microprocessor Relays:** Utilize microprocessors to process and analyze electrical parameters, providing advanced protection and communication capabilities
- **Thermal :** It operates based on the principle of heating caused by current flow.

2. Based on Equipment Protected/ Based on Application:

- **Motor Protection Relays:** Specifically designed to protect motors from conditions like overloading, phase imbalance, and short circuits.
- **Transformer Protection Relays:** Safeguard transformers against faults, including overcurrent, over-voltage, and over-temperature conditions.
- **Generator Protection Relays:** Protect generators from issues like over-excitation, loss of synchronization, and stator winding faults.
- **Transmission line protection relays**
- **Busbar protection relays**

Based on Function:

Primary Protection Relays: These relays are the first line of defense and are installed to protect specific equipment or sections of the power system. They respond to faults within their designated zone.

Backup or Secondary Protection Relays: These relays provide backup protection and operate when the primary protection relays fail or take too long to respond.

Time of operation

- IDMT (inverse definite minimum time)
- Extreme Inverse
- Instantaneous

Common Relay Schemes:

Differential Protection: This scheme compares the current entering and leaving a protected zone. If there's a mismatch, it indicates a fault within the zone, triggering a trip signal.

Overcurrent Protection: Overcurrent relays monitor the magnitude and duration of current. They operate if the current exceeds the preset value, indicating a fault.

Distance Protection: Distance relays use impedance measurements to determine the location of a fault. If a fault is within a predefined distance, the relay operates.

Generator Protection: This scheme includes various relays to protect generators from issues like over-excitation, loss of synchronization, and unbalanced currents.

Transformer Protection: Transformer protection schemes include relays to protect against overcurrent, overvoltage, and temperature rise.

Busbar Protection: Busbar protection schemes monitor the health of the busbar and its connections, ensuring system stability.

Feeder Protection: Feeder relays protect distribution feeders from faults such as short circuits and overloads.

Motor Protection: Motor protection schemes include relays to detect issues like phase imbalance, overcurrent, and locked rotor conditions.

Line Protection: Line protection schemes protect transmission and distribution lines from faults, including short circuits and overloads.

7. Basic relay terminology:

- **Relay:** An electrical or electronic device that uses an electromagnetic coil to control one or more switch contacts. Relays are used to control high-power circuits with a low-power signal.
- **Coil:** The wire-wound component of a relay that generates an electromagnetic field when current flows through it. The coil's magnetic field is used to actuate the relay's switch contacts.
- **Contact:** The movable part of a relay that makes or breaks an electrical connection. Contacts can be normally open (NO), normally closed (NC), or changeover (CO), which means they can switch between NO and NC states.
- **Normally Open (NO):** A contact that is open (non-conductive) when the relay coil is not energized but closes (becomes conductive) when the coil is energized.
- **Normally Closed (NC):** A contact that is closed (conductive) when the relay coil is not energized but opens (becomes non-conductive) when the coil is energized.
- **Common (C):** The common terminal of a changeover (CO) contact. It is the terminal that is connected to either the NO or NC terminal, depending on the state of the relay.
- **Relay Time :** It is the time between the instant of fault occurrence and the instant of closure of relay contacts.

- **Breaker Time** : It is the time between the instant at circuit breaker operates and opens the contacts, to the instant of extinguishing the arc completely.
- **Fault Clearing Time** : The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is fault clearing time. It is sum of the relay time and circuit breaker time.
- **Pickup** : A relay is said to be picked up when it moves from the 'OFF' position to 'ON' position. Thus when relay operates it is said that relay has picked up.
- **Pickup Value** : It is the minimum value of an actuating quantity at which relay starts operating. In most of the relays actuating quantity is current in the relay coil and pickup value of current is indicated along with the relay.
- **Dropout or Reset** : A relay is said to be dropout or reset when it comes back to original position i.e. when relay contacts open from its closed position. The value of an actuating quantity current or voltage below which the relay resets is called reset value of that relay.
- **Time Delay** : The time taken by relay to operate after it has sensed the fault is called time delay of relay. Some relays are instantaneous while in some relays intentionally a time delay is provided.
- **Sealing Relays or Holding Relays** : The relay contacts are designed for light weight and hence they are therefore very delicate. When the protective relay closes its contacts, it is relieved from other duties such as time lag, tripping etc. These duties are performed by auxiliary relays which are also called setting relays or holding relays.
- **Current setting** : the pickup value of current can be adjusted to the required level in the relays which is called current setting of the relay. it is achieved by use of trippings on the relay coil, which are brought out to plug bridge as shown in below figure. The tap values are expressed in terms of percentage full load rating of current transformer (C.T) with which relay is associated.

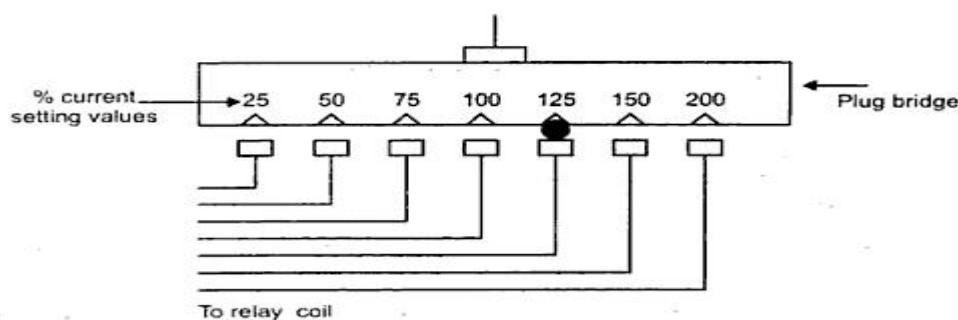


Figure : Tapping of current setting

Thus the value of pick current can be obtained as,

Pickup current = % current setting x rated secondary current of C.T

So if C.T is 500/10A i.e . 150% of 10. So when relay coil current is greater than or equal to pickup values,relay operates.

Plug Setting Multiplier (P.S.M) : The ratio of actual fault current in the relay coil to the pickup current is called plug setting multiplier (P.S.M). mathematically expressed as ,

P.S.M = fault current in the relay coil/pickup value

= fault current in the relay coil / (% current setting x rated secondary current of C.T)

Time/PSM curve : for a relay ,a curve showing relation between time and plug setting multiplier is provided which is called time/PSM curve. A typical curve for a relay is shown in the below figure.

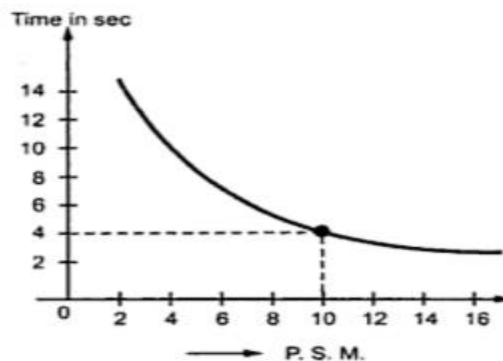


Figure2 : Time/P.S.M curve

It can be observed that for low values of overcurrents the operating time varies inversely with the current. But as the current increases and approaches upto 20 times its rated value then then the tome becomes almost constant. This type of characteristics is necessary to ensure discrimination on very high fault currents flowing through healthy part of the system. Using this curve and time-setting multiplier, the actual time of operation of a relay can be obtained. For example, the time in seconds corresponding to P.S.M. of 10 is 4 seconds as shown in the above Fig. . Multiplying this by a time-setting multiplier, actual time of operation can be obtained.

Time-setting Multiplier : Similar to current setting, a relay is provided with a feature with which its time of operation can be controlled. This feature is known as time-setting multiplier. Its dial is calibrated from 0 to 1 in steps of 0.05 as shown in the below Fig.

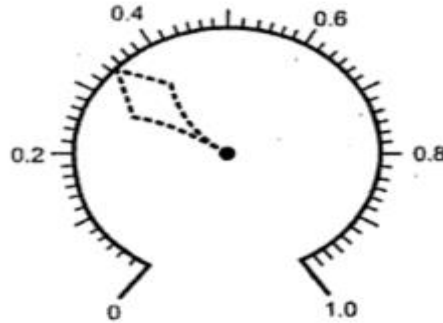


Fig. Time-setting multiplier

The value of time-setting multiplier along with the time obtained from time/P.S.M. curve decides the actual time of operation of the relay. For example if time-setting multiplier is selected as 0.2 while time corresponding to P.S.M. of 10 is 4 seconds then,

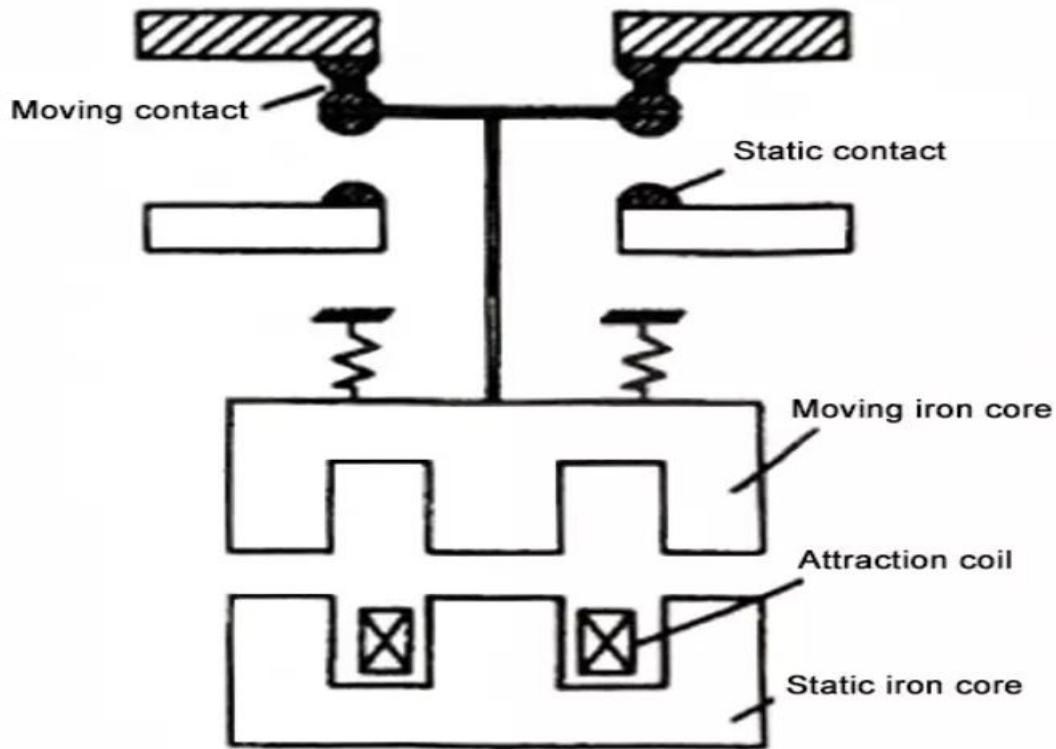
Actual time of operation = time in seconds x time-setting multiplier

$$=4 \times 0.2 = 0.8 \text{ seconds.}$$

Reach : the limiting distance in which protective system in which protective system responds to the faults is called reach of the protective system. The operation beyond the set distance is called **over-reach** while failure of distance relay within set distance is called **under-reach**.

8. Operating principles of contactors:

The working principle structure of the AC contactor is shown in the figure below. When the coil is energized, the iron core is magnetized, attracting the armature to move downward, making the normally closed contact open and the normally open contact closed. When the coil is de-energized, the magnetic force disappears. Under the action of the reaction spring, the armature returns to the original position and the contact returns to the original state.



The AC contactor is an electromagnetic AC contactor with a NO main contact, three poles, and air as the arc extinguishing medium. Its components include: coil, short-circuit ring, static iron core, moving iron core, moving contact, static contact, auxiliary NO contact, auxiliary NC contact, pressure spring sheet, reaction spring, buffer spring, arc extinguishing. The cover is composed of original parts.

Electromagnetic system: It includes coil, static iron core and moving iron core (also called armature).

Contact system: It includes main contacts and auxiliary contacts. The main contact allows a larger current to pass through and plays the role of connecting and cutting off the main circuit. Usually, the maximum current allowed by the main contact (ie, the rated current) is one of the technical parameters of the contactor. Auxiliary contacts are only allowed to pass small currents, and are generally connected to the control circuit when used.

The main contacts of AC contactors are generally NO contacts, and the auxiliary contacts are either NO or NC. A contactor with a smaller rated current has four auxiliary contacts; a contactor with a larger rated current has six auxiliary contacts.

The function of the arc **extinguishing device** is to quickly cut off the arc when the main contact is broken. If it is not cut off quickly, the main contact singeing and welding will occur. Therefore, AC contactors generally have arc extinguishing devices. For AC contactors with larger capacity, arc extinguishing grids are often used.

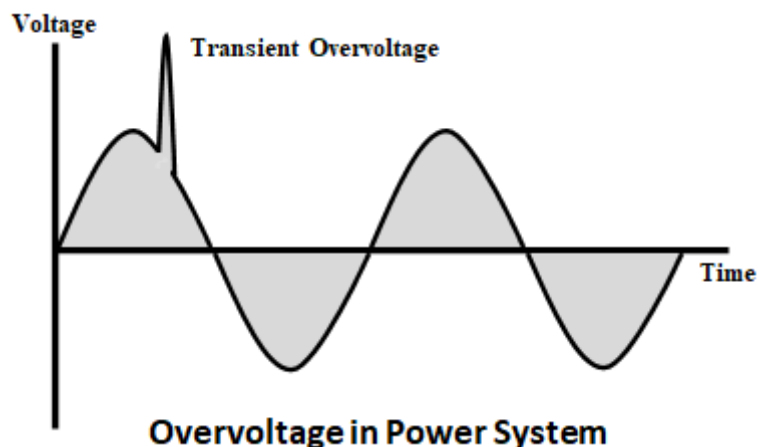
NO and NC refer to the state of the contacts before the electromagnetic system is energized. That is, the NO contact means that when the coil is not energized, its moving and static contacts are in an open state, and the coil is closed after it is energized. NC contact means that when the coil is not energized, its moving and static contacts are closed, and when the coil is energized, it is disconnected.

9. Overview on Generation of Over Voltages in Power Systems

The overvoltage or transients or surge voltages are the voltages whose values are much more than the normal voltages. These are of short duration which can cause malfunction or failure of equipment in the system depending upon the severity of the voltage level.

The overvoltage with a level above twice the standard peak voltage of the system will cause degradation of electronic components and insulation in the equipment of the system. The main causes of overvoltages in power systems are classified as,

- Internal causes, and
- External causes.



Overvoltage due to Internal Causes :

These causes are due to some abnormal conditions generated in the circuit itself. These abnormal conditions not only change the system's parameters but also damage the circuit under severe conditions. Internal causes of overvoltages are mainly due to,

- Switching surges,
- Insulation failure,
- Arcing ground, and
- Resonance

Switching Surges :

- Switching surges are the overvoltages produced on a power system due to switching operations. The study of switching surges is important for designing the insulation of winding and for insulation coordination of EHV lines. Some of the causes for the production of switching surges are listed below,
- Switching of an Unloaded Line or Open Line - Switching surges due to switching of an unloaded line arise due to the traveling wave phenomenon being originated and due to the sudden application of a voltage in the line as soon as the circuit breaker at the sending end is closed. Successive reflection of the voltage wave causes overvoltages in the line.
- Switching of a Loaded Line - Surges are also produced during the switching operation of a loaded line. Let us consider a loaded line that is suddenly interrupted which results in a voltage setup of $2Z_n i$ across the switch. Where i is the initial value of current at the time of opening of the line and Z_n is the natural impedance of the line. If V_p is the phase voltage and V_s is the voltage across the switch, then the maximum value of voltage to which a line may be subjected is,
- $V_m = V_p + V_s$ kV
- Reactor Switching - Reactor switching may cause current chopping. Current chopping is the phenomenon of current interruption before the natural current zero is reached. Current chopping results in the production of high voltages due to the transfer of energy in inductance ($1/2 LI^2$) to capacitance ($1/2 CV^2$) across the contacts of the circuit breaker. Overvoltages due to current chopping can be reduced by resistance switching.
- Short-circuits and Line-faults Interruption - In a circuit breaker, after clearing faults a transient restriking voltage appears which may cause overvoltages.

- Auto-reclosing of Circuit-breaker in Long EHV Lines - High-speed three-phase auto-reclosure generates surges in long lines due to closure on the trapped charge of the line. The surge voltages are influenced by the non-simultaneous reclosure of all the three-phase poles.
- Opening of Only One Phase due to Occurrence of Fault Cable Charging Circuit Switching OFF - In a 3-phase system, when a fault occurs on any one phase, then the phase voltage of the remaining two phases will increase beyond its normal value until the fault is cleared. This rise in voltage across the healthy phases appears as a surge.

Insulation Failure :

The overvoltages are also caused due to the insulation failure between line and ground or the grounding of the conductor in a power system.

Arcing Ground :

Arcing ground is commonly caused in long transmission line operations on high voltages due to oscillation. The high voltage surges produced due to the arcing ground can damage the power system apparatus severely. The voltage produced due to arcing grounds is nearly 3 to 4 times the power frequency voltage. Arcing grounds can be avoided by earthing the neutral.

Resonance :

In an electrical system when inductive reactance of the circuit becomes equal to capacitive reactance, resonance takes place. High voltage surges are produced in the power system due to resonance in transmission lines. Resonance rarely occurs as the capacitance is very small. In the case of cables, resonance may occur due to the 5th harmonic component.

Overvoltage due to External Causes :

- External causes of overvoltages in a power system are mainly due to lightning. The other factors which cause overvoltages are as follows,
- Indirect lightning strokes such as lightning discharge taking place near the line result in electromagnetically induced overvoltages.
- Different atmospheric conditions along the line length will cause overvoltages.
- Overvoltages are produced due to friction between the atmospheric particles such as dust, dry snow, etc.
- Overvoltages are produced due to lightning between the two nearby clouds.

in general, the majority of faults in the power system are transient in nature and caused due to switching operations or lightning surges. However, the surges cause due to lightning strokes have a very high voltage of million volts, which can cause the insulation breakdown and further damage the components of the power system.

Switching surges do not affect systems where operating voltages are below 230kV. However, switching surges cause damage to power systems where the operating voltage is above 230kV and it is worse for operating voltages above 700kV. Hence protection system should be employed.

10. Protection against Lightning Over Voltages :

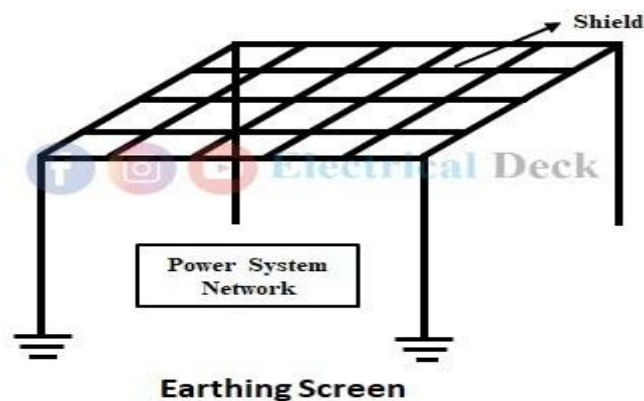
These are mainly three main methods generally used for protection against lightning. They are

- Earthing screen.
- Overhead earth wire.
- Lightning arrester or surge dividers.

Earthing Screen

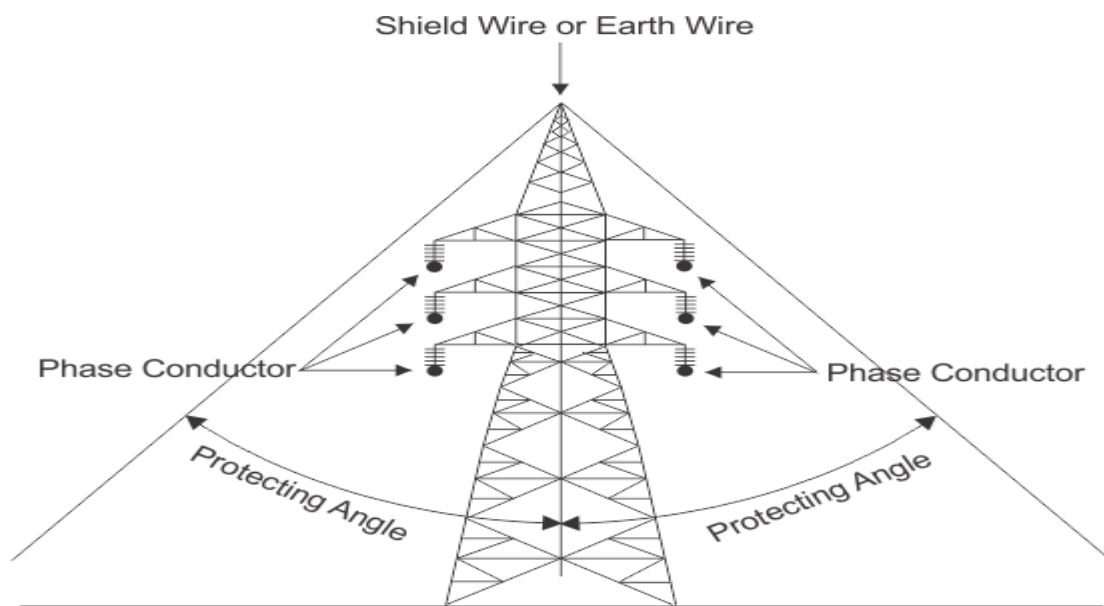
Earthing screen is generally used over electrical substation. In this arrangement a net of GI wire is mounted over the sub-station. The GI wires, used for earthing screen are properly grounded through different sub-station structures. This network of grounded GI wire over electrical sub-station, provides very low resistance path to the ground for lightning strokes.

This **method of high voltage protection** is very simple and economic but the main drawback is, it can not protect the system from travelling wave which may reach to the sub-station via different feeders.



Overhead Earth Wire

This method of over voltage protection is similar as earthing screen. The only difference is, an earthing screen is placed over an electrical sub-station, whereas, overhead earth wire is placed over electrical transmission network. One or two stranded GI wires of suitable cross-section are placed over the transmission conductors. These GI wires are properly grounded at each transmission tower. These overhead ground wires or earth wire divert all the lightning strokes to the ground instead of allowing them to strike directly on the transmission conductors.



Lightning Arrester

The previously discussed two methods, i.e. earthing screen and over-head earth wire are very suitable for protecting an electrical power system from directed lightning strokes but system from directed lightning strokes but these methods can not provide any protection against high voltage travelling wave which may propagate through the line to the equipment of the sub-station.

The lightning arrester is a devices which provides very low impedance path to the ground for highvoltage travelling waves.The concept of a lightning arrester is very simple. This device behaves like a nonlinear electrical resistance. The resistance decreases as voltage increases and vice-versa, after a certain level of voltage.

The functions of a lightning arrester or surge dividers can be listed as below.

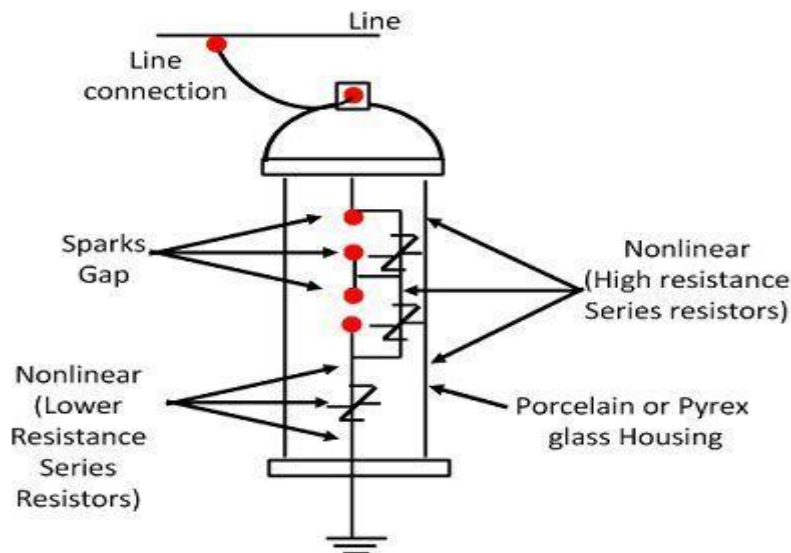
- Under normal voltage level, these devices withstand easily the system voltage as electrical insulator and provide no conducting path to the system current.

- On occurrence of voltage surge in the system, these devices provide very low impedance path for the excess charge of the surge to the ground.
- After conducting the charges of surge, to the ground, the voltage becomes to its normal level. Then lightning arrester regains its insulation properly and prevents regains its insulation property and prevents further conduction of current, to the ground.
- There are different types of lightning arresters used in power system, such as rod gap arrester, horn gap arrester, multi-gap arrester, expulsion type LA, valve type LA. In addition to these the most commonly used lightning arrester for over voltage protection now-a-days gapless ZnO lightning arrester is also used.

11. Valve Type Lightning Arrester

The lightning arrester which consists the single or multi-gaps connected in series with the current controlling element, such type of arrester is known as the lightning arrester. The gap between the electrodes intercepts the flow of current through the arrester except when the voltage across the gap raises beyond the critical gap flashover. The valve type arrester is also known as gap surge diverter or silicon carbide surge diverter with a series gap.

Construction of Valve Type Lightning Arrester



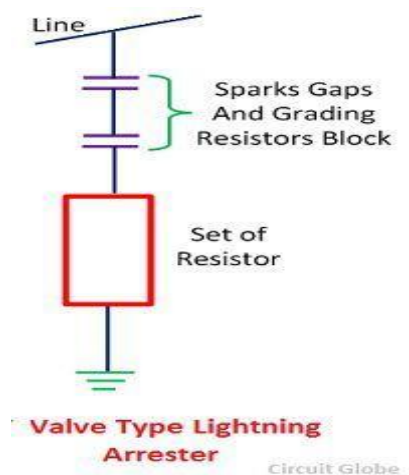
Valve Type Lightning Arrester

Circuit Globe

The resistor elements are made up of silicon carbide with inorganic binders. The whole arrangement is enclosed in a sealed porcelain housing filled with nitrogen gas or SF₆ gas.

Working of Valve Type Lightning Arrester

For low voltage, there is no spark-over across the gaps due to the effect of parallel resistor. The slow changes in applied voltage are not injurious to the system. But when the rapid changes in voltage occur across the terminal of the arrester the air gap spark of the current is discharged to ground through the non-linear resistor which offers very small resistance.



After the passage of the surge, the impressed voltage across the arrester falls, and the arrester resistance increases until the normal voltage restores. When the surge diverter disappears, a small current at low power frequency flow in the path produced by the flash over. This current is known as the power follow current.

The magnitude of the power follows current decreases to the value which can be interrupted by the spark gap as they recover their dielectric strength. The power follow current is extinguished at the first current and the supply remains uninterrupted. The arrester is ready for the normal operation. This is called resealing of the lightning arrester.

Types of Valve Type Lightning Arrester

The valve type lightning arrester may be station types, line types, arresters for the protection of the rotating machine distribution type or secondary type.

Station Type Valve Lightning Arrester – This type of valve is mainly employed for the protection of the critical power equipment in the circuit of 2.2kV to 400kV and higher. They have the high capacity of energy dissipation.

Line Type Lightning Arrester – The line type arresters are used for the protection of substation equipment. Their cross-sectional area is smaller, lighter in weight and cheaper in

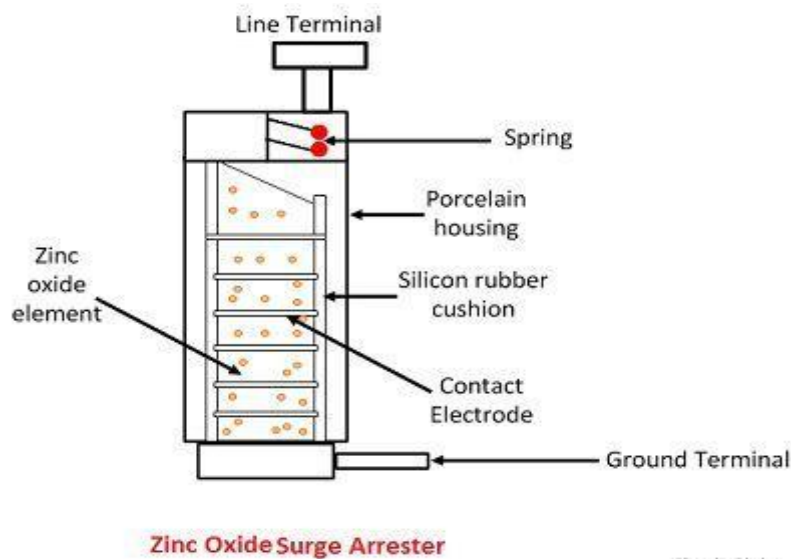
cost. They permit higher surge voltage across their terminal in comparison to station type and have lower surge carrying capacity.

Distribution arrester – Such type of arrester is usually mounted on the pole and are employed for the protection of the generators and motors.

Secondary arrester is meant for the protection of low voltage apparatus. The arrester for the protection of rotating machine is designed for the protection of generators and motors

12. Zinc oxide lightning arrester /Metal Oxide Lightning Arrester

Such Types of diverter are also known as gapless surge diverters, or Zinc oxide diverter. The base material used for manufacturing metal oxide resistor is zinc oxide. It is a semiconducting N-type material. The material is doped by adding some fine power of insulating oxides. The powder is treated with some processes and then it is compressed into a disc-shaped. The disc is then enclosed in a porcelain housing filled with nitrogen gas or SF₆.



This arrester consists a potential barrier at the boundaries of each disc of ZNO. This potential barrier controls the flow of current. At normal operating condition, the potential barrier does not allow the current to flow. When an overvoltage occurs, the barrier collapse and sharp transition from insulating to conducting take place. The current start flowing and the surge is diverted to ground.

In the process of innovation for highly non-uniform V-I characteristics, metal-oxide based surge arresters have been identified as a complete solution for the protection of sub-station

equipment against surge voltages. Let us see the construction and working of the metal-oxide lightning arrester.

Construction of Metal Oxide Lightning Arrester :

The design of a metal oxide surge arrester consists of discs that are made up of metal oxide and of all the metals, zinc oxide (ZnO) is the most commonly used metal due to which metal oxide surge arrester is also called as zinc oxide surge arrester.

Due to the nonlinear characteristics of the zinc oxide element, the series gap is not required in this arrester. Hence, this arrester is built without series-connected spark gaps due to which this type of arrester is also called a metal oxide gapless surge arrester or zinc oxide gapless surge arrester.

The above shows the constructional details of the zinc oxide (ZnO) surge arrester. The discs of metal oxide used in metal oxide surge arresters are arranged in a stack and are enclosed in a suitable insulator such as polymer or porcelain housing.

With the help of spring-loaded cups at the top and bottom, the stack is held in place. Electrodes are placed at both ends, one meant for the earth connection and the other for the line connection. The inner space remaining in the housing is completely filled with fiber-reinforced composite material.

Chapter II

CIRCUIT BREAKERS

Syllabus:

Elementary principles of arc interruption, Restriking Voltage and Recovery voltages. Restriking Phenomenon, Average and Max. RRRV, Current chopping and Resistance Switching - Types Auto reclosures, Construction and Operation of following circuit breakers: Minimum Oil Circuit breakers, Air Blast Circuit Breakers, Vacuum and SF₆ circuit breakers.

Introduction:

During the operation of power system, it is often desirable and necessary to switch on or off the various circuits (e.g., transmission lines, distributors, generating plants etc.) under both normal and abnormal conditions. In earlier days, this function used to be performed by a switch and a fuse placed in series with the circuit. However, such a means of control presents two disadvantages.

1. Firstly, when a fuse blows out, it takes quite some time to replace it and restore supply to the customers.
2. Secondly, a fuse cannot successfully interrupt heavy fault currents that result from faults on modern high- voltage and large capacity circuits.

Due to these disadvantages, the use of switches and fuses is limited to low voltage and small capacity circuits where frequent operations are not expected e.g., for switching and protection of distribution transformers, lighting circuits, branch circuits of distribution lines etc. With the advancement of power system, the lines and other equipment operate at very high voltages and carry large currents. The arrangement of switches along with fuses cannot serve the desired function of switchgear in such high-capacity circuits. This necessitates employing a more dependable means of control such as is obtained by the use of circuit breakers.

A **circuit breaker** can make or break a circuit either manually or automatically under all conditions viz., no-load, full- load and short-circuit conditions.

A circuit breaker is a piece of equipment which can (i) Make or break a circuit either manually or by remote control under normal conditions. (ii) Break a circuit automatically under fault conditions (iii) Make a circuit either manually or by remote control under fault conditions. Thus, a circuit breaker incorporates manual (or remote control) as well as automatic control for switching functions. The latter control employs relays and operates only under fault conditions.

OPERATING PRINCIPLE:

A circuit breaker essentially consists of fixed and moving contacts, called Electrodes. Under normal operating conditions, these contacts remain closed and will not open automatically until and unless the system becomes faulty. Of course, the contacts can be opened manually or by remote control whenever desired. When a fault occurs on any part of the system, the trip coils of the circuit breaker get energized and the moving contacts are pulled apart by some mechanism, thus opening the circuit.

- ❖ When the contacts of a circuit breaker are separated under fault conditions, an arc is struck between them. The current is thus able to continue until the discharge ceases.
- ❖ The production of arc not only delays the current interruption process but it also generates enormous heat which may cause damage to the system or to the circuit breaker itself.
- ❖ Therefore, the main problem in a circuit breaker is to extinguish the arc within the shortest possible time so that heat generated by it may not reach a dangerous value.

Arc Phenomenon:

Electrical Arc:

An electrical arc is a self-sustained electrical discharge that occurs between electrodes, such as circuit breaker contacts, typically in the form of gas or vapor. It exhibits a voltage drop on the order of the minimum ionization voltage of the gas medium.

When a short circuit occurs, a heavy current flow through the contacts of the circuit breaker before they are opened by the protective system. At the instant when the contacts begin to separate, the contact area decreases rapidly and large fault current causes increased current density and hence rise in temperature. The heat produced in the medium between contacts (usually the medium is oil or air) is sufficient to ionize the air or vaporize and ionize the oil. The ionized air or vapor acts as conductor and an arc is struck between the contacts.

- The potential difference between the contacts is quite small and is just sufficient to maintain the arc.
- The arc provides a low resistance path and consequently the current in the circuit remains UN interrupted so long as the arc persists.
- During the arcing period, the current flowing between the contacts depends upon the arc resistance. The greater the arc resistance, the smaller the current that flows between the contacts.

The arc resistance depends upon the following factors:

1. Degree of ionization- the arc resistance increases with the decrease in the number of ionized particles between the contacts.

2. Length of the arc— the arc resistance increases with the length of the arc i.e., separation of contacts.

3. Cross-section of arc— the arc resistance increases with the decrease in area of Xsection of the arc.

Principles of Arc Extinction:

Before discussing the methods of arc extinction, it is necessary to examine the factors responsible for the maintenance of arc between the contacts. These are:

1. Potential difference between the contacts.
2. Ionized particles between contacts taking these in turn.
 - When the contacts have a small separation, the Potential difference between them is sufficient to maintain the arc. One way to extinguish the arc is to separate the contacts to such a distance that Potential difference becomes inadequate to maintain the arc. However, this method is impracticable in high voltage system where a separation of many meters may be required.
 - The ionized particles between the contacts tend to maintain the arc. If the arc path is deionized, the arc extinction will be facilitated. This may be achieved by cooling the arc or by bodily removing the ionized particles from the space between the contacts.

Methods of Arc Extinction (or) Interruption:

There are two methods of extinguishing the arc in circuit breakers viz.

1. High resistance method.
2. Low resistance or current zero method

High resistance method:

In this method, arc resistance is made to increase with time so that current is reduced to a value insufficient to maintain the arc. Consequently, the current is interrupted or the arc is extinguished.

❖ The principal disadvantage of this method is that enormous energy is dissipated in the arc. Therefore, it is employed only in D.C. circuit breakers and low-capacity a.c. circuit breakers. The resistance of the arc may be increased by:

1. Lengthening the arc: The resistance of the arc is directly proportional to its length. The length of the arc can be increased by increasing the gap between contacts.

2. Cooling the arc: Cooling helps in the deionization of the medium between the contacts. This increases the arc resistance. Efficient cooling may be obtained by a gas blast directed along the arc.

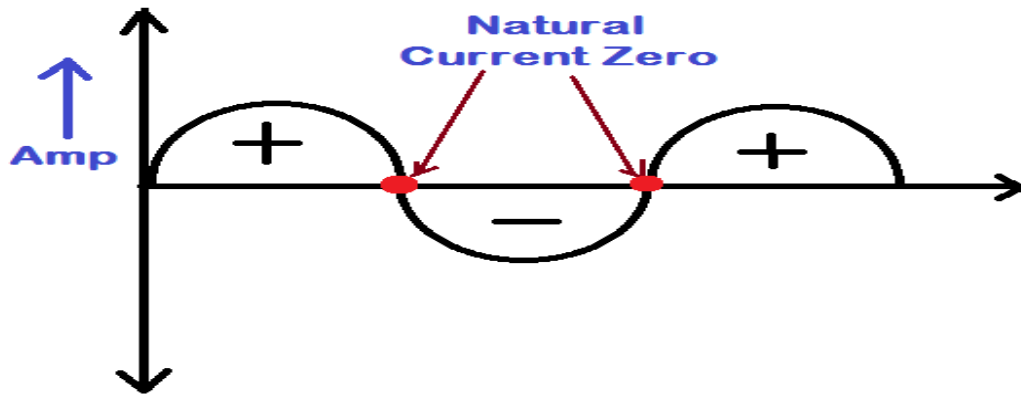
3. Reducing X-section of the arc: If the area of X-section of the arc is reduced, the voltage necessary to maintain the arc is increased. In other words, the resistance of the arc path is increased. The cross-section of the arc can be reduced by letting the arc pass through a narrow opening or by having smaller area of contacts.

4. Splitting the arc: The resistance of the arc can be increased by splitting the arc into a number of smaller arcs in series. Each one of these arcs experiences the effect of lengthening and cooling. The arc may be split by introducing some conducting plates between the contacts.

Low resistance or Current zero method:

In this method is employed for arc extinction in a.c. circuits only. In this method, arc resistance is kept low until current is zero where the arc extinguishes naturally and is prevented from restriking in spite of the rising voltage across the contacts. All Modern high power a.c. circuit breakers employ this method for arc extinction.

❖ In an a.c. system, current drops to zero after every half-cycle. At every current zero, the arc extinguishes for a brief moment.



❖ Now the medium between the contacts contains ions and electrons so that it has small dielectric strength and can be easily broken down by the rising contact voltage known as restriking voltage.

❖ If such a breakdown does occur, the arc will persist for another half cycle.

❖ If immediately after current zero, the dielectric strength of the medium between contacts is built up more rapidly than the voltage across the contacts, the arc fails to restrike and the current will be interrupted.

The rapid increase of dielectric strength of the medium near current zero can be achieved by:

❖ Causing the ionized particles in the space between contacts to recombine into neutral molecules.

❖ Sweeping the ionized particles away and replacing them by un ionized particles.

Therefore, the real problem in a.c. arc interruption is to rapidly de ionize the medium between contacts as soon as the current becomes zero so that the rising contact voltage or restriking voltage cannot breakdown the space between contacts.

The de-ionization of the medium can be achieved by:

1. Lengthening of the gap: The dielectric strength of the medium is proportional to the length of the gap between contacts. Therefore, by opening the contacts rapidly, higher dielectric strength of the medium can be achieved.

2. High pressure: If the pressure in the vicinity of the arc is increased, the density of the particles constituting the discharge also increases. The increased density of particles causes

higher rate of de-ionization and consequently the dielectric strength of the medium between contacts is increased.

3. Cooling: Natural combination of ionized particles takes place more rapidly if they are allowed to cool. Therefore, dielectric strength of the medium between the contacts can be increased by cooling the arc.

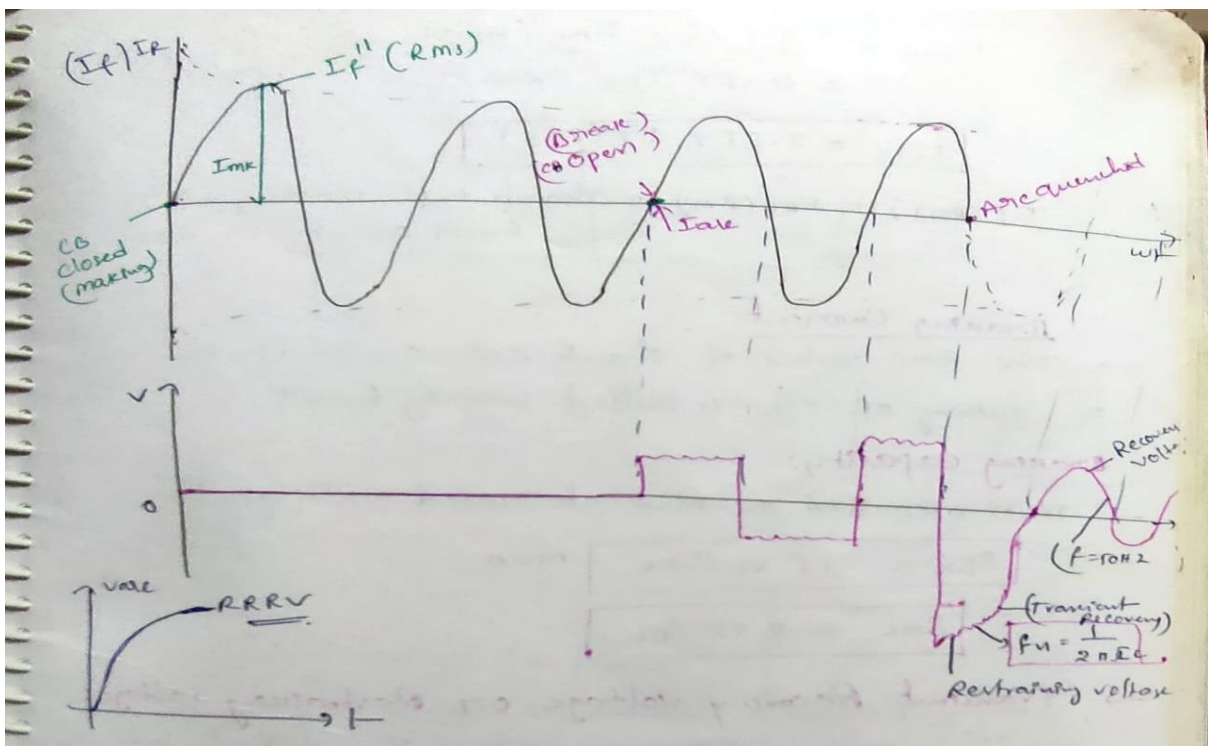
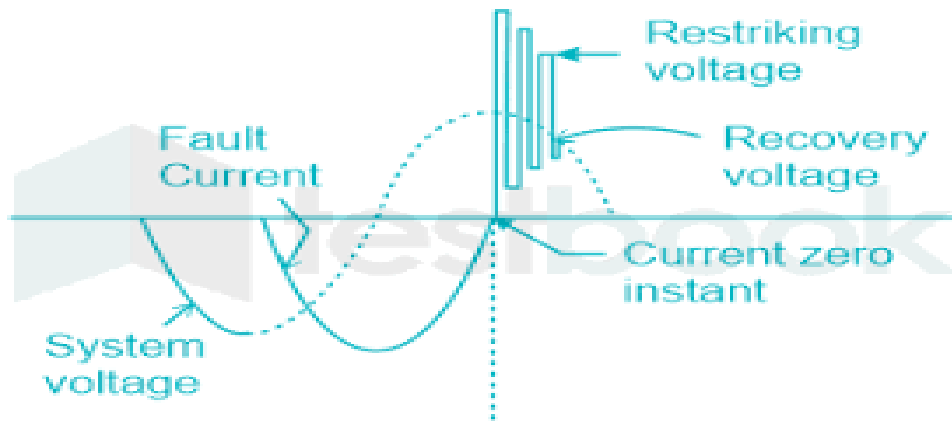
4. Blast effect: If the ionized particles between the contacts are swept away and replaced by UN ionized particles, the dielectric strength of the medium can be increased considerably. This may be achieved by a gas blast directed along the discharge or by forcing oil into the contact space.

Important Terms:

The following are the important terms much used in the circuit breaker analysis:

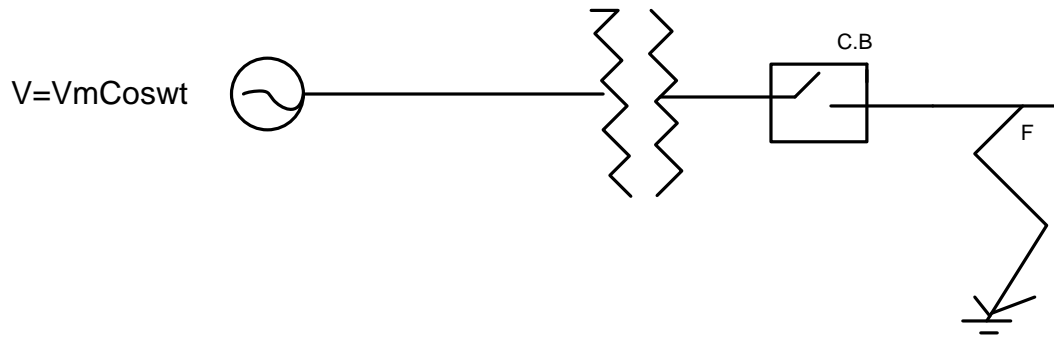
- 1. Arc Voltage:** It is the voltage that appears across the contacts of the circuit breaker during the arcing period. As soon as the contacts of the circuit breaker separate, an arc is formed. The voltage that appears across the contacts during arcing period is called the arc voltage. Its value is low except for the period the fault current is at or near zero current point. At current zero, the arc voltage rises rapidly to peak value and this peak voltage tends to maintain the current flow in the form of arc.
- 2. Restriking voltage:** It is the transient voltage that appears across the contacts at or near current zero during arcing period. At current zero, a high-frequency transient voltage appears across the contacts and is caused by the rapid distribution of energy between the magnetic and electric fields associated with the plant and transmission lines of the system. This transient voltage is known as restriking voltage.

The current interruption in the circuit depends upon this voltage. If the restriking voltage rises more rapidly than the dielectric strength of the medium between the contacts, the arc will persist for another half-cycle. On the other hand, if the dielectric strength of the medium builds up more rapidly than the restriking voltage, the arc fails to restrike and the current will be interrupted.

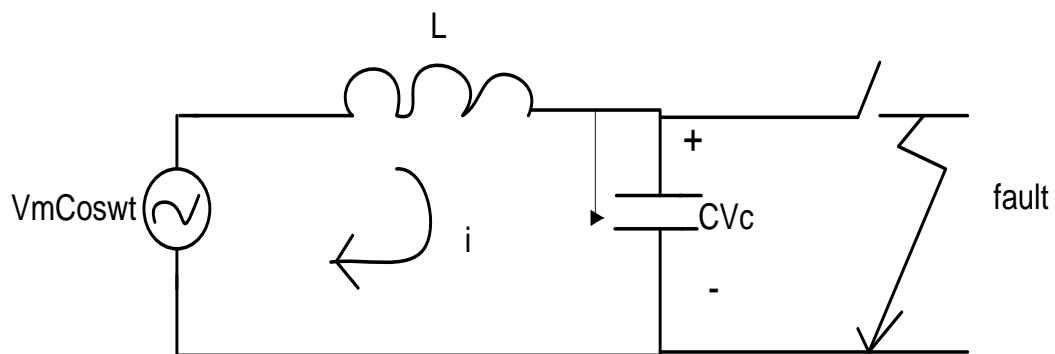


Expression for Restriking voltage and RRRV:

The power system contains an appreciable amount of inductance and some capacitance. When a fault occurs, the energy stored in the system can be considerable. Interruption of fault current by a circuit breaker will result in most of the stored energy dissipated within the circuit breaker, the remainder being dissipated during oscillatory surges in the system. The oscillatory surges are undesirable and, therefore, the circuit breaker must be designed to dissipate as much of the stored energy as possible.



(1)



(2)

Above figure 1 shows a short-circuit occurring on the transmission line. Fig 2 shows its equivalent circuit where L is the inductance per phase of the system up to the point of fault and C is the capacitance per phase of the system. The resistance of the system is neglected as it is generally small.

When the contacts are opened and the arc finally extinguishes at some current zero, the generator voltage e is suddenly applied to the inductance and capacitance in series. This $L - C$ combination forms an oscillatory circuit and produces a transient of frequency: $f_n = \frac{1}{2\pi} \sqrt{LC}$
 The voltage across the capacitance which is the voltage across the contacts of the circuit breaker can be calculated in terms of L , C , f_n and system voltage. The mathematical expression for transient condition is as follows.

As $v_c(t) = 0$ at $t=0$, constant = 0

In this simplified case,

L = Total inductance between circuit breaker and source

C = Capacitance to the earth of circuit.

$$\begin{aligned}
V_m \cos \omega t &= L \frac{di}{dt} + \frac{1}{C} \int 1 dt \\
V_m &= L \frac{de}{dt} + \frac{1}{C} \int idt \\
&= Ld \left(C \frac{dV_c}{dt} \right) + \frac{1}{C} \int idt && \text{here } i = dq/dt = d(CV_c)/dt \\
&= LC \frac{d^2 V_c}{dt^2} + V_c \\
V_m &= V_c \left(LC \frac{d^2}{dt^2} + 1 \right)
\end{aligned}$$

Taking Laplace on both side

$$\begin{aligned}
LCS^2 V_c(s) + V_c(s) &= \frac{V_m}{s} \\
V_c(s)[LCS^2 + 1] &= \frac{V_m}{s} \\
V_c(s) &= \frac{V_m}{LC(s^2 + 1/C)s} \\
&= \frac{V_m \omega_n^2}{s(s^2 + \omega_n^2)} = V_m \omega_n \times \omega_n / s(s^2 + \omega_n^2)
\end{aligned}$$

✓ Takig invers Laplace.

$$\begin{aligned}
V_c(t) &= v_m \omega_n \int_0^t \sin \omega_n t \\
&= V_m \omega_n \left[\frac{-\cos \omega_n t}{\omega_n} \right]_0^t \\
&= V_m (-\cos \omega_n t - (-1))
\end{aligned}$$

$$V_c(t) = V_R = V_m(1 - \cos \omega_n t)$$

$$V_c(t) = V_R = V_m(1 - \cos(t/\sqrt{LC}))$$

$$V_c(t) = V_R = V_m(1 - \cos(t/\sqrt{LC}))$$

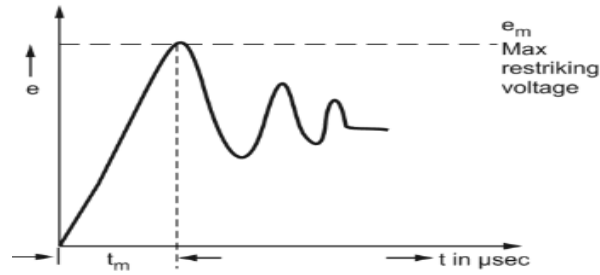
This is an expression for restriking voltage in which

V_m = peak value of recovery voltage phase to neutral in volts

t = time in sec

V_R = Restriking voltage

f_n = natural or oscillation frequency



$$\omega_n = \frac{1}{\sqrt{LC}} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

Expression for maximum value of restriking voltage and corresponding time t.

$$V_R = V_m \left[1 - \cos \left(\frac{t}{\sqrt{LC}} \right) \right]$$

if ' V_R ' is to be maximum

$$\cos \left(\frac{t_m}{\sqrt{LC}} \right) = -1 \quad \text{where } t = t_m$$

$$\therefore \frac{t_m}{\sqrt{LC}} = \pi$$

\therefore Time at which maximum restriking voltage occurs is,

$$t_m = \pi\sqrt{LC}$$

And peak value of restriking voltage,

$$V_{Rm} = 2V_m$$

$$\text{Maximum Restriking voltage } (V_{Rm}) = 2V_m$$

where V_m is equal to active recovery voltage (i.e. instantaneous value of recovery voltage at current zero).

Which appears across the capacitor C and hence across the contacts of the circuit breaker. This transient voltage, as already noted, is known as re-striking voltage and may reach an instantaneous peak value twice the peak phase-neutral voltage i.e. $2V_m$. The system losses cause the oscillations to decay fairly rapidly but the initial overshoot increases the possibility of re-striking the arc.

Expression for rate of rise of restriking voltage (RRRV)

It is the rate of increase of re-striking voltage and is abbreviated by R.R.R.V. usually; the voltage is in kV and time in microseconds so that R.R.R.V. is in kV/ μ sec.

It is the rate of rise of re-striking voltage (R.R.R.V.) which decides whether the arc will re strike or not. If R.R.R.V. is greater than the rate of rise of dielectric strength between the contacts, the arc will re-strike. However, the arc will fail to re-strike if R.R.R.V. is less than the rate of increase of dielectric strength between the contacts of the breaker. The value of R.R.R.V. depends up on:

1. Recovery voltage
2. Natural frequency of oscillations

For a short-circuit occurring near the power station bus-bars, C being small, the natural frequency f_n will be high. Consequently, R.R.R.V. will attain a large value. Thus the worst condition for a circuit breaker would be that when the fault takes place near the bus-bars

$$\begin{aligned}\text{Now } \text{RRRV} &= \frac{dV_R}{dt} = \frac{d}{dt} \left[V_m \left(\cos \left[\frac{t}{\sqrt{LC}} \right] \right) \right] \\ \therefore \text{RRRV} &= \frac{V_m}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}}\end{aligned}$$

$$\text{when } \sin \frac{t}{\sqrt{LC}} = 1$$

$$\text{i.e. } \frac{t}{\sqrt{LC}} = \frac{\pi}{2}$$

$$t = \frac{\pi}{2} \sqrt{LC}$$

$$t = \frac{\pi}{2} \sqrt{LC}$$

$$\text{and Maximum RRRV} = \frac{V_m}{\sqrt{LC}} = V_m \omega_n = V_m 2\pi f_n$$

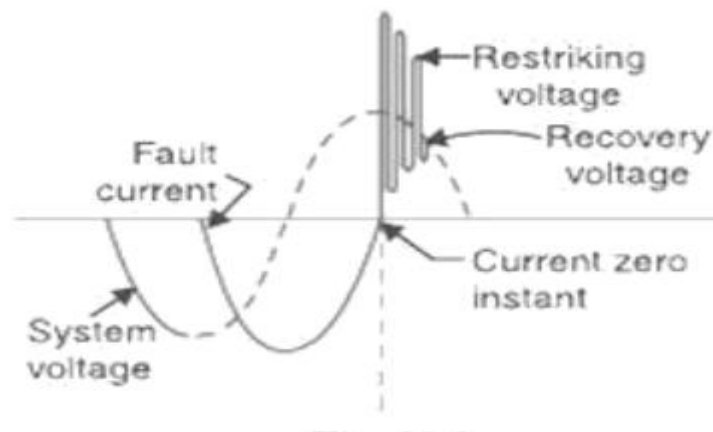
$$\text{Maximum RRRV} = 2IV_m f_n$$

Average RRRV :

$$\text{Average RRRV} = \frac{\text{maximum restriking voltage}}{\text{time to reach maximum resrtriking voltage}} = \frac{2V_m}{IK\sqrt{LC}}$$

3. Recovery voltage:

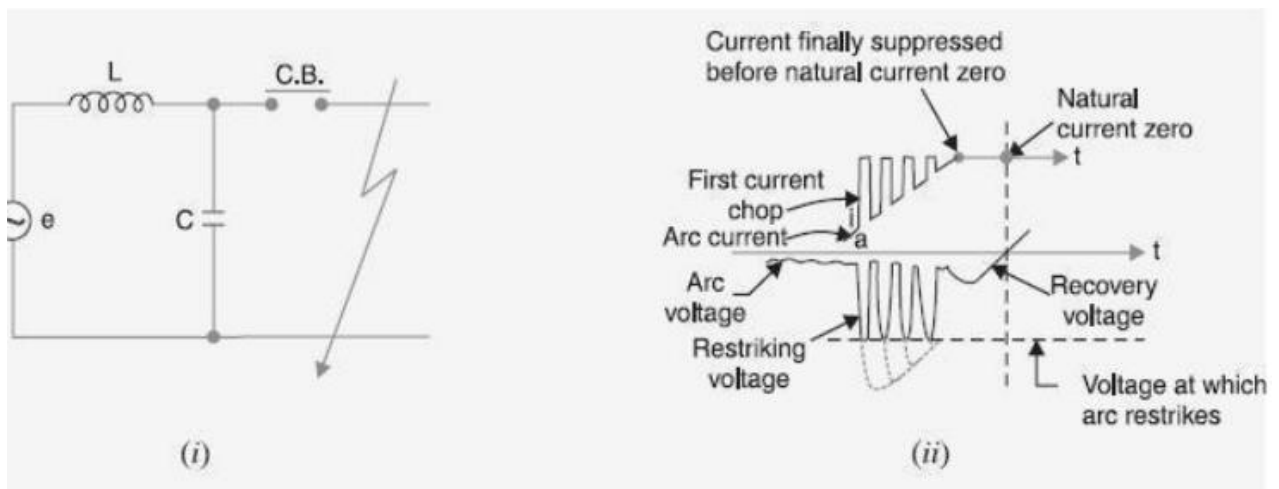
It is the normal frequency (50 Hz) R.M.S. voltage that appears across the contacts of the circuit breaker after final arc extinction. It is approximately equal to the system voltage.



When contacts of circuit breaker are opened, current drops to zero after every half cycle. At some current zero, the contacts are separated sufficiently apart and dielectric strength of the medium between the contacts attains a high value due to the removal of ionized particles. At such an instant, the medium between the contacts is strong enough to prevent the breakdown by the restriking voltage. Consequently, the final arc extinction takes place and circuit current is interrupted. Immediately after final current interruption, the voltage that appears across the contacts has a transient part (See Fig.19.1). However, these transient oscillations subside rapidly due to the damping effect of system resistance and normal circuit voltage appears across the contacts. The voltage across the contacts is of normal frequency and is known as recovery voltage.

Current Chopping

It is the phenomenon of current interruption before the natural current zero is reached. Current chopping mainly occurs in air-blast circuit breakers because they retain the same extinguishing power irrespective of the magnitude of the current to be interrupted. When breaking low currents (e.g., transformer magnetizing current) with such breakers, the powerful de-ionizing effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is known as current chopping and results in the production of high voltage transient across the contacts of the circuit breaker as discussed below:



Suppose the arc current is i when it is chopped down to zero value as shown by point in above Fig. (ii). As the chop occurs at current i , therefore, the energy stored in inductance is $L i^2 / 2$. This energy will be transferred to the capacitance C , charging the latter to a prospective voltage e given by:

$$\frac{L i^2}{2} = \frac{C V^2}{2}$$

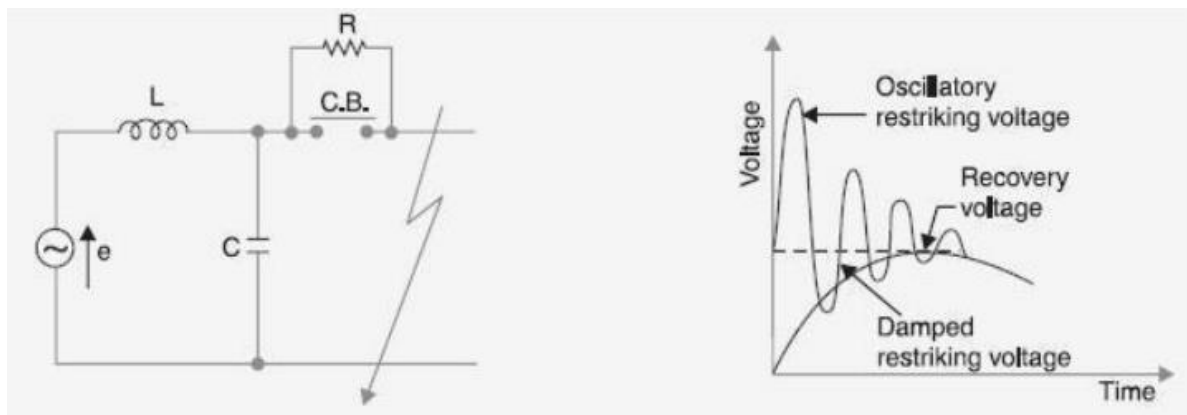
$$V = i \sqrt{\frac{L}{C}}$$

The prospective voltage e is very high as compared to the dielectric strength gained by the gap so that the breaker restrike. As the de-ionizing force is still in action, therefore, chop occurs again but the arc current this time is smaller than the previous case. This induces a lower prospective voltage to re-ignite the arc. In fact, several chops may occur until a low enough current is interrupted which produces insufficient induced voltage to re-strike across the breaker gap. Consequently, the final interruption of current takes place.

Excessive voltage surges due to current chopping are prevented by shunting the contacts of the breaker with a resistor (resistance switching) such that re ignition is unlikely to occur.

RESISTANCE SWITCHING

It has been discussed above that current chopping, capacitive current breaking etc. give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance R connected across the circuit breaker contacts as shown in the equivalent circuit in below Fig. 19. This is known as resistance switching.



Referring to above Fig. when a fault occurs, the contacts of the circuit breaker are opened and an arc is struck between the contacts. Since the contacts are shunted by resistance R, a part of arc current flows through this resistance. This results in the decrease of arc current and an increase in the rate of de-ionization of the arc path. Consequently, the arc resistance is increased. The increased arc resistance leads to a further increase in current through shunt resistance. This process continues until the arc current becomes so small that it fails to maintain the arc. Now, the arc is extinguished and circuit current is interrupted.

The voltage equation is given by

$$L \frac{di}{dt} + \frac{1}{C} \int i_c dt = E \text{ and } i = i_e + i_R$$

Therefore, the above equation become

or

$$L \frac{d(i_c + i_R)}{dt} + v_c = E$$

$$L \frac{di_c}{dt} + L \frac{di_R}{dt} + v_c = E$$

$$i_c = \frac{dq}{dt} = \frac{d(Cv_c)}{dt}$$

Therefore,

$$\frac{di_c}{dt} = \frac{d^2(Cv_e)}{dt^2} = C \frac{d^2v_e}{dt^2}$$

$$\frac{di_R}{dt} = \frac{d(v_e/R)}{dt} = \frac{1}{R} \frac{dv_e}{dt}$$

Substituting these values in the main equation, we get

$$LC \frac{d^2v_e}{dt^2} + \frac{L}{R} \frac{dv_e}{dt} + v_c = E$$

Taking Laplace Transform, we get

$$LCS^2v_c(S) + \frac{L}{R}Sv_c(S) + v_c(S) = \frac{E}{S}$$

Other terms are zero, as $v_c = 0$ at $t = 0$

or

$$LCv_e(S) \left[s^2 + \frac{1}{RC}s + \frac{1}{LC} \right] = \frac{E}{S}$$

$$v_e(s) = \frac{E}{sLC \left[s^2 + \frac{1}{RC}s + \frac{1}{LC} \right]}$$

For no transient oscillation, all the roots of the equation should be real. One root is zero, i.e. $S = 0$ which is real. For the other two roots to be real, the roots of the quadratic equation in the denominator should be real. For this, the following condition should be satisfied.

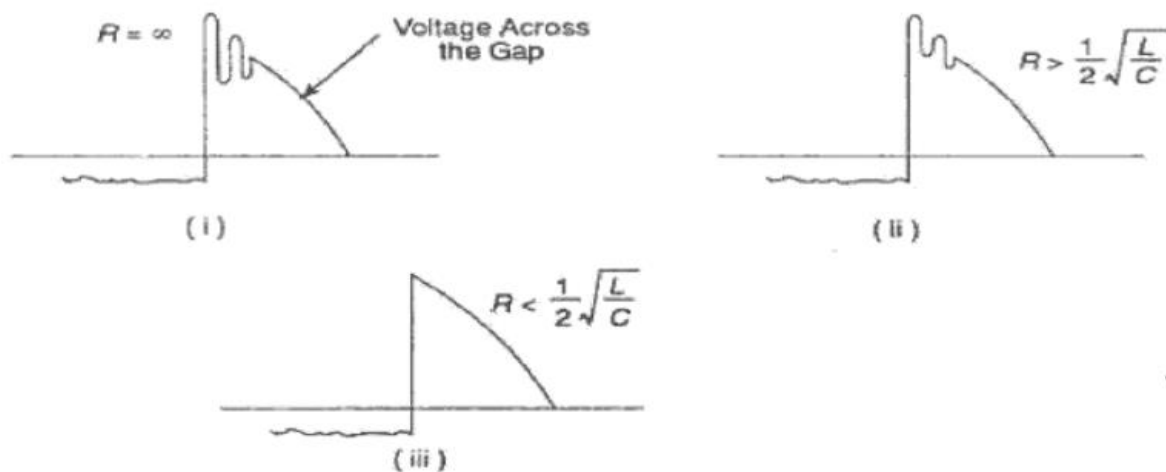
$$\left[\left(\frac{1}{2RC} \right)^2 - \frac{1}{LC} \right] \geq 0 \text{ or } \frac{1}{4R^2C^2} \geq \frac{1}{LC}$$

$$\frac{4}{LC} \leq \frac{1}{R^2C^2} \text{ or } R^2 \leq \frac{LC}{4C^2}$$

Or

$$R^2 \leq \frac{1}{4} \cdot \frac{L}{C}$$

$$\text{or } R \leq \frac{1}{2} \sqrt{\frac{L}{C}}$$



Therefore, if the value of the resistance connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2} \sqrt{\frac{L}{C}}$ there will be no transient oscillation. If $R > \frac{1}{2} \sqrt{\frac{L}{C}}$, there will be oscillation, $R = \frac{1}{2} \sqrt{\frac{L}{C}}$ is known as critical resistance.

The shunt resistor also helps in limiting the oscillatory growth of re-striking voltage. It can be proved mathematically that natural frequency of oscillations (or) the frequency of damped oscillation of the circuit shown in Fig is given by

$$f_n = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}$$

The effect of shunt resistance R is to prevent the oscillatory growth of re-striking voltage and cause it to grow exponentially up to recovery voltage. This is being most effective when the value of R is so chosen that the circuit is critically damped. The value of R required for critical damping is 0.5.

To sum up, resistors across breaker contacts may be used to perform one or more of the following functions.

- ❖ To reduce the rate of rise of re-striking voltage and the peak value of re-striking voltage.
- ❖ To reduce the voltage surges due to current chopping and capacitive current breaking.
- ❖ To ensure even sharing of re-striking voltage transient across the various breaks in multi break circuit breakers.
- ❖ It may be noted that value of resistance required to perform each function is usually different. However, it is often necessary to compromise and make one resistor do more than one of these functions.

Circuit breakers:

A circuit breaker is a mechanical switch that automatically operates to protect a circuit from the damage caused by fault current. It automatically breaks the circuit upon sensing a huge draw of current flow due to overloading or short circuit. It can also manually break open the circuit for maintenance or fault clearance. It can safely close & open a circuit to protect it from damage.

A circuit breaker breaks the supply to the circuit when the current exceeds its rated current. The current may exceed due to numerous reasons such as overloading, short circuit, voltage spikes, etc. Overloading occurs when the load draws a very huge current more than the rated current. A short circuit occurs when two exposed wires come into contact with each other by any means.

What must the Circuit Breaker do?

- It should momentarily withstand the fault current
- It should safely break open the circuit
- It should quickly extinguish the arc.
- Its terminals should withstand the voltage after breaking.
- It should prevent the arc from re-striking.

The circuit breaker withstands the fault current momentarily & allows other circuit breakers to resolve the fault. The CB is designed to tolerate a specific range of fault current without damaging its terminals.

Once it detects the fault current, it trips & interrupts the current flow. It breaks open the circuit using some sort of stored mechanical energy such as spring or a blast of compressed air to separate the contacts. It can also use the fault current to break open the contacts using thermal expansion or an electromagnetic field using a solenoid.

The next step that comes after the separation of contacts is the arc extinction. The arc is generated between the contacts due to the high voltage between them. It can damage the CB contacts or terminals due to excessive heat generated because of high current.

Mediums used for Arc Extinction

The electrical arc tries to make the circuit, so the current still flows in it. It must be extinguished & different kinds of circuit breakers use various insulating or dielectric arc extinction mediums such as.

- Air
- Vacuum
- Insulating Oil
- Insulating gas such as SF₆ (Sulphur hexafluoride)

Other than the medium being used arc quenching, various arc extinction techniques are used to quickly & safely eliminate an arc.

Methods used for Arc Extinction

- **Cooling of Arc:** The arc heats up the air molecule which ionizes & reduces the resistance of the air. Cooling the arc will recombine the ionized particle into its natural state & increase the dielectric strength of the air molecule. As the resistance of the medium increases, the voltage required to maintain the arc also increases & the current starts to drop resulting in arc quenching.
- **Air Blasting:** Such a method is used in the air blast circuit breaker, where the arc is quenched using a blast of compressed air. The ionized air particles are replaced with non-ionized air molecules that have higher dielectric strength. It increases the resistance thus reducing the current which leads to the extinction of the arc.

- **Increasing the length of arc:** The arc length is directly proportional to its voltage. Increasing the length of the arc by separating the contact terminals further apart will increase the voltage required to maintain it. Thus it will extinguish.
- **Reducing cross-section of arc:** Another technique is to reduce the cross-section of arc by reducing the contact sizes. Therefore, the voltage required for arc increases & extinguish it.
- **Deflecting the arc:** In this technique, a magnetic field is created to deflect the arc. it blows out the arc into a section of the circuit breaker called arc chute where it is cooled off & extinguishes.
- **Dividing or splitting the arc:** In this technique, the arc is split into multiple arcs by providing multiple contacts in between. The arc is split into numerous small arc in series which increases its length & resistance. Therefore, reducing the arc current & eventually extinguishing it.
- **Zero current quenching:** this is the most common method used in the AC circuit breaker. There are inherently multiple zero currents in an AC waveform. The circuit is opened at the exact point of zero current. So that the current does not rise to generate arc.
- **Using charged capacitor in parallel:** This technique is used in DC circuit breaker. The DC does not have natural zero currents. Therefore, a charged capacitor with an inductor is used in parallel to introduce an artificial zero current in the line to extinguish the arc.

Basically, a circuit breaker is necessary to install on every line to protect it from any kind of hazard or disasters. Circuit breakers are manufactured by keeping various features in mind such as;

- Intended Voltage Applications
- Alternating or Direct Current
- Location of the installation
- Design Characteristics
- Method and medium used for current interruption (Arc Extinction)

There are various types of circuit breakers that are differentiated based on various characteristics. Circuit breakers are mainly classified into two types;

- AC Circuit Breaker

- DC Circuit Breaker

AC Circuit Breaker

AC refers to alternating current whose voltage & current fluctuates along the zero value many times in a second. The energy at these zero points is null which can be utilized to break the circuit without generating the arc.

Circuit breakers used for AC are quite different than in DC. The inherent zero crossings in AC provide multiple chances in a second for the arc to extinguish itself.

The strength of the arc is directly proportional to the level of the voltage. Therefore, low voltage arcs can be easily quenched but high voltages arc require a more sophisticated approach to extinguish it. therefore, the CB are classified based on their voltage level.

High Voltage AC Circuit Breaker

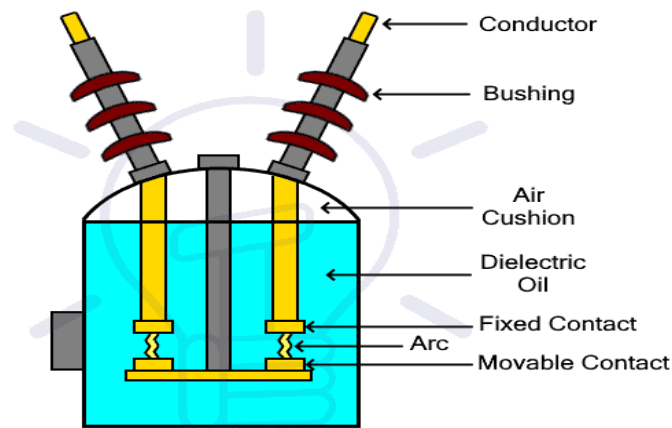
The definition of high voltage depends on context. IEC considers high voltages as the voltage that exceeds 1000v. Such voltage has a tendency to generate an arc that is not easily extinguishable. Circuit breakers used for making & breaking contacts at such voltages are called HV circuit breakers.

The arc extinction can be done using various methods in such high voltages. The HV circuit breaker may or may not use OIL for arc extinction; therefore, they are classified into two types:

- Oil Circuit Breaker
- Oil-Less Circuit Breaker

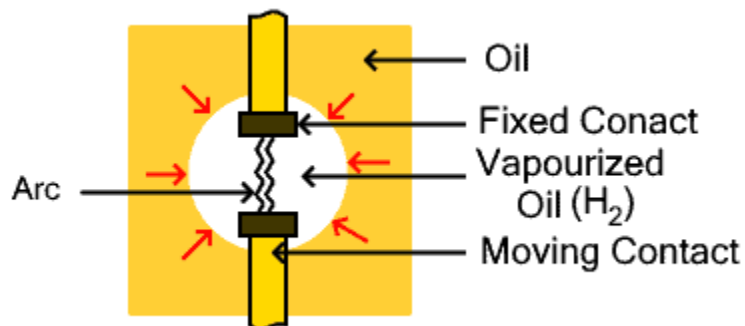
Oil Circuit Breaker

The type of circuit breaker that uses oil as a dielectric or insulating medium to quench the arc is called oil circuit breaker. It is one of the oldest types of high voltage circuit breaker & it mainly uses the **transformer oil**. The oil used in such circuit breakers has very good insulating properties far better than air. The CB contacts are submerged in oil which is used to quench the arc once the contacts separate. The heat generated by the arc is dissipated inside the oil.



Oil Circuit Breaker

When CB breaks its current-carrying contacts inside the oil, the distance between the contacts starts increasing. Initially, there is a very small distance between the contacts but there is also a very high voltage gradient. Due to this, the oil between the contacts starts ionizing & creates an arc between the contacts.



The arc generates a lot of heat & vaporizes the oil surrounding it which is mostly decomposed into hydrogen gas. The hydrogen gas bubbles are rapidly generated surrounding the contact almost ten times the volumes of the oil. This oil surrounding the gas bubbles put a lot of pressure on it increasing de-ionization of the medium. De-ionization of the medium increases its dielectric strength that will quench the arc at zero crossing of the current. Besides that, the cooling effect of the oil & the gas bubbles also helps in arc quenching.

Based on the amount of oil being used in OCB (Oil Circuit Breaker), they are classified into two types

- Bulk Oil Circuit Breaker (BOCB)
- Minimum Oil Circuit Breaker (MOCB)

Minimum Oil Circuit Breaker (MOCB)

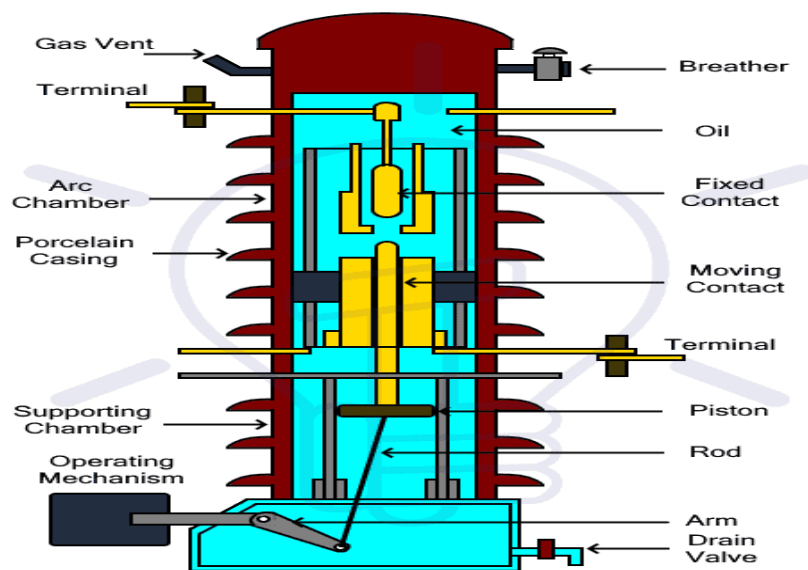
As we know the bulk oil circuit breaker uses a huge amount of oil to quench the arc which may pose a threat for fire hazard. To reduce such risk, the MOCB uses far less oil than in BOCB. The oil is only used for arc quenching & not to isolate the live parts from earthed parts.

MOCB has two chambers: the arc chamber & the supporting chamber. The arc chamber is made from porcelain encased with bakelised paper. It is filled with insulating oil. This chamber is used for quenching the arc. It contains fixed & moving contacts.

The supporting chamber is made from porcelain mounted on top of a metal chamber. This chamber is used for isolating the arc chamber as well as support the arc chamber by mounting it on top of it. this chamber is also filled with oil used only for insulation.

The moving contact moves upwards & downwards with the help of a fixed arm in the supporting chamber. The moving contact has a fixed piston which is used for forcing the oil upwards helping to quench the arc.

Under normal conditions, the lower moving contact makes a connection with the upper fixed contact. Upon fault condition, the arm pulls the moving contact downward & an arc is generated. This arc is extinguished by the pressurized gas in the oil surrounding it & by pushing the oil from the support chamber with the help of the piston. As the contact moves downward, a vent becomes available for the hydrogen gas to exhaust out.



Minimum Oil Circuit Breaker

Advantages

- It requires a very less amount of oil.
- Less amount of oil means the risk of fire hazard is low.
- It has low weight.
- It has small size & takes up small space
- It is cheaper than BOCB.
- It has easier maintenance & oil can be easily replaced.
- Best for installation in places where it is not frequently used.

Disadvantages

- Lesser oil is more affected by the amount of carbonization from the contacts.
- The oil quickly loses its dielectric strength.
- It requires more frequent maintenance.

Oil less Circuit Breaker

Such type of high voltage circuit breaker does not use oil as arc quenching medium. There are different types of arc quenching mediums that can be used instead of oil. Following are the type oil-less CBs using various arc quenching medium;

- Air Circuit Breaker
- Air Blast Circuit Breaker
- SF6 Circuit Breaker
- Carbon Dioxide Circuit Breaker
- Vacuum Circuit Breaker

Air Blast Circuit Breaker

Air Blast Circuit Breaker or ABCB uses a blast of compressed air for the arc interruption. The air is stored & compressed in a tank. This air is released through a nozzle at a very high speed to extinguish the arc. They have high voltage capacity of up to 450KV. They are used for 220KV lines in switchyards.

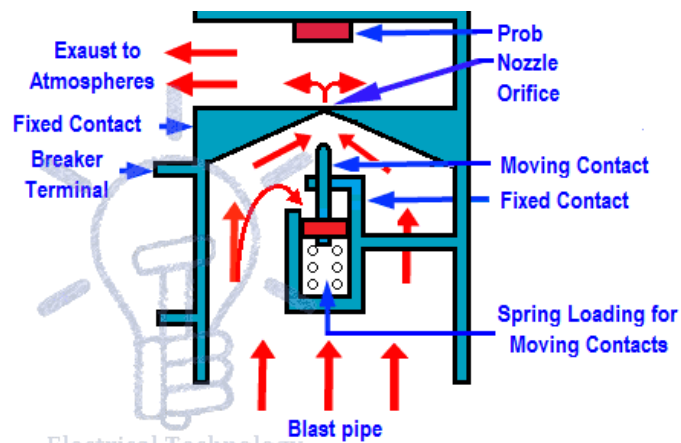
The air blast circuit breaker is further divided into four types

- Axial Blast Air Circuit Breaker
- Axial Blast with sliding moving contact ACB

- Radial Blast Air Circuit Breaker
- Cross Blast Air Circuit Breaker

Axial Blast ACB

In axial blast ACB, the air blast flows axially in the same direction as the arc. The air blast lengthens & cools the arc at the same time & also increases the dielectric strength of the medium to prevent the arc from re-striking.

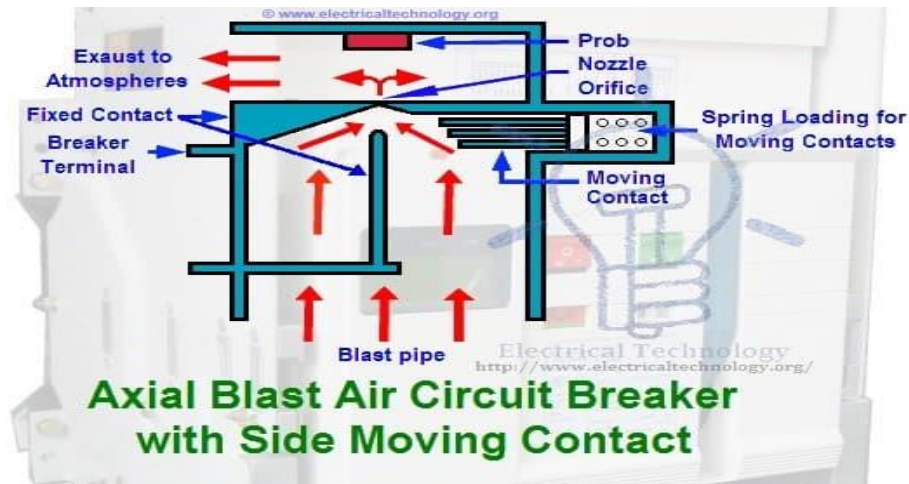


Schematic Diagram of Axial Blast Air Circuit Breaker

The moving contact under the force of spring is in closed position with the fixed contact. The fixed contact has a nozzle orifice blocked by the tip of the moving contact. The compressed air is stored in the tank below it. Upon fault condition, the compressed air is released that pushes the spring to pull the moving contact, thus opening the nozzle orifice in the fixed contact. The arc strikes between the contacts that is lengthened & cooled by the blast of air flowing through the orifice. It all happens simultaneously & the arc is extinguished.

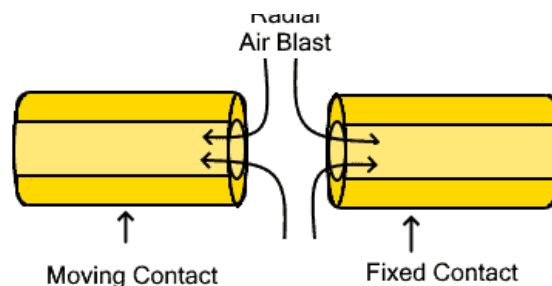
Axial Blast ACB with Sliding Moving Contact

This type of breaker is a modified form of the axial blast ACB. It has a moving contact horizontally fitted on a spring with a piston. The fixed contact has the same kind of nozzle orifice which is blocked by this moving contact. It has the same arc quenching operation as discussed in the previous ACB.



Radial Blast ACB

In radial blast ACB, the contacts are hollow like a tube i.e., there is free space inside the moving contact as well as fixed contact. The free space is used for the flow of compressed air to cool the arc. The air blast flows radially inside the contacts along the arc therefore it is called radial blast ACB.

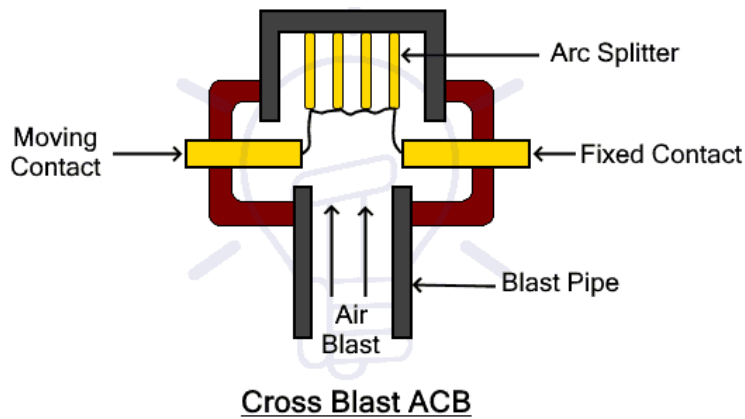


Radial Blast ACB

Under fault conditions, the arc is formed between the contacts when they are separated. The radial blast of air cools off the arc & increases the dielectric strength between the contacts. Upon zero current, the arc is extinguished.

Cross Blast ACB

In cross blast ACB, the air blast is directed at a right angle to the arc. The air blast is used to deflect & lengthen the arc into the arc chamber where arc splitters split & lengthen the arc to extinguish it. There is exhaust in the arc chamber for the air to flow out.



The air tank is fixed in the perpendicular direction to the movement of the contacts. Upon fault condition, the contacts are opened & arc is established. At the same time, the air blast is released that sweeps the arc into the arc chamber. The arc splitters split the arc that is eventually quenched at the zero current. The air blast also increases the dielectric strength of the medium between the contacts to prevent the arc from restriking.

Advantages of ACB

- ACB does not have any fire hazards, unlike oil circuit breakers.
- ACB has a very high speed i.e., its arc quenching is very fast.
- The speed of arc quenching is the same for all values of current.
- It has small size due to small space required for an air blast to cool & quench the arc.
- It is used for frequency operation where circuit breaking & making is done often such as in switchyards.
- It is very reliable & consistent because short arcing time cannot wear the contact quickly.
- It requires less maintenance due to less wearing of the contacts.
- ACB is fairly cheaper as air is used as the arc quenching medium.

Disadvantages of ACB

- The air compressor needs to be maintained to have the correct pressure at all the time.
- The air compressor takes up a large space.
- The air pipes junction may leak air pressure.
- There is a chance of a high rate rise of re-striking voltage and current chopping.
- The air release produces a noise.

- Air as compared to other insulating gases has lower extinguishing properties.

Sulphur Hexafluoride (SF₆) Circuit Breaker

Sulphur Hexafluoride or shortly known as SF₆ is a non-flammable & insulating gas that has very high electronegativity. It has a high tendency to absorb electrons.

When the arc is struck between the contacts, the medium is ionized due to free electrons. The SF₆ absorbs the free electrons & form negative ions that are far heavier than free electrons. Due to their heavyweight, they are immobile & reduces the mobility of charges. This enhances the dielectric strength of the medium where the arc is quenched. The SF₆ has far more superior insulating & arc quenching capabilities than air almost 100 times better.

The SF₆ is very expensive & a greenhouse gas. SF₆ itself is not toxic but its product gases are toxic & Its emission is dangerous for the environment. Therefore, a close circuit gas system is designed for such breaker where the SF₆ gas is reutilized after each operation. The system also monitors its pressure which is directly proportional to its dielectric strength.

There are three types of SF₆ Circuit Breakers

- Non-Puffer Type SF₆ Circuit Breaker
- Single Pressure Puffer Type SF₆ Circuit Breaker
- Double Pressure Type SF₆ Circuit Breaker

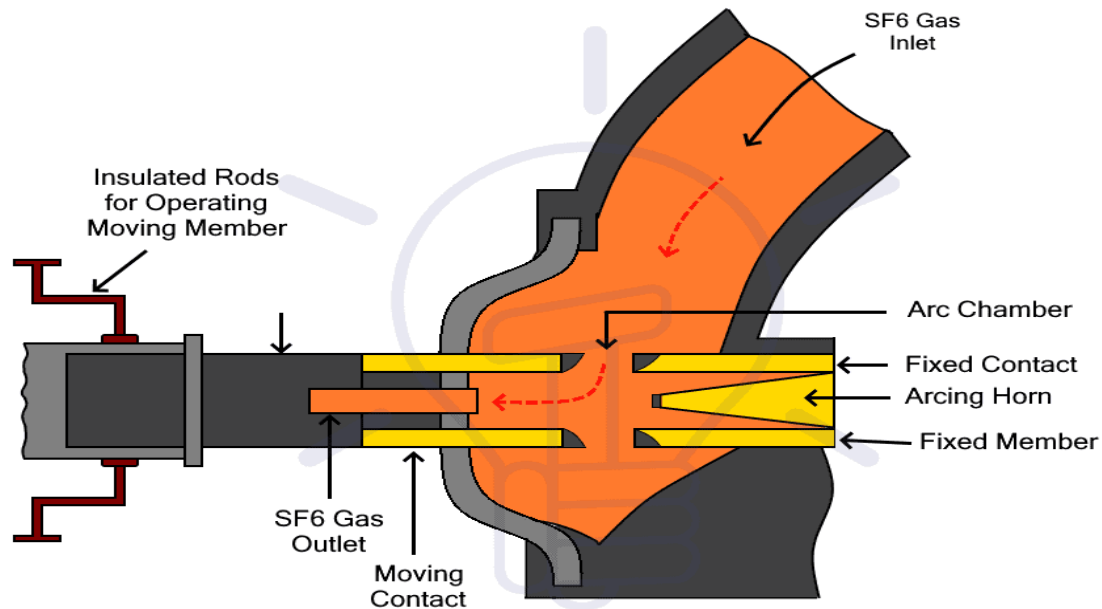
Non-Puffer Type

In non-Puffer SF₆ CB, pressurized SF₆ gas is stored in the gas chamber. While the arc quenching is done inside an interrupter unit. This unit has moving & fixed contacts that are basically hollow cylinders. The fixed contact has arc horns while the moving contact has vents for pressurized gas to flow.

Under a fault condition, the moving contact is moved apart from the fixed contact. Its movement is synchronized with the valve of the gas chamber. as soon as the contacts open, the valve is opened & pressurized SF₆ is introduced into the arc chamber.

The SF₆ quench the arc & flows through the hollow moving contact. This gas is then recombined & pumped back into the gas chamber for re-utilization.

Non-Puffer SF6 circuit breakers were used when they were first invented. Nowadays easier & simple SF6 breakers are used that utilize the puffer cylinder.



Sulphur Hexafluoride SF6 Circuit Breaker

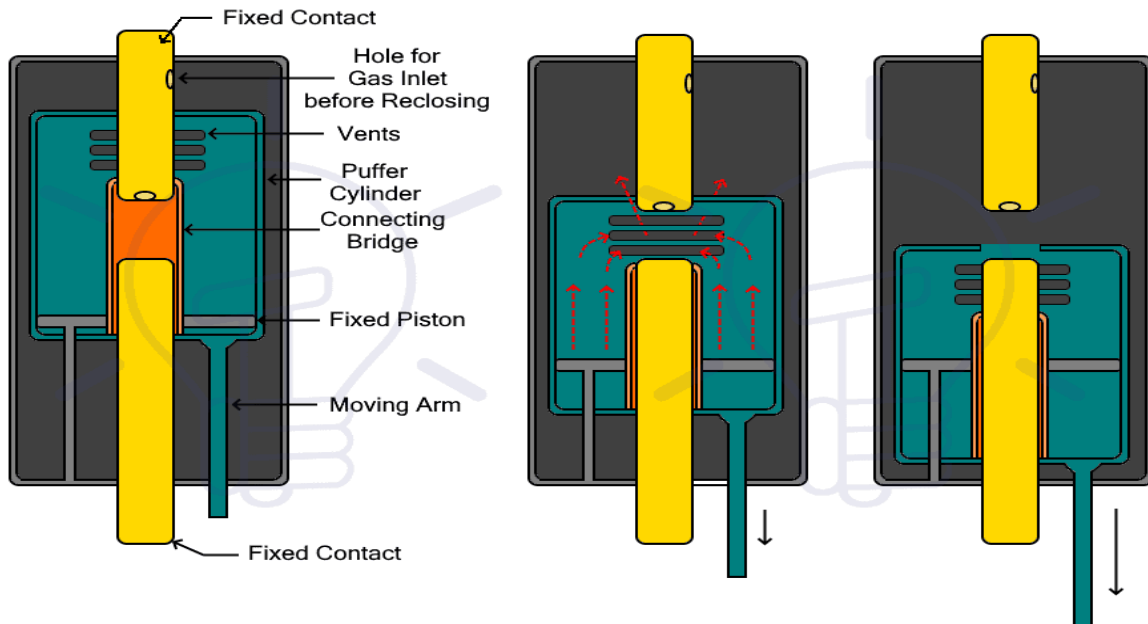
Single Pressure Puffer Type SF6 Circuit Breaker

Such type of SF6 CB has a Puffer cylinder. A puffer cylinder is a hollow cylinder that acts as a bridge between two fixed contacts. The cylinder can slide upward & downward axially along the contacts. There is a stationary piston inside the puffer cylinder as shown in the figure. By moving the cylinder, its internal volume can be varied.

The movable cylinder is filled with SF6 gas. During circuit breaking operation, the cylinder moves downward against the piston to break the connection between the fixed contacts. Consequently, it reduces the volume inside the cylinder, compressing the SF6 inside it.

At this point, the upper fixed contact blocks the vents in the puffer cylinder, therefore the SF6 cannot flow out. By moving the cylinder further down, the vents are unblocked & the contacts are opened. An arc is generated as well as the SF6 starts flowing out through the hollow contacts. This pressurized SF6 quenches the arc.

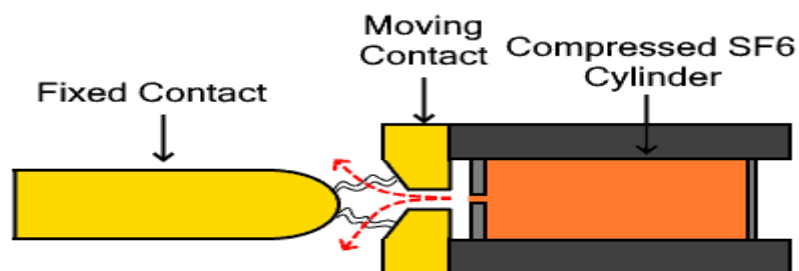
The same process is done in reverse to close the circuit. by moving the cylinder upwards, its volume is increased as well as a low pressure is generated. Due to this, the SF6 from the surrounding flows into the cylinder through the contacts & the vents.



Puffer type SF6 Circuit Breaker

Double Pressure Type SF6 Circuit Breaker

Such types of SF6 Circuit breakers are obsolete. In such breakers, the gas is compressed & stored in a chamber which is released upon opening of the contacts to quench the arc. It has the same operation as air blast CB except the gas is recompressed & stored in the gas chamber.



Double Pressure SF6 Circuit Breaker

There is SF6 cylinder inside the moving contact that is blocked by fixed contact in closed position. When the contacts separate, an arc is produced. At the same time, the highly

pressurized gas from the cylinder rushes out to the low-pressure area. The blast of SF₆ quenches the arc as discussed earlier. The gas is filtered, compressed & restored in the cylinder for reuse. It is obsolete due to the complicated gas system required to maintain the gas. It also includes a heater in case the gas is liquefied due to low temperature.

Advantages of SF₆ Circuit Breaker

- Sulphur Hexafluoride SF₆ has superior arc quenching property almost 100 times more effective than air.
- The arcing time of the SF₆ circuit breaker is very short.
- The dielectric strength of SF₆ gas is 2 to 3 times higher than air. It also increases with increasing pressure.
- Due to high dielectric strength, the required contact separation is small to prevent arc restriking.
- High dielectric strength leads to large current interruption capabilities.
- The SF₆ CB has a compact design. Thus require small space & cost for installation.
- SF₆ gas can handle all kinds of switching phenomena.
- SF₆ CB has a closed-circuit gas system with no leakage. Therefore, best for any installation in any kind of (extreme) environment.
- No carbon particles are formed with arcing; thus, the dielectric strength does not reduce.
- It does not require an expensive & bulky air compressing system except for double pressure type which is obsolete.
- The operation of SF₆ CB is noiseless.
- SF₆ gas is non-toxic in its pure state.
- SF₆ gas is non-flammable, thus no chance of fire hazards.
- Since its operation is flawless, it requires less maintenance.

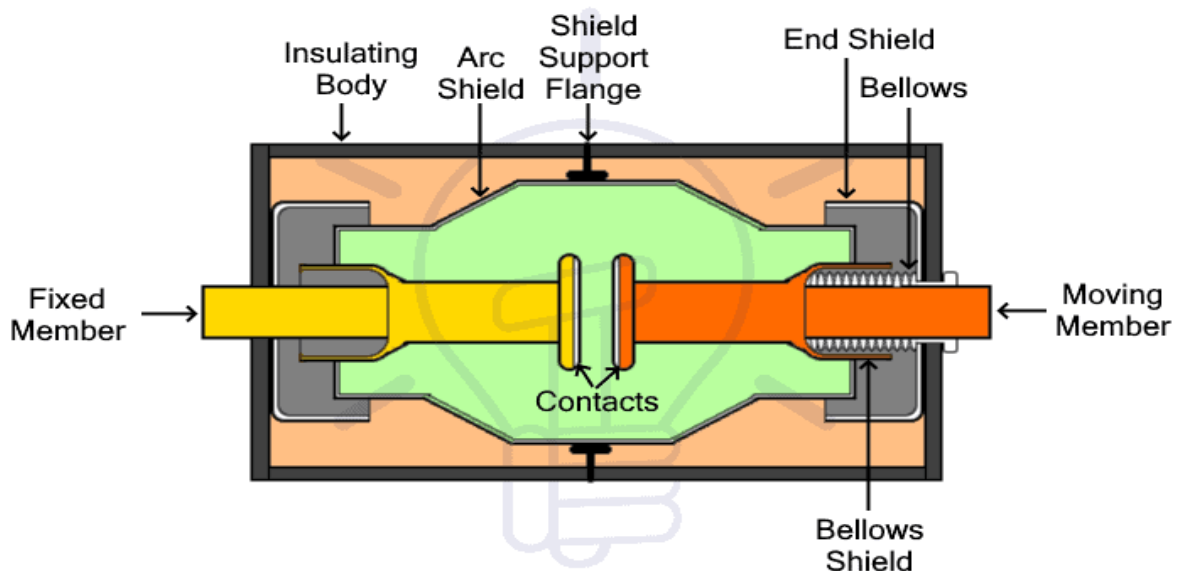
Disadvantages of SF₆ Circuit Breaker

- The byproducts formed from SF₆ gas during arcing are toxic for the environment but they are mostly recombined into SF₆
- The decomposed SF₆ is toxic.
- SF₆ is an expensive gas so these circuit breakers are costly.
- Leakage of SF₆ from the joints must be continuously monitored.
- It requires special transportation & maintaining of the quality of gas.
- The SF₆ is heavier than oxygen & can cause difficulty in breathing.

- Recombination & reconditioning of the SF6 gas requires additional equipment

Vacuum Circuit Breaker (VCB)

A Vacuum Circuit Breaker or VCB is a type of circuit breaker that uses the vacuum as the arc quenching medium. The vacuum has very high dielectric strength & arc quenching properties far more superior than any other medium. It can quickly recover its dielectric strength. Due to its high dielectric strength, VCB requires a very small gap between its contacts to prevent restriking. The pressure of the vacuum used in VCB is in the range of 10^{-7} to 10^{-5} torr (1 torr = 1mm of Hg). It is suitable for switching medium-voltage ranging from 22kV to 66 kV.



Vacuum Circuit Breaker

The switching operation of current-carrying contacts & the arc interruption occurs inside a closed chamber called Vacuum interrupter. Its outer insulating body is made up of glass or ceramic material. It consists of fixed & movable contacts surrounded by arc shield. The arc shield is used for the prevention of the deterioration of the dielectric strength of the vacuum by preventing the ionized metallic vapors on the inner side of the outer insulating body. The movable member is connected to a controlled mechanism (for movement) using bellow. The bellow completely seals the vacuum chamber & prevents any leak.

The operation of VCB is very simple, the arc interruption occurs inside the vacuum upon first zero current. When a fault condition occurs, the contacts are separated. During separation, the contacts do not separate at once but its contact area is reduced which eventually reduces to a

single point. The amount of current passing through this single point heats up the contact & vaporizes (reducing the dielectric strength of the vacuum) to create a medium for the arc. Thus the arc is generated. At next zero current, the conducting metallic vapors re-condenses on the contact surface & the dielectric strength of the vacuum is recovered. Since the contacts are separated & there are no vapors between them, the arc cannot re-strike. In simple words, a VCB quenches the arc by producing the high dielectric strength to prevent arc re-striking after the current zero.

Since the arc is generated due to the ionization of the contacts, its material plays a vital role in keeping the CB reliable & maintenance-free. Therefore, the VCB contact material must have the following properties

- It must have high electrical conductivity to avoid overheating upon normal load currents.
- It must have high thermal conductivity to dissipate large heat produced during arcing.
- It should have high arc withstanding capabilities & low current chopping level.
- It must have low resistance with high density.
- The contacts are made from copper alloy such as Copper-bismuth, copper-lead, and copper-chromium material.

Advantages of VCB

- Vacuum is the absence of matter thus VCB has no fire hazards
- The Vacuum has very high dielectric strength & superior arc quenching properties than air & SF6.
- Due to high dielectric strength, VCB requires a small contact gap to extinguish the arc.
- VCB is compact & requires small installation space.
- It is free of maintenance thus it's reliable having a long life.
- It does not produce any noise doing the operation.
- There are no toxic exhaust gases.
- Its operation is very fast.
- It is suitable for repeated use.
- It can break all types of fault currents.
- Since there is a vacuum, the control mechanism requires less power to move the contacts.

Disadvantages of VCB

- A single vacuum interrupter can only interrupt up to 38kV.
- For interrupting voltages more than 38kV, multiple vacuum interrupters must be connected in series.
- It's uneconomical for voltages exceeding 38Kv since it requires more than one VCB & the total cost increases.
- In case of loss of vacuum, the VCB becomes useless.

Chapter 3

Electromagnetic Relays

Types of an Electromagnetic Relay

By their working principle, the electromagnetic relay is mainly classified into two types. These are

1. Electromagnetic Attraction Relay
2. Electromagnetic Induction Relay

Electromagnetic Attraction Relay:

Electromagnetic attraction relays are a type of electromagnetic relay that operates based on the principle of attracting an armature (a movable component) with electromagnetic force when the relay coil is energized. This attraction causes a change in the relay's state, such as closing or opening its electrical contacts. Here are some key features and characteristics of electromagnetic attraction relays:

Operating Principle:

Coil Energization: When an electric current is applied to the relay's coil, it generates a magnetic field around it.

Armature Movement: This magnetic field attracts the armature towards the core of the coil. The armature is typically spring-loaded in its normal (resting) position.

Contact Actuation: The movement of the armature results in the opening or closing of electrical contacts, depending on the specific design of the relay. This contact actuation controls the flow of electrical current in a circuit.

Characteristics:

Fast Response: Electromagnetic attraction relays are known for their rapid response times, making them suitable for applications requiring quick switching.

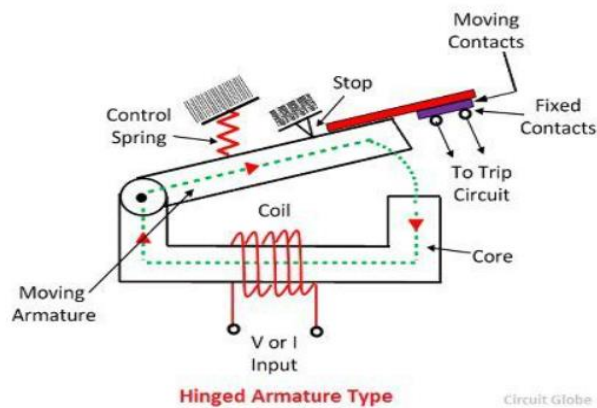
Mechanical Design: They have a relatively simple and robust mechanical design with fewer moving parts, contributing to their reliability.

Low Power Consumption: These relays often require relatively low power to operate the coil, making them energy-efficient.

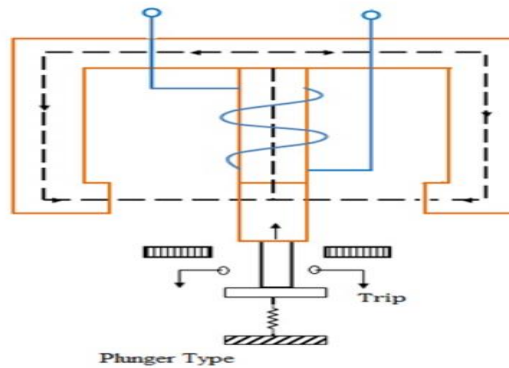
Attraction Armature Type Relay:

This has four types i.e., hinged armature, plunger, balanced beam and moving iron polarized. These are the simplest types which responds to AC and DC.

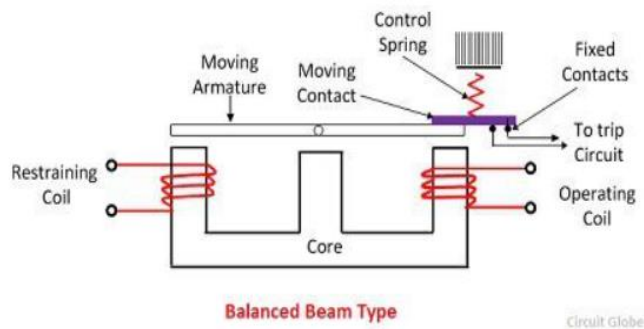
1. Hinged Type.



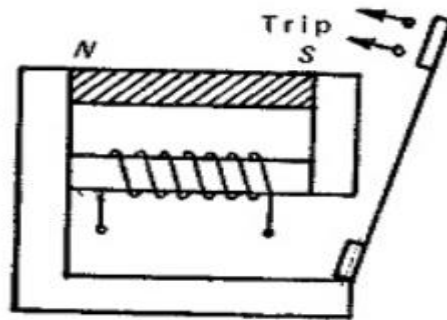
2. Plunger type



3. Balanced beam type



4. Polarized Moving Iron type



All these relays have the same principle, that is, an electromagnetic force is produced by the magnetic flux which in turn is produced by the operating quantity. The electromagnetic force exerted on the moving element is proportional to the square of the flux in the air gap or the square of the current. In d.c. Types of Electromagnetic Relays this force is constant; if this force exceeds the restraining force, the relay operates reliably. In a.c. electromagnetic relays the electromagnetic force is given by

$$\begin{aligned}
 F_e &= KI^2 \\
 &= K(I_{\max} \sin \omega t)^2 \\
 &= \frac{1}{2} K(I_{\max}^2 - I_{\max}^2 \cos 2\omega t)
 \end{aligned}
 \tag{3.1}$$

It shows that the electromagnetic force consists of two components, one constant independent of time ($\frac{1}{2} KI_{\max}^2$) and another dependent on time and pulsating at double the frequency of the applied alternating quantity ($\frac{1}{2} KI_{\max}^2 \cos 2\omega t$). The total electromagnetic force thus pulsates at double the frequency. The force Eq. (3.1) is plotted graphically in Fig. (3.2) which shows that F_e equals zero every half period.

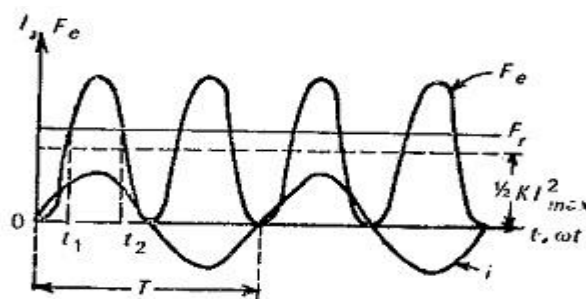


FIGURE 3.2 Curves of current and electromagnetic force applied to armature.

If the restraining force F_r which is produced with the help of a spring is constant, the relay armature will be picked up at t_1 and the armature drops off at t_2 . Hence the relay armature

vibrates at double the frequency. This causes the relay to hum and produces noise and also is a source of damage to the relay contacts. This leads to sparking and unreliable operation of the relay operative circuit contacts due to make and break of the circuit.

To overcome this difficulty in a.c. Types of Electromagnetic Relays the flux producing the electromagnetic force is divided into two fluxes acting simultaneously but differing in time phase, so that the resultant electromagnetic force is always positive and if this is always greater than the restraining force F_r then the armature will not vibrate. This is easily achieved by providing shading in the electromagnet as shown in Fig. (3.3).

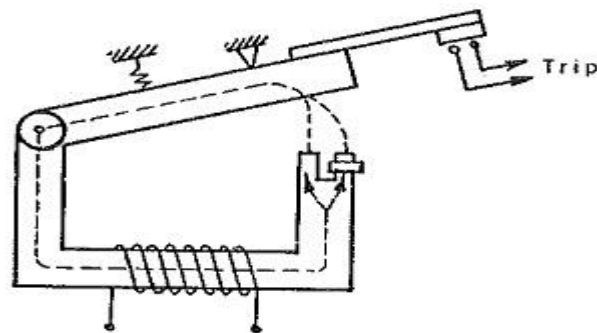


FIGURE 3.3 Electromagnetic relay with shading.

The flux through the shaded pole lags behind the flux through the unshaded pole.

The same thing can also be achieved by providing two windings on the electromagnet having a phase shifting circuit. One simple circuit is shown in Fig. (3.4a) having two windings W_1 and W_2 on the same electromagnet. Figure (3.4b) shows the vector diagram. However, the shading coil method is more simple and is used widely.

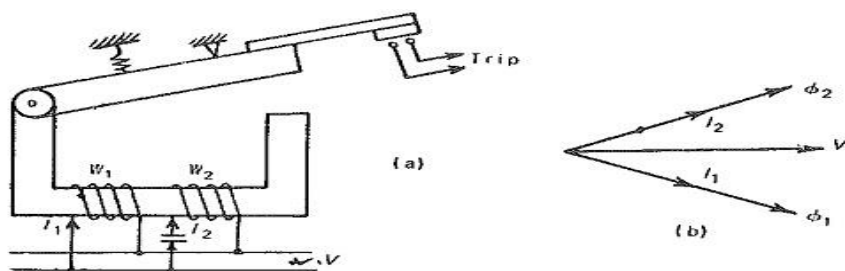


FIGURE 3.4 Electromagnetic relay with two windings: (a) schematic diagram; (b) vector diagram.

Hinged armature relays are mainly used as auxiliary relays, e.g. tripping relays, a.c. and d.c. voltage and current relays. Their volt-ampere consumption is low being of the order of 0.05 watt at pickup with one contact. The volt-ampere consumption increases with the number of contacts.

In the case of balanced beam type two quantities A and B are compared. Actually $|A|^2$ and $|B|^2$ are compared because the electromagnetic forces are proportional to $(\text{ampere-turn})^2$. It has low ratio of reset/operating current. If set for fast operation, there is a tendency to overreach on transient conditions.

The sensitivity of the hinged armature relays can be increased for d.c. operation by the addition of a permanent magnet. This is known as a polarized moving iron relay. It is more robust in construction; most of these use leaf-spring supported armatures.

INDUCTION TYPE RELAYS

Induction relay is a type of electromagnetic relay, that works on the principle of electromagnetic induction and it resembles a split-phase induction motor. The operating force developed will be due to the interactions of fluxes displaced in time and space in the rotor (movable element). The relays are mostly employed for the protection of lines and apparatus. Induction relays are classified into two types as follows,

- Induction disc relay,
- Induction cup relay.

Induction Disc Relay :

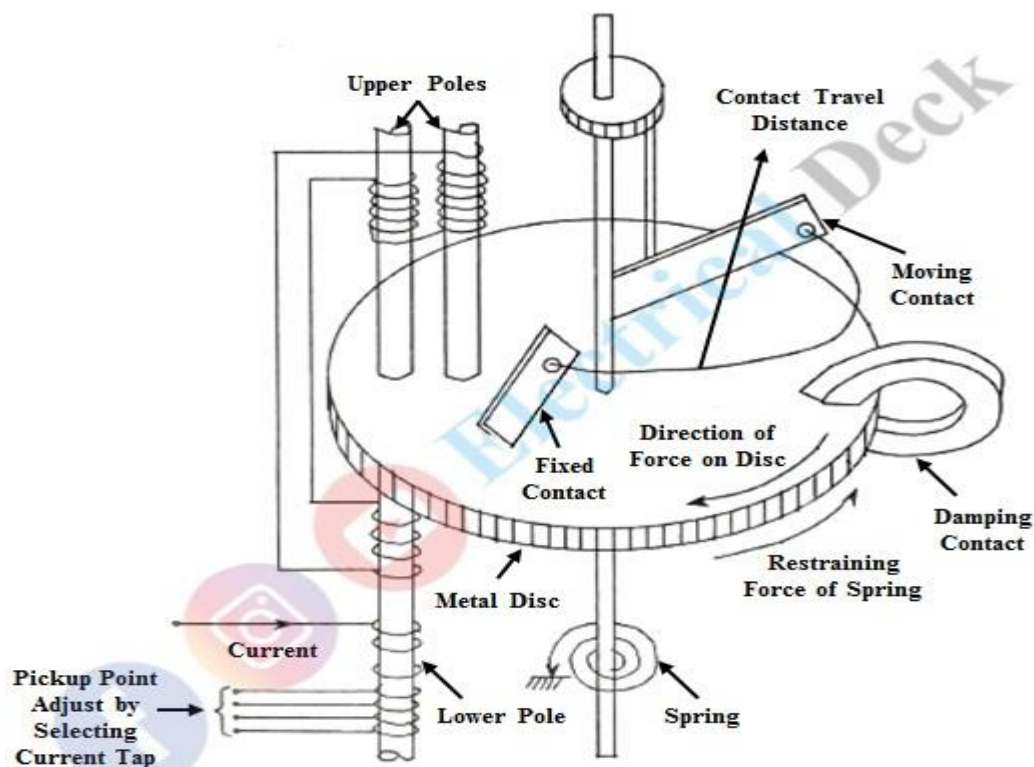
Principle of Induction Disc Relay:

- The induction disc relay operates on the principle of electromagnetic induction similar to an induction motor. The torque produced in these relays is by the interaction of alternating flux with one of the magnets and eddy currents induced in the rotor (disc) with the other alternating flux.
- The frequency of both the fluxes are same, but there will be a phase delay between them. These relays thus operate only on ac circuits. In this relay, the moving element is a disc on which the moving contact of the relay is fixed.

Construction of Induction Disc Relay:

- The below shows the construction of the induction disc relay. It consists of a rotating disc mounted on a shaft placed between two electromagnets. The coils of the electromagnet are energized by the operating current in which the relay is connected for protection.

- When there is a fault in the system, the coils get excited and produce a magnetic field. This magnetic field will induce eddy currents in the disc and these eddy currents will create their own magnetic field.
- The magnetic field produced by the eddy currents when interacts with the magnetic field produced by the coil results in the production of torque on the disc. These cause disc to rotate and brings the moving contact towards the fixed contact which makes the trip circuit close.



Induction Disc Relay

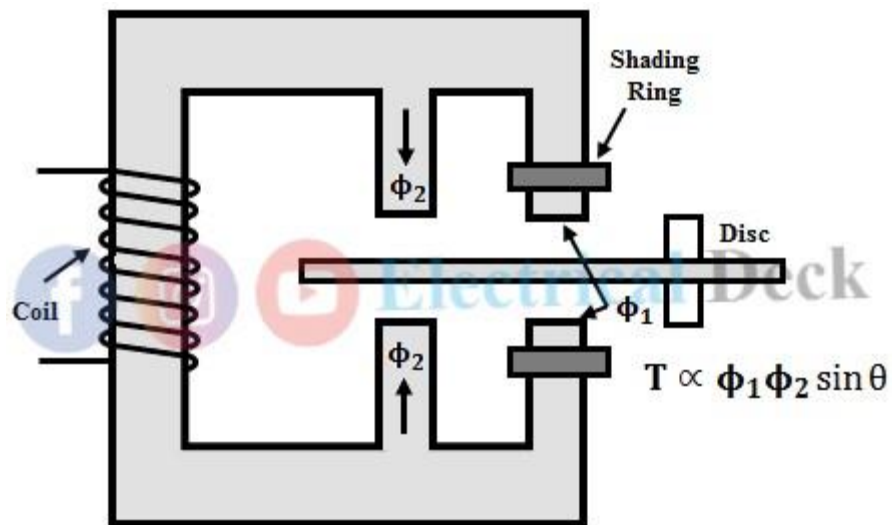
Once the fault current falls below the pickup value, the spring resists the movement of the disc due to its restraining force and makes the trip circuit open by moving the moving contact away from the fixed contact. The time to close the contact depends on the contact travel distance which is set by a time delay.

Induction disc relays are of two types. They are,

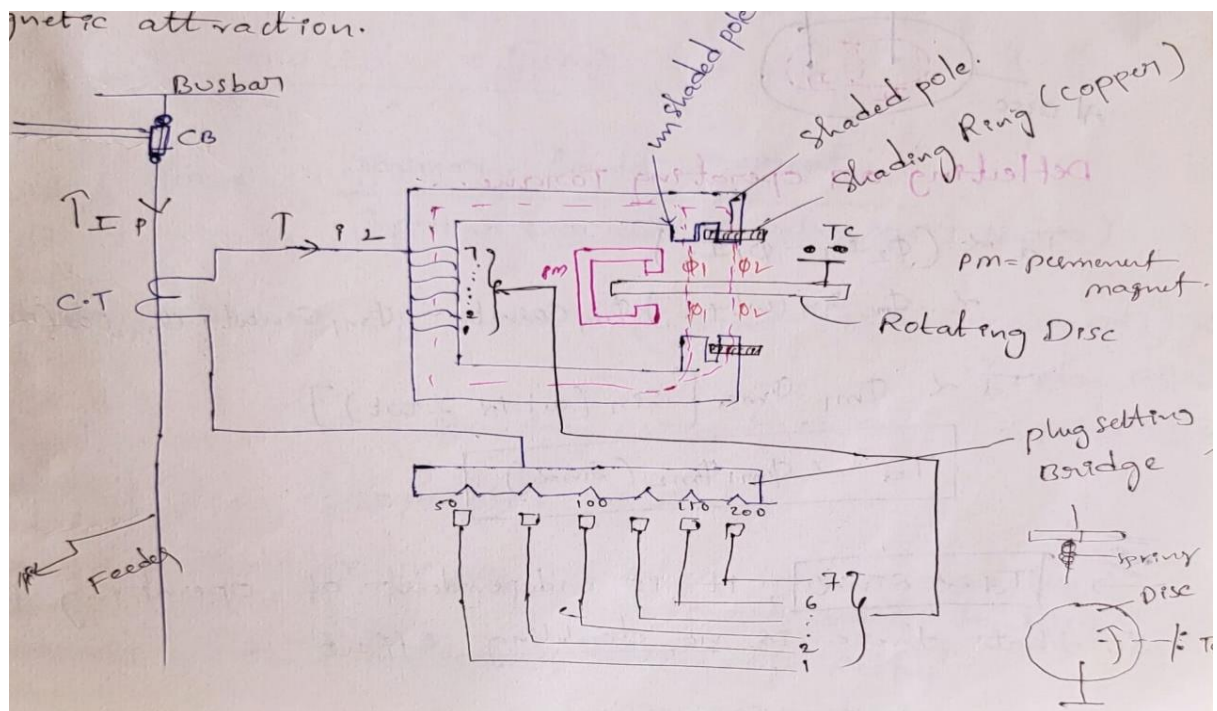
- Shaded pole type induction relay,
- Watt-hour meter type induction relay.

Shaded Pole Type Induction Relay:

- The below shows the construction of the shaded pole type induction disc relay. In this, the main flux is split into two fluxes displaced in time and space with the help of a shading ring.
- A shading ring or coil is made of copper (Cu) and encircles the part of the pole face of each pole at air-gap. Thus, two alternating fluxes are produced and are displaced in time and space. The air-gap flux of the shaded poles lags behind that of the non-shaded poles.



Shaded Pole Type Induction Relay



Hence, the torque is produced by the interaction of one flux with the eddy current produced by another flux. This resultant torque rotates the disc, which in turn operates the relay contact mounted on it. A permanent magnet is provided to produce eddy current braking in the disc.

$$i_2 = I_m \sin \omega t$$

$$\Phi_1 = \Phi_{m1} \sin \omega t$$

$$\Phi_2 = \Phi_{m2} \sin(\omega t + \alpha)$$

$$V_1 \propto -\frac{d\Phi_1}{dt}$$

$$V_1 \propto -\frac{d}{dt}[\Phi_{m1} \sin \omega t]$$

$$V_1 \propto -\Phi_{m1} \omega \cos \omega t$$

$$V_1 \propto \Phi_{m1} \omega \sin(\omega t - 90^\circ)$$

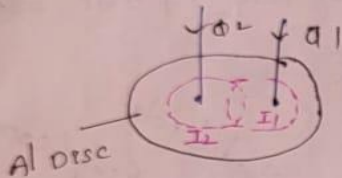
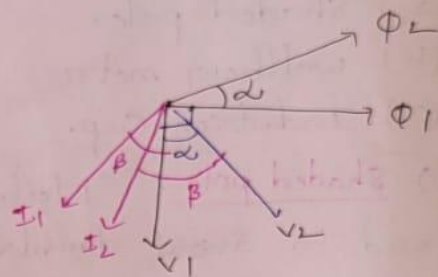
$$V_2 \propto \left(-\frac{d\Phi_2}{dt}\right)$$

$$V_2 \propto \Phi_{m2} \omega \sin[(\omega t + \alpha) - 90^\circ]$$

$$Z = \text{Impedance of Disc}$$

$$= (R + j\omega L) = |Z| \angle \beta$$

$$\beta = \tan^{-1}(\omega L/R)$$



Deflecting or operating Torque.

$$T_d \propto (\Phi_2 I_1 - \Phi_1 I_2)$$

$$\propto \Phi_{m2} \sin(\omega t + \alpha) \Phi_{m1} \cos \omega t - \Phi_{m1} \sin \omega t \Phi_{m2} \cos(\omega t + \alpha)$$

$$T_d \propto \Phi_{m1} \Phi_{m2} [\sin(\omega t + \alpha - \omega t)]$$

$$T_d \propto \Phi_{m1} \Phi_{m2} (\sin \alpha)$$

$\Rightarrow T_d \propto \sin \alpha$, it is independent of operating frequency so that there is no doubling effect

- If $\alpha = 90^\circ$ T_d is maximum.
- Control Torque is provided by Spring.
- Damping Torque is provided by permanent magnet.
by adjusting the position of permanent magnet the speed of Disc is adjusted.
- The disc rotate from unshaded pole towards shaded pole because flux is leading in the unshaded pole.
- For different currents plug setting bridge is used.
- For different time multiplier setting is adjusted by adjusting the distance b/w fixed plunger and the trip contacts [moving contacts, & fixed contacts.]

Watt-hour Meter Type Induction Relay:

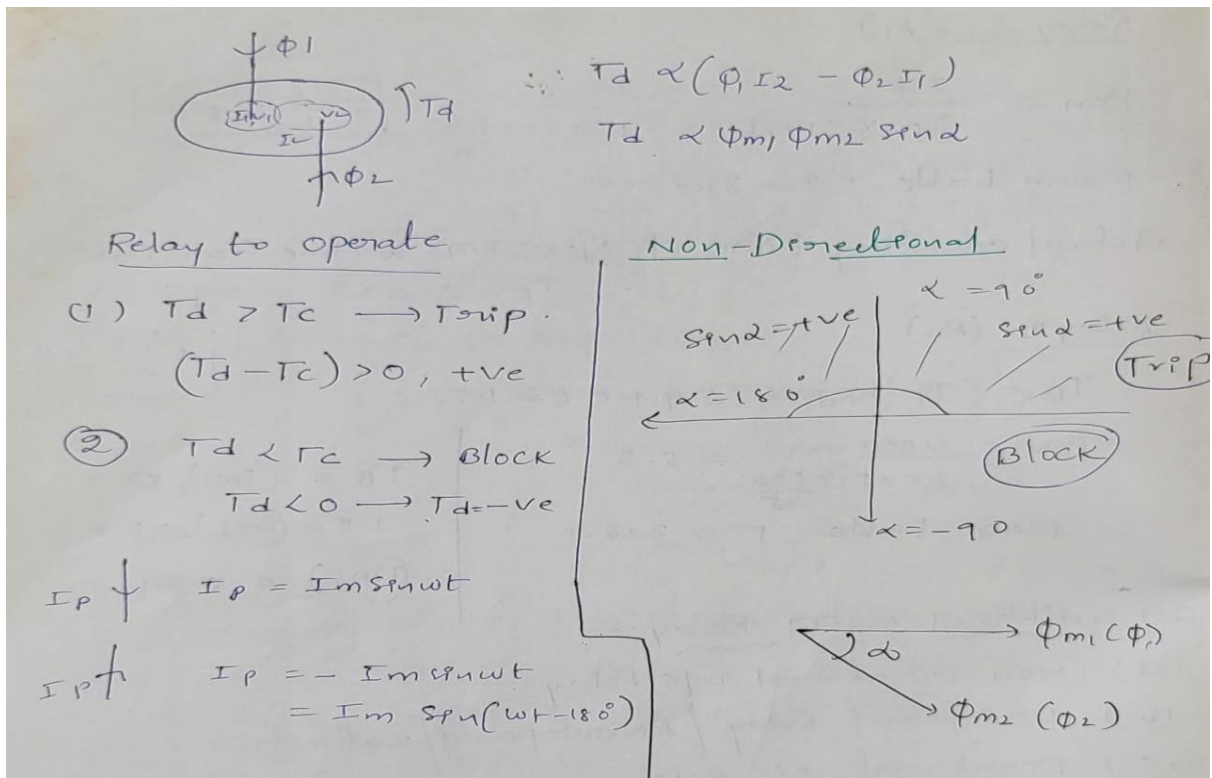
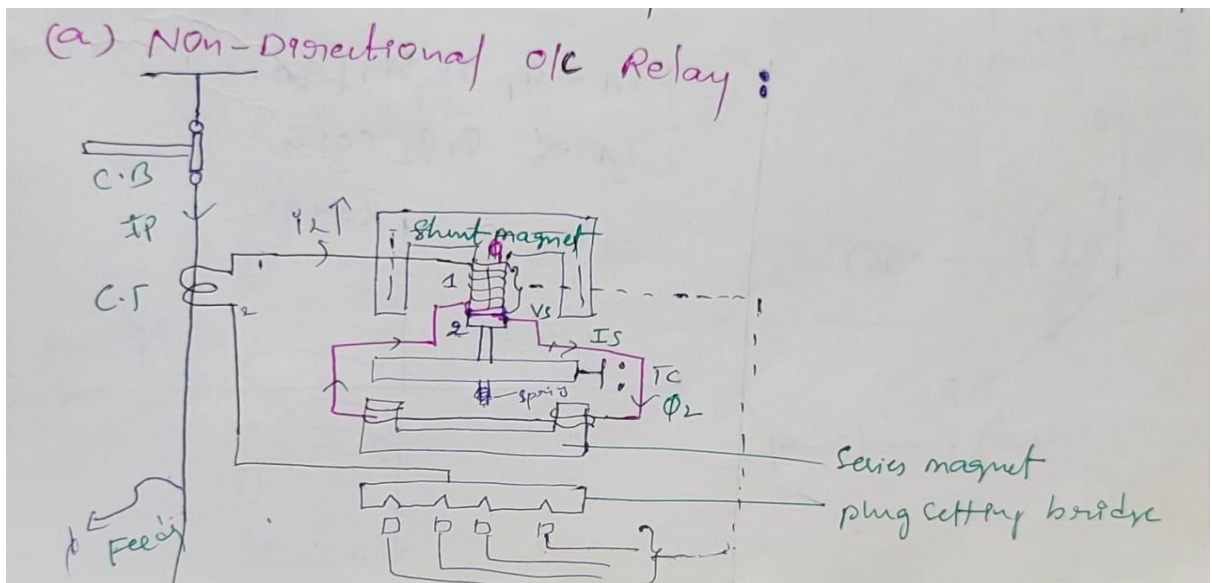
- 1) Non directional over current relay
- 2) Directional relay/reverse power /watt metric relay
- 3) Directional overcurrent relay

1. Non directional over current relay

- The construction of this type of relay is similar to the watt-hour meter which measures the electric power flowing through a circuit. It consists of two electromagnets and a disc that is free to rotate in between two electromagnets.
- The upper electromagnet is E-shaped and the lower electromagnet is U-shaped. The upper electromagnet carries two windings (primary and secondary winding) on the

central limb. While the lower magnet consists of secondary winding as shown below.

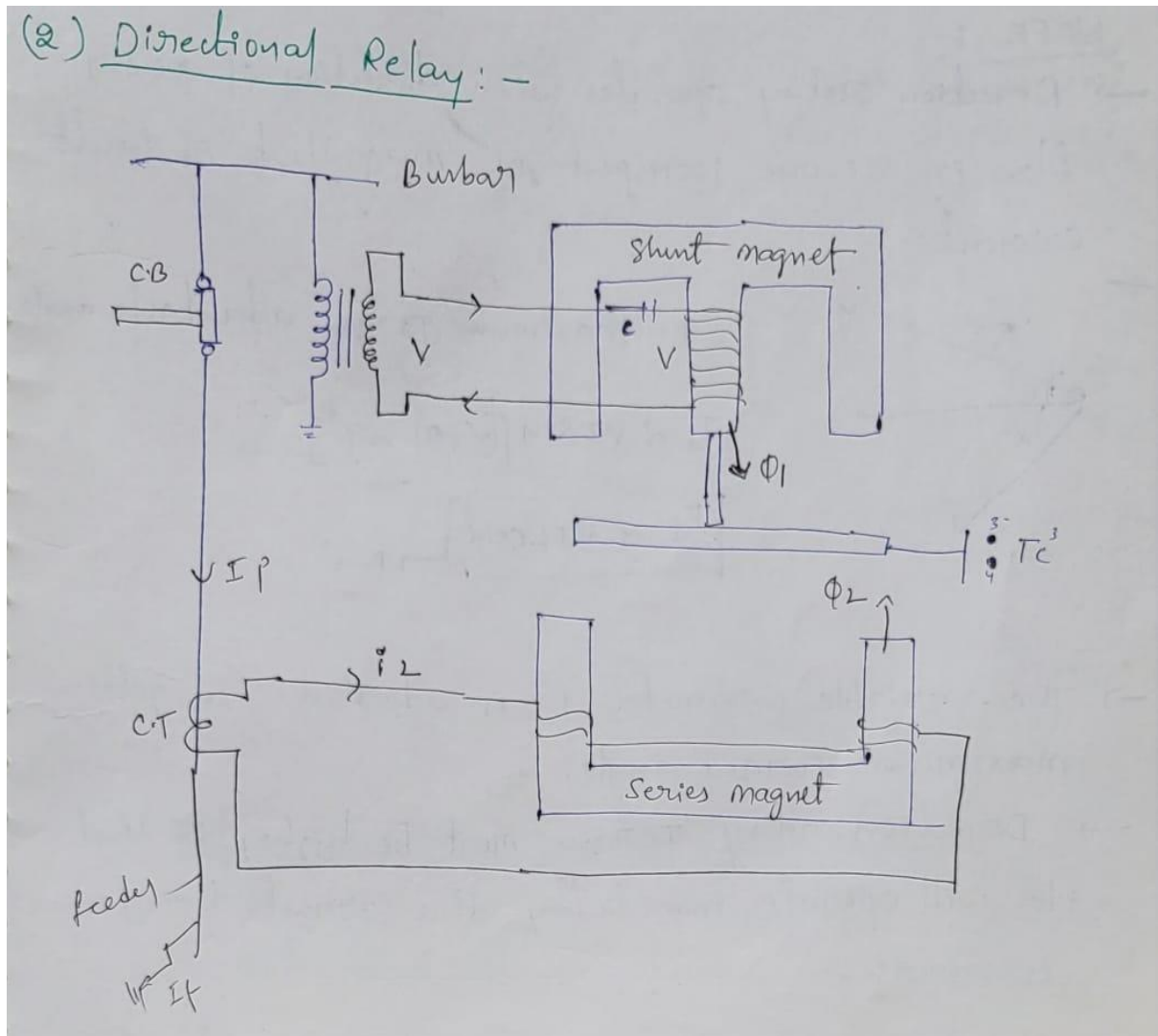
- The two windings produce an alternating flux when they are energized. Let the fluxes be Φ_1 and Φ_2 respectively. The phase angle θ between the fluxes can be adjusted by using reactance in parallel with the secondary winding. The resultant torque produced by the interaction of flux of one of the magnets with the eddy currents of the other in the disc is proportional to $\Phi_1 \Phi_2 \sin\theta$.



- in non-directional over current relay, relay will operate irrespective of current direction and if the current magnitude exceeding the setting value of relay (PSM) when the relay operates.
- Spring used for controlling torque, permanent magnet used for damping torque.

Application: used for overcurrent protection of transformer, generator, feeders

2. Directional relay

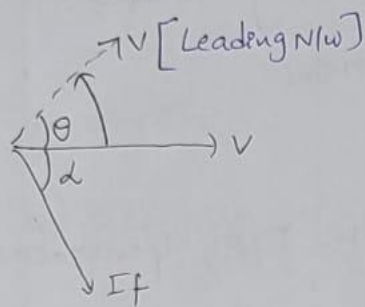


$$\Phi_1 \propto V$$

$$\Phi_2 \propto i_2 \propto I_p \propto I_f$$

$$T_d \propto \Phi_1 \Phi_2 \sin \alpha$$

$$T_d \propto V I_f (\sin \alpha)$$



$$T_d \propto V I_f \sin[\alpha + \theta]$$

$$\theta = 90^\circ,$$

$$T_d \propto V I_f \sin(\alpha + 90^\circ)$$

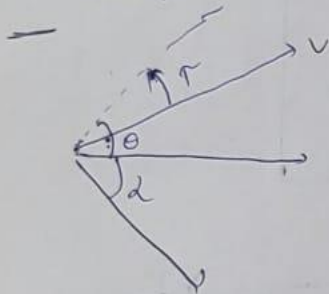
$$T_d \propto V I_f \cos \alpha$$

$$T_d \propto P$$

$$P = \text{power} = V I_f \cos \alpha$$

NOTE :-

→ Direction relay operates with direction of power flow is reverse irrespective of magnitude of fault current.



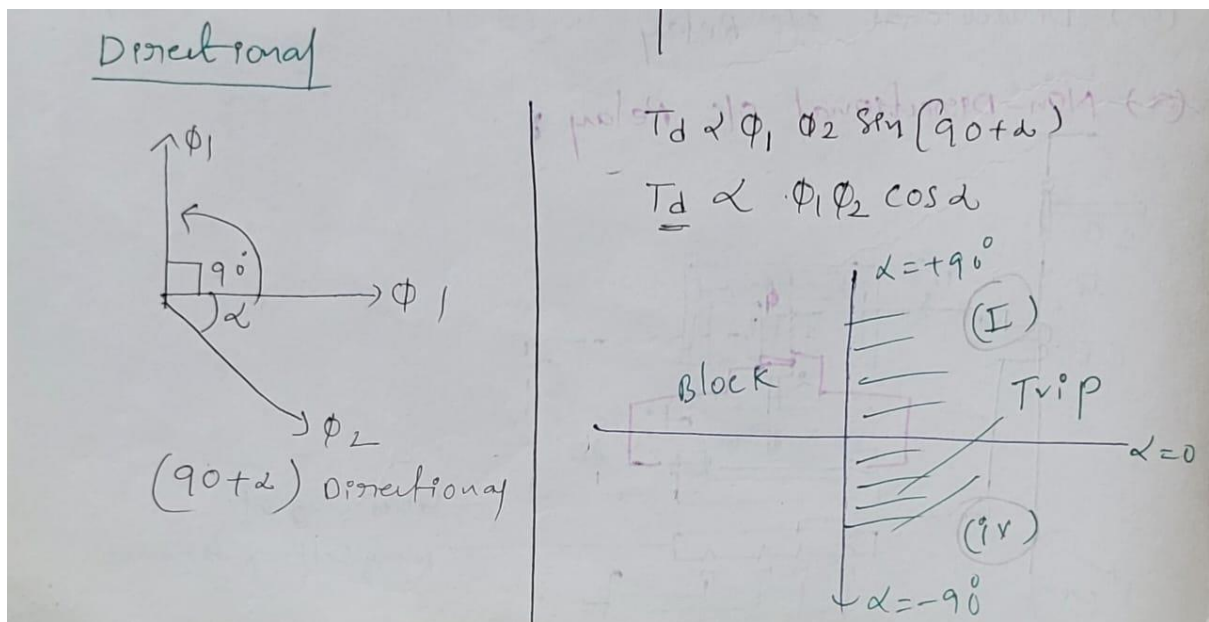
r = maximum torque adjustable angle

$$T_d \propto V I_f \sin[(\alpha + \theta) - r]$$

$$T_d \propto V I_f \cos \alpha \quad \rightarrow \quad r = 0^\circ$$

→ The variable parameter r is adjusted for getting maximum torque angle.

→ Direction relay torque must be higher so that it will operate immediately the current direction is reverse.



Application:

1. Failure of prime mover of generator :

Under health condition generator is delivering both active and reactive powers to the other loads. If the primemover or turbine of the generator is failed and excitation is present then the generator is draws active power from the other generators and starts working as a synchronous motor for which turbine is a load . because of heavy mass of turbine for running this heavy load the motor draws huge current which damage to the winding of stator and some times shaft connected b/w turbine and the generator may be damaged.

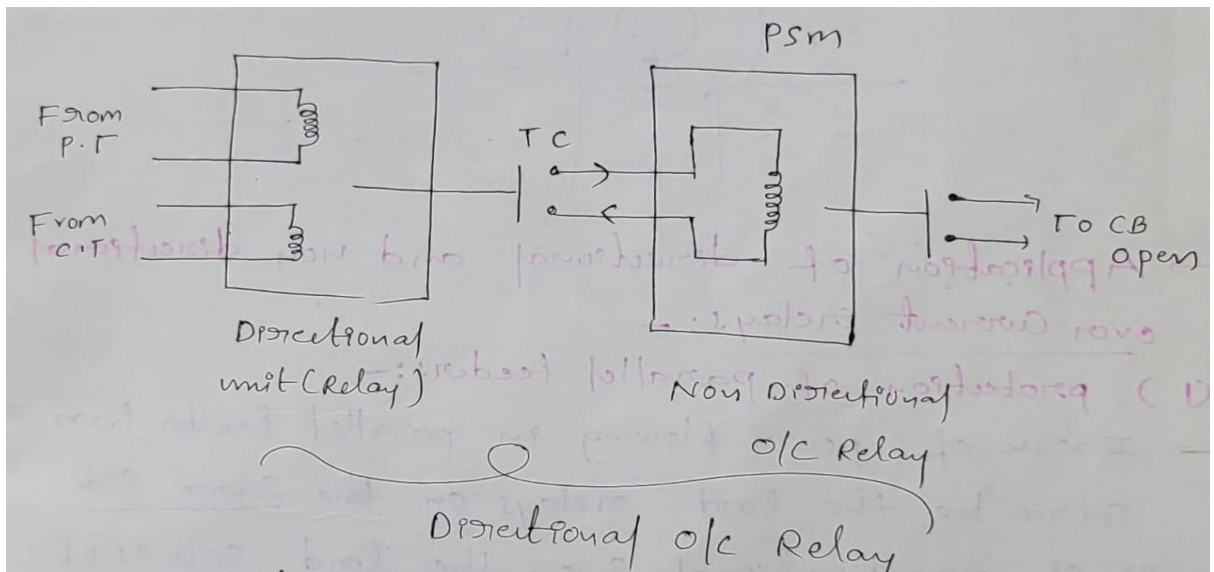
To protect the generator under these condition a reverse power or wattmetric or directional relay used.

- Incase of transformers the power is flow from HV side to LV side if due to some fault on HV side the power direction is reverse i.e LV side to HV side under these condition transformer is protected using directional or reverse power relay(directional overcurrent relay is practically used)

3. Directional over current relay

- It contains both directional relay and non-directional relay.

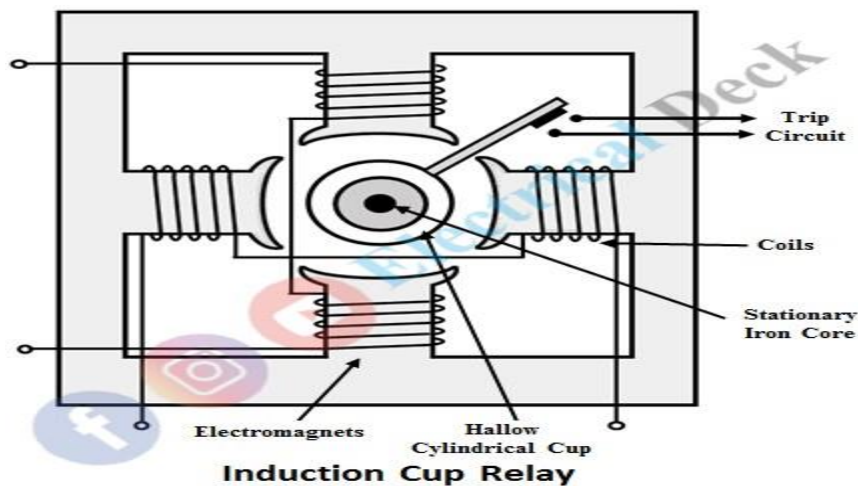
- The directional unit initially operates and closes the trip contacts and if the current value of the reverse current exceeding the PSM of the non-directional relay then only the relay operates and open the circuit breaker.



Induction cup relay

The construction of an induction cup relay is similar to an induction motor. The below shows the construction of the induction cup relay. The induction cup relay consists of the following parts,

- (i) Stationary iron core (stator),
- (ii) Hollow cylindrical cup (rotor),
- (iii) Electromagnet, and
- (iv) Coils.



- The stationary iron core acts as a stator which consists of two, four, or more poles. Nowadays it is constructed for 4 or more poles. The hollow cylindrical cup acts as a rotor similar to a disc in the other two relays. It is free to rotate in the air gap between electromagnets and stationary iron core.
- Due to these fluxes, eddy currents are made to circulate in the rotor. Thus it will give rise to a force that acts on the rotor. So, the hollow cup rotates in the direction of the magnetic field between magnets and stationary iron core as the rotor of the induction motor.
- This makes the fixed contacts of the trip circuit close and sends a trip signal to the breaker to open the circuit. There is a control spring backstop attached to the spindle of the cup to avoid rotation of the rotor continuously.

Application:

The speed of the relay is higher and hence it is used in the application of directional and distance relay.

Types of Overcurrent Relays:

Based on the relay operating time-characteristics, overcurrent relay can be classified into the following types,

- Definite time overcurrent relay
- Instantaneous overcurrent relay
- Inverse time overcurrent relay
- Inverse definite minimum time (IDMT) overcurrent relay
- Extremely inverse time overcurrent relay.

Definite Time Overcurrent Relays:

- These relays operate after a predetermined time when the current exceeds its pick-up value. Here, the operating time of the relay does not depend on the magnitude of the current above the pick-up value. A time delay mechanism is provided to get desired operating time.
- They are used in applications where impedance Z_S between the source and relay is small compared with the impedance Z_L of the section to be protected. They are also used to serve as a check against short-time asymmetrical currents.

Instantaneous Overcurrent Relays:

- They operate immediately when the current exceeds its pick-up value without intentional time delay. It is given as,
 $I^2 t = k$ (constant)
- Where I is the current in the relay coil and t is Relay time.
- They are used for fast relaying operations having an operating time of less than 0.1 seconds.
- Used for differential protection of transformers inrush currents.
- Back-up protection for differential and distance types of relays.
- They are used when the impedance between source and relay is less with respect to the impedance of the system to be protected.

Inverse Time Overcurrent Relays:

In these, the operating time of the relay reduces as the fault quantity increases in magnitude. Normal practice is such that they are more inverse when nearer to pick-up value and become less inverse as it increases. Inverse time relays are used where the source impedance is much smaller than the line impedance.

Inverse Definite Minimum Time (IDMT) Overcurrent Relays:

These relays have the combined characteristics of definite time and inverse time relays. The IDMT relays operate as inverse time relay i.e., there exists an inverse relationship between time and current for lower values of fault current. While for higher values of fault current the relay acts as the definite time relay where the operating time is independent of fault current.

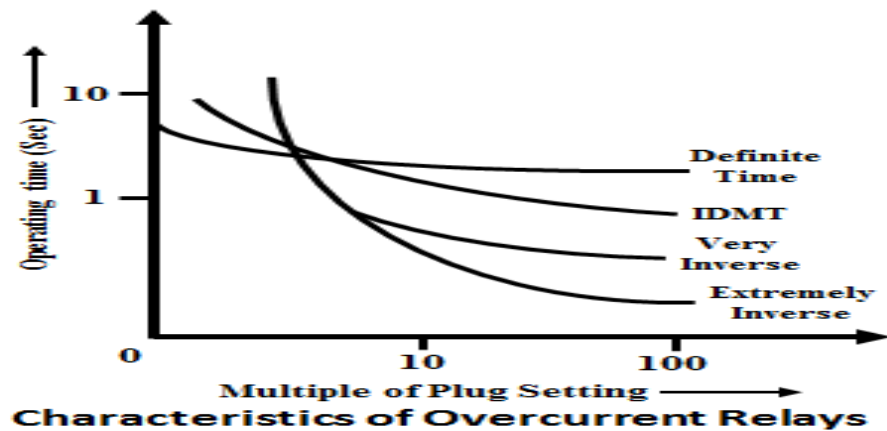
The relay exhibits an inverse relation between operating time and fault current near pick-up value and becomes almost constant just above the pick-up value. IDMT relays are widely used for the protection of distribution lines or distribution feeders.

Extremely Inverse Time Overcurrent Relays:

The time-current characteristics for these relays are steeper than that of very inverse overcurrent characteristics. They are required for fuse coordination and thermal protection of transformers, induction motors, alternators, expensive cables, etc. These relays are used for reclosing distribution circuits after a long outage. Also used for load restoration purposes.

Time-Current Characteristics:

The time-current characteristics of different types of overcurrent relays are shown in the below figure.



Universal Torque equation

Universal Torque Equation :-

$$T_d = K_1 I^2 + K_2 V^2 + K_3 V I \cos(\theta - T) - K_4$$

T_d = Deflecting (or) operating Torque.

$K_1 I^2$ = over current relay.

$K_2 V^2$ = over voltage relay.

$K_3 V I \cos(\theta - T) \Rightarrow$ Directional relay.

K_4 = Restoring Torque due to Spring.

Applications:

(1) Over Current Relay :

Assume $K_3 = K_2 = 0$

$$T_d = K_1 I^2 - K_4$$

(1) Block

$$K_1 I^2 < K_4, T_d < 0, I < \sqrt{\frac{K_4}{K_1}}$$

(2) Trip:

$$I > K_5$$

$I \rightarrow$ Current flowing through at the fault point

$K_5 \rightarrow$ setting value of o/c Relay (psm)

(2) Over voltage relay : (p. 10/11)

Assume $K_1 = K_3 = 0$

$$T_d = K_2 V^2 - K_4$$

(1) Trip

$$K_2 V^2 > K_4$$

$$V > \sqrt{\frac{K_4}{K_2}}$$

$$\boxed{V > K_6}$$

$K_6 =$ Relay setting value.

(2) Block

$$\boxed{V < K_6}$$

$V =$ voltage at the fault (or) voltage of system.

$$K_6 = \sqrt{\frac{K_4}{K_2}}$$

(3) Directional Relay :- (p. 10/11)

Assume $K_1 = K_2 = 0$

$$T_d = K_3 V I \cos(\theta - \tau) - K_4$$

(1) Trip

$$K_3 V I \cos(\theta - \tau) > K_4$$

$$V I \cos(\theta - \tau) > \left(\frac{K_4}{K_3}\right)$$

$$\frac{K_4}{K_3} = K_7$$

$$\boxed{V I \cos(\theta - \tau) > K_7}$$

(2) Block

$$\boxed{V I \cos(\theta - \tau) < K_7}$$

$K_7 =$ Setting value of relay

$V I \cos(\theta - \tau) =$ power flow in the system

Distance relays

- Distance relays are a type of protective relay used in power systems to detect and respond to faults based on the impedance (or distance) between the relay location and the fault point. These relays are widely employed for the protection of transmission lines and other high-voltage electrical equipment.
- The key principle behind distance relays is that the impedance to the fault location changes in a predictable way based on the distance of the fault from the relay. Hence clearly operation or working principle of distance relay depends upon the ratio of system voltage and current. As the ratio of voltage to current is nothing but impedance so a distance relay is also known as impedance relay.
- The operation of such relay depends upon the predetermined value of voltage to current ratio. This ratio is nothing but impedance.

- The relay will only operate when this voltage to current ratio becomes less than its predetermined value. Hence, it can be said that the relay will only operate when the impedance of the line becomes less than predetermined impedance (voltage/current).
- As the impedance of a transmission line is directly proportional to its length, it can easily be concluded that a distance relay can only operate if fault is occurred within a predetermined distance or length of line.

There are main 3 types of distance relays :

1. Impedance relay
2. Reactance relay
3. Mho relay

Impedance relay or Z relay

(a) Impedance (or) Z Relay: (OR)
[Voltage Restraining o/c Relay]

Assume: $K_3 = 0$, $K_4 \Rightarrow$ Very Small

$K_2 = -Ve$

$$T_d = \underbrace{K_1 I^2}_{\text{operating Torque}} - \underbrace{K_2 V^2}_{\text{Restraining Torque}}$$

(1) Trip

$$K_1 I^2 > K_2 V^2$$

$$\sqrt{\frac{K_1}{K_2}} > \left(\frac{V}{I}\right)$$

$$K_8 > \frac{V}{I}$$

$$z_l > z_m$$

$z_m < z_l$

where: $z_l =$ line Actual impedance = setting value of Relay = K_8

$z_m =$ Measured value (or) Impedance Seen by the Relay during fault.

(2) Block:

$z_m > z_l$

Characteristics of 'Z' Relay

$$z_l = (R + jX_L)$$

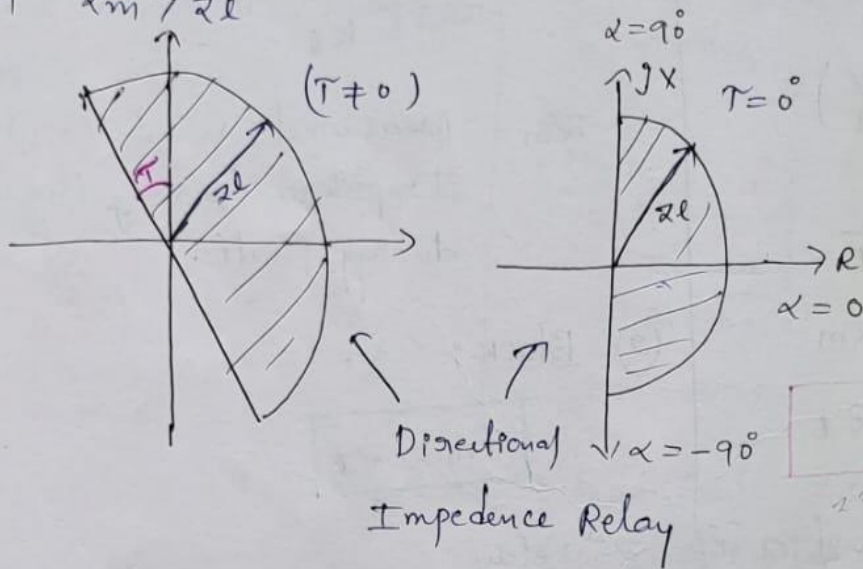
$R =$ Line Actual resistance under healthy condition.
 $X_L =$ " " Reactance " "

$$|z_l| = \sqrt{R^2 + X_L^2}$$

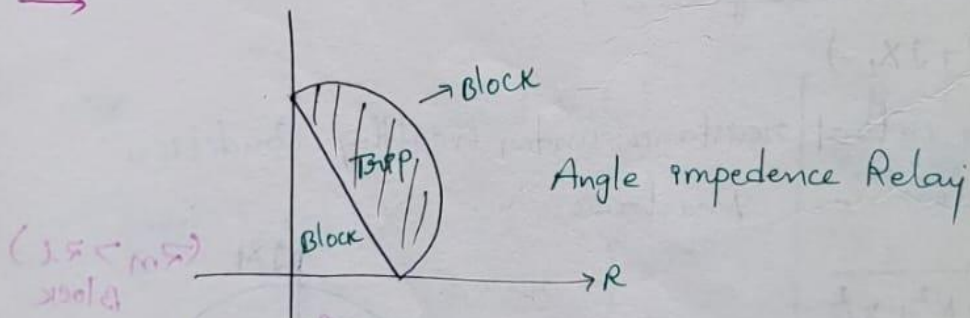
* The locus of z relay is a "circle" in R-X plane with $r = |z_l|$ centre: (0,0)

- Impedance Relay is Non-directional relay
- It is voltage restrain over current relay.
- The impedance relay can be converted into Directional impedance relay by the addition of directional unit (Relay) this directional relay initially checks the direction of the fault and initiates the signal to the impedance relay. which checks the condition $Z_m < Z_L$

or $Z_m > Z_L$



→



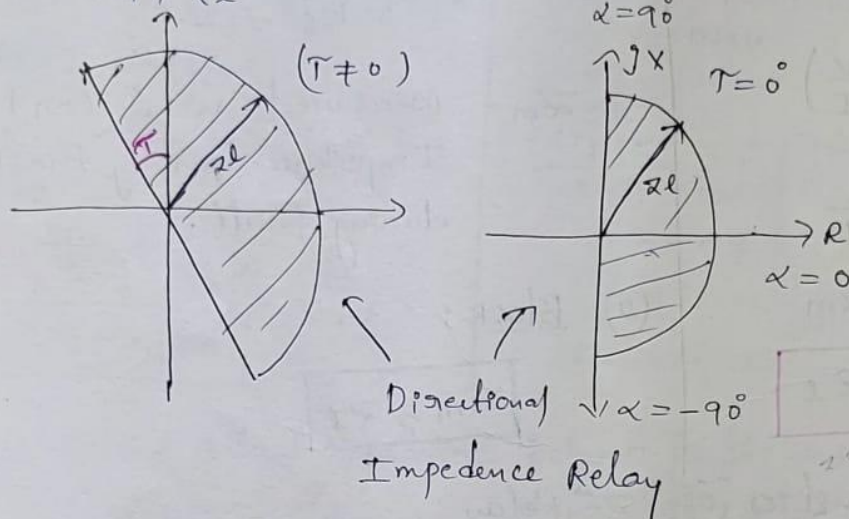
applications:-

- Impedance Relay is used for the protection of Medium Transmission lines.

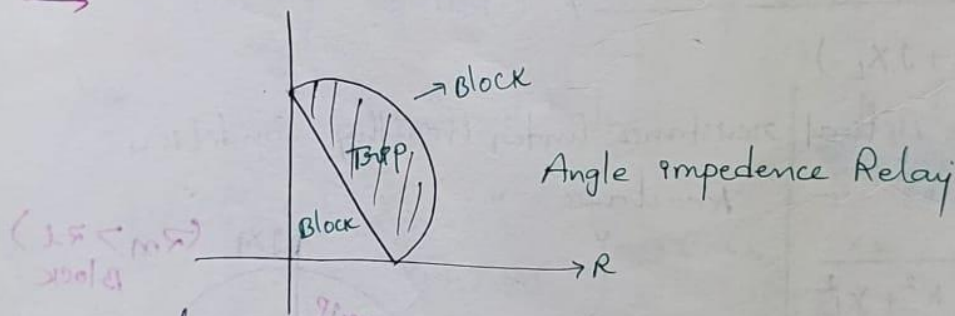
limitation: (1) Z-Relay is not prefer for protection of

- Impedance Relay is Non-directional relay
- It is voltage restrain over current relay.
- The impedance relay can be converted into Directional impedance relay by the addition of directional unit (Relay) this directional relay initially checks the direction of the fault and initiates the signal to the impedance relay. which checks the condition $Z_m < Z_L$

or $Z_m > Z_L$



→



applications:-

- Impedance Relay is used for the protection of medium transmission lines.

limitation: (1) Z -Relay is not prefer for protection of short transmission lines because ~~highly~~ LG-faults

are more frequent in short line which produces arc resistances so that impedance relay may not operate even though fault is present.

NOTE: For protection of short trans-line Reactance relay is used which is independent of Resistance.

(2) Impedance Relay is not used for protection of long trans-line, because imp relay operates for the power swings produce in the long trans-line.

NOTE: Admittance or Mho relay is used for protection of long transmission line. which will not operate for the power swings.

(b) Reactance (or) X-Relay :- [Directional Restraint of Relay]

Assume $k_2 = 0$, $k_4 = \text{Very Small}$

$$k_3 = -ve$$

$$T_d = \underbrace{k_1 I^2}_{\text{operating Torque (O/C)}} - \underbrace{k_3 V I \cos(\theta - \tau)}_{\text{Restraining Torque (Directional)}}$$

operating
Torque (O/C)

Restraining Torque
(Directional)

(1) Trip

$$k_1 I^2 > k_3 V I \cos(\theta - \tau)$$

$$\frac{k_1}{k_3} > \frac{V}{I} \cos(\theta - \tau)$$

$$k_q > Z_m \cos(\theta - \tau)$$

$$\text{Let } \tau = 90^\circ$$

$$k_q > Z_m \cos(\theta - 90^\circ)$$

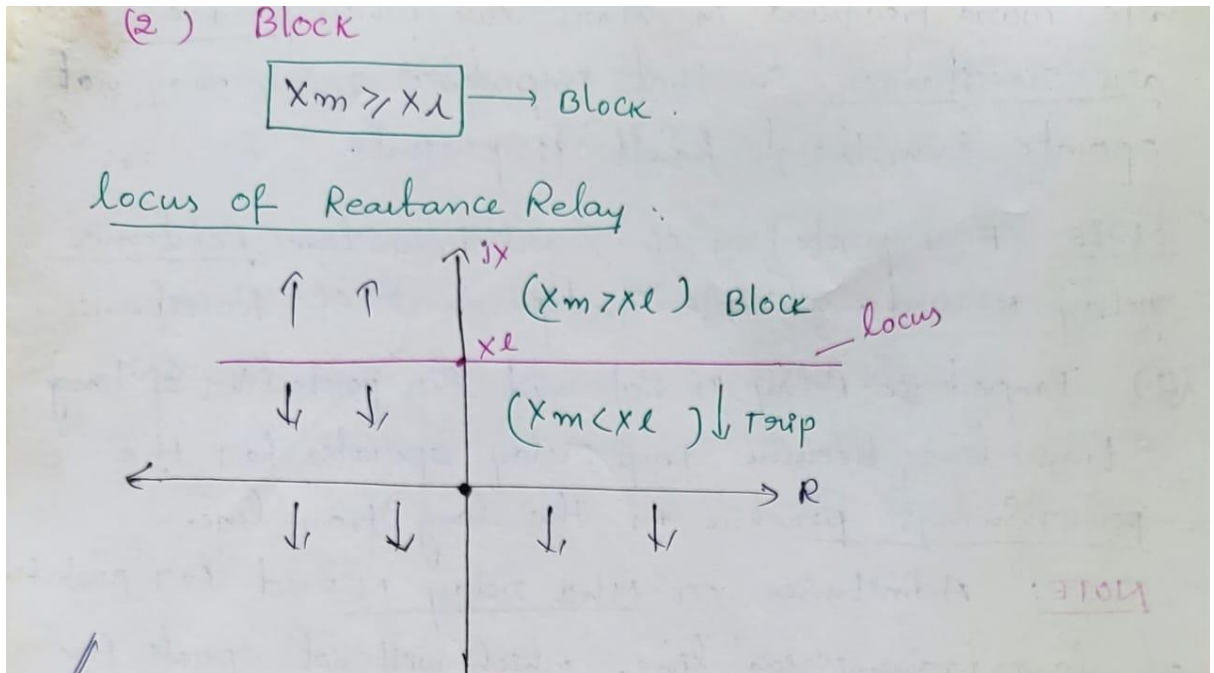
$$k_q > Z_m \sin \theta$$

$k_q = X_L = \text{Reactance of line under healthy condition}$

$Z_m \sin \theta = X_m = \text{Reactance Seen by the relay during fault}$

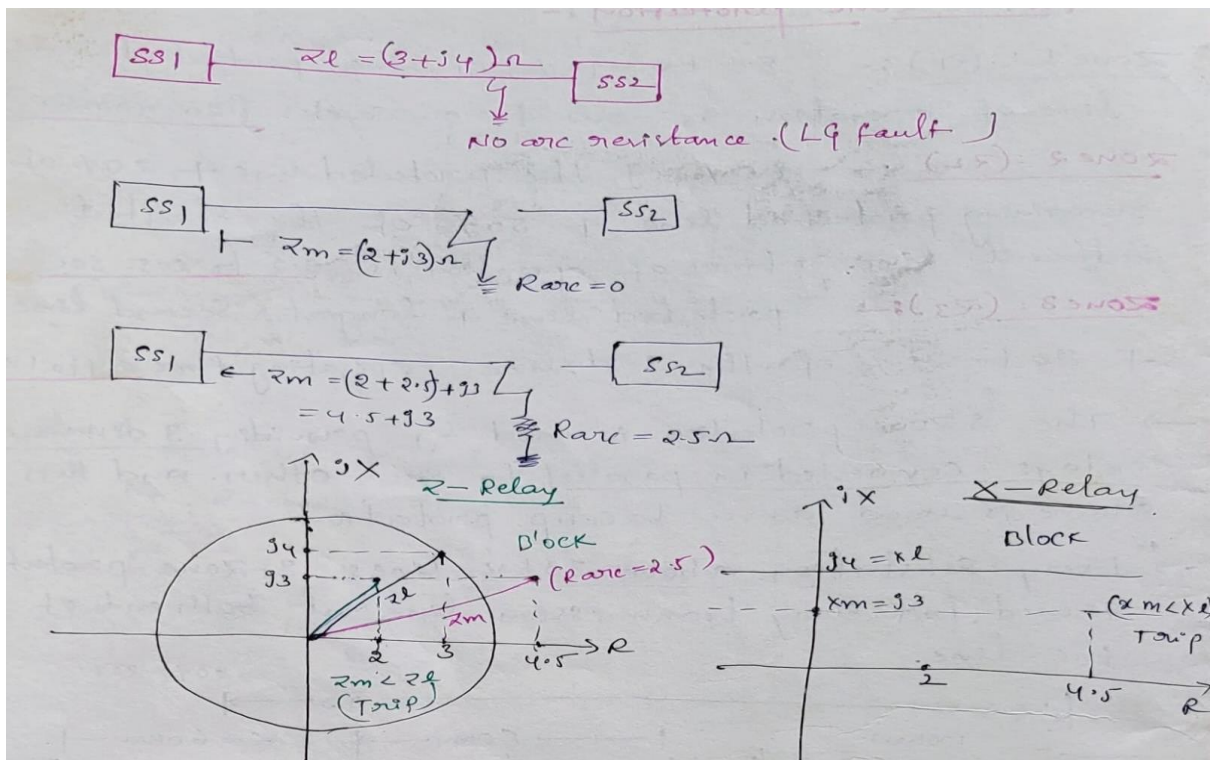
$$X_L > X_m$$

$$\boxed{X_m < X_L} \rightarrow \text{Trip.}$$



Reactance relay is independent on arc resistance hence it is used for protection of short transmission line where LG faults are more frequent due to this arcing ground and arc resistance exist.

Example :



Admittance or Mho or Y relay:

(c) Admittance (or) mho (or) Y relay :-

Assume $k_1 = 0$, $k_4 \Rightarrow$ Very Small [Voltage Restraint Directional Rel]

$k_2 = -ve$

$T_d = \underbrace{k_3 V I \cos(\theta - T)}_{\text{Directional (operating Torque)}} - \underbrace{k_2 V^2}_{\text{over voltage (Restraining)}}$

(1) Trip

$k_3 V I \cos(\theta - T) > k_2 V^2$

$\frac{V I \cos(\theta - T)}{V^2} > \frac{k_2}{k_3}$

$\frac{I}{V} \cos(\theta - T) > k_{10}$

$Y_m \cos(\theta - T) > Y_L$

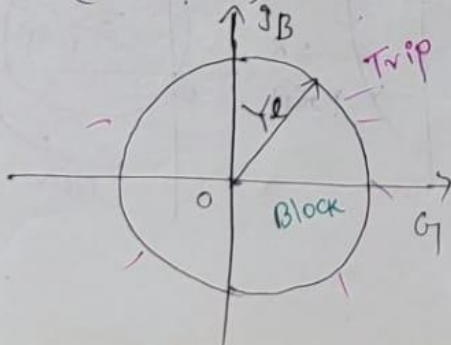
$Y_m = \frac{I}{V} =$ measured admittance

= Admittance seen by relay during fault

Locus of mho relay

(1) G-B plane

$Y_L = (G_L + jB_L)$



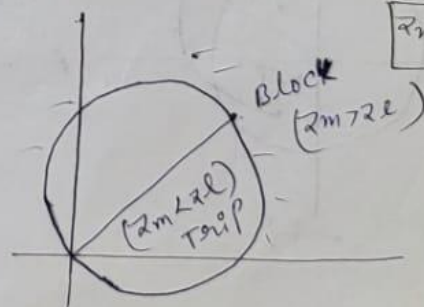
$Y_L =$ Line actual admittance under healthy condition $= k_{10}$

(2) Block

$Y_m \cos(\theta - T) < Y_L$

(2) R-X plane

$Z_L = \frac{1}{Y_L} = \frac{1}{G_L + jB_L} \Rightarrow \frac{G_L}{G_L^2 + B_L^2} - \frac{jB_L}{G_L^2 + B_L^2}$



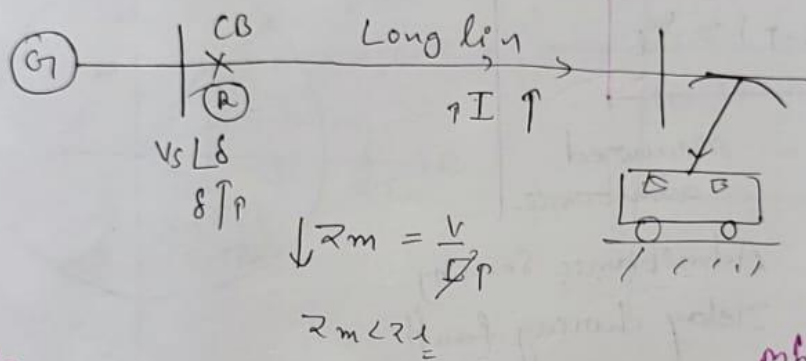
$Z_m = 1/Y_m$

→ The Locus of γ -Relay is a Circle passing through the origin in the $R-X$ plane. the diameter of circle equal to $2L$

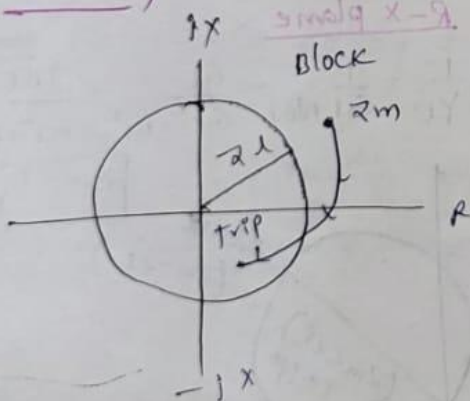
application :

(1) it is used for protection of Long Tran- line.

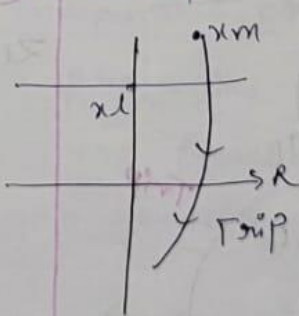
→ incase of long tran- line power Swings are frequent this are not the faults the impedance of Reliance relay operates due to power Swings. but mho relay will not operate for the power Swings and hence it is used for protection long- lines. This relay is only operate for only faults.



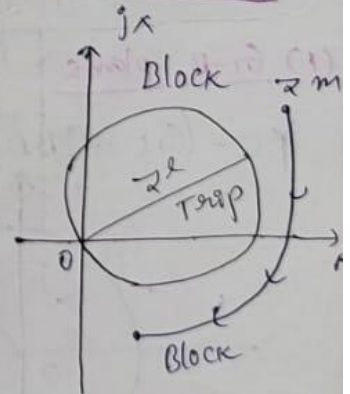
Z-Relay



X-Relay

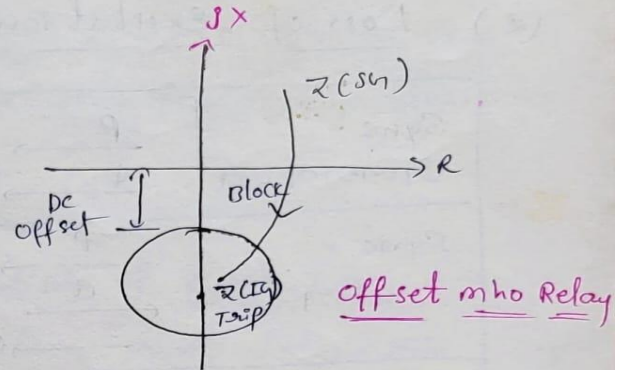
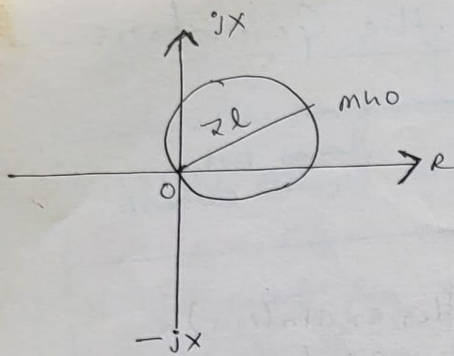
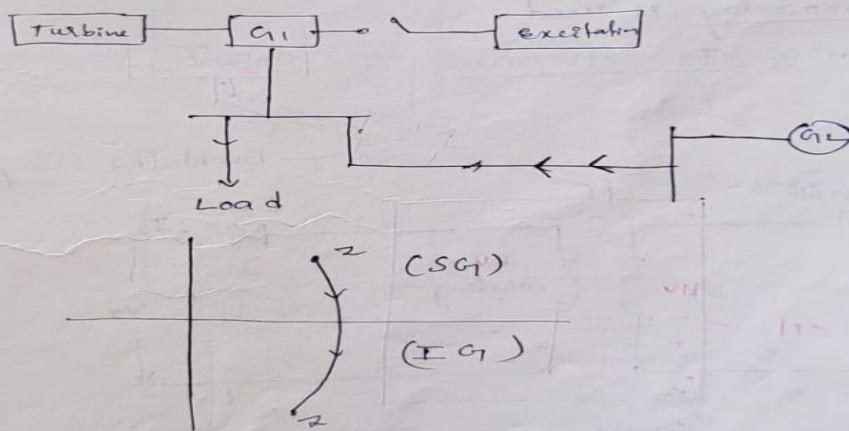


mho-Relay



(2) Loss of Excitation of the Generators -

Sync Generator	$\begin{matrix} \xrightarrow{P} \\ \xrightarrow{Q} \end{matrix}$	$\begin{matrix} \xrightarrow{\text{Deliver}} \\ \xleftarrow{\text{absorb}} \end{matrix}$
Sync motor	$\begin{matrix} \xrightarrow{P} \\ \xleftarrow{Q} \end{matrix}$	$\begin{matrix} \text{(under excitation)} \\ \text{(over excitation)} \end{matrix}$
Induction motor	$\begin{matrix} \xleftarrow{P} \\ \xleftarrow{Q} \end{matrix}$	
Induction Generator	$\begin{matrix} \xrightarrow{P} \\ \xleftarrow{Q} \end{matrix}$	

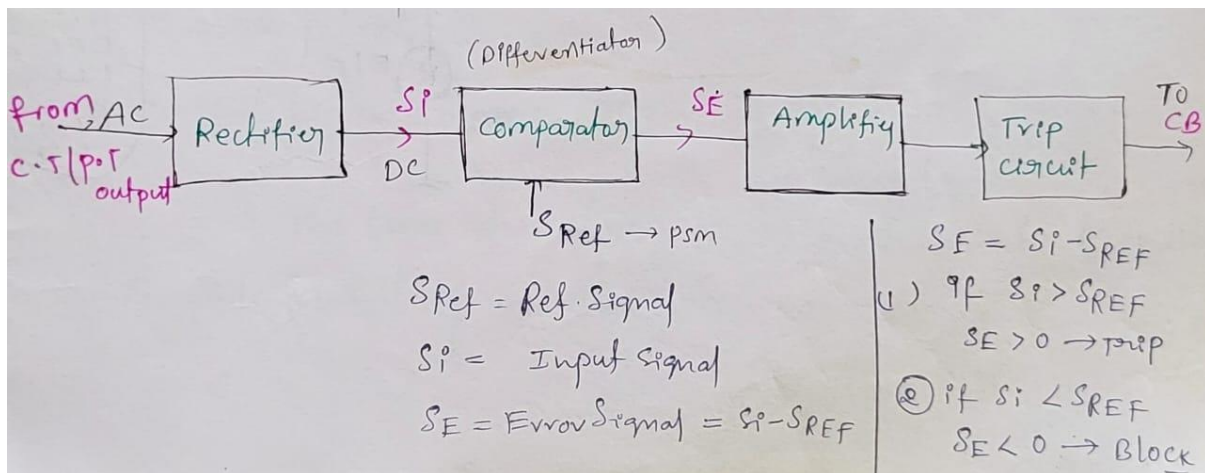


offset mho Relay

→ Failure of excitation of the Sync generator causes the absorbs now reactive power from the other generators and working as a induction generator
 → which causes over heating of generator and hence to protect the generator from loss of excitation offset mho relay is used.

Static relays

Static relay compares two electrical quantities using a static circuit and sends a tripping signal to the circuit breaker. The static circuit includes semiconductor diodes, transistors, thyristors, logic gates, diodes etc., static relays use electromagnetic or dc polarized relays as slave relays. Slave relay does not actually measure the electrical quantity but it simply closed contact.



Static relays verses electromagnetic relays:

The advantages of static relays over electromagnetic are as follows:

- 1 Static relay is compact in size
- 2 Less maintenance is required
- 3 High resistance to shocks
- 4 Static relays consume less power. So, it provides fewer burdens of potential transformers and current transformers.
- 5 There are no moving contacts.
- 6 A single static relay is used for several functions.
- 7 A static relay employs logic circuits. So, it can do the process of reasoning.
- 8 It is used for remote back-up and network monitoring.

But the limitations of static relays are

- 1 The price of static relays is higher than the electromagnetic relays.
- 2 The device in the static circuit is very much affected by temperature.
- 3 Static devices such as thyristors are sensitive electro-static discharges (ESD).
- 4 The semiconductor devices are sensitive to voltage transients. So, they may get damaged.

Chapter 4:

ALTERNATOR & TRANSFORMER PROTECTION

Differential Protection of Alternators, Modified Differential Protection for Alternators, Balanced or Restricted Earth-fault Protection, Stator Interturn Protection. PROTECTION OF TRANSFORMERS: Percentage Differential Protection, Buchholtzrelay Protection.

Differential protection:

Differential Relay.

At Node A

$$i_R + i_2 = i_1$$

$$\bar{i}_R = (\bar{i}_1 - \bar{i}_2)$$

<p>(1) $i_1 = i_2$ $i_R = 0 \leftarrow$ Block</p>	<p>(2) $(i_1 - i_2) \neq 0$ $i_R \neq 0 \leftarrow$ Trip</p>
--	---

→ A differential relay operates to if the vector difference (magnitude & phase) b/w two electrical quantities like voltage, current etc...

→ under normal condition $I_1 = I_2$ so that $i_1 = i_2$ and $i_R = 0$ then the relay will not operate.

→ if a fault occurred in the winding b/w CT₁ & CT₂ then $I_1 \neq I_2$, $i_1 \neq i_2$ and $i_R \neq 0$ this current

If initiate relay operating coil and this operating torque more than controlling or restraining torque then the relay operate open the C.B.

Applications

1. Used for protection of Generator, stator winding
if these both C.T's CT₁ & 2 has same ratio.

2. Used for protection of power Transformer winding on H.V & L.V side. The C.T ratios are different on H.V and L.V side because

$$\frac{V_2}{V_1} = \frac{I_1}{I_2}$$

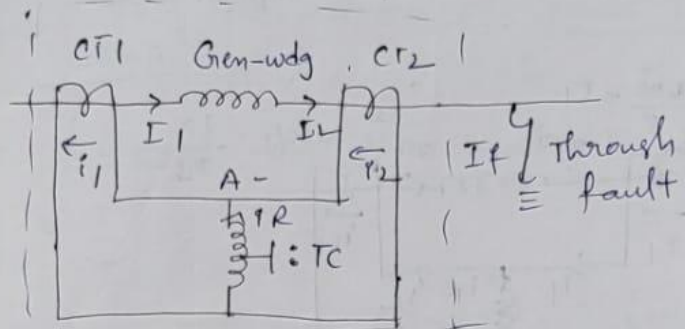
3. Used as a pilot wire protection scheme for protection of Busbars and Tran-lines by phase comparison or direction comparison or magnitude comparison of the busbar and Tran-line. It is also called "circulating current protection". In this protection C.T's ratios are also same.

→ pilot: It is a channel used for communicating electrical signals like current, voltage, frequency from one place to other place using electrical cables or radio links.

Difficulties of ordinary differential relay :

Through fault :-

- If the fault is outside the protected zone (unit protection) then it is called through fault.
- For through fault the unit protection relay (differential relay) must not operate.



→ Saturation of core of one of CT's :-

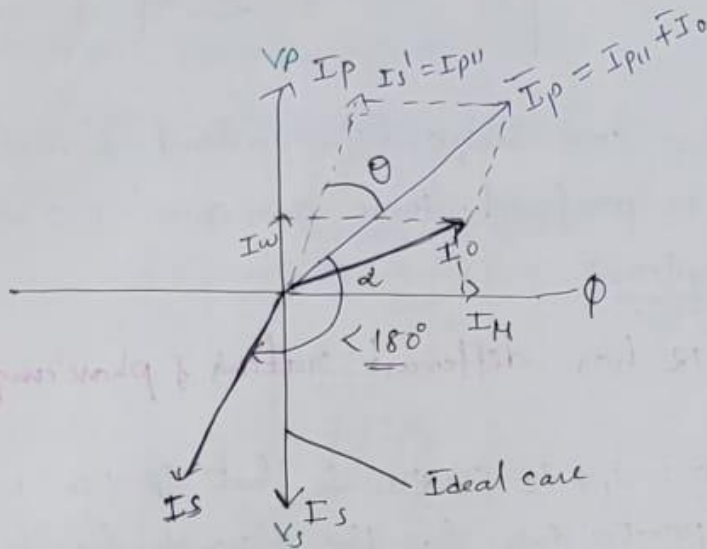
- For the through faults the core of one CT is saturated then $I_R \neq 0$ occurs, so that Relay operates for the through faults.

If	CT1 100/1A	CT2 100/1A	$I_R = I_1 - I_2$
100	$I_1 = 1$	$I_2 = 1$	$I_R = 0 \leftarrow$ Block
200	2	2	$= 0 \leftarrow$ "
400	3	2	1 \leftarrow Trip
600	4	2	2 \leftarrow Trip

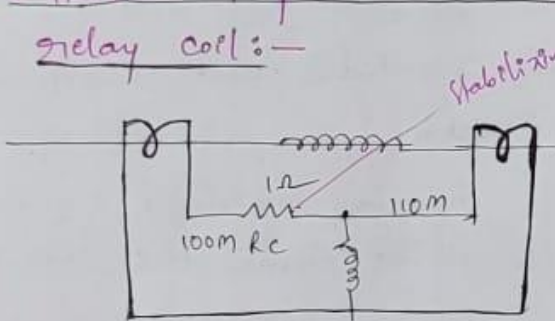
CT2 core saturation

phase angle error:

→ The phase angle b/w I_s & I_p is 180° for ideal C.T or p.T, due to I_0 Component the phase angle is $< 180^\circ$ occurs this is called phase angle error.



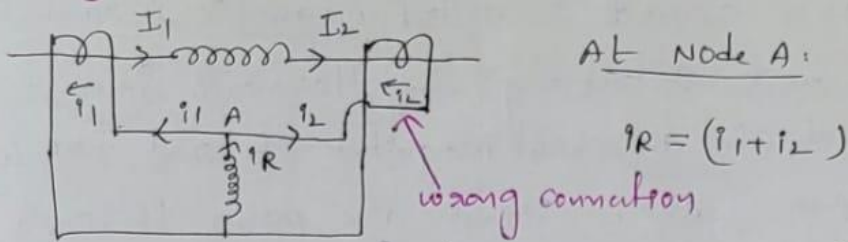
Difference in pilot wire lengths from CT₁ to CT₂ to the relay coil:-



→ If the pilot wires have different lengths then their resistances also differ. So that potential difference across the relay is not equal to zero and hence relay operate without fault for compensating this effect a stabilizing or compensating resistor is connected in series to the short length ^(low resistance) pilot wire (71)

parallel to the relay coil.

→ wrong connections of pilot wire on one side of C.T.:-



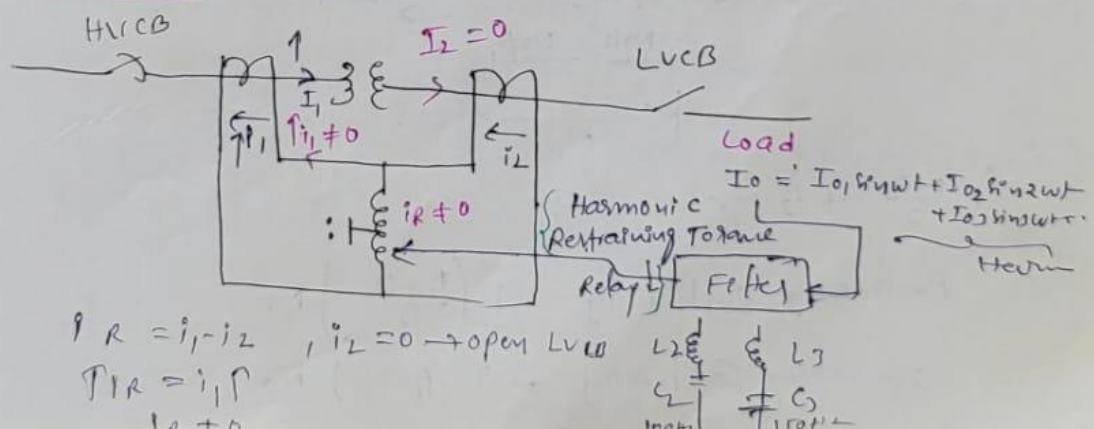
→ Due to wrong connection of CT on one side maximum current will flow through relay, so that relay operate without any fault:

NOTE: The wrong connection is done on both side then $I_R = i_1 - i_2$ relay will not operate under normal condition.

→ Tap changing Transformer mal operation:-

→ The taps on the H.V side change then the the currents changes so that Secondary current of CT is also changes and this causes $I_R \neq 0$ and hence relay operates without any fault.

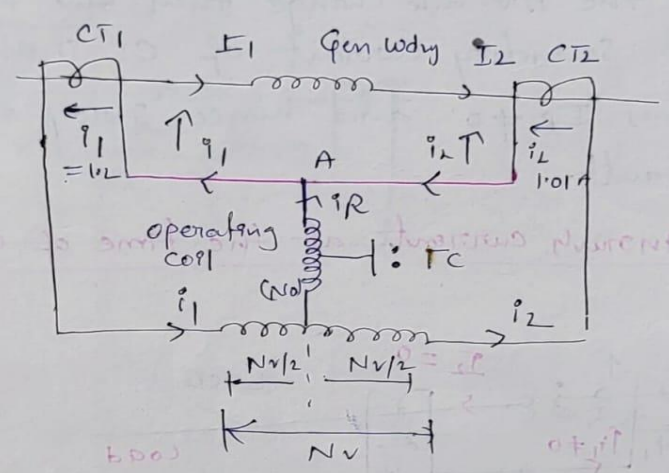
→ magnetic inrush current at the time of charging of T/F:-



→ at the initial charging of T/F The No-load initial current is very high that is 5 to 10 times full load current this current is called magnetic inrush current
 → this current consisting of Harmonic signals like 2nd, 3rd etc in which magnitude of 2nd, 3rd harmonics are higher, these signals are passed through the filter called harmonic restrain relay, which will produce additional restraining torque so that operating coil of the relay will not operate at the time of charging T/F.

% Differential or Merz price or balanced beam or biased relay

% Differential (or) merz price (or) Balanced beam (or) Biased relay:-



$$i_1 \frac{N_0}{2} + i_2 \frac{N_0}{2}$$

Restrainig coil mmf $\Rightarrow \left(\frac{i_1 + i_2}{2} \right) N_v$

operating coil mmf $\Rightarrow (i_1 - i_2) N_0$

Relay operation:

$$(i_1 - i_2) N_0 > \left(\frac{i_1 + i_2}{2} \right) N_1 \leftarrow \text{Trip [NO Spring Torque]}$$

$$\boxed{\frac{(i_1 - i_2)}{\left(\frac{i_1 + i_2}{2} \right)} = \frac{N_1}{N_0} \Rightarrow K} = \text{pick up value of the Relay}$$

→ with Spring Torque: $[K_c]$

$$(i_1 - i_2) = K \left[\frac{i_1 + i_2}{2} \right] + K_c$$

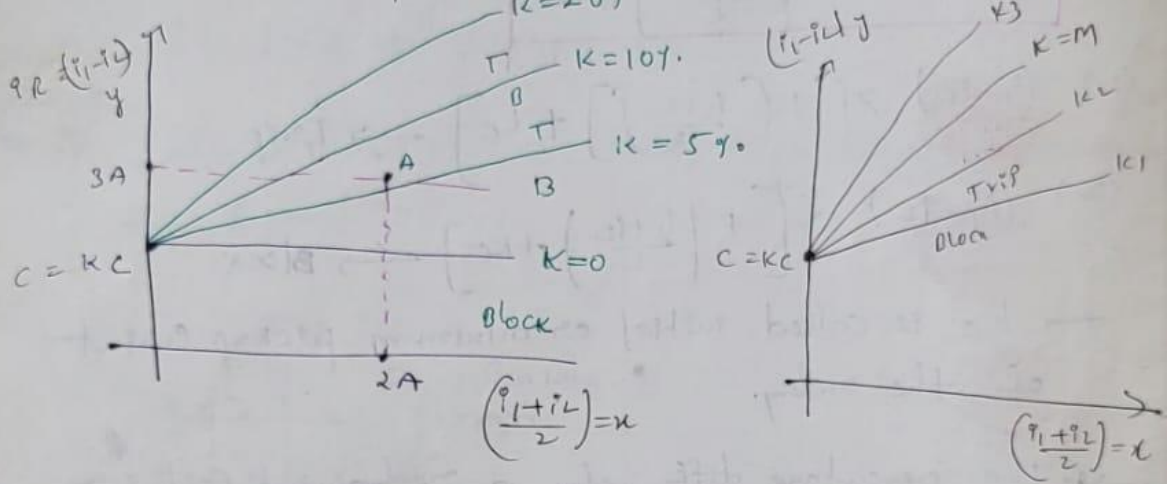
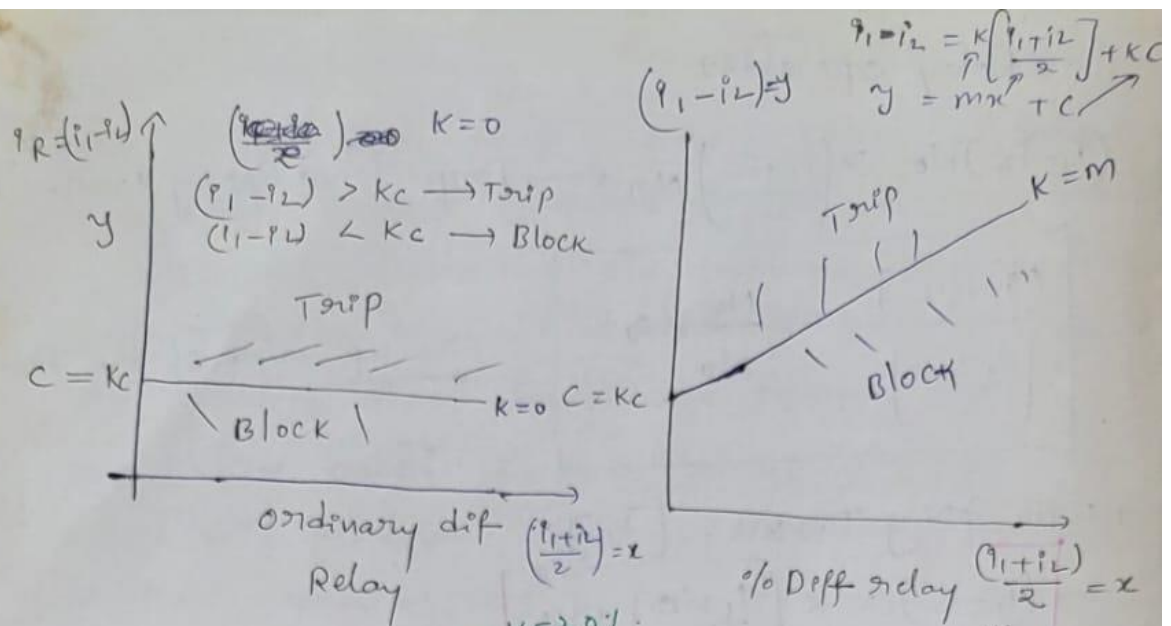
$$(1) (i_1 - i_2) > \left[K \left(\frac{i_1 + i_2}{2} \right) + K_c \right] \rightarrow \text{Trip}$$

$$(2) (i_1 - i_2) < \left[K \left(\frac{i_1 + i_2}{2} \right) + K_c \right] \rightarrow \text{Block}$$

→ K_c is called initial or minimum pickup current of the relay.

→ The percentage diff vely a restraining coil is provided it produces additional rotating torque in case of mal operation of relay due to difficulties of ordinary ^{diff} relay, so that relay will not operate under fault conditions.

→ under fault conditions if $(i_1 - i_2) > K_c + K \left(\frac{i_1 + i_2}{2} \right)$ then only relay operates.



→ In % Diff relay the percentage setting value 'K' is an adjustable parameter similar to psm.
 → The normal range of K is b/w 5 to 25% in steps of 5

K
25%
20%
15%
10%
5%

Alternator Protection

Stator winding faults: These faults occur mainly due to the insulation failure of the stator windings. The main types of stator winding faults, in order of importance are:

1. Fault between phase and ground
2. Fault between phases
3. Inter-turn fault involving turns of the same phase winding

The stator winding faults are the most dangerous and are likely to cause considerable damage to the expensive machinery. Therefore, automatic protection is absolutely necessary to clear such faults in the quickest possible time in order to minimize the *extent of damage. For protection of alternators against such faults, differential method of protection (also known as Merz - Price system) is most commonly employed due to its greater sensitivity and reliability. This system of protection is dis-cussed in the following section.

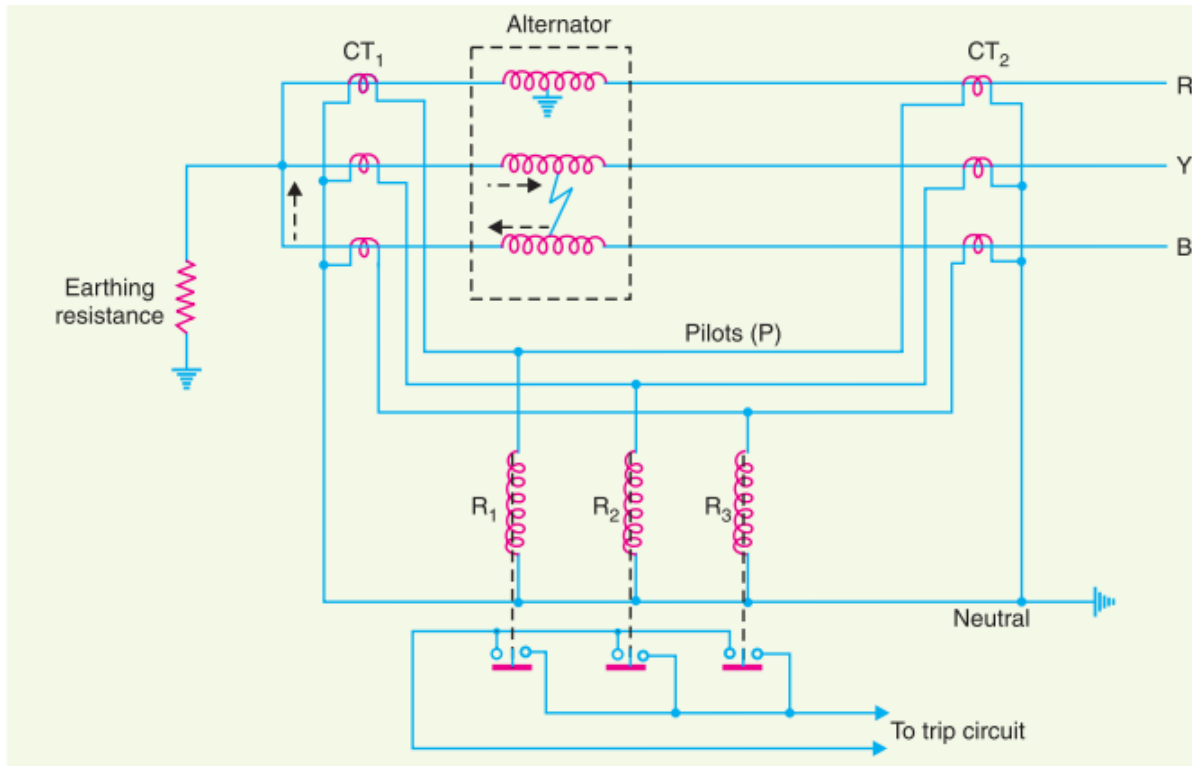
DIFFERENTIAL PROTECTION OF ALTERNATORS

- The most common system used for the protection of stator winding against earth faults and phase to phase faults (internal faults only).
- It employs circulating current principle. In this scheme of protection, currents at the two ends of the protected section are compared.
- CTs on both side of winding have same ratio.
- Under normal operating conditions, these currents are equal but may become unequal on the occurrence of a fault in the protected section. The difference of the currents under fault conditions is arranged to pass through the operating coil of the relay. The relay then closes its contacts to isolate protected section from the system.
- This form of protection is also known as Merz-Price circulating current scheme.
- This relay will not operate for external faults i.e earth fault and phase faults outside of the protected zone.

Schematic arrangement.

Below Fig. shows the schematic arrangement of current differential protection for a 3-phase alternator. Identical current transformer pairs CT1 and CT2 are placed on either side of each phase of the stator windings. The secondaries of each set of current transformers are connected in star; the two neutral points and the corresponding terminals of the two-star groups being

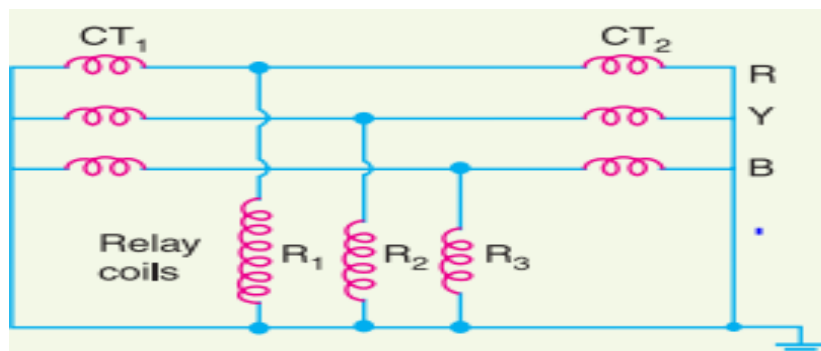
connected together by means of a four-core pilot cable. Thus, there is an independent path for the currents circulating in each pair of current transformers and the corresponding pilot P.



The relay coils are connected in star, the neutral point being connected to the current-transformer common neutral and the outer ends one to each of the other three pilots. In order that burden on each current transformer is the same, the relays are connected across equipotential points of the three pilot wires and these equipotential points would naturally be located at the middle of the pilot wires. The relays are generally of electromagnetic type and are arranged for instantaneous action since fault should be cleared as quickly as possible.

Operation.

it is clear that the relays are connected in shunt across each circulating path. Therefore, the circuit be shown in a simpler form in below Fig.



- Under normal operating conditions, the current at both ends of each winding will be equal and hence the currents in the secondaries of two CTs connected in any phase will also be equal. Therefore, there is balanced circulating current in the pilot wires and no current flows through the operating coils (R1, R2 and R3) of the relays.
 - When an earth-fault or phase-to-phase fault occurs, this condition no longer holds good and the differential current flowing through the relay circuit operates the relay to trip the circuit breaker.
- (i) Suppose an earth fault occurs on phase R due to breakdown of its insulation to earth as shown in Fig. The current in the affected phase winding will flow through the core and frame of the machine to earth, the circuit being completed through the neutral earthing resistance. The currents in the secondaries of the two CTs in phase R will become unequal and the difference of the two currents will flow through the corresponding relay coil (i.e., R1), returning via the neutral pilot. Consequently, the relay operates to trip the circuit breaker.
- (ii) Imagine that now a short-circuit fault occurs between the phases Y and B as shown in Fig. The short-circuit current circulates via the neutral end connection through the two windings and through the fault as shown by the dotted arrows. The currents in the secondaries of two CTs in each affected phase will become unequal and the differential current will flow through the operating coils of the relays (i.e. R2 and R3) connected in these phases. The relay then closes its contacts to trip the circuit breaker.

Limitations.

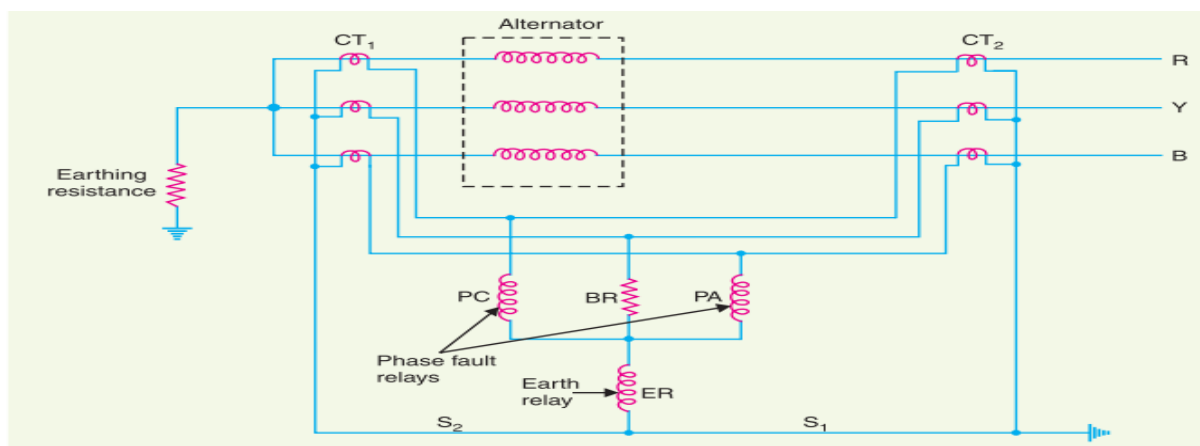
- The two circuits for alternator protection shown above have their own limitations. It is a general practice to use neutral earthing resistance in order to limit the destructive effects of earth-fault currents. In such a situation, it is impossible to protect whole of the stator windings of a star-connected alternator during earth-faults. When an earth-fault occurs near the neutral point, there may be insufficient voltage across the short-circuited portion to drive the necessary current round the fault circuit to operate the relay.
- The magnitude of unprotected zone depends upon the value of earthing resistance and relay setting. Makers of protective gear speak of “protecting 80% of the winding” which means that faults in the 20% of the winding near the neutral point cannot cause tripping i.e., this portion is unprotected. It is a usual practice to protect only 85% of the

winding because the chances of an earth fault occurring near the neutral point are very rare due to the uniform insulation of the winding throughout.

Modified Differential Protection for Alternators:

- If the neutral point of a star-connected alternator is earthed through a high resistance, protection schemes will not provide sufficient sensitivity for earth-faults. It is because the high earthing resistance will limit the earth-fault currents to a low value, necessitating relays with low current settings if adequate portion of the generator winding is to be protected.
- However, too low a relay setting is undesirable for reliable stability on heavy through phase-faults. In order to overcome this difficulty, a modified form of differential protection is used in which the setting of earth faults is reduced without impairing stability.
- The modified arrangement is shown in below Fig. The modifications affect only the relay connections and consist in connecting two relays for phase-fault protection and the third for earth-fault protection only.
- The two-phase elements (PC and PA) and balancing resistance (BR) are connected in star and the earth relay (ER) is connected between this star point and the fourth wire of circulating current pilot-circuit.

Operation. Under normal operating conditions, currents at the two ends of each stator winding will be equal. Therefore, there is a balanced circulating current in the phase pilot wires and no current flows through the operating coils of the relays. Consequently, the relays remain inoperative.

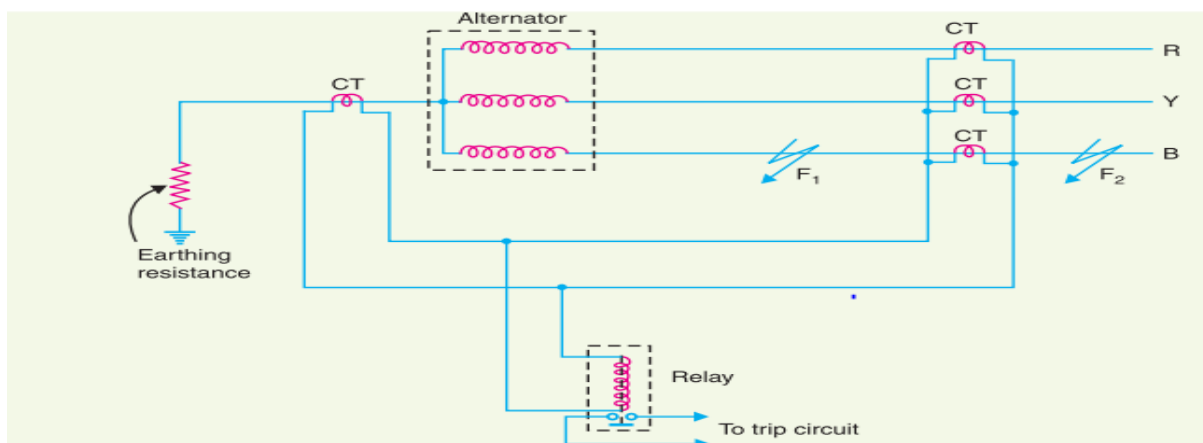


- If an earth-fault occurs on any one phase, the out-of-balance secondary current in CTs in that phase will flow through the earth relay ER and via pilot S1 or S2 to the neutral of the current transformers. This will cause the operation of earth relay only.
- If a fault occurs between two phases, the out of-balance current will circulate round the two transformer secondaries via any two of the coils PA, BR, PC (the pair being decided by the two phases that are faulty) without passing through the earth relay ER. Therefore, only the phase-fault relays will operate.

Balanced/restricted Earth-fault Protection

- In small-size alternators, the neutral ends of the three-phase windings are often connected internally to a single terminal. Therefore, it is not possible to use Merz-Price circulating current principle described above because there are no facilities for accommodating the necessary current transformers in the neutral connection of each phase winding.
- Under these circumstances, it is considered sufficient to provide protection against earth-faults only by the use of balanced earth-fault protection scheme.
- This scheme provides no protection against phase-to-phase faults, unless and until they develop into earth-faults, as most of them will.

Schematic arrangement. Below Fig. shows the schematic arrangement of a balanced earth-fault protection for a 3-phase alternator. It consists of three-line current transformers, one mounted in each phase, having their secondaries connected in parallel with that of a single current transformer in the conductor joining the star point of the alternator to earth. A relay is connected across the transformer's secondaries. The protection against earth faults is limited to the region between the neutral and the line current transformers.

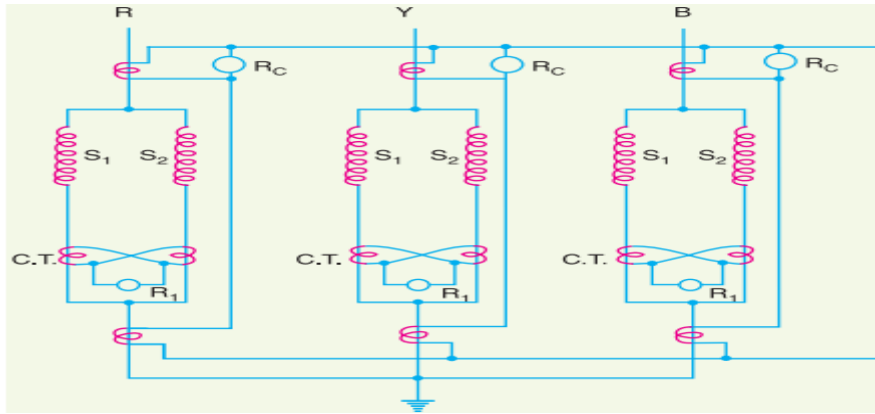


Operation.

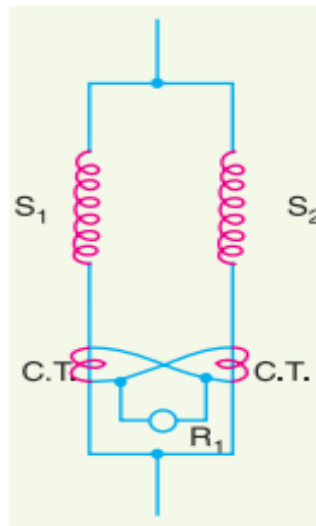
Under normal operating conditions, the currents flowing in the alternator leads and hence the currents flowing in secondaries of the line current transformers add to zero and no current flows through the relay. Also under these conditions, the current in the neutral wire is zero and the secondary of neutral current transformer supplies no current to the relay. If an earth-fault develops at F2 external to the protected zone, the sum of the currents at the terminals of the alternator is exactly equal to the current in the neutral connection and hence no current flows through the relay. When an earth-fault occurs at F1 or within the protected zone, these currents are no longer equal and the differential current flows through the operating coil of the relay. The relay then closes its contacts to disconnect the alternator from the system.

Stator Inter Stator Inter-Turn Protection

- Merz-price circulating-current system protects against phase-to-ground and phase-to-phase faults. It does not protect against turn-to-turn fault on the same phase winding of the stator. It is because the current that this type of fault produces flows in a local circuit between the turns involved and does not create a difference between the currents entering and leaving the winding at its two ends where current transformers are applied. However, it is usually considered unnecessary to provide protection for inter-turn faults because they invariably develop into earth-faults.
- In single turn generator (e.g. large steam-turbine generators), there is no necessity of protection against inter-turn faults. However, inter-turn protection is provided for multi-turn generators such as hydro-electric generators. These generators have double-winding armatures (i.e. each phase winding is divided into two halves) owing to the very heavy currents which they have to carry.
- Advantage may be taken of this necessity to protect inter-turn faults on the same winding. Below figure shows the schematic arrangement of circulating-current and inter-turn protection of a 3-phase double wound generator. The relays RC provide protection against phase-to-ground and phase-to-phase faults whereas relays R1 provide protection against inter-turn faults.



Below Fig. shows the duplicate stator windings S1 and S2 of one phase only with a provision against inter-turn faults. Two current transformers are connected on the circulating-current principle. Under normal conditions, the currents in the stator windings S1 and S2 are equal and so will be the currents in the secondaries of the two CTs. The secondary current round the the loop then is the same at all points and no current flows through the relay R1. If a short-circuit develops between adjacent turns, say on S1, the currents in the stator windings S1 and S2 will no longer be equal. Therefore, unequal currents will be induced in the secondaries of CTs and the difference of these two currents flows through the relay R1. The relay then closes its contacts to clear the generator from the system.



Protection of 3 phase transformer using % differential or Merz price protection.

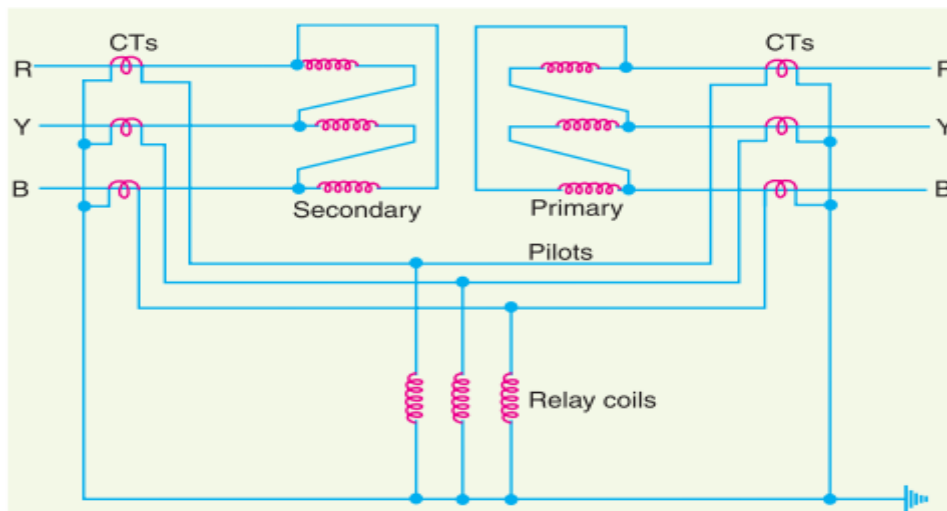
Merz-Price circulating -current principle is commonly used for the protection of power transformers against earth and phase faults. The system as applied to transformers is fundamentally the same as that for generators but with certain complicating features not encountered in the generator application. The complicating features and their remedial measures are briefed below:

- (i) The difference in the magnitude of currents in the primary and secondary of power transformer is compensated by different turn ratios of CTs. Here different ratios CT1 and CT2 used. Consequently, no differential current will flow through the relay and it remains inoperative.
- (ii) There is usually a phase difference between the primary and secondary currents of a 3-phase power transformer. Even if CTs of the proper turn-ratio are used, a differential current may flow through the relay under normal conditions and cause relay operation. The correction for phase difference is affected by appropriate connections of CTs. The CTs on one side of the power transformer are connected in such a way that the resultant currents fed into the pilot wires are displaced in phase from the individual phase currents in the same direction as, and by an angle equal to, the phase shift between the power-transformers primary and secondary currents. The table below shows the type of connections to be employed for CTs in order to compensate for the phase difference in the primary and secondary currents of power transformer.

S. No.	Power transformer connections		Current transformer connections	
	Primary	Secondary	Primary	Secondary
1	Star with neutral earthed	Delta	Delta	Star
2	Delta	Delta	Star	Star
3	Star	Star with neutral earthed	Delta	Delta
4	Delta	Star with neutral earthed	Star	Delta

- (iii) Most transformers have means for tap changing which makes this problem even more difficult. Tap changing will cause differential current to flow through the relay even under normal operating conditions. The above difficulty is overcome by adjusting the turn-ratio of CTs on the side of the power transformer provided with taps.

(iv) Another complicating factor in transformer protection is the magnetizing in-rush current. Under normal load conditions, the magnetizing current is very small. However, when a transformer is energized after it has been taken out of service, the magnetizing or in-rush current can be extremely high for a short period. Since magnetizing current represents a current going into the transformer without a corresponding current leaving, it appears as a fault current to differential relay and may cause relay operation. While applying circulating current principle for protection of transformers, above precautions are necessary in order to avoid inadvertent relay operation.

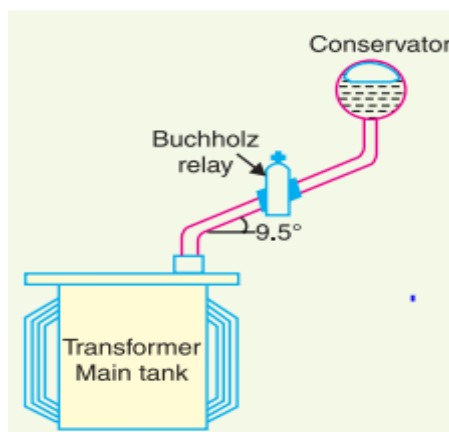


- Above Fig. shows Merz-Price circulating-current scheme for the protection of a 3-phase delta/delta power transformer against phase-to-ground and phase-to-phase faults. Note that CTs on the two sides of the transformer are connected in star. This compensates for the phase difference between the power transformer primary and secondary. The CTs on the two sides are connected by pilot wires and one relay is used for each pair of CTs.
- During normal operating conditions, the secondaries of CTs carry identical currents. Therefore, the currents entering and leaving the pilot wires at both ends are the same and no current flows through the relays. If a ground or phase-to-phase fault occurs, the currents in the secondaries of CTs will no longer be the same and the differential current flowing through the relay circuit will clear the breaker on both sides of the transformer. The-protected zone is limited to the region between CTs on the high-voltage side and the CTs on the low-voltage side of the power transformer.
- It is worthwhile to note that this scheme also provides protection for short-circuits between turns on the same phase winding. When a short-circuit occurs between the

turns, the turn-ratio of the power transformer is altered and causes unbalance between current transformer pairs. If turn-ratio of power transformer is altered sufficiently, enough differential current may flow through the relay to cause its operation. However, such short-circuits are better taken care of by Buchholz relays.

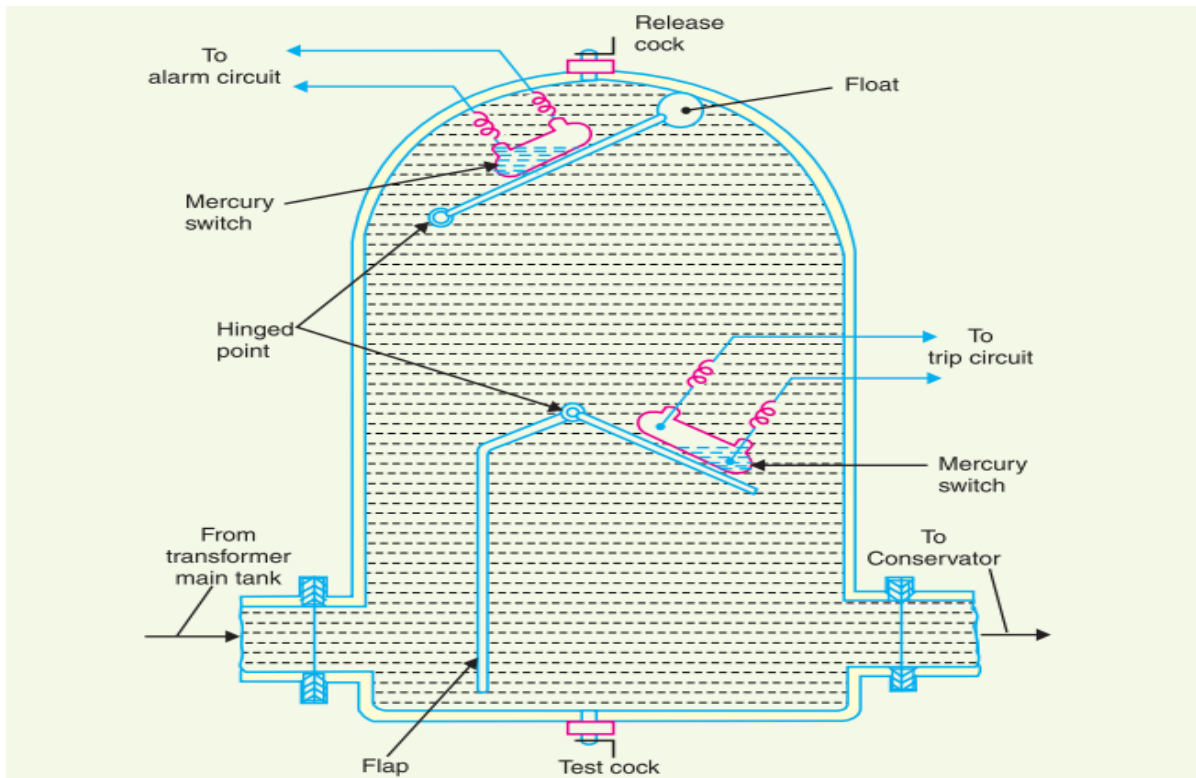
Buchholz Relay:

Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against all kinds of faults. Named after its inventor, Buchholz, it is used to give an alarm in case of incipient (i.e. slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults. It is usually installed in the pipe connecting the conservator to the main tank as shown in below Fig. It is a universal practice to use Buchholz relays on all such oil immersed transformers having ratings in *excess of 750 kVA.



Construction.

Below Fig. shows the constructional details of a Buchholz relay. It takes the form of a domed vessel placed in the connecting pipe between the main tank and the conservator. The device has two elements. The upper element consists of a mercury type switch attached to a float. The lower element contains a mercury switch mounted on a hinged type flap located in the direct path of the flow of oil from the transformer to the conservator. The upper element closes an alarm circuit during incipient faults whereas the lower element is arranged to trip the circuit breaker in case of severe internal faults.



Operation.

The operation of Buchholz relay is as follows:

- (i) In case of incipient faults within the transformer, the heat due to fault causes the decomposition of some transformer oil in the main tank. The products of decomposition contain more than 70% of hydrogen gas. The hydrogen gas being light tries to go into the conservator and in the process gets entrapped in the upper part of relay chamber. When a predetermined amount of gas gets accumulated, it exerts sufficient pressure on the float to cause it to tilt and close the contacts of mercury switch attached to it. This completes the alarm circuit to sound an alarm.
- (ii) If a serious fault occurs in the transformer, an enormous amount of gas is generated in the main tank. The oil in the main tank rushes towards the conservator via the Buchholz relay and in doing so tilts the flap to close the contacts of mercury switch. This completes the trip circuit to open the circuit breaker controlling the transformer.

Advantages

- (i) It is the simplest form of transformer protection.

- (ii) It detects the incipient faults at a stage much earlier than is possible with other forms of protection.

Disadvantages

- (i) It can only be used with oil immersed transformers equipped with conservator tanks.
- (ii) The device can detect only faults below oil level in the transformer. Therefore, separate protection is needed for connecting cables.

Chapter 5

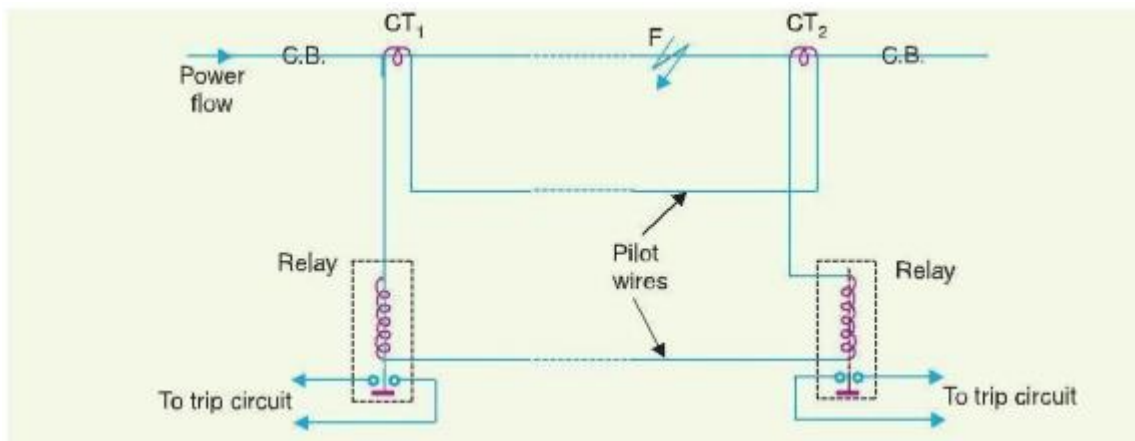
DIFFERENTIAL PILOT-WIRE PROTECTION

The differential pilot-wire protection is based on the principle that under normal conditions, the current entering one end of a line is equal to that leaving the other end. As soon as a fault occurs between the two ends, this condition no longer holds and the difference of incoming and outgoing currents is arranged to flow through a relay which operates the circuit breaker to isolate the faulty line. There are several differential protection schemes in use for the lines. However, only the following two schemes will be discussed:

- * Merz-Price voltage balance system
- * Translay scheme

1. MERZ-PRICE VOLTAGE BALANCE SYSTEM:

Below Figure shows the single line diagram of Merz-Price voltage balance system for the protection of a 3-phase line. Identical current transformers are placed in each phase at



both ends of the line. The pair of CTs in each line is connected in series with a relay in such a way that under normal conditions, their secondary voltages are equal and in opposition i.e. they balance each other. Under healthy conditions, current entering the line at one-end is equal to that leaving it at the other end. Therefore, equal and opposite voltages are induced in the secondaries of the CTs at the two ends of the line. The result is that no current flows through the relays. Suppose a fault occurs at point F on the line as shown in below Fig. This will cause

a greater current to flow through CT1 than through CT2. Consequently, their secondary voltages become unequal and circulating current flows through the pilot wires and relays. The circuit breakers at both ends of the line will trip out and the faulty line will be isolated

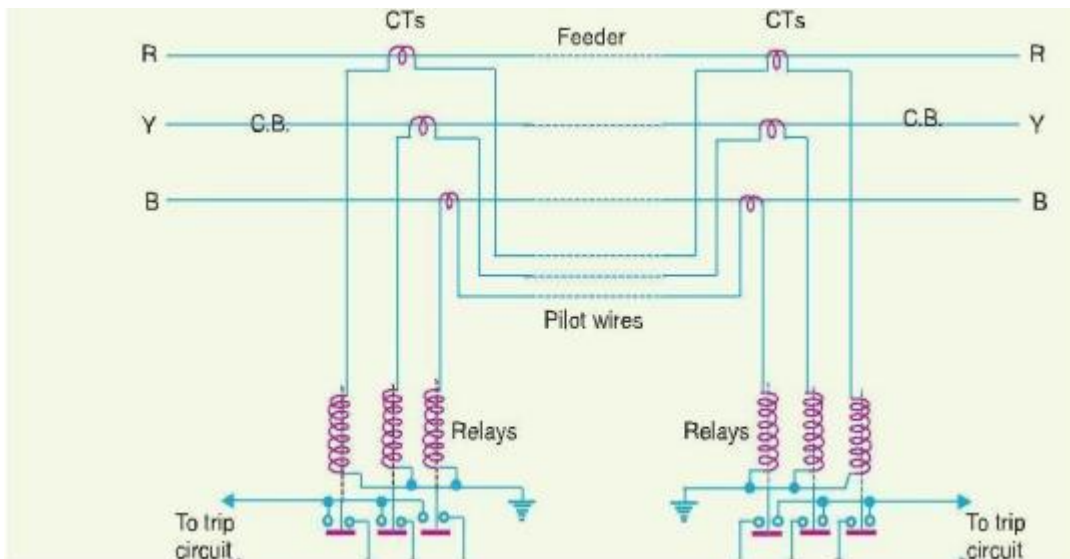


Fig. shows the connections of Merz-Price voltage balance scheme for all the three phases of the line.

Advantages

- This system can be used for ring mains as well as parallel feeders.
- This system provides instantaneous protection for ground faults. This decreases the possibility of these faults involving other phases.
- This system provides instantaneous relaying which reduces the amount of damage to overhead conductors resulting from arcing faults.

Disadvantages

- Accurate matching of current transformers is very essential.
- If there is a break in the pilot-wire circuit, the system will not operate.
- This system is very expensive owing to the greater length of pilot wires required.
- In case of long lines, charging current due to pilot-wire capacitance* effects may be sufficient to cause relay operation even under normal conditions.

- This system cannot be used for line voltages beyond 33 kV because of constructional difficulties in matching the current transformers.

2. **TRANSLAY SCHEME.** This system is similar to voltage balance system except that here balance or opposition is between the voltages induced in the secondary windings wound on the relay magnets and not between the secondary voltages of the line current transformers. This permits to use current transformers of normal design and eliminates one of the most serious limitations of original voltage balance system, namely; its limitation to the system operating at voltages not exceeding 33 kV.

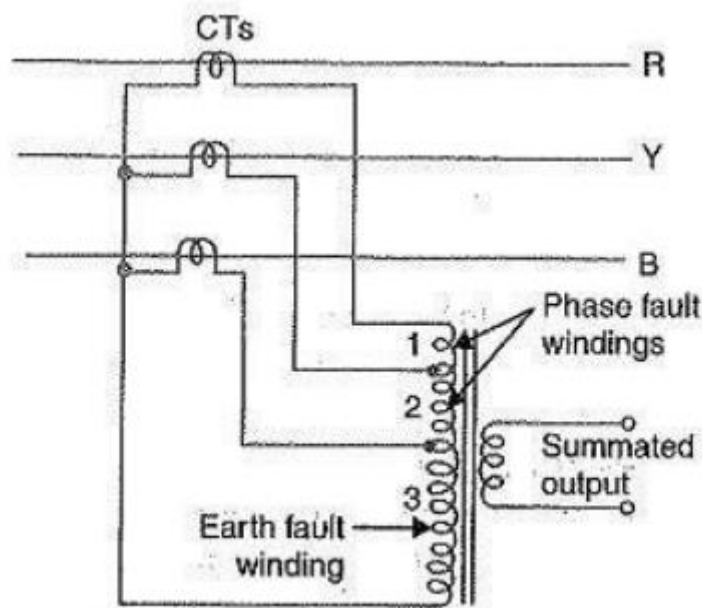


Figure: summation transformer

A summation transformer is a device that reproduces the polyphase line currents as a single-phase quantity. The three line CTs are connected to the tapped primary of summation transformer. Each line CT energizes a different number of turns (from line to neutral) with a resulting single-phase output. The use of summation transformer permits two advantages viz (i) primary windings 1 and 2 can be used for phase faults whereas winding 3 can be used for earth fault (ii) the number of pilot wires required is only two.

SCHEMATIC ARRANGEMENT:

The Translay scheme for the protection of a 3-phase line is shown in Fig. 23.11. The relays used in the scheme are essentially overcurrent induction type relays. Each relay has two electromagnetic elements. The upper element carries a winding (11 or 11 a) which is energised

as a summation transformer from the secondaries of the line CTs connected in the phases of the line to be protected. The upper element also carries a secondary winding (12 or 12 a) which is connected in series with the operating winding (13 or 13 a) on the lower magnet. The secondary windings 12, 12 a and operating windings 13, 13 a are connected in series in such a way that voltages induced in them oppose each other. Note that relay discs and tripping circuits have been omitted in the diagram for clarity. This drawback is overcome in the Beard-Hunter system. In this system, each pilot-wire is surrounded by an insulated metallic sheath with a break half-way along its length. Half the pilot charging current thus comes from the sending end and half from the receiving end. Therefore, voltage applied to the relay at the sending end is balanced by an equal voltage at the receiving end.

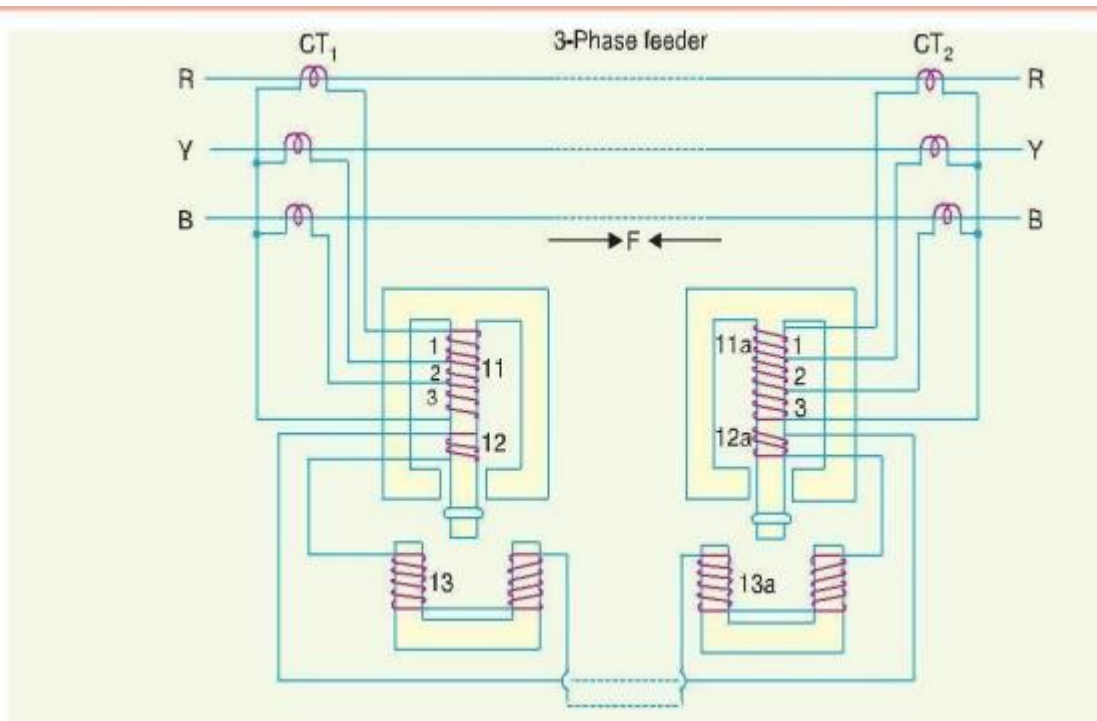


Figure: Translay scheme

OPERATION:

When the feeder is sound, the currents at its two ends are equal so that the secondary currents in both sets of CTs are equal. Consequently, the currents flowing in the relay primary winding 11 and 11 a will be equal and they will induce equal voltages in the secondary windings 12 and 12a. Since these windings are connected in opposition, no current flows in them or in the operating windings 13 and 13a. In the event of a fault on the protected line, the line current at one end must carry a greater current than that at the other end. The result is that voltages induced in the secondary windings 12 and 12 a will be different and the current will flow

through the operating coils 13, 13a and the pilot circuit. Under these conditions, both upper and lower elements of each relay are energized and a forward torque acts on each relay disc. The operation of the relays will open the circuit breakers at both ends of the line.

- Suppose a fault F occurs between phases R and Y and is fed from both sides as shown in Fig. 23.11. This will energize only section 1 of primary windings 11 and 11a and induce voltages in the secondary windings 12 and 12a. As these voltages are now additive, therefore, current will circulate through operating coils 13, 13a and the pilot circuit. This will cause the relay contacts to close and open the circuit breakers at both ends. A fault between phases Y and B energizes section 2 of primary windings 11 and 11a whereas that between R and B will energize the sections 1 and 2.
- ❖ Now imagine that an earth fault occurs on phase R. This will energize sections 1, 2 and 3 of the primary windings 11 and 11a. Again if fault is fed from both ends, the voltages induced in the secondary windings 12 and 12a are additive and cause a current to flow through the operating coils 13, 13a. The relays, therefore, operate to open the circuit breakers at both ends of the line. In the event of earth fault on phase Y, sections 2 and 3 of primary winding 11 and 11a will be energized and cause the relays to operate. An earth fault on phase B will energize only section 3 of relay primary windings 11 and 11a.

Advantages

- ❖ The system is economical as only two pilot wires are required for the protection of a 3-phase line.
- ❖ Current transformers of normal design can be used.
- ❖ Pilot wire capacitance currents do not affect the operation of relays.
- ❖ Because the fault is being fed from both sides.

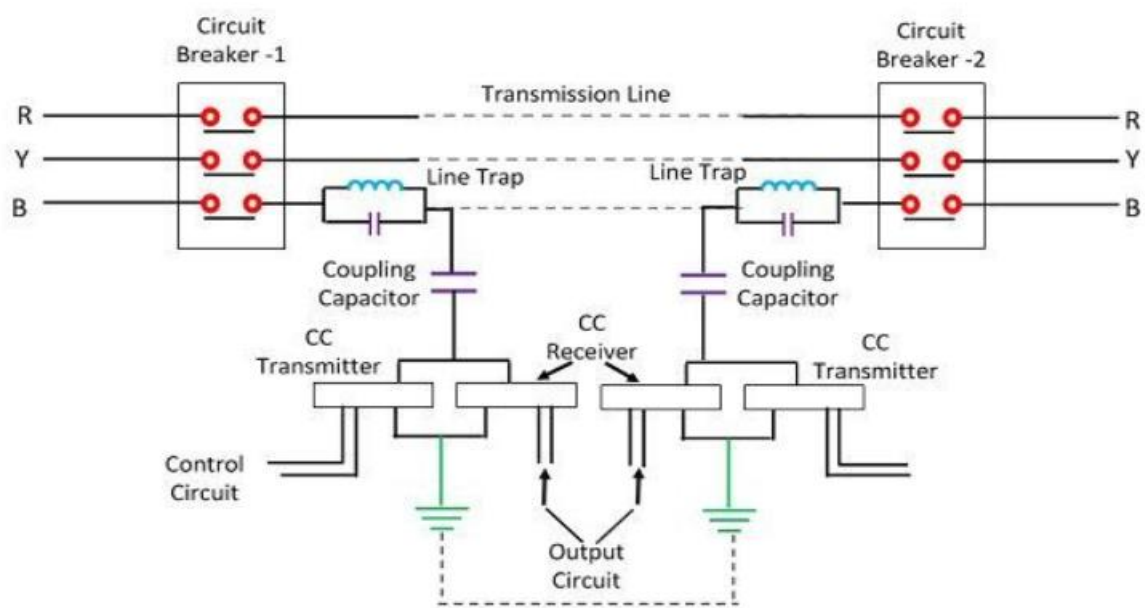
Carrier Current Protection of Transmission Lines

Carrier current protection scheme is mainly used for the protection of the long transmission line. In the carrier, current protection schemes, the phase angle of the current at the two phases of the line are compared instead of the actual current. And then the phase angle of the line

decides whether the fault is internal and external. The main elements of the carrier channel are a transmitter, receiver, coupling equipment, and line trap.

The carrier current receiver receives the carrier current from the transmitter at the distant end of the line. The receiver converts the received carrier current into a DC voltage that can be used in a relay or other circuit that performs any desired function. The voltage is zero when the carrier current, is not being received.

Line trap is inserted between the bus-bar and connection of coupling capacitor to the line. It is a parallel LC network tuned to resonance at the high frequency. The traps restrict the carrier current to the unprotected section so as to avoid interference from the with or the other adjacent carrier current channels. It also avoids the loss of the carrier current signal to the adjoining power circuit.



Carrier Current Transmission Line Protection Scheme

Circuit Globe

The coupling capacitor connects the high-frequency equipment to one of the line conductors and simultaneously separate the power equipment from the high power line voltage. The normal current will be able to flow only through the line conductor, while the high current carrier current will circulate over the line conductor fitted with the high-frequency traps, through the trap capacitor and the ground.

Methods of Carrier Current Protection

The different methods of current carrier protection and the basic form of the carrier current protection are

1. Directional Comparison protection
2. Phase Comparison Protection

These types are explained below in details

1. Directional Comparison Protection

In this protection schemes, the protection can be done by the comparison of a fault of the power flow direction at the two ends of the line. The operation takes place only when the power at both the end of the line is on the bus to a line direction. After the direction comparison, the carrier pilot relay informs the equipment how a directional relay behaves at the other end to a short circuit.

The relay at both the end removes the fault from the bus. If the fault is in protection section the power flows in the protective direction and for the external fault power will flow in the opposite direction. During the fault, a simple signal through carrier pilot is transmitted from one end to the other. The pilot protection relaying schemes used for the protection of transmission are mainly classified into two types. They are

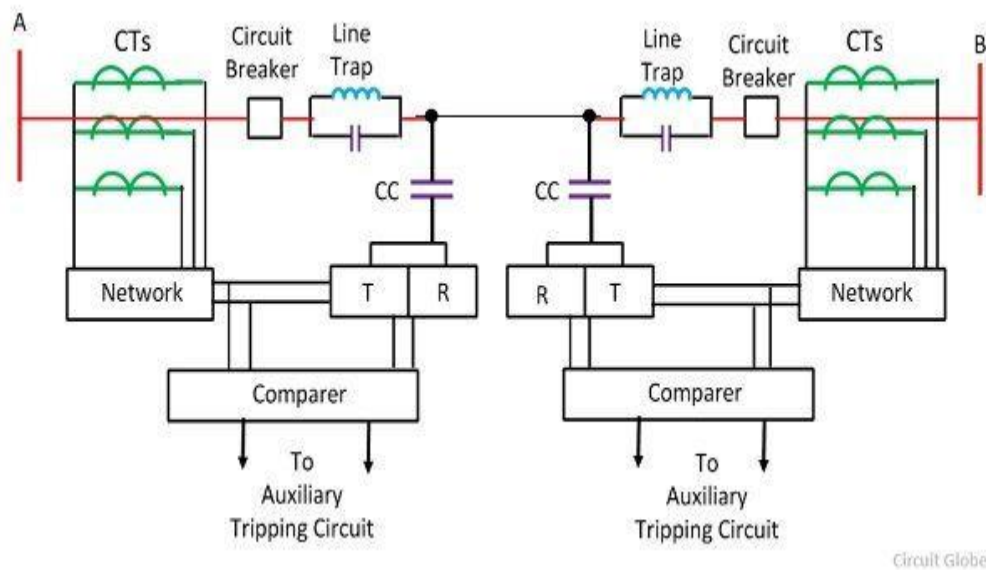
Carrier Blocking Protection Scheme – The carrier blocking protection scheme restricts the operation of the relay. It blocks the fault before entering into the protected section of the system. It is one of the most reliable protecting schemes because it protects the system equipment from damage.

Carrier Permitting Blocking Scheme – The carrier, protective schemes allows the fault current to enter into the protected section of the system.

2. Phase Comparison Carrier Protection

This system compares the phase relation between the current enter into the pilot zone and the current leaving the protected zone. The current magnitudes are not compared. It provided only

main or primary protection and backup protection must be provided also. The circuit diagram of the phase comparison carrier protection scheme is shown in the figure below.



The transmission line CTs feeds a network that transforms the CTs output current into a single phase sinusoidal output voltage. This voltage is applied to the carrier current transmitter and the comparer. The output of the carrier current receiver is also applied to the comparer. The comparer regulates the working of an auxiliary relay for tripping the transmission line circuit breaker.

Advantage of Carrier Current Protection

The following are the advantage of the carrier current protection schemes. These advantages are

1. It has a fast and simultaneous operation of circuit breakers at both the ends.
2. It has a fast, clearing process and prevents shock to the system.
3. No separate wires are required for signalling because the power line themselves carry the power as well as communication signalling.
4. It's simultaneously tripping of circuit breakers at both the end of the line in one to three cycles.
5. This system is best suited for fast relaying also with modern fast circuit breakers.

The main operation of power line carrier has been for the purpose of supervisory control, telephone communication, telemeter and relaying.

BUS-BARPROTECTION

When the fault occurs on the bus bars whole of the supply is interrupted, and all the healthy feeders are disconnected. The majority of the faults is single phase in nature, and these faults are temporary. The bus zone fault occurs because of various reasons likes failure of support insulators, failure of circuit breakers, foreign object accidentally falling across the bus bar, etc., for removing the bus fault, all the circuits connecting to the faulty section needs to be open. The most commonly used schemes for bus zone protection are:

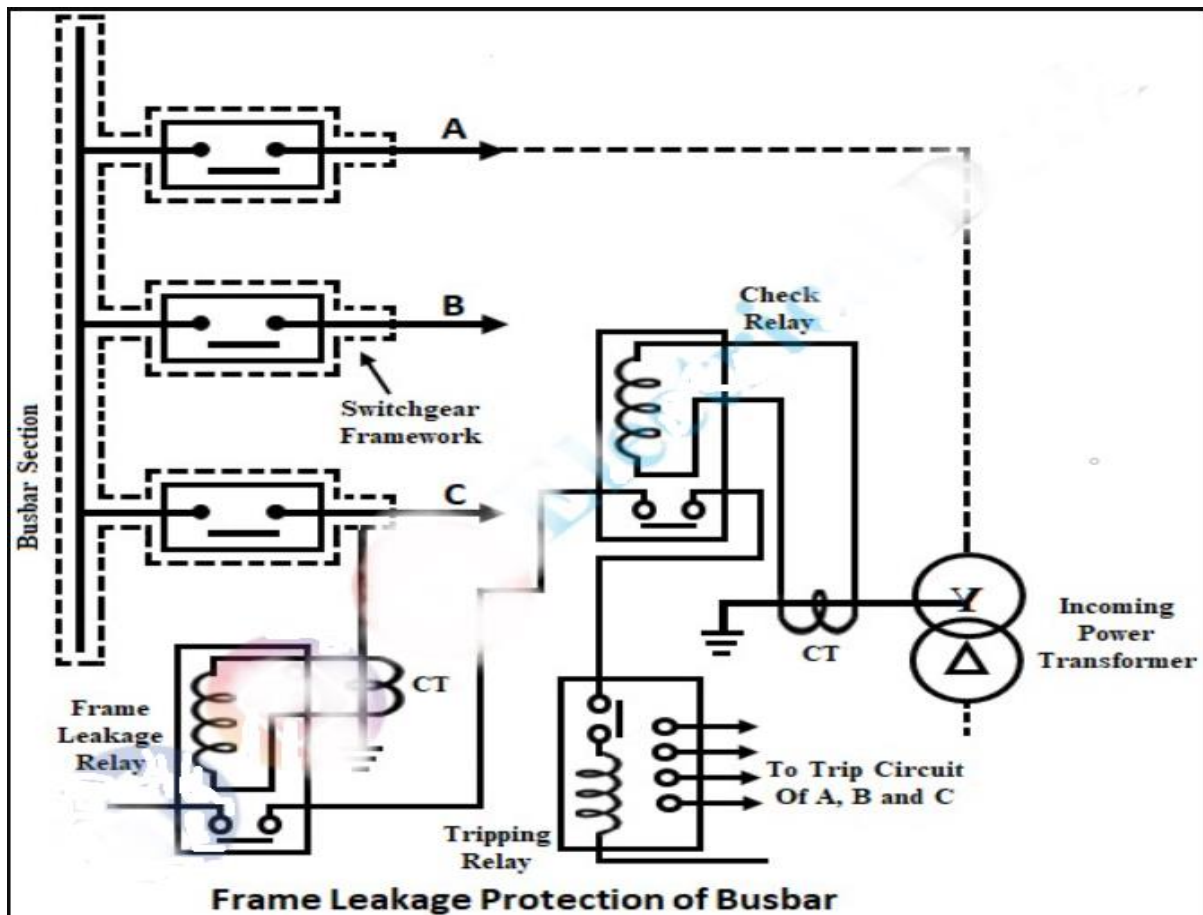
- Backup protection
- Differential Overcurrent Protection
 - o Circulating current protection
 - o Voltage Overvoltage Protection
- Frame leakage protection

Frame Leakage Protection of Busbar

- Frame leakage protection is one of the most simple forms of bus-bar protection available, suitably designed to withstand the earth faults occurring within the indoor installations. This type of protection is applicable to metal-clad switchgear of small size. All the metal frameworks are attached together and insulated from the ground.
- It is essential to isolate the switchgear framework from lead cable sheaths, such that when a leakage to the framework occurs then the leakage current will pass through the primary of the current transformer provided in the earth connection. The current transformer secondary is connected to an earth leakage relay.
- The metal-clad switchgear is grounded through a current transformer, the secondary of which is connected to an overcurrent relay. Under normal working conditions, the overcurrent relay remains inoperative but when a fault takes place, the leakage current will pass through the faulted section to the ground causing the relay to operate resulting in tripping of the circuit breaker connecting equipment to the bus.

Working Principle of Frame Leakage Protection:

The below shows the frame leakage scheme of protection applied to a single busbar substation.



Supply is provided to the station busbars having earthed star-connected secondary also to which a current transformer is connected which energizes the operating coil of the check relay connected to its secondary. When an earth fault occurs within the protected area, the contacts of both the leakage and check relay are closed energizing the tripping relay and enabling the operation of the circuit breaker.

Differential Protection:

Current Differential Protection

The basic method for busbar protection is the differential scheme in which currents entering and leaving the bus are totalized. During normal load condition, the sum of these currents is

equal to zero. When a fault occurs, the fault current upsets the balance and produces a differential current to operate a relay.

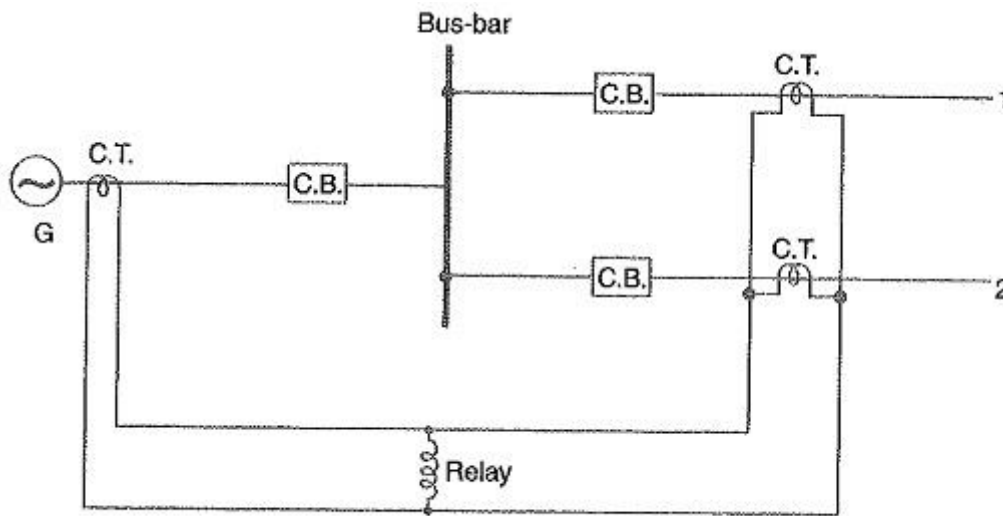
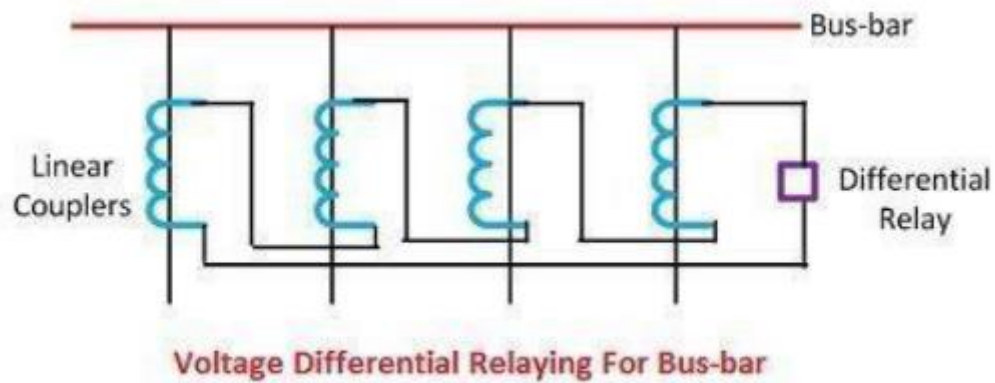


Fig. 23.1

- Fig. 23.1 shows the single line diagram of current differential scheme for a station busbar. The Busbar Protection is fed by a generator and supplies load to two lines. The secondaries of current transformers in the generator lead, in line 1 and in line 2 are all connected in parallel. The protective relay is connected across this parallel connection. All CTs must be of the same ratio in the scheme regardless of the capacities of the various circuits.
- Under normal load conditions or external fault conditions, the sum of the currents entering the bus is equal to those leaving it and no current flows through the relay. If a fault occurs within the protected zone, the currents entering the bus will no longer be equal to those leaving it. The difference of these currents will flow through the relay and cause the opening of the generator, circuit breaker and each of the line circuit breakers.

VOLTAGE DIFFERENTIAL PROTECTION RELAY

In this scheme, the coreless CTs are used. The linear couplers are used to increase the number of turns on the secondary sides of the CTs. The secondary relays are connected in series with the help of the pilot wires. The relay coil is also connected in series with the second terminal.



When the system is free from fault or external fault occurs on the system, the sum of secondary current of CTs becomes zero. On the occurrence of the internal fault, the fault current flows the differential relay. The relay becomes operative and gives command to the circuit breaker to open their contacts. Thus, protects the system from damage.