SWITCHGEAR AND PROTECTION

Chapter: Introduction to Protective System

Introduction

Power system protection is the process of making the production, transmission, and consumption of electrical energy as safe as possible from the effects of failures and events that place the power system at risk. It is cost prohibitive to make power systems 100 percent safe or 100 percent reliable.

System protection is the art and science of detecting problems with power system components and isolating these components. So, the objective of **power system protection** is to isolate a faulty section of electrical power system from rest of the live system so that the rest portion can function satisfactorily without any severe damage due to fault current.

Fault and Nature of Faults

A fault is any condition that causes abnormal operation for the power system or equipment serving the power system. Faults include but are not limited to: short- or low-impedance circuits, open circuits, power swings, over voltages, elevated temperature, off-nominal frequency operation.

Causes of Faults

1. Insulation failure or conducting path failures.
2. Overvoltage due to lightning or switching surges.
3. Punctured or breaking of insulator.
4. Conducting objects falling on the overhead lines like tree branches.
5. Poor quality of the system components or because of a faulty system design.

Causes of fault on overhead lines are direct lightning strokes, abnormal loading, storms, earthquake, etc. On the other hand, cables, transformers, generators and other equipment, the cause of faults is the failure of solid insulations due to aging, heat, moisture or overvoltage, mechanical damage, accidental contact with the earth, or earthed screens, flashover due to overvoltage, etc.

Types of fault

- Short circuit fault- current
- Open circuit fault- voltage

In terms of seriousness of consequences of a fault, short circuits are of far greater concern than open circuits, although some open circuits present some potential hazards to personnel

Classification of short circuited Faults

Symmetrical faults

These are very severe faults and occur infrequently in the power systems. These are also called as balanced faults and are of two types namely

- Line to line to line to ground (L-L-L-G) and
- Line to line to line (L-L-L).

Only 2-5 percent of system faults are symmetrical faults. If these faults occur, system remains balanced but results in severe damage to the electrical power system equipment's.

Unsymmetrical faults

These are very common and less severe than symmetrical faults. There are mainly three types,

- Line to ground (L-G),
- Line to line (L-L) and
- Double line to ground (LL-G) faults.

Line to ground fault (L-G) is most common fault and 65-70 percent of faults are of this type.
15 to 20 percent of faults are double line to ground and. Line to line faults occurs 5- 10 percent of the faults.
These are also called unbalanced faults since their occurrence causes unbalance in the system. Unbalance of the system means that that impedance values are different in each phase causing unbalance current to flow in the phases. These are more difficult to analyze and are carried by per phase basis similar to three phase balanced faults.

Classification of Open Circuit Faults

• Single Phase open Circuit
• Two Phase open circuit
• Three Phase open circuit

Essential Qualities of Protective Relaying

The principal function of Protective Relay is to cause the prompt removal from service of any element of the power system when it starts to operate in an abnormal manner or interfere with the effective operation of the rest of the system. In order that protective relay system may perform this function satisfactorily, it should have the following qualities:

1. **Selectivity**
2. **Speed**
3. **Sensitivity**
4. **Reliability**
5. **Simplicity**
6. **Economy**
7. **Fast operation**

Selectivity

It is the ability of the protective system to select correctly that part of the system in trouble and disconnect the faulty part without disturbing the rest of the system.

A well designed and efficient relay system should be selective i.e. it should be able to detect the point at which the fault occurs and cause the opening of the circuit breakers closest to the fault with minimum or no damage to the system.
In order to provide selectivity to the system, it is a usual practice to divide the entire system into several protection zones. When a fault occurs in a given zone, then only the circuit breakers within that zone will be opened. This will isolate only the faulty circuit or apparatus, leaving the healthy circuits intact.

Speed

The relay system should disconnect faulty section as fast as possible for the following reasons:

- Electrical apparatus may be damaged if they are made to carry the fault currents for a long time.
- A failure on the system leads to a great reduction in the system voltage. If the faulty section is not disconnected quickly, then the low voltage created by the fault may shut down consumers motors and the generators on the system may become unstable.
- The high-speed relay system decreases the possibility of development of one type of fault into the other more severe type.

The ultimate goal of protective relaying is to disconnect a faulty system element as quickly as possible. Sensitivity and selectivity are essential to assuring that the proper circuit breakers will be tripped, but speed is the ‘pay-off’.

Sensitivity

It is the ability of the relay system to operate with a low value of actuating quantity.
The sensitivity of a relay is a function of the volt-amperes input to the coil of the relay necessary to cause its operation.

- The smaller the volt-ampere input required to cause relay operation, the more sensitive is the relay.

Thus, a 1 VA relay is more sensitive than a 3 VA relay. It is desirable that the relay system should be sensitive so that it operates with low values of volt-ampere input.

Reliability

It is the ability of the relay system to operate under pre-determined conditions. Without reliability, the protection would be rendered largely ineffective and could even become a liability.
That protective-relaying equipment must be reliable is a basic requirement. When protective relaying fails to function properly, the allied mitigation features are largely ineffective.
Therefore, it is essential that protective-relaying equipment be inherently reliable, and that its application, installation, and maintenance be such as to assure that its maximum capabilities will be realized.

Simplicity
The relaying system should be simple so that it can be easily maintained. Reliability is closely related to simplicity. *The simpler the protection scheme, the greater will be its reliability.*

Economy
The most important factor in the choice of a particular protection scheme is the economic aspect. Sometimes it is economically unjustified to use an ideal scheme of protection and a compromise method has to be adopted.

- *As a rule, the protective gear should not cost more than 5% of the total cost.*

However, when the apparatus to be protected is of utmost importance (e.g. generator, main transmission line etc.), economic considerations are often subordinated to reliability.

Fast operation
It is essential that a protective system is fast enough to isolate the faulty element of a system as soon as possible to minimize damages to the equipment and to ensure system stability. A protective system operating time should not exceed the critical clearing time to prevent loss of synchronism. If fault currents are carried for a long time, electrical equipment may be damaged. The voltage will drop gradually resulting in crawling and overloading of industrial drives with a persistent fault. Because of these reasons, protective relays need to be quick-acting.
As the fault persists for a shorter period of time, a greater amount of load can be transferred between two points on the power system without loss of synchronism.

Stability
Protective systems should remain stable even when a large current is flowing through their protective zones as a result of an external fault that is not in their zone. The concerned circuit breakers should clear the fault immediately. Although the protective system will not wait indefinitely if the zone in which the fault occurs is unable to detect the fault. A relay will operate after a predetermined delay to trip the circuit breaker.

Zones of Protection in Power System

A power system deals with generation, transmission, and distribution of electrical power. Transformers, generators, bus bars, transmission & distribution lines, circuit breakers, etc. are the elements or equipment of a power system. Each element or equipment of the power system has its own protective scheme. For example, transformer protection, generator protection, bus bar protection, transmission line protection, etc. In this way, a power system is divided into several protection zones.
A protective zone is a separate zone that is established around each system element.
The significance of such a protective zone is that any fault occurring within cause the tripping of relays which causes the opening of all the circuit breakers within that zone.
The circuit breakers are placed at the appropriate points such that any element of the entire power system can be disconnected for repairing work, usual operation and maintenance

requirements and also under abnormal conditions like short circuits. Thus a protective covering is provided around the rich elements of the system.

The various components which are provided with the protective zone are generators, transformers, transmission lines, bus bars, cables, capacitors, etc. No part of the system is left unprotected. The figure below shows the various protective zones used in a system.

Why Protection Zones are overlapped?

It is necessary to overlap adjacent protective zones so that each and every element of the system is completely safe. In case the adjacent protective zones are not overlapped, circuit breakers would not trip for a fault on the boundary of zones, which lies outside any of the zones. As a result, adjacent protective zones must overlap in order to ensure full protection.

The boundaries of protective zones are decided by the locations of the current transformer. In practice, various protective zones are overlapped.

In a properly protected scheme, if a fault occurs in the overlap zone, more circuit breakers would trip than are necessary to isolate the faulty element. Having relatively low overlap should reduce the likelihood of faults occurring in this region, so that tripping of too many breakers should not happen very frequently.

The extent of the overlapping of protective zones is relatively small. The probability of the failures in the overlapped regions is very low; consequently, the tripping of the too many circuit breakers will be frequent. The figure shows the overlapping of protective zones in primary relaying.

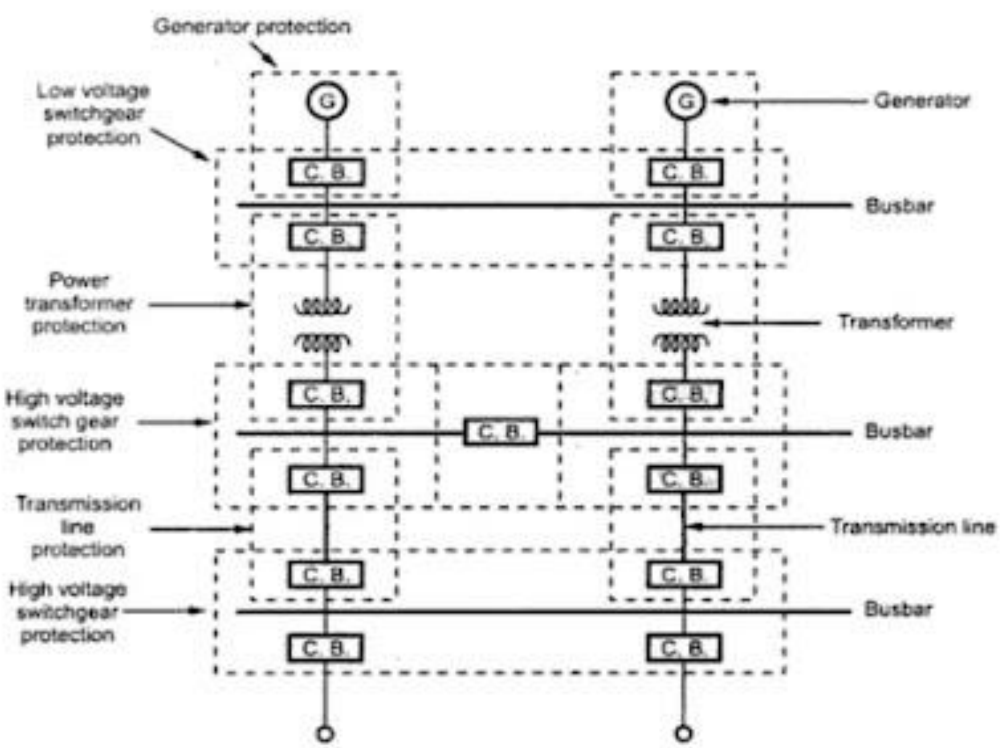


Fig: Overlapping Protective Zones in Power System

The figure shows Overlapping zones in primary relaying. It can be seen from the figure that the circuit breakers are located in the connections to each power system element. This provision makes it possible to disconnect only the faulty element from the system.
Occasionally for the economy in the number of circuit breakers, a breaker between the two adjacent sections may be omitted but in that case, both the power system is required to be disconnected for the failure in either of the two. Each protective zone has a certain protective scheme and each scheme has the number of protective systems.

What is a dead spot?
A **dead spot** is a zone that is unprotected. Since adjacent protective zones overlap each other as explained in the above paragraph. As a result, there are no dead spots in a system due to the overlap of zones. A dead spot may result from an absence of overlaps of adjacent protective zones. It means that if a fault occurs, circuit breakers lying within the zone will not trip. The healthy system may be damaged in this way. This is why adjacent protective zones are overlapped.

Primary and Backup Protection in Power System

In order to ensure the safety of the power system, it is divided into different zones. For each zone, there is an appropriate protective scheme. Here, we will learn about two types of protection in a power system i.e. **primary protection** and **back up protection**. Let us understand both types of protection.

Primary Protection

The relays used in primary protection are called **primary relays**. The primary relays of a zone are responsible for isolating the faulty component in the event of a fault occurring in that zone. The primary relay serves as the first line of defense. If the primary relay fails to operate then back up protection is used to isolate the faulty component from the system.

Back up Protection

When the relay used in primary protection fails to operate then back up protection is used to clear the fault. The relays used in back up protection are called **back up relays**. It is important to note that backup relays are independent of factors that might cause primary relays to fail to operate. In order to give the primary relay sufficient time to operate, a backup relay operates after a time delay. In the event that a back up relay is operated, a large part of the electrical system will be disconnected from the local power source and it cannot be avoided. The back up relay serves as the second line of defense.

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

1. Relay Back-up
2. Breaker Back-up

3. Remote back-up
4. Centrally Coordinated Back-up

Relay Back-up

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

The relay back up protection is costly. The relay back up protection is recommended in situations where a remote backup is not feasible.

Breaker Back-up

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

Generally, this type of backup is utilized for bus bars that are connected to a number of circuit breakers. In the event that a protective relay operates in response to a fault, but the circuit breaker does not trip, it is treated as a bus bar fault. This is the case when it is necessary to trip all other circuit breakers within the bus bar. If the appropriate circuit breaker fails to trip in the specified time period after its trip coil is energized, the main relay closes the contact of a back-up relay, which trips all other circuit breakers on the bus.

Remote back-up

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

As the name implies, there is a backup relay located at a nearby station. The function of remote back up is to back up the primary protective scheme (equipment such as relays, circuit breaker, CT, VT, bus bar, etc.) in case of a failure of the primary protective scheme. It's the most cost-effective and easiest type of back up protection. This is a widely used backup protection system for transmission lines.

Centrally Coordinated Back-up

The system having central control can be provided with centrally controlled back-up. Central control continuously supervises the load flow and frequency in the system. The information about load flow and frequency are assessed continuously.

If one of the components in any part of the-system fails, (e.g. a fault on a transformer, in some station) the load flow in the system is affected. The central coordinating station receives information about the abnormal condition through high-frequency carrier signals.

The stored program in the digital computer determines the correct switching operation, as regards severity of fault, system stability,

Advantages of Back-up Protection

Back-up protection is provided for the following reasons

- If due to some reason, the **Main protection** fails, the Back-up protection serves the purpose of protection.

- **Main protection** can fail due to failure of one of the components in the protective system such as a relay, auxiliary relay Current Transformer, PT, trip circuit, circuit-breaker, etc. If the **primary protection** fails, there must be an additional protection, otherwise, the fault may remain uncleared, resulting in a disaster.
- When main protection is made inoperative for the purpose of maintenance, testing, etc. the **Back-up protection** acts like main protection.
- As a measure of the economy, **Back-up protection** is given against short-circuit protection and generally not for other abnormal conditions. The extent to which back-up protection is provided depends upon economic and technical considerations,

The cost of **back-up protection** is justified on the basis of the probability of failure of individual component in the protection system, cost of the protected equipment, the importance of protected equipment, location of protected equipment, etc.

Back up Protection by Time Grading Principle

The current is measured at various points along the current path, e.g., at source, intermediate locations, consumer end. The tripping time at these locations are graded in such a way that the circuit-breaker/fuse nearest the faulty part operate first, giving primary protection. The'circuit breaker/fuse at the previous station operates only as **back-up**.

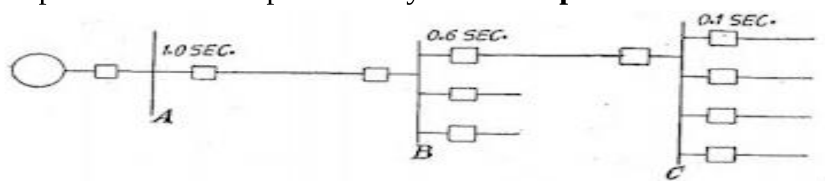
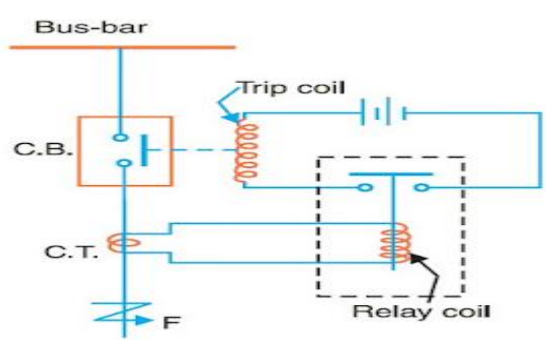


Fig: Time Grading

Referring to the figure, the tripping time at station C, B and A are graded such that for a fault beyond C breaker at C operates as primary protection. Meanwhile, the relays at A and B also may start operating but they are provided with enough time lag so that the circuit-breaker at B operates only if the circuit-breaker at C does not.

Relay Circuit Diagram

A typical relay circuit is shown in the figure below. This diagram shows one phase of a 3-phase system for simplicity.



Typical Relay Circuit Diagram

The relay circuit connections can be divided into three parts viz.

- The first part is the primary winding of a current transformer (C.T.) which is connected in series with the line to be protected.
- The second part consists of the secondary winding of the current transformer and circuit breaker and the relay operating coil.
- The third part is the tripping circuit which may be either Ac or DC. It consists of a source of supply, the trip coil of the circuit breaker and the relay stationary contacts.

Protective Relay Working

- When a short circuit occurs at point F on the transmission line, the current flowing in the line increases to an enormous value.
- This results in a heavy current flow through the relay coil, causing the relay to operate by closing its contacts.
- In turn, closes the trip circuit of the breaker, making the circuit breaker open and isolating the faulty section from the rest of the system.
- This way, the relay ensures the safety of the circuit equipment from damage and normal working of the healthy portion of the system.

Functions of Protective Relays

The various functions of protective relaying are to:

1. To sound an alarm or to close the trip circuit of a circuit breaker so as to disconnect Faulty Section.
2. The prompt removal of the component which is behaving abnormally by closing the trip circuit of the circuit breaker or to sound an alarm.
3. Disconnect the abnormally operating part so as to avoid the damage or interference within the effective operation of the rest of the system.
4. Prevent the subsequent faults by disconnecting the abnormally operating part.
5. Disconnect the faulty part as quickly as possible so as to minimize the damage to the faulty part itself. For example, if there is a winding fault in a machine and if it persists for a long time then there is a possibility of the damage of the entire winding. As against this, if it is disconnected quickly then only a few coils may get damaged instead of the entire winding.
6. Restrict the spreading of the effect of the fault causing the least interference to the rest of the healthy system. Thus by disconnecting the faulty part, the fault effects get localized.
7. To improve system performance, system reliability, system stability, and service continuity.

The faults cannot be completely avoided but can be minimized.

Thus the protective relaying plays an important role in sensing the faults, minimizing the effects of faults and minimizing the damage due to the faults.

Basic Protective Relays Types

Most of the relays in service on the electric power system today are of electromechanical type.

They work on the following two main operating principles:

1. **Electromagnetic attraction**

2. **Electromagnetic induction**

Electromagnetic attraction relays operate by virtue of an armature being attracted to the poles of an electromagnet or a plunger being drawn into a solenoid. Such relays may be actuated by d.c. or a.c. quantities.

Electromagnetic induction relays operate on the principle of the induction motor and are widely used for protective relaying purposes involving a.c. quantities. They are not used with dc quantities owing to the principle of operation.

Electromagnetic Attraction Type Relays

The electromagnetic attraction type relays operate on the principle of attraction of an armature by the magnetic force produced by undesirable current or movement of plunger in a solenoid. These relays can be actuated by AC or DC quantities. The various types of these relays are.

1. Solenoid Type
2. Attracted Armature Type
3. Balanced Beam Type

1. Solenoid Type

In this relay, the plunger or iron core moves into a solenoid and the operation of the relay depends on the movement of the plunger.

2. Attracted Armature Type:

This relay operates on the current setting. When currant in the circuit exceeds beyond the limit, the armature gets attracted by the magnetic force produced by the undesirable current. The current rating of the circuit in which relay is connected plays an important role in the operation of the relay.

3. Balanced Beam Type:

In this relay, the armature is fastened to a balanced beam. For normal current, the beam remains horizontal but when current exceeds, the armature gets attracted and beam gets tilted causing the required operation

Induction Type Relays

These relays work on the principle of an electromagnetic induction. The use of these relays is limited to AC quantities. The various types of these relays are,

1. Induction Disc Type
2. Induction Cup Type

1. Induction Disc Type

In this relays a metal disc is allowed to rotate between the two electromagnets. The electromagnets are energised by alternating currents. The two types of constructions used for this type are shaded pole type and watthour meter type.

2. Induction Cup Type:

In this relay, electromagnets act as a stator and energised by relay coils. The rotor is metallic cylindrical cup type.

Classification or Types of Protective Relays

Protection relays can also be classified in accordance with their construction, actuating signal, application and function.

Classification based on Construction/generation

Depending upon the principle of construction, the following four broad categories are found.

- Electromechanical Relay
- Solid State Relay/static Relay
- Microprocessor Relay
- Numerical Relay/Digital Relay

Electromechanical Relay

- First generation oldest relaying system and they have been in use for many years.
- Earned a well-deserved reputation for accuracy, dependability, and reliability.
- Two basic types of operating mechanisms: **electromagnetic-attraction relay and electromagnetic-induction relay.**
- **Measuring Principles:** Converts voltages and currents to magnetic and electric forces and torques that press against spring tensions in the relay. Tension of the spring & taps on the electromagnetic coils in the relay are the main processes by which a user sets in a relay.

Limitations of Electromagnetic relays:

- Low speed of operation.
- Change in characteristics over a period due to ageing effect.
- Component failure leading to relay failure.
- Relay is Bulky: Because there are internal mechanical components with physical dimension restraints, the package size of an electromechanical Relay can limit the size of a PCB design Excessive power consumption.
- Imposes high burden on CT
- No fault data available except phase indication.
- Inherent in its design, the Electromechanical Relay must make mechanical contacts in order to switch a load. At the point of these contacts, oxidation breakdown occurs over extended life cycling (typically 106 operations), and the relay will need to be replaced.
- When an electromechanical Relay is activated, bounce occurs at the contact site. Bounce creates a window of time where the load circuit is flickering between open and closed, a condition which may need to be considered in load design.
- Isolation voltage is another area where Electromechanical Relays are limited.

Solid State Relay (Static Relay)

- Second generation relay and was first introduced in 1960’s. The term ‘static’ implies that the relay has no moving mechanical parts in it.

- Compared to the Electromechanical Relay, the Solid Static relay has longer life-span, decreased noise when operates and faster respond speed. However, it is not as robust as the Electromechanical Relay.
- Static relays were manufactured as semi-conductor devices which incorporate transistors, ICs, capacitors, small micro-processors etc.
- The static relays have been designed to replace almost all the functions which were being achieved earlier by electromechanical relays.
- **Measuring principles:** use analogue electronic devices instead of magnetic coils and mechanical components to create the relay characteristics. the measurement is carried out by static circuits consisting of comparators, level detectors, filter etc while in a conventional electro-magnetic relay it is done by comparing operating torque (or force) with restraining torque (or force).
- User programming was restricted to the basic functions of adjustment of relay characteristic curves. Therefore it can be viewed in simple terms as an analogue electronic replacement for electromechanical relays, with some additional flexibility in settings and some saving in space requirements.

Advantages of Solid State Relay:

- Static Relay burden is less than Electromagnetic type of relays. Hence error is less.
- Low Weight, Required, Less Space, Fast response, Long life (High Reliability),
- High Range of Setting compared to electromechanical Relay
- Arc less switching and No acoustical noise.
- Multi-function integration.
- Low Electromagnetic Interference and Less power consumption.
- Shock and vibration resistant
- No contact bounce
- Microprocessor compatible.
- Isolation of Voltage
- No moving parts: There are no moving parts to wear out or arcing contacts to deteriorate that are often the primary cause of failure with an Electro Mechanical Relay.
- No mechanical contact bounce or arcing: A solid-state relay doesn't depend on mechanical forces or moving contacts for its operation but performs electronically. Thus, timing is very accurate even for currents as low as the pickup value. There is no mechanical contact bounce or arcing, and reset times are extremely short.
- Low input signal levels: Ideal for Telecommunication or microprocessor control industries. Solid state relays are fast becoming the better choice in many applications, especially throughout the telecommunication and microprocessor control industries.
- Cost Issues: In the past, there has been a rather large gap between the price of an electromechanical relay and the price of a solid state relay. With continual advancement in manufacturing technology, this gap has been reduced dramatically making the advantages of solid state technology accessible to a growing number of design engineers.

Limitations of static relays:

- Auxiliary voltage requirement for Relay Operation.
- Static relays are sensitive to voltage transients which are caused by operation of breaker and isolator in the primary circuit of CTs and PTs.
- Serious over voltage is also caused by breaking of control circuit, relay contacts etc. Such voltage spikes of small duration can damage the semiconductor components and also cause mal operation of relays.
- Temperature dependence of static relays: The characteristics of semiconductor devices are affected by ambient temperature.
- Highly sophisticated isolation and filter circuits are required to be built into the relay design to take care of electromagnetic interference and transient switching disturbances in the power system.
- Highly reliable power supply circuits are required.
- Effect of environmental conditions like humidity, high ambient temperature, dust accumulation on PCB leading to tracking.
- The component failure.
- Non availability of fault data.
- Characteristic variations with passage of time.

Digital Relay:

- **History of Relay:** Around 1980s the digital relay entered the market. Compared to the Solid State Relay, the digital relay takes the advantages of the development of microprocessors and microcontrollers. Instead of using analog signals, the digital relay converts all measured analog quantities into digital signals.
- **Measuring principles:** Compared to static relays, digital relays introduce Analogue to Digital Convertor (A/D conversion) of all measured analogue quantities and use a microprocessor to implement the protection algorithm. The microprocessor may use some kind of counting technique, or use the Discrete Fourier Transform (DFT) to implement the algorithm.
- The Microprocessors used in Digital Relay have limited processing capacity and memory compared to that provided in numerical relays.
- Digital relaying involves digital processing of one or more analog signals in three steps: Conversion of analogue signal to digital form Processing of digital form Boolean decision to trip or not to trip

Advantages of Digital Relay:

- High level of functionality integration.
- Additional monitoring functions.
- Functional flexibility.
- Capable of working under a wide range of temperatures.
- They can implement more complex function and are generally more accurate
- Self-checking and self-adaptability.

- Able to communicate with other digital equipment (pear to pear).
- Less sensitive to temperature, aging
- Economical because can be produced in volumes
- More Accurate.
- plane for distance relaying is possible
- Signal storage is possible

Limitations of Digital Relay:

- Short lifetime due to the continuous development of new technologies.
- The devices become obsolete rapidly.
- Susceptibility to power system transients.
- As digital systems become increasingly more complex they require specially trained staff for Operation.
- Proper maintenance of the settings and monitoring data.

Numerical Relay:

- The first protection devices based on microprocessors were employed in 1985. The widespread acceptance of numerical technology by the customer and the experiences of the user helped in developing the second generation numerical relays in 1990.
- Numeric relays are programmable relays. The characteristics and behaviour of the relay are can be programmed.
- First generation numerical relays were mainly designed to meet the static relay protection characteristic, whereas modern numeric protection devices are capable of providing complete protection with added functions like control and monitoring. Numerical protection devices offer several advantages in terms of protection, reliability, and trouble shooting and fault information.
- **Measuring principles:** The input analogue signals are converted into a digital representation and processed according to the appropriate mathematical algorithm. Processing is carried out using a specialized microprocessor that is optimized for signal processing applications, known as a digital signal processor or DSP for short. Digital processing of signals in real time requires a very high power microprocessor.
- Numerical relays are microprocessor based relays and having the features of recording of parameter used as disturbance recorder flexibility of setting & alarms & can be used one relay for all type of protections of one equipment hence less area is required. Wide Range of setting, more accurate, Low burden hence low VA of CT is required which minimize the cost. Numeric relays take the input analog quantities and convert them to numeric values. All of the relaying functions are performed on these numeric values.

Advantages of Numerical relays:

- **Compact Size**
- **Flexibility:** A variety of protection functions can be accomplished with suitable modifications in the software only either with the same hardware or with slight modifications in the hardware.

- **Reliability:** A significant improvement in the relay reliability is obtained because the use of fewer components results in less interconnections and reduced component failures.
- **Multi Function Capability:** Traditional electromechanical and static protection relays offers single-function and single characteristics. Range of operation of electromechanical relays is narrow as compared to numerical relay.
- **Different types of relay characteristics:** It is possible to provide better matching of protection characteristics since these characteristics are stored in the memory of the microprocessor.
- **Digital communication capabilities:** The microprocessor based relay furnishes easy interface with digital communication equipments. Fibre optical communication with substation LAN
- **Modular frame:** Relay hardware consists of standard modules resulting in ease of service.
- **Low burden:** Microprocessor based relays have minimum burden on instrument transformers.
- **Sensitivity:** Greater sensitivity and high pickup ratio.
- **Speed:** With static relays, tripping time of ½ cycle or even less can be obtained.
- **Fast Resetting:** Resetting is less.
- **Data History:** Availability of fault data and disturbance record. Helps analysis of faults by recording details of (1) Nature of fault, (2) Magnitude of fault level, (3) Breaker problem, (4) C.T. saturation , (5) Duration of fault.
- **Auto Resetting & Self Diagnosis:** Electromechanical relay do not have the ability to detect whether the normal condition has been attained once it is activated thus auto resetting is not possible and it has to be done by the operating personnel. while in Numerical Relay auto Resetting is Possible
- By combining several functions in one case, numerical relays also save capital cost and maintenance cost over electromechanical relays
- Separate connection is not required, zero sequence voltages and currents can be derived inside the processor
- Basic hardware is shared between multiple functions, the cost of individual protection functions can be reduced significantly.
- Loss of voltage feature helps block the relay in case of momentary/permanent loss of voltage.

Limitations of Numerical Relay:

- Numerical Relay offers more functionality, and greater precision. Unfortunately, that does not necessarily translate into better protection.
- Numerical Relay can make faster decisions. However, in real, faster protection itself is of no value because circuit breakers are still required to interrupt at the direction of the protective equipment, & ability to make circuit breakers interrupt faster is very limited.
- Numerical Relay protection often relies on non-proprietary software, exposing the system to potential risk of hacking.

- Numerical Relay protection sometimes has exposure to externally-sourced transient interference that would not affect conventional technology.
- Numerical Relay protection shares common functions i.e. there are common failure modes that can affect multiple elements of protection. For eg, failure of a power supply or an input signal processor may disable an entire protective device that provides many different protection functions. This problem has receive a lot of design attention, and experience generally has supported the notion that the equipment has a very high reliability once it is past the infant mortality stage.
- A multifunction numeric relay can provide three phase, ground, and negative sequence directional or non-directional over current protection with four shot recloser, forward or reverse power protection, breaker failure, over/under frequency, and over/under voltage protection, sync check, breaker monitoring and control, It would take 10 – 11 single function Solid State or Electromechanical relays at least 5 to 6 times the cost. Additionally Numeric relays have Communications capabilities, sequence-of-events recording, fault reporting, rate-of-change frequency, and metering functions, all in an integrated system.

Directional Type Relays

These relays work on the direction of current or power flow in the circuit and are of two types

1. Reverse Current Type
2. Reverse Power Type

Reverse Current Type: The relay is actuated when the direction of the current is reversed or the phase of the current becomes more than the predetermined calve

Reverse Power Type: The relay is actuated when the phase displacement between applied voltage and current attains a specified value.

Differential Type Relays

A differential relay operates when the vector difference of two or more electrical quantities in the circuit in which relay is connected. exceeds a set value. These are classified as,

1. Current Differential Type
2. Voltage Differential Type

Current Differential Type: In this type, the relay compares the current entering a section of the system and the current leaving the section. Under fault condition, these currents are different.

Voltage Differential Type: In this type, two transformers are used. The secondaries of the transformers are connected in series with the relay in such a way that the induced e.m.fs are in opposition under normal conditions. Under fault condition, primaries carry different currents due to which induced e.m.f.s no longer remain in opposition and the relay operates.

Classification based on Actuating Signals

The actuating signal may be any of the following signals including a numbers of different combinations of these signals depending upon whether the designed relay require a single or multiple inputs for its realization.

• Current
• Voltage
• Power
• Frequency
• Temperature
• Pressure
• Speed
• Others

Classification based function in the protective scheme,

1. Main relays
2. Auxiliary relays and
3. Signal relays.

Main Relays: The main relays are the protective elements which respond to any change in the actuating quantity, e. g. current, voltage, power, etc.
Auxiliary Relays: The auxiliary relays are those which are controlled by other relays to perform some auxiliary function such as introduction of a time delay, increasing the number of contacts, increasing the making or breaking capacity of the contacts of another relay, passing a signal from one relay to another, tripping of circuit breaker, energizing a signal or an alarm, etc.
Signal relays: Signal relays function to register the operation of some relay by, flag indication, simultaneously it can also actuate an audible alarm circuit. The choice of signal relay depends upon the importance of the associated switchgear, the method of control and the number of alarm indications to be displayed.

Classification based on Function

Based on the functions for which the protection system is designed, relays are categories as
• Directional Over current Relay
• Distance Relay
• Over voltage Relay
• Differential Relay
• Reverse Power Relay
• Others
It is important to notice that the same set of input actuating signals may be utilized to design to relays having different function or application.
For example, the voltage and current input relays can be designed both as a Distance and/ or a Reverse Power relay.

Relays Based on Timing
In relays the time between instant of relay operation and instant at which tripping of contacts takes place can be controlled. The time is called operation time. Based om this, the time relays are classified as,

1. Instantaneous Type
2. Definite Time Lag Type

Inverse Time Lag type: Instantaneous Type: In this type no time is lust between operation of relay and tripping of contacts. No intentional time delay is provided.

Definite Time Lag Type: In this type intentionally a definite time lag is provided between operation of relay and tripping of contact.

Inverse Time Lag type: In this type, the operating time Is approximately Inversely proportional to the magnitude of the actuating quantity.

Distance Type Relays

These relays work on the principle of measurement of voltage to current ratio. In this type, there are two coils. One coil is energized by current while other by voltage.

The torque produced is proportional to the ratio of the two quantities. When the ratio reduces below a set value, the relay operates.

The various types of these relays are,

1. Impedance Type
2. Reactance Type
3. Admittance Type

Impedance Type: In this type, the ratio of voltage to current is nothing but an impedance which is proportional to the distance ol the relay form the fault point.

Reactance Type: The operating time is proportional to the reactance which is proportional to the distance of the relay from the fault point.

Admittance Type*:* This is also called mho type. In this type, the operating time is proportional to the admittance.

Other Types of Relays

Various other types of relays which are used in practice are,

1. Under voltage, current, power relay: Under voltage, current, power relay operates when the voltage, current or power in a circuit falls below a set value

2. Over voltage, current, power relay: Over voltage, current, power relay actuates when the voltage, current or power In a circuit rises above a set value.

3. Thermal Relay: Thermal Relay actuates due to heat produced by the current in the relay coil.

4. Rectifier Relay: In this relay, the quantities to be sensed are rectified and then given to the moving coil unit of the relay.

5. Permanent Magnet Moving Coil Relay: In Permanent Magnet Moving Coil Relay, the coil carrying current is free to rotate in the magnetic field of a permanent magnet.

6. Static Relay: Static Relay uses some electronic method for sensing the actuating quantity. It uses a stationary circuit.

7. Gas Operated Relay: The gas pressure is adjusted according to the variations in the actuating quantity. This gas pressure is used to actuate the relay. Buchholz relay is an example of such type of relay.

Terms Related to Protective Relay

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 Level of Actuating Signal: The value of actuating quantity (voltage or current) which is on threshold above which the relay initiates to be operated.
If the value of actuating quantity is increased, the electromagnetic effect of the relay coil is increased, and above a certain level of actuating quantity, the moving mechanism of the relay just starts to move.

Reset Level: The value of current or voltage below which a relay opens its contacts and comes in original position.

Operating Time of Relay: Just after exceeding pickup level of actuating quantity the moving mechanism (for example rotating disc) of relay starts moving and it ultimately closes the relay contacts at the end of its journey. The time which elapses between the instant when actuating quantity exceeds the pickup value to the instant when the relay contacts close.

Reset Time of Relay: The time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay contacts return to its normal position.

Reach of Relay: A distance relay operates whenever the distance seen by the relay is less than the pre-specified impedance. The actuating impedance in the relay is the function of distance in a distance protection relay. This impedance or corresponding distance is called the reach of relay. The limiting distance 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.

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.

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 sealing relays or holding relays.

Current Setting :

The pick up value of current can be adjusted to the required level in the relays which is called current setting of that relay. So, Current Setting is the process of adjusting the minimum value of current at which a relay will operate. It is achieved by use of tappings on the relay coil, which are brought out to a plug bridge as shown in the Fig. The tap values are expressed in terms of percentage full load rating of current transformer (C.T.) with which relay is associated.

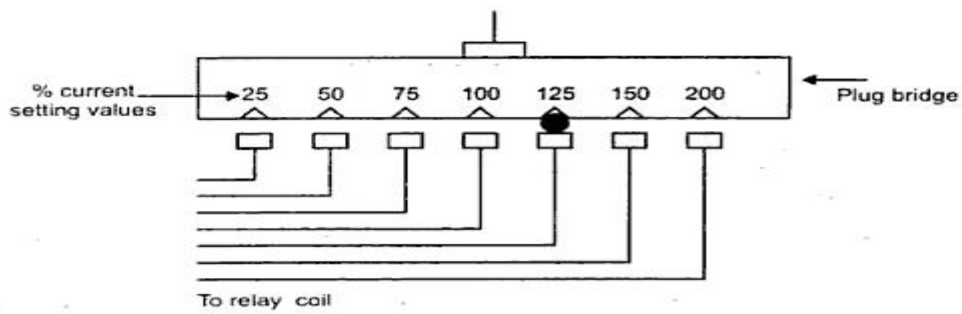


Fig. Tapping for current setting

Thus the value of pickup current can be obtained as,

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

So if C.T. is 500 / 10 A i.e. rated secondary current is 10A and the current setting is 150 then pickup current is 1.5 x 10 = 15 A i.e. 150% of 10. So when relay coil current is greater than or equal to pickup values, relay operates.

In simpler terms, current setting is a way to set the sensitivity of the protective relay. It allows you to adjust the minimum current level that the relay will respond to. This is a very important feature as it allows you to set the relay to trip at the right time, avoiding false tripping or not tripping when a real fault occurs.

Plug Setting Multiplier (P.S.M.) :

Plug Setting Multiplier (P.S.M.) is a measure of the sensitivity of a protective relay. The ratio of actual fault current in the relay coil to the pickup current is called plug setting multiplier (P.S.M.) Mathematically it can be expressed as,

$$\text{P.S.M.} = \frac{\text{fault current in relay coil}}{\text{pickup value}}$$

$$= \frac{\text{fault current in relay coil}}{\text{\% current setting} \times \text{rated secondary current of C.T.}}$$

For example, if the actual fault current in the relay coil is 30A and the pickup current of the relay is 15A, the P.S.M. would be 2. This means that the fault current is 2 times the pickup current of the relay.

The P.S.M. is an important factor to consider when setting the relay's sensitivity. If the P.S.M. is too low, the relay may not trip even when a fault occurs. On the other hand, if the P.S.M. is too high, the relay may trip unnecessarily, resulting in false tripping. Therefore, the P.S.M. should be set to a value that is appropriate for the specific electrical system being protected.

Time/P.S.M. Curve : For a relay, a curve showing relation between time and plug-setting multiplier is provided which is called time/P.S.M. curve. A typical curve for a relay is shown in the Fig. 2.

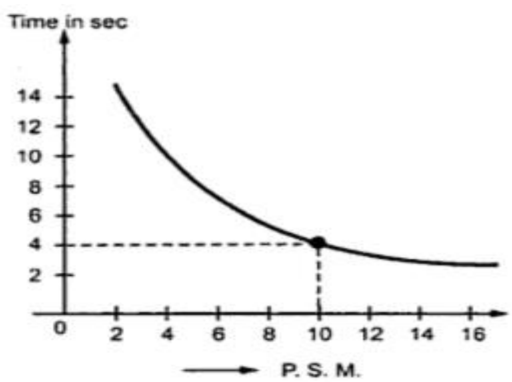


Fig. 2 Time / P.S.M. curve

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 Fig. 2. Multiplying this by a time-setting multiplier, actual time of operation can be obtained.

Time-setting Multiplier :

A time-setting multiplier is a feature on a relay that allows the user to adjust the time delay before the relay operates. 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 Fig.

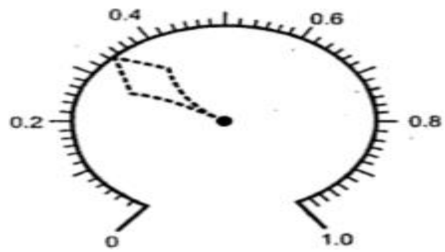


Fig. Time-setting multiplier

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

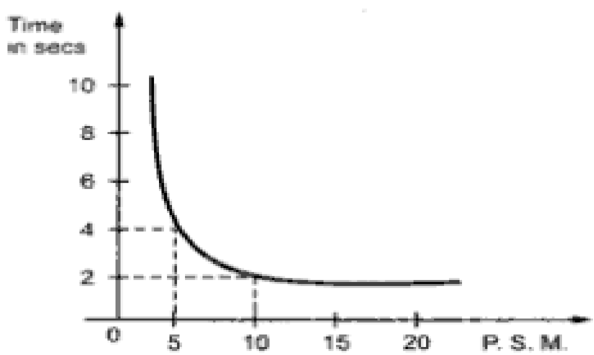
= 4 x 0.2 = 0.8 seconds

So, the time-setting multiplier allows the user to adjust the time delay based on the specific needs of the electrical system that the relay is protecting. It is an important tool for fine-tuning the protection of the system and ensuring that the relay operates correctly in the event of a fault

Trip Circuit : The opening operation of circuit breaker is controlled by a circuit which consists of trip coil, relay contacts, auxiliary switch, battery supply etc. which is called trip circuit.

Numerical on PSM and TSM

Example 1) An IDMT overcurrent relay has a current setting of 150% and a time multiplier setting of 0.6. The primary of relay is connected to secondary of CT having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 5000A. The time current characteristics of relay is shown in figure below.



Solution:

Fault current in relay coil = Line fault current /CT ratio

= 5000 x 5/400 = 62.5 A

Rated secondary current of CT = 5A

Current setting = 150% = 1.5

PSM = Fault current in relay/ (% current setting x rated secondary current of CT)

= 62.5 / (1.5 x 5) = 8.333

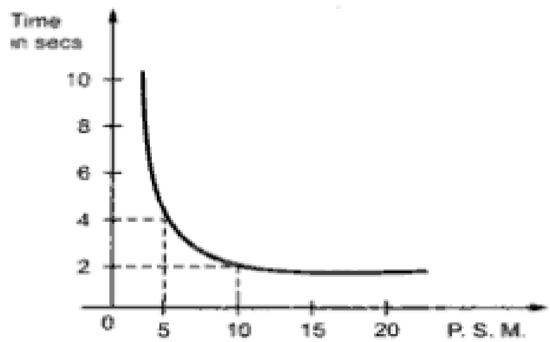
From figure above approx time for PSM of 8.33 is 2.2 sec

Actual operation time = Time for PSM obtained x Time setting multiplier

= 2.2 x 0.6

= 1.08 sec

Example 2) An IDMT overcurrent relay has a current setting of 150% and a time multiplier setting of 0.6. The primary of relay is connected to secondary of CT having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 4000A. The time current characteristics of relay is shown in figure below.



Solution:

Fault current in relay coil = Line fault current /CT ratio

= 4000 x 5/400 = 50 A

Rated secondary current of CT = 5A

Current setting = 150% = 1.5

PSM = Fault current in relay/ (% current setting x rated secondary current of CT)

= 50 / (1.5 x 5) = 6.666

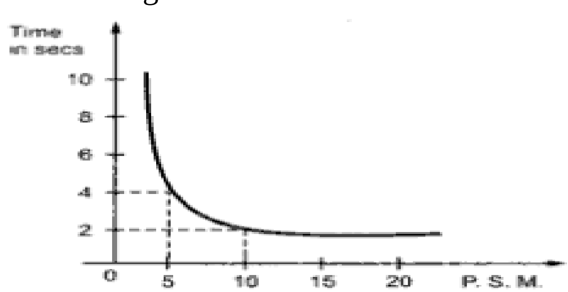
From figure above approx time for PSM of 6.67 is 3 sec

Actual operation time = Time for PSM obtained x Time setting multiplier

= 3 x 0.6

= 1.8 sec

Example 3) An IDMT overcurrent relay has a current setting of 150% and a time multiplier setting of 0.6. The primary of relay is connected to secondary of CT having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 7000A. The time current characteristics of relay is shown in figure below.



Solution:

Fault current in relay coil = Line fault current /CT ratio

= 7000 x 5/400 = 87.5 A

Rated secondary current of CT = 5A

Current setting = 150% = 1.5

PSM = Fault current in relay/ (% current setting x rated secondary current of CT)

= 87.5 / (1.5 x 5) = 11.67

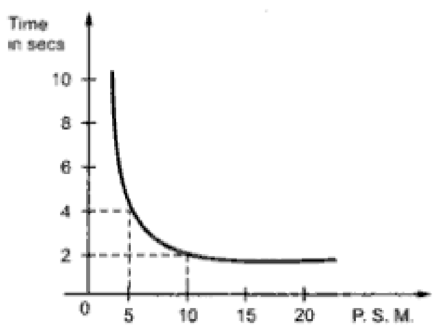
From figure above approx time for PSM of 11.67 is 1.8 sec

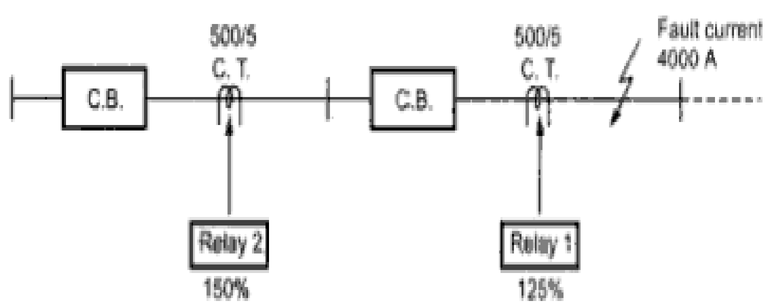
Actual operation time = Time for PSM obtained x Time setting multiplier

= 1.8 x 0.6

= 1.08 sec

Example 4) The figure below shows the part of a typical power system. If for the discrimination, the time grading margin between the relays is o.6 sec. Calculate the time of operation of relay 1 and time setting multiplier for relay 2. The time current characteristics of relay is shown in figure. The time setting multiplier of relay 1 is 0.3.





Solution:

For relay 1; Current setting = 125% = 1.25

Fault current = 4000A

CT ratio = 500/5

Fault current in relay = 4000 x 5/500 = 40 A

PSM = 40/(5 x 1.25) = 6.4

From the time current characteristics, the corresponding time for 6.4 PSM is approx. 3 seconds.

Actual time of operation = 3 x 0.3 = 0.9 sec

For relay 2; Current setting = 150% = 1.5

Actual time of operation = 0.9 + 0.6 = 1.5 sec

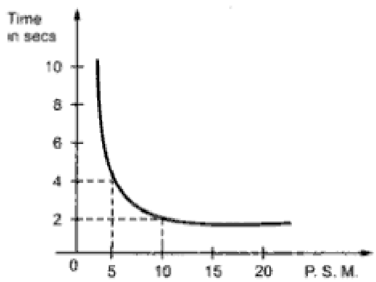
Fault current in relay = 4000 x 5/500 = 40 A

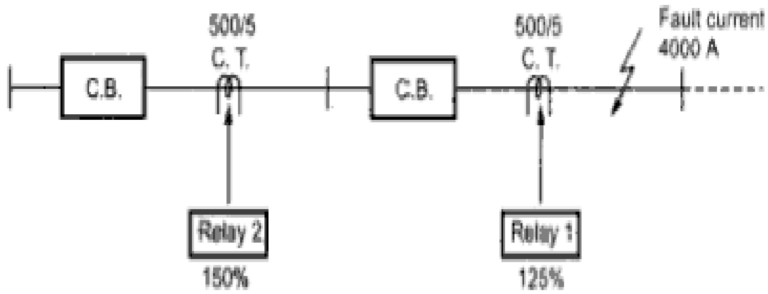
PSM = 40 / (5 x 1.5) = 5.33

From the time current characteristics, the corresponding time for 5.33 PSM is approx. 3.8 seconds.

Time setting multiplier = 1.5/3.8 = 0.385 = 0.4 sec

Example 5) The figure below shows the part of a typical power system. If for the discrimination, the time grading margin between the relays is o.6 sec. Calculate the time of operation of relay 1 and time setting multiplier for relay 2. The time current characteristics of relay is shown in figure. The time setting multiplier of relay 1 is 0.5.





Solution:

For relay 1; Current setting = 125% = 1.25

Fault current = 4000A

CT ratio = 500/5

Fault current in relay = 4000 x 5/500 = 40 A

PSM = 40/(5 x 1.25) = 6.4

From the time current characteristics, the corresponding time for 6.4 PSM is approx. 3 seconds.

Actual time of operation = 3 x 0.5 = 1.5 sec

For relay 2; Current setting = 150% = 1.5

Actual time of operation = 1.5 + 0.6 = 2.1 sec

Fault current in relay = 4000 x 5/500 = 40 A

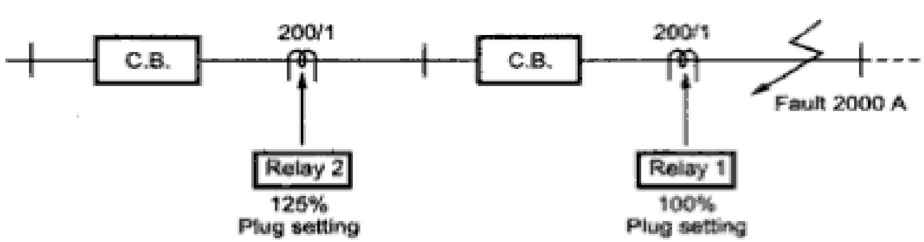
PSM = 40 / (5 x 1.5) = 5.33

From the time current characteristics, the corresponding time for 5.33 PSM is approx. 3.8 seconds.

Time setting multiplier = 2.1/3.8 = 0.385 = 0.55 sec

Example 6) Given; fault current = 2000 A; Relay 1 set on 100%; CT ratio = 200/1; Relay 2 set on 125%; time gradient margin between relays is 0.5 sec. Determine the time of operation of the two relays assuming that both the relays have characteristics as shown in the following table and the relay no. 1 has a time multiplier setting of 0.2

PSM	2	3.6	5	8	10	15	20
Time in sec	10	6	3.9	3.15	2.8	2.2	2.1



Solution;

Relay 1; Relay current = 2000/200 = 10 A

Pickup current = 1 x 1 = 1 A

PSM = 10/1 = 10

Time of operation of relay 1 corresponding to PSM 10 is 2.8 seconds

Actual operating time of relay 1 with TSM of 0.2

= 2.8 x 0.2 = 0.56 seconds

Relay 2; Relay current = 2000/200 = 10 A

Pick up current = 1.25 x 1 = 1.25 A

PSM = 10/1.25 = 8

Time of operation of relay 2 corresponding to PSM 8 is 3.15 seconds

Actual operating time of relay 2 = 0.56 + 0.5 = 1.06 seconds

Time setting multiplier of relay 2 = 1.06/3.15 = 0.3365

Calculation of Relay Operation Time

Step – 1

From CT ratio, we first see the rated secondary current of CT. Say the CT ratio is 100 / 1 A, i.e. secondary current of CT is 1 A.

Step – 2

From current setting we calculate the trick current of the relay. Say current setting of the relay is 150% therefore pick up current of the relay is 1 × 150% = 1.5 A.

Step – 3

Now we have to calculate PSM for the specified faulty current level. For that, we have to first divide primary faulty current by CT ratio to get relay faulty current. Say the faulty current level is 1500 A, in the CT primary, hence secondary equivalent of faulty current is 1500/(100/1) = 15 A

Step – 4

Now, after calculating PSM, we have to find out the total time of operation of the relay from Time / PSM curve. From the curve, say we found the time of operation of relay is 3 second for PSM = 10.

Step – 5

Finally that operating time of relay would be multiplied with time setting multiplier, in order to get actual time of operation of relay. Hence say time setting of the relay is 0.1.

Therefore actual time of operation of the relay for PSM 10, is 3 × 0.1 = 0.3 sec or 300 ms.

RELAY APPLICATION AND CHARACTERISTICS

Directional And Non-Directional Overcurrent Relays

Directional overcurrent relays are used to detect an overcurrent in a specific direction, typically in electrical power systems. These relays have a built-in mechanism that allows them to distinguish between current flowing in the normal direction, and current flowing in the opposite direction. This feature is useful for protecting equipment and power systems from damage caused by faults and other abnormal conditions.

Non-directional overcurrent relays, on the other hand, do not have this built-in mechanism and simply detect an overcurrent regardless of the direction in which it is flowing i.e. non directional are independent of the flow of the direction of the current. These relays are typically used in situations where the direction of the current is not important or is not known. The overcurrent unit may be of either a shaded pole type or wattmeter type

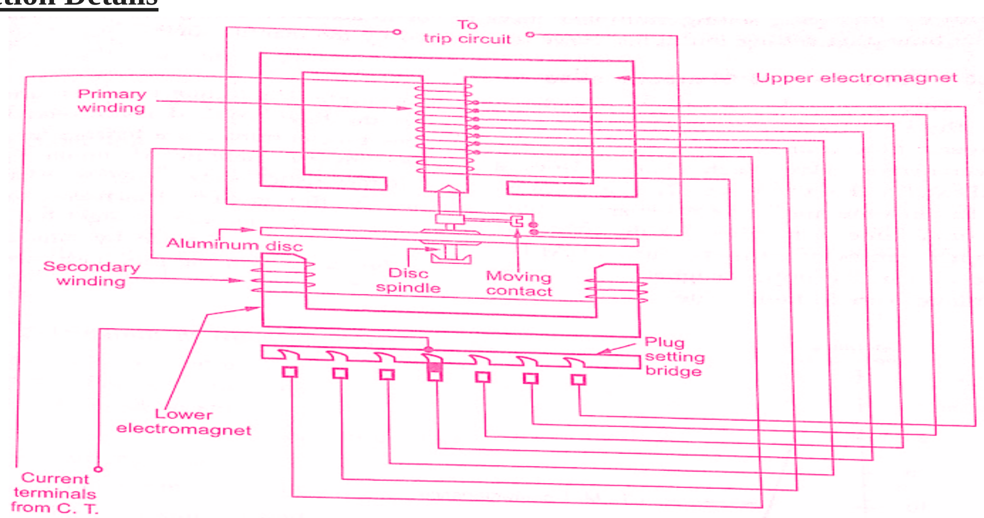
Directional relays sense the flow of current in a particular direction only for which they are installed. Directional relays are generally installed at the load end and non-directional at the source end. The directional feature gives us an advantage for sensing the reverse power flow when the excitation of the generator is suddenly stopped also when a fault takes place in one of the parallel feeder the directional relay at the load end side can still allow the flow of current through healthy lines and thus provide a reduced power flow instead of complete of system.

Non-Directional Induction type over-current Relay

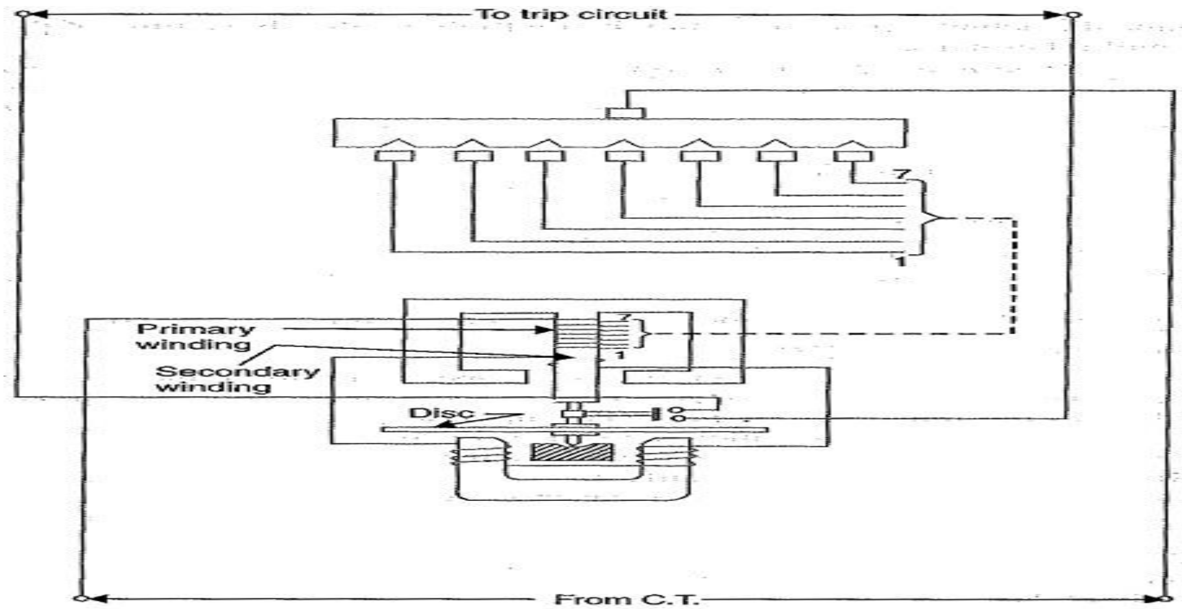
This relay is also called earth leakage induction. Overcurrent relay operates when the current in the circuit exceeds a specific preset value. The actuating source is a current in the circuit supplied to the relay from a current transformer. These relays are used on a .c circuit only and can operate for fault current flow in either direction.

Induction type non-directional overcurrent relays can be constructed in the same way as a wattage meter with some modifications.

Construction Details



Or,



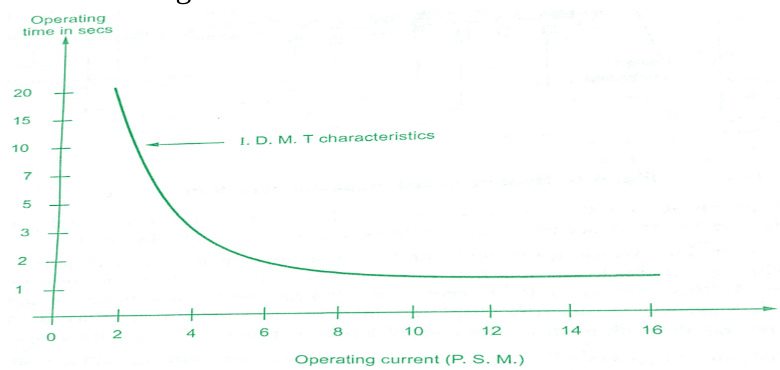
- It consists of two electromagnets. The upper is E shaped while the lower is U shaped.
- The aluminium disc is free to rotate between the two magnets. The spindle of the disc carries moving contacts and when the disc rotates the moving contacts come in contact with fixed contacts which are the terminals of a trip circuit.
- The upper magnet has two windings, primary and secondary. The **primary is connected to the secondary of C.T on the line to be protected**. This winding is tapped at intervals. The tappings are connected to plug setting bridge. With the help of this bridge, the number of turns of the primary winding can be adjusted. Thus the desired current setting for the **Non-Indirectional Induction Overcurrent Relay** can be obtained. There are usually seven sections of tapping's to have the overcurrent range from 50% to 200% in steps of 25%. These values are the percentage of the relay's current rating.
- **The secondary winding is energized by induction from primary and is connected in series with the winding on** the lower magnet. The controlling torque, is provided by a spiral spring.
- The spindle of the disc carries a moving contact which bridges two fixed contacts (connected to trip circuit) when the disc rotates through a pre-set angle. This angle can be adjusted to any value between 0° and 360^{0}. By adjusting this angle, the travel of the moving contact can be adjusted and hence the relay can be given any desired time setting.

Operation: The driving torque on the aluminium disc is set up due to the induction principle. This torque is opposed by the restraining torque provided by the spring. Under normal operating conditions, restraining torque is greater than the driving torque produced by the relay coil current, Therefore, the aluminium disc remains stationary. However, if the current in the protected circuit exceeds the pre-set value, the driving torque becomes greater than the restraining torque. Consequently, the disc rotates and the moving contact bridges the fixed contacts when the disc has rotated through a pre-set angle. The trip circuit operates the circuit breaker which isolates the faulty section.

Time-Current characteristics

The time required to rotate the disc depends on a torque. The torque varies as current in the primary circuit. More the torque, lesser is the time required hence **Non-Indirectional Overcurrent relay** has inverse time characteristics. The figure below shows the **time-current characteristics for the Non-Indirectional overcurrent relay**. Such characteristics are called Inverse Definite Minimum Type (I.D.M.T.) characteristics.

This is because the characteristics show the inverse relation between time and current for small values of currents. But as current increases, some definite time is required by the relay. So the characteristics becomes straight line for higher values of currents. Such IDMT characteristics can be obtained by saturating the iron in the upper magnet so that there cannot be increase in the flux once current achieves certain high value.



The P.S.M can be obtained,

$$P.S.M. = \frac{\text{Fault current in relay coil}}{\text{Rated secondary C.T. current} \times \text{Current setting}}$$

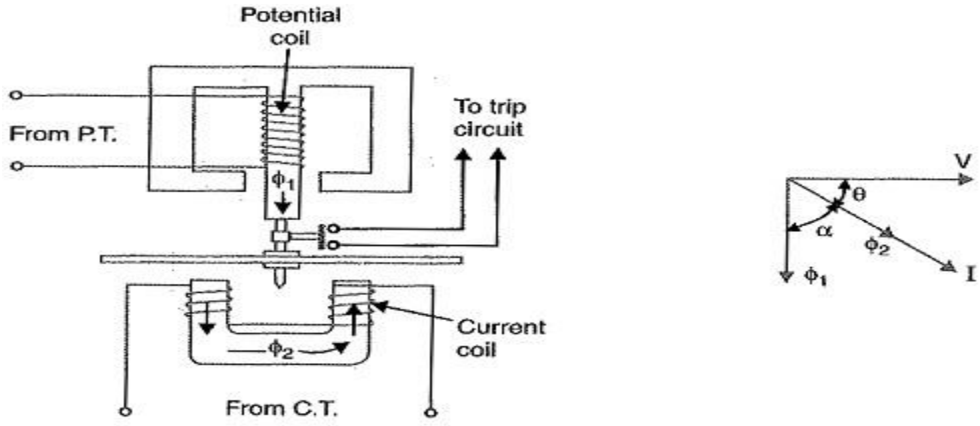
Fault current in relay coil = Line fault current × C.T Ratio

Directional Power Relay (Induction Type)

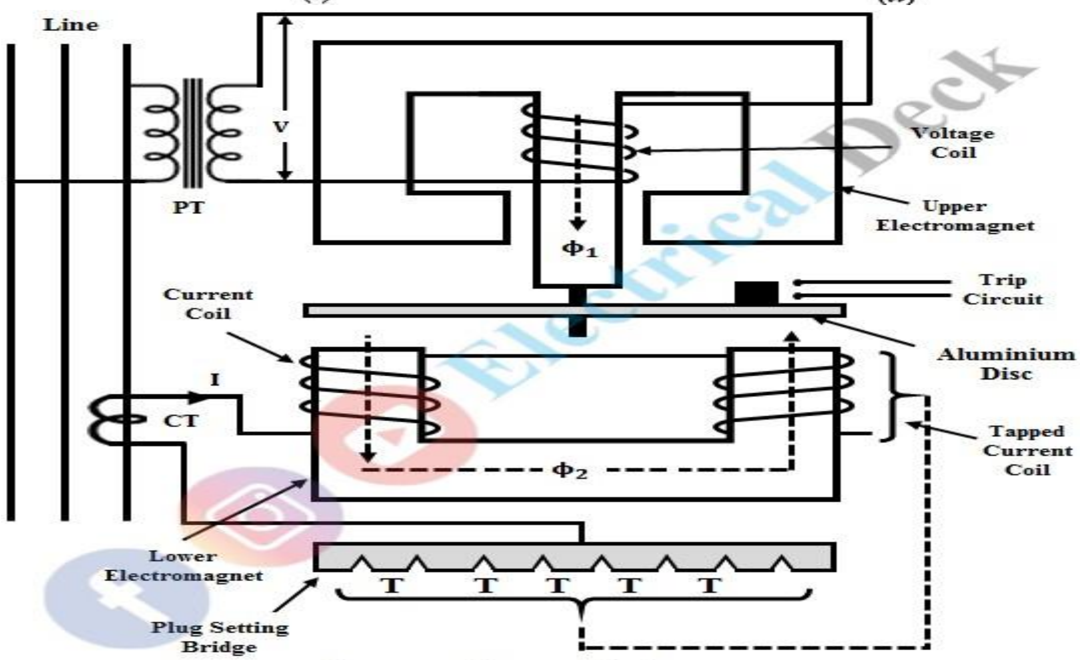
This Induction Type Directional Power Relay operates when power in the circuit flows in a specific direction Unlike a non-directional overcurrent relay, a directional power relay is so designed that it obtains its operating torque by the interaction of magnetic fields derived from both voltage and current source of the circuit it protects. Thus this type of relay is essentially a wattmeter and the direction of the torque set up in the relay depends upon the direction of the current relative to the voltage, with which it is associated.

in a directional power relay, the operating torque is produced by the interaction of fields given by both voltage and current sources of the circuit it protects. The relay operates when the current exceeds a predetermined set value in a specified direction.

Construction



(i) *(ii)*



Reverse Power Relay

It consists of an aluminum (metallic) disc which rotates freely in between two electromagnets. The central limb of the upper electromagnet consists of winding called potential coil. The potential coil is connected to the system voltage through a potential transformer.

The lower electromagnetic has a separate winding called current coil which is magnetized proportional to operating current. It is connected in series with the line through a current transformer and is tapped at intervals. The tappings are connected to a plug setting bridge to get the required current setting of the relay which can be done by changing the number of turns of the current coil.

The torque is controlled by a spiral spring. A moving contact is present on the disc and lt links two fixed contacts when the disc rotates through a preset angle. This angle can be adjusted to any value (0-360°) and the moving contact path can be set. Hence the relay can be assigned to any time setting.

Working of Induction Type Directional Relay:

The two fluxes are produced by the two quantities for the production of torque. Let the two fluxes be Φ_1 and Φ_2. The current in the potential coil lags behind the applied voltage V nearly by 90°. Hence the flux Φ_1 produced by the potential coil also lags behind the applied voltage.

While the flux Φ_2 produced by the current coil will be in phase with the line current. The torque produced on the disc is due to the interaction of eddy currents with the flux imposed by the potential and current coils and it is called driving torque. The driving torque is given by,

$$T \propto \Phi_1 \Phi_2 \sin \alpha$$

Since, $\Phi_1 \propto V$, $\Phi_2 \propto I$ and $\alpha = 90° - \theta$

$$T \propto V I \sin (90° - \theta)$$

$$T \propto V I \cos \theta \text{ (power in the circuit)}$$

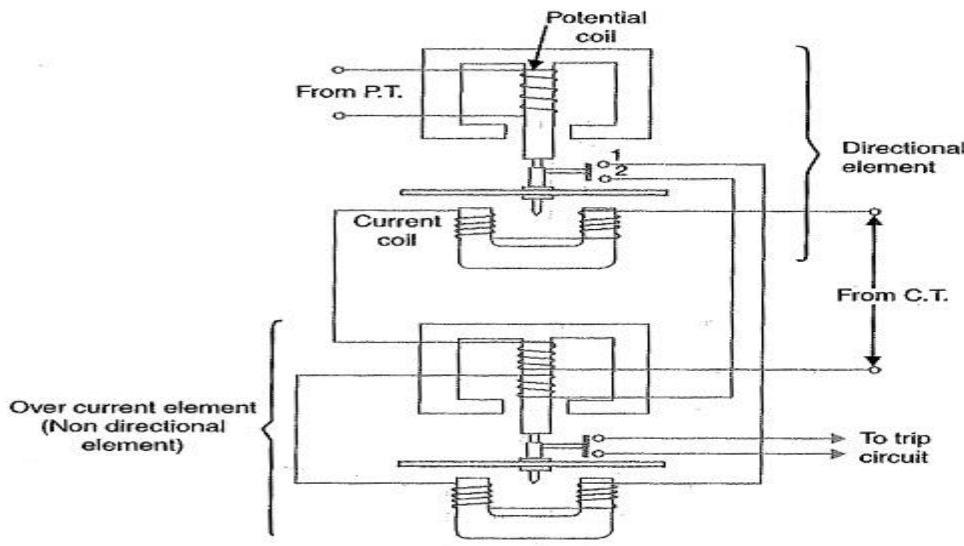
From the above expression, it is clear that the relay connection for the power in the circuit decides the direction of driving torque produced on the disc of the relay. Under normal conditions i.e., when there is no reverse power flow in the circuit.

The driving torque and restraining torque (produced due to spring) on the disc will be in such a way that, the moving contact on the disc turns away from the fixed contact and it doesn't make the trip circuit close. Hence the relay does not operate.

However, when the operating current in the circuit reverses, it reverses the driving torque produced on the disc. The disc starts rotating in the reverse direction once the reversed driving torque becomes large enough. This causes moving contact to close the fixed contact i.e., the trip circuit closes and the trip signal to disconnect the circuit is initiated by the relay to the circuit breaker.

Induction Type Directional Overcurrent Relay

The directional power relay is unsuitable for use as a directional protective relay under short-circuit conditions. When a short-circuit occurs, the system voltage falls to a low value and there may be insufficient torque developed in the relay to cause its operation. This difficulty is overcome in the Induction Type Directional Overcurrent Relay which is designed to be almost independent of system voltage and power factor



Constructional details: Fig. shows the constructional details of a typical Induction Type Directional Overcurrent Relay. It consists of two relay elements mounted on a common case viz.

1. **Directional element and**
2. **Non-directional element.**

1. Directional element: It is essentially a directional power relay which operates when power flows in a specific direction. The potential coil of this element is connected through a potential transformer (P.T.) to the system voltage. The current coil of the element is energized through a C.T. by the circuit current. This winding is carried over the upper magnet of the non-directional element. The trip contacts (1 and 2) of the directional element are connected in series with the secondary circuit of the overcurrent element. Therefore, the latter element cannot start to operate until its secondary circuit is completed. In other words, the directional element must operate first (i.e. contacts I and 2 should close) in order to operate the overcurrent element.

2. Non-directional element: It is an overcurrent element similar in all respects to a non-directional overcurrent relay. The spindle of the disc of this element carries a moving contact which closes the fixed contacts (trip circuit contacts) after the operation of directional element.

It may be noted that plug-setting bridge is also provided in the relay for current setting but has been omitted in the figure for clarity and simplicity. The tappings are provided on the upper magnet of overcurrent element and are connected to the bridge.

Operation: Under normal operating conditions, power flows in the normal direction in the circuit protected by the relay. Therefore, Induction Type Directional Overcurrent Relay (upper element) does not operate, thereby keeping the overcurrent element (lower element) unenergised. However, when a short-circuit occurs, there is a tendency for the current or power to flow in the reverse direction. Should this happen, the disc of the upper element rotates to bridge the fixed contacts 1 and 2. This completes the circuit for overcurrent element.

The disc of this element rotates and the moving contact attached to it closes the trip circuit. This operates the circuit breaker which isolates the faulty section. The two relay elements are so arranged that final tripping of the current controlled by them is not made till the following conditions are satisfied:

1. **Current flows in a direction such as to operate the directional element.**
2. **Current in the reverse direction exceeds the pre-set value.**
3. **Excessive current persists for a period corresponding to the time setting of overcurrent element.**

Differential Relay

Differential relays are very sensitive to the faults occurred within the zone of protection but they are least sensitive to the faults that occur outside the protected zone. Most of the relays operate when any quantity exceeds beyond a predetermined value.

The relay whose operation depends on the phase difference of two or more similar electrical quantities is known as the differential protection relay. It works on the principle of comparison between the phase angle and the magnitude of the same electrical quantities.

For instance, in comparison to the entering current & leaving current in a line, if a huge current goes through the protected line as compared to the current leaving from it, then additional current must supply within the fault. So, the difference between the two electrical quantities can control a relay to separate the circuit.

In normal operating conditions, the entering & leaving currents are equivalent in phase & magnitude thus the relay will not work. However, if any fault occurs within the system, then these flow of currents will be no longer equivalent in phase & magnitude.

This kind of relay is used in such a way that the difference between the entering & leaving current supplies throughout the relay's operating coils. So, the relay coil can be energized in fault conditions because of the various quantity of the current. So, this relay functions & opens the circuit breaker for tripping the circuit

Following are the essential condition requires for the working of the differential protection relay.

- The network in which the relay use should have two or more similar electrical quantities.
- The quantities have the phase displacement of approximately 180º.

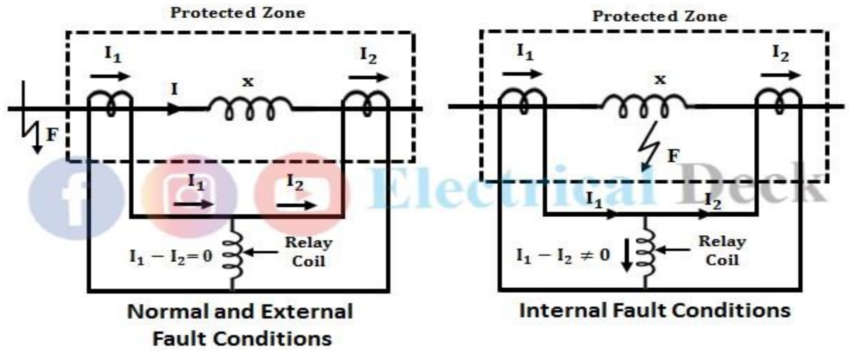
The differential protection relay is used for the protection of the generator, transformer, feeder, large motor, bus-bars etc. The following are the classification of the differential protection relay.

- Current Differential Relay
- Biased or Percentage Differential Relay
- Voltage Balance Differential Relay

Current Differential Relay

It works on the principle that, when there is a fault within the protected zone, then there will be a difference in the current entering and current leaving of that protected zone. Thus by comparing the entering and leaving currents of the protected zone either in magnitude or in phase or both we can detect the fault in the protected zone. The relay compares the two currents and sends a trip signal to the circuit breaker if the difference exceeds a predetermined set value.

The circuit connections of differential relay protection for external fault or normal condition and during internal fault are shown in the below figures respectively.



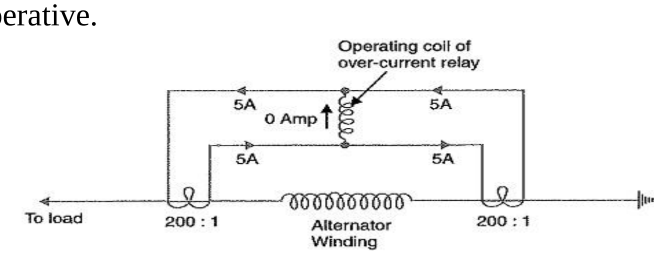
Current Differential Relay Protection

From the above figure during normal and external fault conditions, the current entering the protected zone is equal to the current leaving the protected zone (i.e., I_1 - I_2 = 0). Thus no current will flow through the relay coil and hence it remains inoperative.

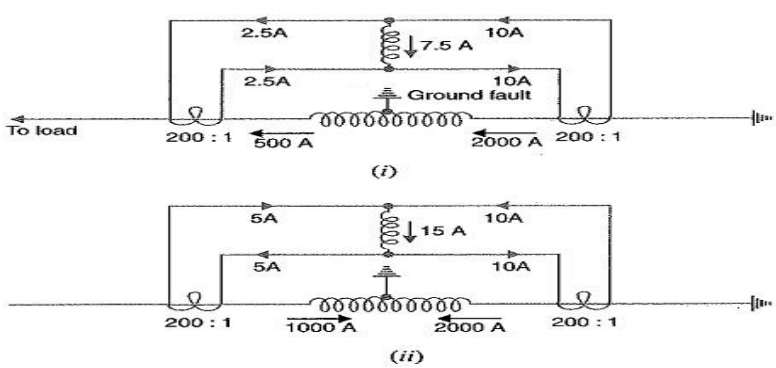
During an internal fault, the current entering the protected zone is different from the current leaving it (i.e., I_1 - $I_2 \neq 0$). The difference of these currents called the circulating current is fed to the relay operating coil and the relay operates if the operating torque is greater than the restraining torque.

Example:

Under normal operating conditions, suppose the alternator winding carries a normal current of 1000 A. Then the currents in the two secondaries of CT's are equal. These currents will merely circulate between the two CT's and no current will flow through the differential relay. Therefore, the relay remains inoperative.



If a ground fault occurs on the alternator winding as shown in Fig, the two secondary currents will not be equal and the current flows through the operating coil of the relay, causing the relay to operate. The amount of current flow through the relay will depend upon the way the fault is being fed.



(i) If some current (500 A in this case) flows out of one side while a larger current (2000 A) enters the other side as shown in Fig. (i), then the difference of the CT secondary currents i.e. 10 – 2 5 = 7.5 A will flow through the relay.
(ii) If current flows to the fault from both sides as shown in Fig. (ii), then sum of CT secondary currents i.e. 10 + 5 = 15 A will flow through the relay.

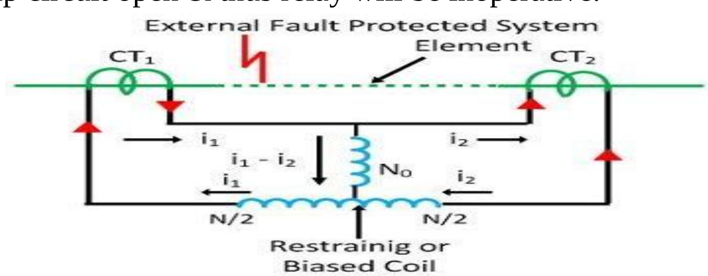
Disadvantages of Current Differential Relay:

- Under heavy flow of currents, the accuracy of the relay gets affected due to the capacitance of the pilot cable.
- Due to heavy currents under short circuit conditions, it may saturate the current transformer and results in the unequal flow of currents in the secondaries of CTs. These unequal currents cause inaccurate operation of the relay.
- The current transformers used here cannot have 100% similar ratings or characteristics due to constructional errors and pilot cable impedances. This causes a sensitive relay to operate inaccurately.

These disadvantages can be overcome by modifying the current differential relay and is known as percentage differential relay or biased differential relay.

Percentage Differential Relay

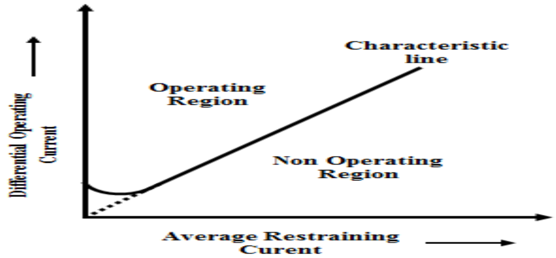
The circuit includes mainly two coils like restraining & an operating coil. Here, the operating coil is simply connected to the restraining coil's center point. The operating coil generates the operating torque so that the relay operates whereas the restraining coil generates a bias force or restraining torque which is quite reverse to the operating torque. This relay operates with the differential current which is flowing throughout the protected region.
Whenever there is no fault within the protected region or there is a fault outside of the protected region then restraining torque produced by restraining coils due to current $(I_1+ I_2)/2$ will be higher as compared to the operating torque produced by operating coil due to current $I_1 - I_2$. So this will make the trip circuit open & thus relay will be inoperative.



However, if there is a fault within the protected region then the operating torque will be higher as compared to the restraining torque. Because of this, the beam simply closes the trip circuit so which initiates a trip signal through the relay to the CB or circuit breaker.

$$Bias\ setting\ in\ percentage = \frac{I_1 - I_2}{(I_1 + I_2)/2} \times 100\%$$

So, ratio of i2 – i1 (differential operating current) to (i1 + i2)/2 (restraining current) has a fixed percentage always. Therefore, this relay is known as a **percentage differential relay**. To operate this relay, the differential current should be higher as compared to this fixed percentage.



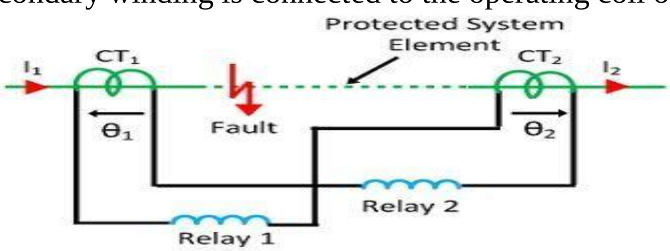
Operating Characteristics

The above shows the operating characteristics of the percentage differential relay. It can be seen that the characteristics are a straight line except at low currents.

Voltage Balance Differential Relay

The two CTs in the voltage balance differential relay are simply connected at any side of the element to be protected that is alternator winding which is shown in the above figure. This type of relay simply compares two voltages either in phase or magnitude or in both & it trips the relay circuit if the difference exceeds a fixed set value.

The CT's primary windings have similar current ratios which are connected with the pilot wire in series. These wires are connected always by simply connecting two circuit ends as shown in the above figure & CTs secondary winding is connected to the operating coil of the relay.



Balance Voltage Differential Protection

In the above relay circuit, the flow of current in both the main windings of CTs will be the same at normal operating conditions. So when the flow of current is the same, then the voltage within the secondary winding will be the same. So, there is no flow of current in the operating coil of a relay.

Similarly in the faulty conditions, a phasor difference will exist within the primary coil's currents. Thus, there is a difference in voltage at the second winding. Now a phasor difference will exist in the secondary coil's voltage which is fed to the operating coil of the relay and it is connected with the secondary winding in series. Because of this, the flow of current will be there throughout the operating coil of the relay.

Disadvantages of Voltage Balance Differential Relay:

- The construction becomes complex for achieving the perfect balance between CT pairs.
- Under heavy flow of currents, the accuracy of the relay gets affected due to the capacitance of the pilot cable.

- This type of differential relay protection can be effectively used for shorter length lines.

Applications of differential relay

- This relay is widely used to safeguard transformers and generators from localized disturbances.
- These relays are often employed primarily to shield the machinery from internal defects. In order to protect the stator winding of the alternator from internal problems, Merz price protection is one sort of differential relay.
- The winding of a transformer is safeguarded by this type of relay.
- These are ideal for protecting small objects as well as the many components of the power system, such as bus bars, generators, reactors, transmission lines, transformers, feeders, etc.

Universal Torque Equation of Relays

Protection relays consist of electromagnets with armature or induction disc, which carry contacts. The relays also carry the closing or opening of contacts control devices like trip coils of the circuit breaker. The electromagnets are wound with either current coil, voltage coil, or both current and voltage coils.

The coils produce magnetic flux which develops torque in the rotor when interacts with the eddy currents that are induced in the rotor by these fluxes. The universal torque equation of relay gives the torque exerted on the rotor by all the quantities. Let us see the expression for the universal torque equation of relay.

Let us assume the following,

V = Voltage applied
I = Current through winding
θ = Angle between voltage and current
τ = Maximum torque angle
T_1 = Torque set up by the current coil
T_2 = Toque set up by the voltage coil
T_3 = Torque set up by both voltage and current coil
T_4 = Torque produced by control spring
K_1, K_2, K_3, K_4 = Constants.

The protective relay consists of electromagnets with armature or induction disc. Some of the electromagnets will have windings for current or voltage, or for both current and voltage.

- The torque set by the current coil is directly proportional to the square of the current i.e.,

$$T_1 = K_1 I^2$$

- The torque set by the voltage coil is directly proportional to the square of the voltage i.e.,

$$T_2 = K_2 V^2$$

- The torque produced by both the voltage and current coils is directly proportional to the product of voltage and current i.e.,

$$T_3 = K_3 V I \cos(\theta - \tau)$$

The torque set up by the control spring is given by,

$$T_4 = K_4$$

The universal torque equation is obtained when all the elements are considered in the relay i.e.,

$$T = T_1 + T_2 + T_3 + T_4$$

Substituting equations of T_1, T_2, T_3, and T_4 in the above equation, we get,

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

The above equation represents the universal torque equation of relay. The operating characteristic of all types of relays is obtained by adding and subtracting all the other constants and letting others be zero or by adding other similar terms.

Distance or Impedance Relay

A transmission line must ensure the continuity of the supply with the least possible interruptions, but at the same time, there is a need for shorter operating time protective relays on faulted sections to preserve the system stability. In order to meet these modern requirements, two major types of transmission lines schemes are used, namely,

- Distance relaying system
- Carrier current system or pilot wire system.

Due to the high cost and unreliability of the pilot wire system, it is not used for the protection of long transmission lines. Hence a distance relaying system is well suited for the protection of long transmission lines.

These are placed at various points along the transmission lines. **On the occurrence of a fault, the relay measures the length of the line to the fault.** Also, the operation of the relays is such that the nearest to the fault will operate quicker than other relays which are farther to the fault.

Distance protection relay is the name given to the protection, whose action depends on the distance of the feeding point to the fault. **The time of operation of such protection is a function of the ratio of voltage and current, i.e., impedance.** This impedance between the relay and the fault depends on the electrical distance between them. As the measured quantity is proportional to the distance along the line, the measuring relay is called the distance relay.

The impedance value determines how well this relay works. **When the impedance of the defective point is less than the impedance of the relay, it trips the circuit breaker and shuts the connections.** The relay continually monitors the voltage and current passing through the PT and CT, and it only operates when the ratio of voltage and current (impedance value) is less than the relay's specified impedance value.

The various features offered by the distance relays are,

- These are used for the protection of transmission and sub-transmission lines.
- These are operated at higher speeds to clear the fault.
- These are mainly used where the overcurrent relays become slow, and there is difficulty in grading time-over current relays.
- The measured quantity is proportional to the line length between the location of the relay and the point where the fault has occurred.

The principal type of distance relays is

a) impedance relays,
b) reactance relays, and
c) mho relays.

Choice between Impedance Type, Reactance Type and Mho Type Relays:

The choice between impedance types, reactance type and mho type relays should be properly done with reference to their application to transmission line protection.

The ground resistance is variable. The ground distance relays must be unaffected by variation in fault resistance. Reactance type relays are preferred for ground fault relaying. **For short line sections, reactance type relays are preferred as they are not affected by the arc resistance and more percentage of the line can be protected at high speed.** The drawback of reactance relays, however, is that they are likely to operate undesirably on severe synchronising power swings at certain locations unless additional relay equipment is provided.

Mho type relays are best suited for phase fault relaying for long lines and particularly where a severe synchronizing power surge may occur. They are most sensitive of all the distance relays. The mho relay is reliable because it combines both the directional and distance measuring functions in one unit.

The impedance type relay is suitable for phase fault relaying for lines of moderate length. The arc affects the impedance relay more than the reactance relay but less than the mho relay. The impedance relay along with the directional unit can be made to change its characteristics and the modified impedance relay may resemble the reactance or mho unit. There is considerable overlap in the application of these relay.

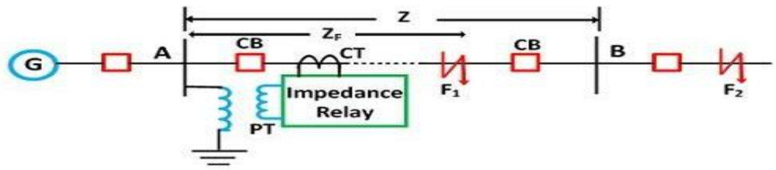
Impedance Type Distance Relay

The relay measures the impedance of the faulty point, if the impedance is less than the impedance of the relay setting; it gives the tripping command to the circuit breaker for closing their contacts. The impedance relay continuously monitors the line current and voltage flows through the CT and PT respectively. If the ratio of voltage and current is less than the relay starts operating then the relay starts operating.

Principle of Operation of Impedance Relay

In the normal operating condition, the value of the line voltage is more than the current. But when the fault occurs on the line the magnitude of the current rises and the voltage becomes less. The line current is inversely proportional to the impedance of the transmission line. Thus, the impedance decreases because of which the impedance relay starts operating.

Consider the impedance relay is placed on the transmission line for the protection of the line AB. The Z is the impedance of the line in normal operating condition. If the impedances of the line fall below the impedance Z then the relay starts working.



Principle of operation of an Impedance Relay

Let, the fault F1 occur in the line AB. This fault decreases the impedance of the line below the relay setting impedance. The relay starts operating, and its send the tripping command to the circuit breaker. If the fault reached beyond the protective zone, the contacts of the relay remain unclosed.

Operating Characteristic of an Impedance Relay

The voltage and the current operating elements are the two important component of the impedance relay. **The current operating element generates the deflecting torque while the voltage storage element generates the restoring torque.** The torque equation of the relay is shown in the figure below

$$T = K_1I^2 - K_2V^2 - K_3$$

The $-K_3$ is the spring effect of the relay. The V and I are the value of the voltage and current. When the relay is in normal operating condition, then the net torque of the relay becomes zero.

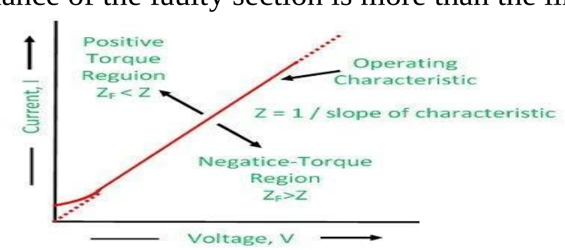
$$K_2V^2 = K_1I^2 - K_3$$

If the spring control effect becomes neglected, the equation becomes

$$\frac{V}{I} = Z = \sqrt{\frac{K1}{K2} - \frac{K3}{K2\,I^2}}$$

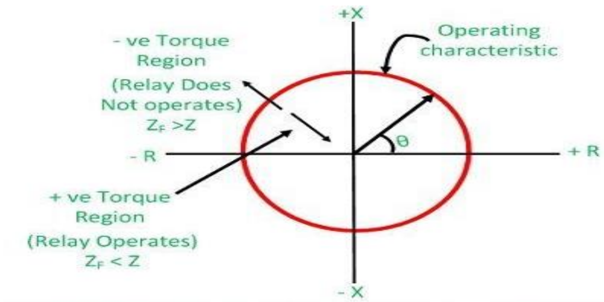
The operating characteristic concerning the voltage and current is shown in the figure below. The dashed line in the image represents the operating condition at the constant line impedance.

The operating characteristic of the impedance relay is shown in the figure below. The positive torque region of the impedance relay is above the operating characteristic line. In positive torque region, the impedance of the line is more than the impedance of the faulty section. Similarly, in negative region, the impedance of the faulty section is more than the line impedance.



Opening Characteristic of an Impedance Relay

The impedance of the line is represented by the radius of the circle. The phase angle between the X and R axis represents the position of the vector. If the impedance of the line is less than the radius of the circle, then it shows the positive torque region. If the impedance is greater than the negative region, then it represents the negative torque region.



Operating Characteristic of an Impedance Relay on an R-X Diagram

This type of relay is called the high-speed relay.

Advantages

- The addition of the directional element can be used for better performance.
- It is used in the protection of medium transmission lines.

Disadvantages

- It is a non-directional relay that is the relay will respond to the fault on either side of a CT
- The characteristics curve is too large, so mal-operation is possible
- It can not be used for long transmission lines.

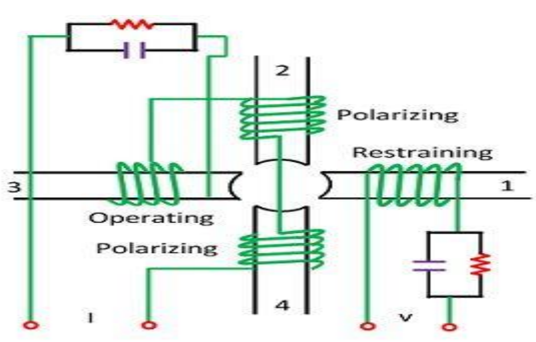
Reactance Relay

The reactance relay is a high-speed relay. This relay consists of two elements an overcurrent element and a current-voltage directional element. The **current element developed positive torque and a current-voltage developed directional element which opposes the current element depending on the phase angle between current and voltage.**

Reactance relay is an overcurrent relay with directional limitation. The directional element is arranged to develop maximum negative torque when its current lag behinds its voltage by 90°. The induction cup or double induction loop structures are best suited for actuating reactance type distance relays.

Construction of Reactance Relay

A typical reactance relay using the induction cup structure is shown in the figure below. It has a four-pole structure carrying operating, polarizing, and restraining coils, as shown in the figure below. The operating torque is developed by the interaction of fluxes due to current carrying coils, i.e., the interaction of fluxes of 2, 3 and 4 and the restraining torque is produced by the interaction of fluxes due to poles 1, 2 and 4.



Reactance Type Distance Relay

The operating torque will be proportional to the square of the current while the restraining torque will be proportional to VI cos (Θ – 90°). The desired maximum torque angle is obtained with the help of resistance-capacitance circuits, as illustrated in the figure. If the control effect is indicated by $-k_3$, the torque equation becomes

$$T = K_1 I^2 - K_2 VIcos(\theta - 90^\circ) - K_3$$
$$T = K_1 I^2 - K_2 sin\theta - K_3$$

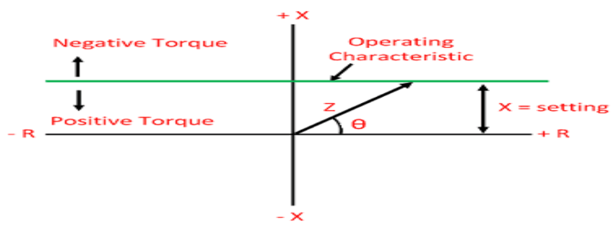
where Θ, is defined as positive when I lag behind V. At the balance point net torque is zero, and hence

$$K_1 I^2 - K_2 VIcos(\theta - 90^\circ) - K_3$$
$$K_1 I^2 = K_2 VIsin\theta + K_3$$
$$K_1 = K_2 \frac{V}{I} sin\theta + \frac{K_3}{I^2}$$
$$\frac{V}{I} sin\theta = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$
$$Zsin\theta = \frac{K_1}{K_2}$$

the spring control effect is neglected in the above equation, i.e., $K_3 = 0$.

Operating Characteristic of Reactance Relay

The operating characteristic of a reactance relay is shown in the figure below. X is the reactance of the protected line between the relay location and the fault point, and R is the resistance component of the impedance. The characteristic shows that the resistance component of the impedance has no consequence on the working of the relay, the relay reacts solely to the reactance component. The point below the operating characteristic is called the positive torque region.



Operating Characteristic of Reactance Type Distance Relay

If the value of τ, in the general torque equation, expressed below is made any other 90º, a straight line characteristic will still be obtained, but it will not be parallel to R-axis. Such a relay is called an angle impedance relay.

$$T = K_1 I^2 - K_2 VIcos(\theta - \tau) - K_3$$

This type of relay is not capable of selecting whether the fault has taken place in the section where the relay is located, or it has taken place in the adjoining section when used on the transmission line. The directional unit used with the reactance relay will not be same as used with the impedance type relay because the restraining reactive volt-ampere, in that case, will be nearly equal to zero.

Therefore the reactance type distance relay needs a directional unit that is inoperative under load conditions. Reactance type relay is very suitable as a ground relay for ground fault because its reach is not affected by fault impedance.

Advantages

- It will not respond to ARC
- It can be used for **small transmission lines**
- It can be able to sense the fault fast

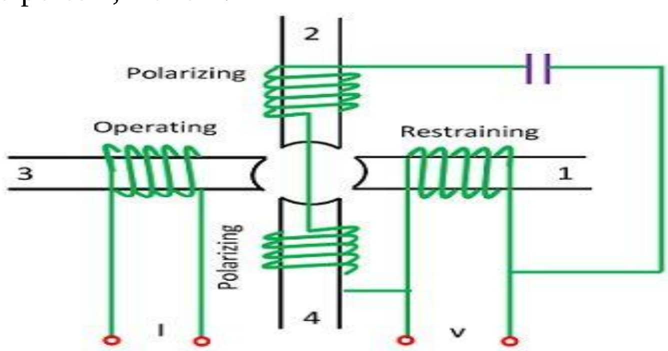
Disadvantages

- In reactance characteristics, can-not be used for fault locating relay
- It will not be able to distinguish between the fault in our station or other station
- It is not suitable for the long transmission line.

Admittance Relay

A mho Relay is a high-speed relay and also known as the admittance relay. In this relay **operating torque is obtained by the volt-amperes element and controlling element is developed due to voltage element**. It means a mho relay is a voltage controlled directional relay.

A mho relay using the induction cup structure is shown in the figure below. The operating torque is developed by the interaction of fluxes due to pole 2, 3, and 4 and the controlling torque is developed due to poles 1, 2 and 4.



If the spring controlling effect is indicated by $-K_3$, the torque equation becomes,

$$T = K_1 VI cos(\theta - 90°) - K_3$$

Where Θ and τ are defined as positive when I lag behind V. At balance point, the net torque is zero, and hence the equation becomes

$$K_1 VI cos(\theta - \tau) - K_2 V^2 - K_3 = 0$$

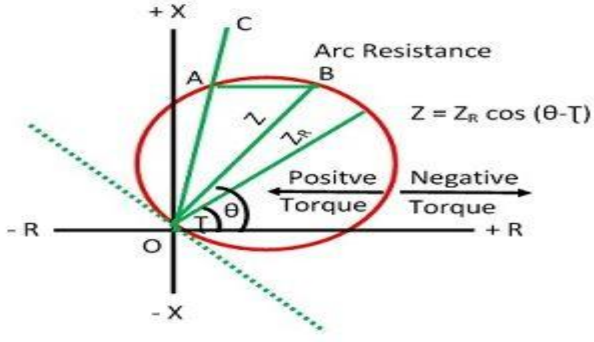
$$\frac{K_1}{K_2} \text{Cos}(\theta - \tau) - \frac{K_3}{K_2 VI} = \frac{V}{I} = Z$$

If the spring controlled effect is neglected i.e., $k_3 = 0$.

$$Z = \frac{K_1}{K_2} \text{Cos } (\theta - \tau)$$

Operating Characteristic of Mho Relay

The operating characteristic of the mho relay is shown in the figure below. The diameter of the circle is practically independent of V and I, except at a very low magnitude of the voltage and current when the spring effect is considered, which causes the diameter to decrease. The diameter of the circle is expressed by the equation as $Z_R = K_1 / K_2$ = ohmic setting of the relay

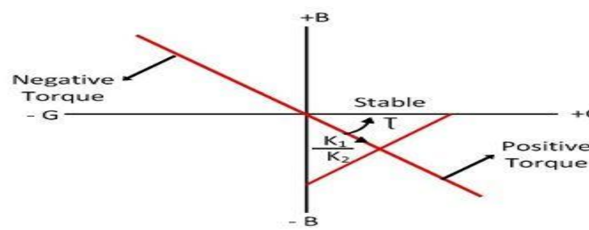


Operating Characteristic of Mho Relay

The relay operates when the impedance seen by the relay within the circle. The operating characteristic showed that circle passes through the origin, which makes the relay naturally directional. The relay because of its naturally directional characteristic requires only one pair of contacts which makes it fast tripping for fault clearance and reduces the VA burdens on the current transformer.

The impedance angle of the protected line is normally 60º and 70º which is shown by line OC in the figure. The arc resistance R is represented by the length AB, which is horizontal to OC from the extremity of the chord Z. By making the τ equal to, or little less lagging than Θ, the circle is made to fit around the faulty area so that the relay is insensitive to power swings and therefore particularly applicable to the protection of long or heavily loaded lines.

For a given relay the τ is constant, and the admittance phasor Y will lie on the straight line. The characteristic of mho relays on the admittance diagram is, therefore, a straight line and is shown in the figure below.



Characteristic of Mho Type Relay on Admittance Diagram

Mho relay is suitable for EHV/UHV heavily loaded transmission lines as its threshold characteristic in Z-plane is a circle passing through the origin, and its diameter is Z_R. Because of this, the threshold characteristic is quite compact enclosing faulty area compactly and hence, there is lesser chance to operate during power swing and also it is directional.

Advantages

- The fault area is well-defined
- It is directional, so it can be designed to operate for a particular side
- It can be used for **long transmission lines**. It will respond to both resistive fault and reactive fault

Disadvantages

- It can-not be used for small transmission lines.

Q. On the R-X diagram show a line having an impedance of 3+4j ohms. On the same diagram show the operating characteristics of
a) Impedance relay
b) Reactance relay
c) Mho relay
Assume that these relays are adjusted to just operate for a zero impedance short circuit at the end of the line section.
If an arcing short circuit fault having an impedance of 1+j0 ohms occurs anywhere on the line, find for each type of distance relay, the maximum portion of the line that can be protected.
Solution:

The line OA is the impedance vector with impedance 3+j4 ohms

OB = 3

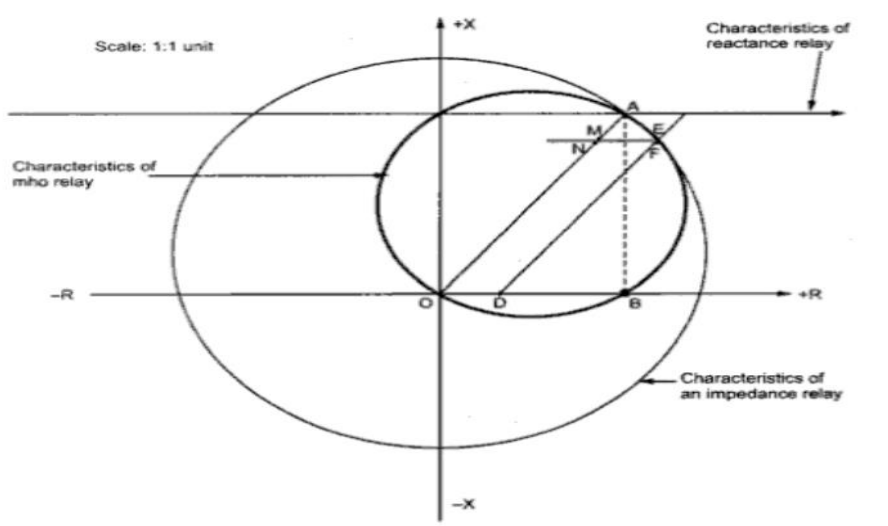
BA = 4

The circle with O as a center and OA as radius represents the characteristics of an impedance relay.

The line parallel to the resistance axis at a distance of 4, passing through point A corresponding to reactance of the impedance given, represent the characteristics of a reactance relay.

Draw the circle with OA as the diameter passing through O and A represent Characteristics of mho relay.

The characteristics are shown in figure



The impedance of arcing fault is 1+j0, is represented by OD

The line parallel to the OA is drawn from point D, cutting the mho circle at the point F and cutting the impedance circle at the E.

Draw the line FN parallel to R-axis to cut OA at n and draw EM parallel to R-axis to cut OA at M.

Then the ratio ON/OA represents the line protected by mho relay

So, $\frac{ON}{OA} * 100$ = % of line protected by mho relay

$= \frac{4}{5} * 100$

= 80 %

While the ratio $\frac{OM}{OA} * 100$ = % of the line protected by impedance relay

$= \frac{4.25}{5} * 100$ = 85%

Now, the reactance relay is unaffected by the presence of the arc resistance and hence even with the arc present of the % line protected by the reactance relay is 100%.

Q. A line section has an impedance of 3.6 + j6 ohms. Show it on R-X diagram as impedance phasor. If the relay is adjusted to operate for zero impedance short circuit at the end of the line section, show on the same R-X diagram operating characteristics of-

(i) An impedance relay

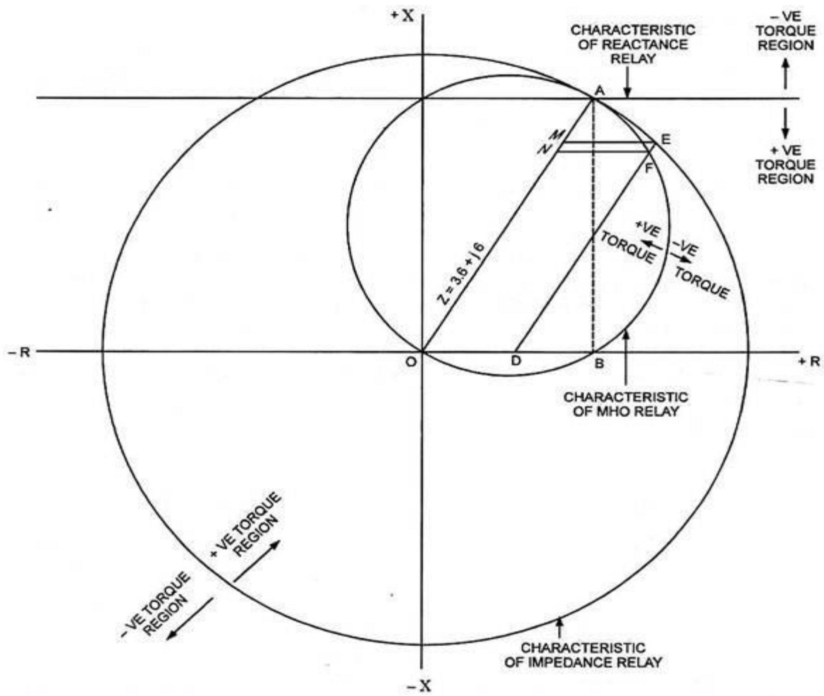
(ii) A reactance relay and

(iii) Admittance or mho relay, used for the purpose.

Assume that the centre of the mho relay operating characteristic lies on the line impedance phasor. If an arcing short circuit occurs having an impedance of 2 + j 0 Ω anywhere along the line, determine for each type of distance relay the maximum portion of the line that can be protected.

Solution:

The characteristics of the relays are shown in Fig. 3.56. OA is the impedance phasor of (3.6 + j 6) ohms; OB = 3.6 units and BA = 6 units. The circle with O as center and OA as radius represents the characteristic of impedance relay. A straight line drawn parallel to the R-axis at a distance of 6 units corresponding to the reactance of the line represents the characteristic of the reactance relay. The circle drawn on OA as diameter represents the characteristic of the admittance or mho relay for the protection of the given line.



If the impedance of short circuit due to arcing is (2 + j 0) ohms, this is represented by taking OD = 2 units and drawing a line parallel to the impedance phasor OA cutting the mho relay characteristic at F and impedance relay characteristic at E. Then draw EM and FN parallel to R-axis to cut impedance phasor OA at M and N respectively.

Then (OM/OA) x 100 gives the percentage of line protected by the impedance relay and (ON/OA) x 100 gives the percentage of line protected by the mho relay.

On measurement the impedance relay is found to protect 82% of the line while the mho relay is found to protect 77% of the line.

The reactance relay is unaffected by the presence of the arc resistance and hence even with arc present; the percentage of the line that is protected by the reactance relay is 100%.

Circuit Breaking and Arc Quenching

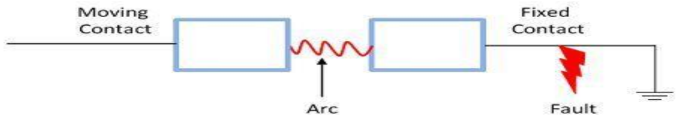
Introduction to Circuit Breaker

A circuit breaker is an electrical switch designed to protect an electrical circuit from damage caused by overcurrent/overload or short circuit. Its basic function is to interrupt current flow after protective relays detect a fault.

A circuit breaker is an electrical switch designed to protect an electrical circuit from damage caused by overcurrent/overload or short circuit. Its basic function is to interrupt current flow after protective relays detect a fault.

When the current carrying contacts of the circuit breaker are moved apart, an arc is formed, which insist for a short period after the separation of contacts. This arc is dangerous on account of the energy generated in it in the form of heat which may result in explosive force.

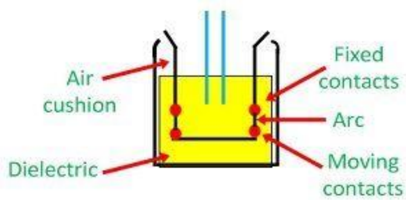
The circuit breaker should be capable of extinguishing the arc without causing any disturbances to the equipment or danger to the personnel. The arc plays a vital role in the behaviour of the circuit breaker. The interruption of DC arc is relatively more difficult than AC arcs. In an AC arc, as the current becomes zero during the regular wave, the arc vanishes and it is interrupted from restriking.



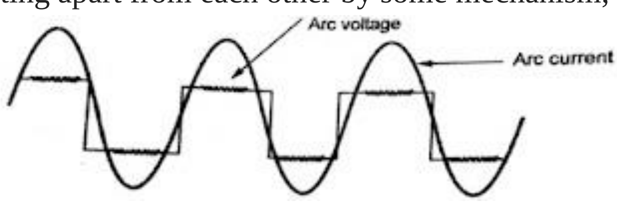
Working Principle of Circuit Breaker

Circuit breaker essentially consists of fixed and moving contacts. These contacts are touching each other and carrying the current under normal conditions when the circuit is closed. When the circuit breaker is closed, the current carrying contacts, called the electrodes, engaged each other under the pressure of a spring.

During the normal operating condition, the arms of the circuit breaker can be opened or closed for a switching and maintenance of the system. To open the circuit breaker, only a pressure is required to be applied to a trigger.



Whenever a fault occurs on any part of the system, the trip coil of the breaker gets energized and moving contacts are getting apart from each other by some mechanism, thus opening the circuit.



Method of ARC EXTINCTION

The conductances of the arc are proportional to the number of electrons per cubic centimetre produced by ionisation, the square of the diameter of the arc and the reciprocal of the length. For arc extinction, it is, therefore, necessary to reduce the density of free electrons, i.e., reduces the ionisation and decrease the diameter of the arc.

There are two methods of arc extinction in circuit breakers. These methods are

High Resistance method

In this method, the arc is controlled in such a way that its effective resistance increase with the time, so that the current is reduced to such a value that heat formed by it is not sufficient to maintain the arc or thus arc is extinguished.

Because of the resistive nature of the arc discharge, most of the energy in the system will be dissipated within the circuit breaker. This is the main drawback of this method of arc extinction. The following are the reasons which can increase the resistance of the arc.

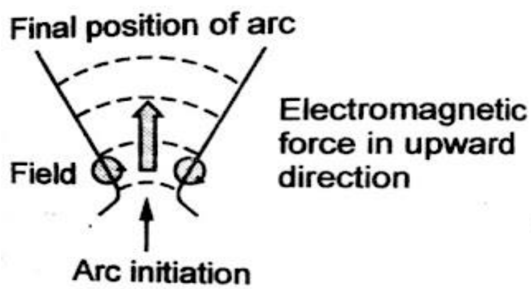
- Cooling of arc
- Increasing the length of the arc
- Reducing the cross section of the arc
- Splitting of arc

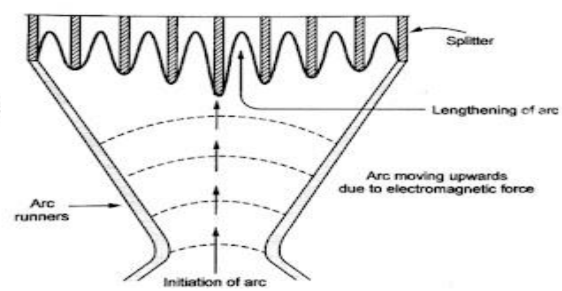
Increasing the Length of the arc – The resistance of the arc is directly proportional to its length. The length of the arc can be increased by increasing the gap between contacts.

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

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.

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 Zero Current Interruption method

This method is applicable only in AC circuit interruption because there are natural zero of current, 100 times in a second for 50Hz three-phase supply system. This is one of the most significant advantages of AC circuit for arc interruption purpose because the current is not allowed to rise again.

In this method, the arc resistance is kept low until the current is zero where the arc extinguishes naturally, and it’s prevented from restriking after it has gone out at a particular.

If such a break-down 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

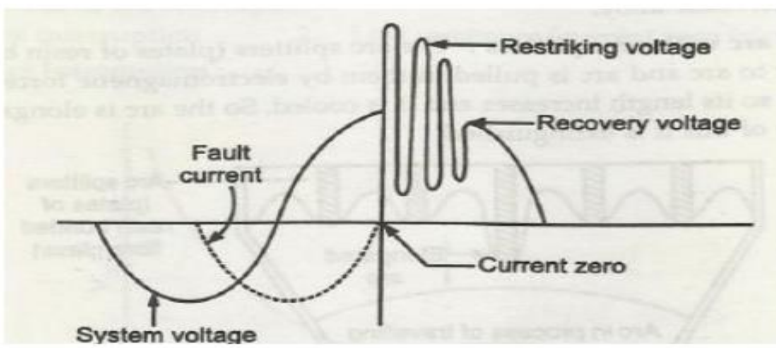
(a) Causing the ionised particles in the space between contacts to recombine into neutral molecules.

(b) Sweeping the ionised particles away and replacing them by unionised particles.

Therefore, the real problem in AC arc interruption is to rapidly deionise 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-ionisation 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-ionisation and consequently the dielectric strength of the medium between contacts is increased.
3. **Cooling**: Natural combination of ionised 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 ionised particles between the contacts are swept away and replaced by un-ionised particles, the dielectric strength of the medium can be increased consider-ably. This may be achieved by a gas blast directed along the discharge or by forcing oil into the contact space.

Some Terminology



Restriking voltage: It may be defined as the voltage that appears across the breaking contact at the instant of arc extinction.

Recovery voltage: It is defined as the voltage that appears across the breaker contact after the complete removal of transient oscillations and final extinction of arc has resulted in all the poles.

Active recovery voltage: It may be defined as the instantaneous recovery voltage at the instant of arc extinction.

Arc voltage: It may be defined as the voltage that appears across the contact during the arcing period, when the current flow is maintained in the form of an arc. It assumes low value except for the point at which the voltage rise rapidly to a peak value and current reaches to zero.

Arc Interruption Theory

When there is a fault in the system, an arc is formed between the contacts and the circuit breaker must extinguish the arc. The arc formed is a type of electric discharge that generates a huge amount of heat energy. If the arc is not quenched immediately, it may result in an explosion and damage the equipment to be protected. However, the arc extinction is very complicated and the circuit breaker must be capable of extinguishing the arc without getting damaged and making damage to the equipment. There are two theories that give a concept of the phenomenon of arc extinction in circuit breakers. They are,

I. *Slepian's Theory or Recovery Rate Theory*

II. *Energy Balance Theory.*

Slepian's Theory or Recovery Rate Theory :

In circuit breakers, the arc is formed due to the ionization of the gap between its contacts. So, in order to extinguish the arc, the electrons and ions present in the gap are to be removed immediately after the current reaches a natural zero.

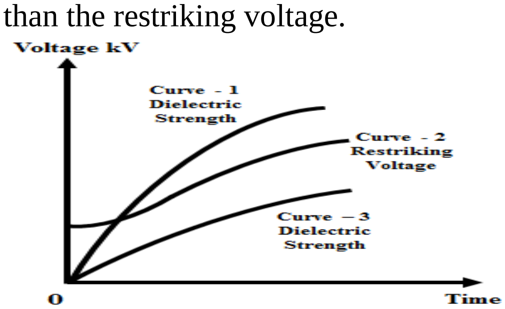
Because the ionization will be minimum at current zero instant. The removal of electrons and ions from the gap is possible in either of the two different ways. They are,

- Recombining them into neutral molecules.
- Sweeping them away by inserting a suitable insulating medium into the gap.

The arc is interrupted if the rate of removal of ions from the gap is faster than the rate of ionization in the gap. In other words, if the dielectric strength of the medium between the contacts is increased such that it is always greater than the restriking voltage, the arc does not restrike after the current zero interruption.

As this theory describes the **arc extinction process as a rate between dielectric strength and restriking voltage,** it is also called Voltage Rate Theory.

The figure below shows, if the dielectric strength builds as in curve-1 when compared with that of the restriking voltage as in curve-2, then the arc will be extinguished. Since the dielectric strength builds more rapidly than the restriking voltage.



Build-up of Dielectric Strength and Restriking Voltage

If the dielectric strength builds as in curve-3, the arc restrikes. Since the restriking voltage rises more rapidly than the dielectric strength due to which the ionization persists and the breakdown of the gap occurs.

Limitations of Slepian's Theory :

- In this theory, the restriking voltage and rate of rising of dielectric strength are assumed as comparable quantities but in actuality, this is wrong as the two quantities are not similar.
- In this theory, the energy relation in the arc extinction is not considered.
- This theory is incomplete, as the concept of arcing phase is not covered.
- The assumption of restriking voltage and increase in dielectric strength as independent quantities is not acceptable, as the dielectric strength calculations and observation values do not match.

Energy Balance Theory :

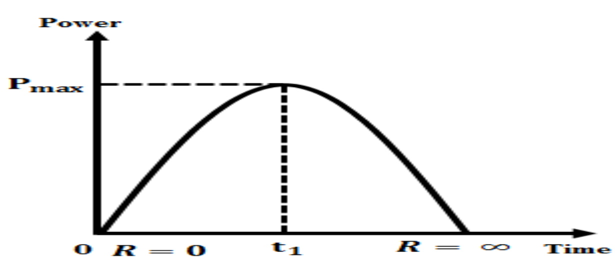
This theory is also known as Cassie's theory. The following assumptions are made in the theory,

- The arc is composed of a cylindrical column, which has a constant temperature at its cross-section. There is a uniform distribution of energy in this column.
- There will be no change in temperature.
- In order to accommodate the arc current, the cross-section of the arc adjust itself.
- The power dissipation and the cross-sectional area of the arc column are proportional to each other.

This theory explains, how the arc is extinguished or restrict i.e. **when the rate of heat removal between the contacts is lower than the rate at which the heat is generated, then the arc will restrike.** When the rate of generation of heat between the contacts is lower than the rate of removal of heat, then the arc will be extinguished.

The generation of heat depends upon the separation of contacts. At the current zero instant, the restriking voltage will be zero and hence the power will be zero. At the next instant, the gap between the contacts contains some ions. Therefore, the gap will have finite post-zero resistance.

As the restriking voltage exists its associated current and power will have some finite value. At the instant of final arc extinction, as no ions are present in the gap, its resistance will be infinite so, the power will be zero. Hence in between the instants of current zero and final arc extinction, the power increases to a maximum value at an instant, t_1 and from there it falls back to zero as shown below.



Variation of Power

As the power exists in the gap for a finite duration of time energy appears in the gap in the form of heat. So, the circuit breaker has to remove the heat generated by suitable means.

DC and AC circuit breaking

The ways in which AC and DC breakers are designed to extinguish the arc are very different and this is why AC and DC breakers are not interchangeable. Only breakers that are labeled as DC rated should be used for DC applications.

An AC-rated breaker should never be used in a DC circuit. AC circuit breakers are not designed to handle the problems of arcing associated with DC. DC circuit breakers include additional arc-extinguishing measures to dissipate the electrical arc when opening and closing and elongate the device lifetime.

AC Arc Suppression

Arc extinction in ac is easier. An AC arc self-extinguishes when the set of contacts opens. An AC supply has a voltage that reverses its polarity 100 times a second when operated on a 50 Hz line frequency and 120 times a second when operated on a 60 Hz line frequency. The alternation allows the arc to have a maximum duration of no more than a half-cycle.

When AC reaches zero, no current flows, and therefore the arc is extinguished.

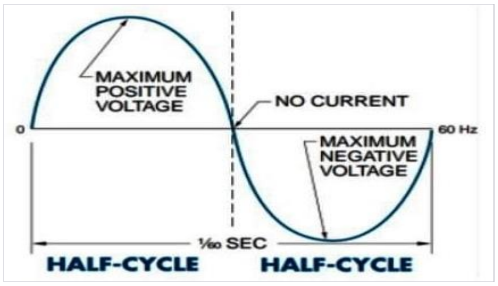


Figure. When AC current reaches zero, no current flows, and therefore the arc is extinguished.

DC Arc Suppression

DC arcs are considered the most difficult to extinguish because the continuous DC supply causes current to flow constantly and with great stability across a much wider gap than an AC supply of equal voltage. To reduce arcing in DC circuits, the switching mechanism must be such that the contacts separate rapidly and with enough of an air gap to extinguish the arc as soon as possible when opening.

It is worthwhile to mention that when a short circuit occurs across the terminals of a DC circuit, the current increases from the operating current to the short-circuit current depending on the resistance and the inductance of the short-circuited loop.

Transient recovery voltage

The Transient Recovery Voltage (TRV) is the voltage which appears across electrical equipment shortly after a current interruption. The waveform of the recovery voltage actually depends on the circuit configuration (inductive or capacitive nature). For example, a circuit breaker should be able to interrupt a given current for any recovery voltage provided that this value does not exceed its assigned TRV value.

TRV can be defined as voltage appearing across a circuit breaker after a switching action. Typical of every transient TRV also has high amplitude and high frequency. The figure below shows an example of TRV,

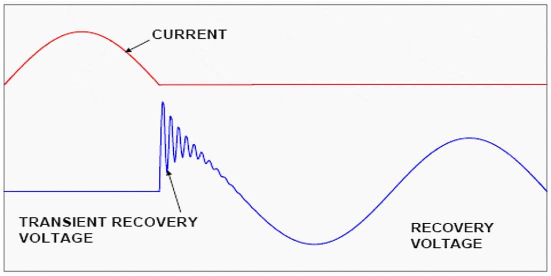
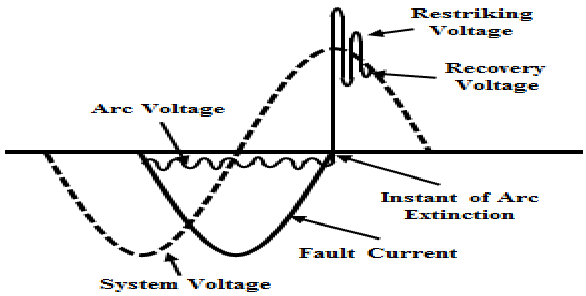


Figure 1 – Transient Recovery Voltage

TRV is a point by point difference of voltage at the incoming side and at the outgoing side of a circuit breaker. When a circuit breaker interrupts, the incoming side or the side to bus or supply is connected tries to return to power frequency voltage level and the outgoing side depending on what is connected also oscillates. **The difference between these voltages is recovery voltage.**
TRV is associated with every interruption, but the ones resulting because of interruption of fault current are the most ominous TRV. Thus the choice of circuit breakers or introduction of means and methods for safeguarding the circuit and circuit breaker has to be considered.

Recovery Voltage

It is defined as the voltage appearing across the circuit breaker contacts after the final arc extinction and after all the transients die out (or disappears). The frequency of recovery voltage is the same as the supply frequency.
Consider a circuit breaker whose contacts are opened, then the fault current drops to zero. At zero current instant, no ions are present in the gap between the contacts. At this condition, the dielectric strength of the medium (air or oil) between the contacts will be high, which is strong enough to avoid the breakdown by the restriking voltage. As a result the final arc extinction takes place and circuit current is interrupted.
As soon as the current is interrupted after the final arc extinction, the voltage appears across the circuit breaker contacts, which has a transient part. Therefore, the voltage appearing across the circuit breaker contacts after all transient oscillations die out or disappear is known as recovery voltage. This voltage is of normal frequency RMS voltage which is approximately equal to the system voltage.



Recovery Voltage, Restriking Voltage and Arc Voltage

The waveforms of arc voltage, recovery voltage and restriking voltage are shown above. From the waveform, it can be seen that restriking voltage and recovery voltage are simply the voltage across the circuit breaker contacts. The only difference between them is their period of existence

Restriking Voltage :

Whenever arc interruption occurs at zero current instant, the voltage across the circuit breaker gap will suddenly rise from zero to a very high value. This high voltage will be transient in nature.

The transient voltage that appears across the circuit breaker contacts immediately after the arc extinction or at current zero during the arcing period is called Restriking Voltage.

This voltage is so named because the arc can restrike only during the existence period of this transient voltage. If the arc does not restrike during this transient period, it will not restrike later. This restriking voltage is also known as Transient Recovery Voltage.

When the circuit breaker interrupts the current flow, it causes the voltage across the circuit breaker gap to suddenly rise from zero to a very high value. This high voltage is caused by the rapid change in the current and the energy stored in the inductance of the system.

The restriking voltage is a critical factor in the performance of a circuit breaker. If the restriking voltage is too high, it can cause the arc to restrike and interrupt the current again, which can cause damage to the contacts and surrounding equipment. On the other hand, if the restriking voltage is too low, the arc may not be able to restrike, and the interruption of the current may not be successful.

Arc Voltage :

Arc voltage is the voltage that is responsible for maintaining the arc between the contacts of the circuit breaker. At the time of circuit breaker contacts opening, an arc is struck between the contacts due to ionization of medium surrounding the contacts. A small potential difference exists between the contacts and it is responsible for maintaining the arc. This voltage is called the Arc Voltage.

Arc voltage is an important factor to consider when designing a circuit breaker. If the arc voltage is too high, it can cause damage to the contacts or the surrounding equipment. On the other hand, if the arc voltage is too low, the arc may not be able to sustain itself, resulting in an unreliable interruption of the current.

To reduce the arc voltage and improve the reliability of the interruption, different techniques are used such as using arc chutes, shields, and magnetic fields. These techniques help to contain and control the arc, making it more stable and reducing the potential for damage. Additionally, using a high-pressure gas or vacuum inside the breaker can also help to reduce the arc voltage.

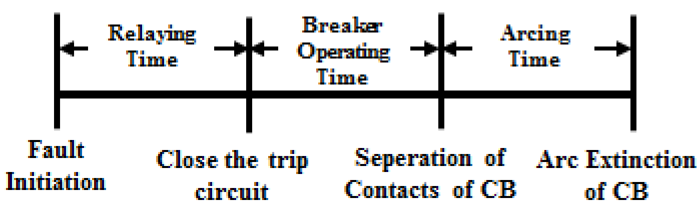
Fault Clearing Time:

Whenever a fault (short-circuit fault) occurs, the current rises to a very high value and the voltage falls to a low value. These abnormal conditions are sensed by the relays connected in secondaries of CTs and/or PTs.

As the corresponding quantities go beyond their prescribed limits, the relay receives its actuating amount of the corresponding quantity. The moving system of the relay starts moving as it receives sufficient operating torque. The moving system finally closes the trip circuit of the circuit breaker.

The trip coil of the circuit breaker will be energized and so the circuit breaker opens its contact. Obviously, an arc will appear between the contacts. The voltage across the circuit breaker contacts (i.e., arc voltage) will be quite small and will be in phase with the arc current. The arc will be extinguished using suitable techniques at zero current instant.

- Time from fault initiation to close the trip circuit of the circuit breaker is called relaying time.
- Time from the closure of the contacts of the trip circuit to the separation of the circuit breaker contacts is called breaker operating time.
- Time from contact separation of the circuit breaker to the arc extinction of the circuit breaker is called arcing time.



Fault Clearing Time of Circuit Breaker

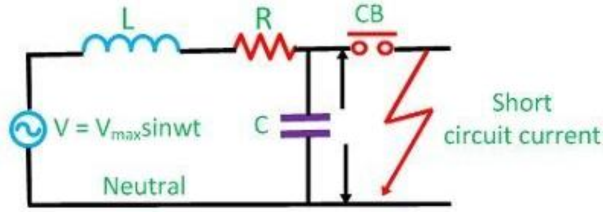
The sum of relaying time, breaker operating time, and arcing time is called fault clearing time.

Fault Clearing Time = Relaying Time + Breaker Operating Time + Arcing Time

This means that the total time it takes for a circuit breaker to detect and interrupt a fault is the sum of the time it takes for the relays to detect the fault and send a signal to the circuit breaker, the time it takes for the circuit breaker to open its contacts, and the time it takes for the arc to be extinguished after the contacts have been separated.

Mathematical expression for Restriking Voltage Transient

Consider a simple circuit, having a circuit breaker CB, as shown in the figure below. Let L be the inductance per phase of the system up to the fault point; R be the resistance per phase of the system up to the fault point, and C be the capacitance of the circuit.



Fault and its Equivalent Circuit

When the fault occurs in the system under fault condition the contacts of the breaker are open, and the capacitance C is short-circuited by the fault, and the short circuit current is limited by the resistance and the inductance.

When the breaker contacts are opened, and the arc certainly quenches at some current zero, a voltage v is suddenly applied across the capacitor and therefore across the circuit breaker contacts. The current i which would flow to the fault is not injected in the capacitor and inductor. Thus

$$i = i_L + i_C$$

$$i = \frac{1}{L}\int vdt + C\frac{dv}{dt}$$

$$\frac{di}{dt} = \frac{v}{L} + C\frac{d^2s}{dt^2} \dots\dots\dots\dots\dots equ(1)$$

Assuming Zero time at zero currents when t = 0 and the value of current and voltage before opening of circuit breaker is expressed as

$$v = V_{max}coswt$$

$$i = \frac{V_{mt}}{wl}sinwt$$

$$\frac{di}{dt} = \frac{V_{max}}{wl} \times w \times coswt$$

$$t = 0; \qquad \left|\frac{di}{dt}\right| = \frac{V_{max}}{L}$$

On substituting the above values in equation (1), we get

$$\frac{V_{max}}{L} = \frac{v}{L} + C\frac{d^2v}{dt^2}$$

The solution of the standard equation is

$$v = V_{max}\left[1 - cos\frac{1}{\sqrt{LC}}\right] = V_{max}(1 - 2\pi f_n t) \dots\dots\dots equ(3)$$

From the equation,

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

The above expression is for restriking voltage where V_{max} is the peak value of recovery voltage (phase -to-neutral) t is time is seconds. L is inductance in Henrys, C is the capacitance in farads and v is the restriking voltage in volts. The maximum value of restriking voltage is $2V_{max}$ and occurs at

$$t = \frac{\pi}{w} \ or \ t = \pi\sqrt{LC}$$

The maximum value of restriking voltage v_c is 2 E_{max} and occurs at $t = \pi/\omega$ or equal to $\pi\sqrt{LC}$. The oscillatory transient voltage has a frequency of $1/2\pi\sqrt{LC}$ Hertz.

Characteristic of Restriking Voltage

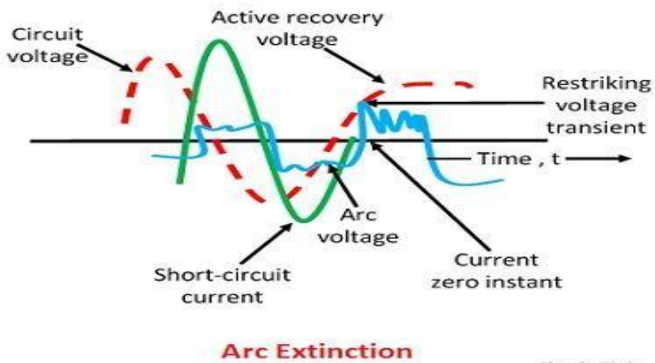
The important characteristic of restriking voltage which affects the performance of the circuit breaker is as follows –

Amplitude Factor – It is defined as the ratio of the peak of transient voltage to the peak system frequency voltage.

The rate of Rising of Restriking Voltage – It is defined as the slope of the steepness tangent of the restriking voltage curve. It is expressed in kV/μs. RRRV is directly proportional to the natural frequency. The expression for the restriking voltage is expressed as

$$RRRV_{max} = \frac{V_{max}}{\sqrt{LC}}$$

The transient voltage vanishes rapidly due to the damping effect of system resistance, and the normal frequency system voltage is established. This voltage across the breakers contact is called recovery voltage.

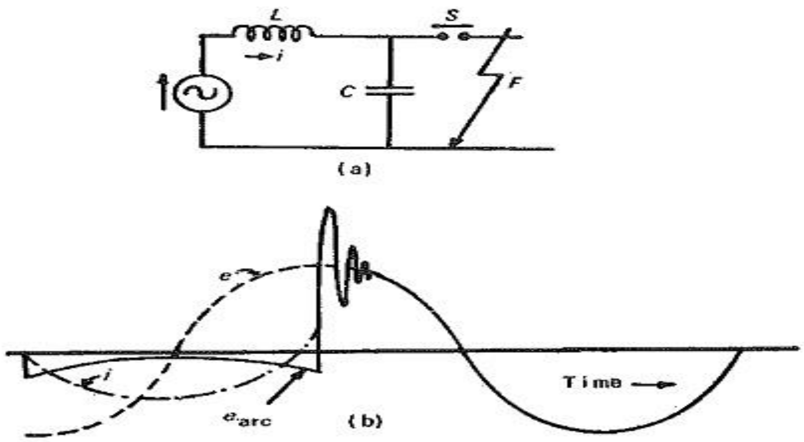


The waveforms of recovery and the restricting voltage are shown in the figure above. After the current zero, the voltage appearing across the breaker contacts is composed of transient restriking voltage and power frequency recovery voltage.

Classification of Restriking Transients:

Restriking voltage transients, and consequently their respective circuits can generally be placed under two main headings.

(1) Single Frequency Oscillatory Transients: Conditions are as shown in Fig.a The voltage wave form is shown in Fig.b When the switch contacts part an arc is formed which normally extinguishes at a current zero, the circuit voltage then being at its peak. This voltage tries to appear across the circuit breaker but is delayed in doing so due to presence of capacitance C, which gets charged and then establishes the voltage across the circuit breaker. However a. transient (restriking) voltage at the natural frequency of the simple L-C series circuit is superimposed on that already existing in the circuit (recovery voltage) as shown in Fig.b The natural frequencies are of the order of 1000 to 10,000 Hz.



(2) Double Frequency Transients: It is quite possible that the circuit breaker S may have L and C parameters on its two sides, as shown in Fig. Before clearance the points a and b are at the same potential. After the fault is cleared, i.e. the arc has been extinguished, both the circuits oscillate at their own natural frequencies a composite double frequency transient appears across the circuit breaker S

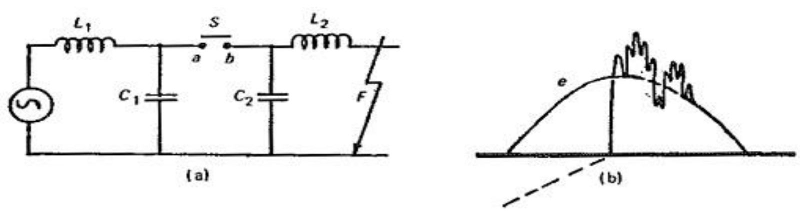


FIGURE 14.10 Double frequency restriking transient.

Expression for RRRV:

The expression for the restriking voltage has already been derived as

$$v_c = E_{max}\ (1 - \cos\ \omega t)$$

$$\text{RRRV} = \frac{dv_c}{dt}$$

$$\frac{dv_c}{dt} = E_m \omega \sin\ \omega t$$

Maximum value of RRRV occurs when

$$\omega t = \frac{\pi}{2}$$

$$t = \frac{\pi}{2\omega}$$

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

Hence maximum value of RRRV

$$RRRV_{max} = E_m\omega$$

Further, the peak restriking voltage occurs when v_c is maximum, i.e. at

$$\frac{dv_c}{dt} = 0$$

$$\omega t = \pi$$

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

Interruption of capacitive current and current chopping

Switching Surges-Interruption of Capacitive Circuits

The interruption of capacitive circuits is shown in Figure. At the instant of arc interruption, the capacitor is left charged to value H. If the capacitance C, is large then the voltage across the capacitor decays slowly. The voltage across the circuit breaker is the difference between the system voltage and the voltage across the capacitor. At the negative crest of the system voltage, that is —*V*, the gap voltage is 2У. If the gap breaks down, an oscillatory transient is set up, which can increase the gap voltage to up to 3 V, as shown in Figure.

Current Chopping

Current Chopping in circuit breaker is defined as a phenomena in which current is forcibly interrupted before the natural current zero Current chopping is predominant while switching Shunt Reactor or unloaded Transformer.

Current chopping arises with vacuum circuit breakers or with air-blast circuit breakers which operate on the same pressure and velocity for all values of interrupted current. Hence, on low-current interruption the breaker tends to open the circuit

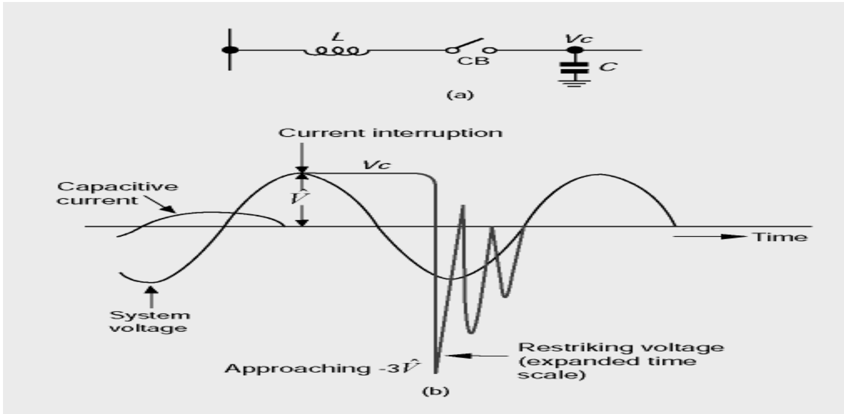


Figure: Voltage waveform when opening a capacitive circuit

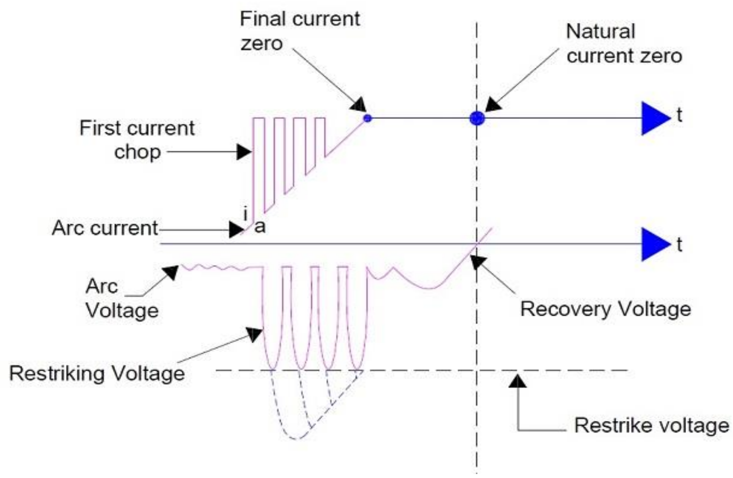
Before the current natural-zero, and the electromagnetic energy present is rapidly converted to electrostatic energy, that is.

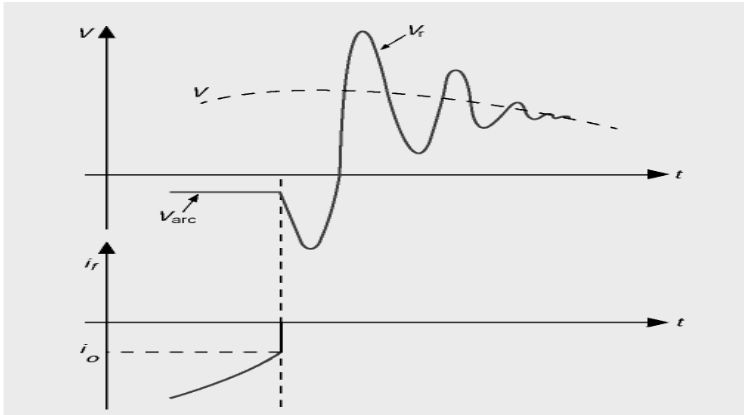
$$\frac{1}{2}Li_0^2 = \frac{1}{2}Cv^2 \text{ and } v = i_0\sqrt{\frac{L}{C}}$$

This is the prospective voltage across the capacitor during current chopping. Notice that this prospective voltage is above the natural voltage of the system. This means that there will be a high voltage stress on the shunt reactor during current chopping. Note, the prospective voltage V is directly proportional to the value of current chopped and the surge impedance of the reactor.
The voltage wavekoform is shown in Figure below
The restriking voltage v_r, can be obtained from equation above by including resistance and time:

$$v_r = i_0\sqrt{\frac{L}{C}}e^{-\alpha t}\sin\omega_0 t$$

where «0 = ,_and *ig* is the value of the current at the instant of chopping. High LC transient voltages may be set up on opening a highly inductive circuit such as a transformer on no-load.





Numerical

Example *A 50 Hz generator has e.m.f. to neutral 7.5 kV (r.m.s.). The reactance of generator and the connected system is 4 Ω and distributed capacitance to neutral is 0.01 μF with resistance negligible . Find,*

i) maximum voltage across the circuit breaker contacts

ii) frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Solution :

$$X = 2\pi fL = 4\ \Omega$$

$$L = 4 / 2\pi \times 50 = 0.0127\ \text{H.}$$

$$E_m = \sqrt{2} \times 7.5 = 10.606\ \text{kV}$$

1) Maximum voltage $= 2 \times E_m$

$$= 2 \times 10.606 = 21.212\ \text{kV}$$

2) $$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0127 \times 0.01 \times 10^{-6}}}$$

$$= 14.1227\ \text{kHz}$$

3) Maximum time to reach maximum voltage is,

$$t_m = \pi\sqrt{LC} = \frac{1}{2f_n} = \frac{1}{2 \times 14.1227 \times 10^3}\ \text{sec}$$

$\therefore$ Average RRRV $= \dfrac{\text{Maximum voltage}}{t_m}$

$$= \frac{21.212}{[1 / (2 \times 14.1227 \times 10^3)]}$$

$$= 0.599\ \text{kV}/\mu\ \text{sec}$$

Example *A 50 Hz, 3 ph alternator, has rated voltage 13.5 kV, connected to circuit breaker, inductive reactance 4 Ω/ph, C = 2 μF.*
Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

Solution :

$$E_m = \frac{\sqrt{2} \times 13.5}{\sqrt{3}} = 11.0227 \text{ kV}$$

$$X = 2\pi f L \qquad \therefore L = 0.0127323 \text{ H and } C = 2\ \mu\text{F}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = 0.997 \text{ kHz}$$

$$\text{Maximum restriking voltage} = 2\,E_m$$

$$= 22.0454 \text{ kV}$$

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$$

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}}$$ This is the expression of RRRV

$$\therefore \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \quad \text{and} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum RRRV} = 2\pi f_n E_m$$

$$= \pi \times 0.997 \times 10^3 \times 22.0454 \text{ kV/sec}$$

$$= 0.06907 \text{ kV}/\mu\text{sec}$$

Example : *In a short circuit test on a 130 kV, 3 phase system, the breaker gave the following results : p.f. of fault 0.45, recovery voltage 0.95 times full line voltage, breaker current symmetrical, and restriking transient had a natural frequency 16 kHz. Determine average RRRV. Assume fault is grounded.*

Solution :

$$E_m = \frac{\sqrt{2} \times 130}{\sqrt{3}} = 106.144 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m \qquad \text{where } K_1 = \sin\phi = 0.8930$$

$$= 0.8930 \times 0.95 \times 1 \times 106.144 \qquad K_2 = 0.95$$

$$= 90.047262 \text{ kV} \qquad K_3 = 1$$

$$\therefore \quad \text{Maximum } e = 2\,V_{ar} = 180.09452 \text{ kV}$$

$$\text{Maximum time} = \pi\sqrt{LC} \quad \text{and} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum } t = \frac{1}{2 f_n} = \frac{1}{2 \times 16 \times 10^3}$$

$$\therefore \quad \text{Average RRRV} = \frac{\text{Maximum } e}{\text{Maximum } t} = \frac{180.09452}{1/2 \times 16 \times 10^3}$$

$$= 5.76302 \text{ kV}/\mu\text{sec}$$

Example [illegible] : *In a system having 220 kV, the line to ground capacitance 0.015 μF, inductance 3.5 H. Determine voltage appearing across pole of circuit breaker if a magnetising current of 6.5 A instantaneous, is interrupted. Determine also the value of resistance to be used across the contacts to eliminate the restriking voltage.*

Solution :

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$$

$$\frac{1}{2}L\,i^2 = \frac{1}{2}C\,e^2$$

Energy stored in 'L' = energy given to capacitor

$$\therefore \quad e = i\sqrt{L/C} \qquad \text{where } i = \text{instantaneous value}$$

$$= 6.5\sqrt{\frac{3.5}{(0.015\times10^{-6})}}$$

$$= 99.3 \text{ kV}$$

To eliminate restriking voltage and critical damping condition,

$$R = 0.5\sqrt{L/C}$$

$$= 0.5\sqrt{\frac{3.5}{(0.015\times10^{-6})}} = 7.635 \text{ k}\Omega$$

Example [illegible] : *In 132 kV transmission system, the phase to ground capacitance is 0.01 μF. The inductance being 6 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetizing current of 10 A is interrupted. Find the value of resistance to be used across contact space to eliminate the striking voltage transient.*

Solution :

$$L = 6 \text{ H}$$

$$C = 0.01\ \mu\text{F} = 0.01\times10^{-6} \text{ F}$$

$$i = 10 \text{ A}$$

Voltage appearing across poles of circuit breaker, is given by,

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

$$= 10\sqrt{\frac{6}{0.01\times10^{-6}}}$$

$$= 10\,(24494.89)$$

$$\therefore \quad V = 245 \text{ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= \frac{1}{2}\sqrt{\frac{6}{0.01\times10^{-6}}}$$

$$= \frac{1}{2}(24494.89)$$

$$\therefore \quad R = 12.24 \text{ k}\Omega$$

Exampled [illegible] : *In a short circuit test on a circuit breaker the following readings were observed on a single frequency transient time to reach the peak recovery voltage 40 μsec and the peak restriking voltage 100 kV. Determine the average RRRV and the frequency of oscillations.*

Solution : Average RRRV is given as,

$$\text{Average RRRV} = \frac{\text{Peak restriking voltage } (E_m)}{\text{Time to reach the peak } (t_m)}$$

$$= \frac{100 \times 10^3}{40} = 2500$$

$\therefore$ **Average RRRV = 2500 V/μsec**

Natural frequency f_n is given by,

$$f_n = \frac{1}{2 \cdot t_m} = \frac{1}{2(40 \times 10^{-6})}$$

$$= \frac{1}{80 \times 10^{-6}} = 12500 \text{ Hz}$$

$$\therefore \quad \mathbf{f_n = 12.5 \text{ kHz.}}$$

Examplen : : *Calculate the RRRV of 132 kV circuit breaker with neutral earthed. S.C. data as follows: Broken current is symmetrical, restriking voltage has frequency 20 kHz, p.f. 0.15. Assume fault is also earthed.*

Solution :

$$K_1 = \sin \phi = \sin (\cos^{-1} 0.15) = 0.9886$$

$$K_2 = 1$$

$$K_3 = 1 \qquad \text{both grounded}$$

$$E_m = \frac{\sqrt{2} \times 132}{\sqrt{3}} = 107.77755 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m$$

$$= 106.54889 \text{ kV}$$

$$\therefore \quad \text{Maximum } e = 2 V_{ar}$$

$$= 213.09778 \text{ kV}$$

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

and

$$f_n = \frac{1}{2\pi\sqrt{LC}} \qquad \therefore \quad \pi\sqrt{LC} = t_m = \frac{1}{2 f_n} \text{ sec}$$

$$\therefore \quad \text{Maximum } t_m = \frac{1}{2 \times 20 \times 10^3} \text{ sec}$$

$$\therefore \quad \text{RRRV} = \frac{e_{max}}{t_{max}} = \frac{213.09778}{[1 / (20 \times 10^3 \times 2)]}$$

$$= 8.52 \text{ kV/ μsec}$$

Example ∴ : *A 50 Hz, 3 ph alternator, has rated voltage 13.5 kV, connected to circuit breaker, inductive reactance 4 Ω/ph, C = 2 μF.*
Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

Solution :

$$E_m = \frac{\sqrt{2} \times 13.5}{\sqrt{3}} = 11.0227 \text{ kV}$$

$$X = 2\pi f L \qquad \therefore L = 0.0127323 \text{ H and } C = 2 \mu\text{F}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = 0.997 \text{ kHz}$$

$$\text{Maximum restriking voltage} = 2 E_m$$

$$= 22.0454 \text{ kV}$$

$$e = E_m \left(1 - \cos \frac{t}{\sqrt{LC}}\right)$$

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}} \quad \text{This is the expression of RRRV}$$

$$\therefore \text{ Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \qquad \text{and} \qquad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum RRRV} = 2\pi f_n E_m$$

$$= \pi \times 0.997 \times 10^3 \times 22.0454 \text{ kV/sec}$$

$$= 0.06907 \text{ kV/}\mu\text{sec}$$

Example ⊥ : *In 132 kV transmission system, the phase to ground capacitance is 0.01 μF. The inductance being 6 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetizing current of 10 A is interrupted. Find the value of resistance to be used across contact space to eliminate the striking voltage transient.*

Solution :

$$L = 6 \text{ H}$$

$$C = 0.01 \mu\text{F} = 0.01 \times 10^{-6} \text{ F}$$

$$i = 10 \text{ A}$$

Voltage appearing across poles of circuit breaker, is given by,

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

$$= 10\sqrt{\frac{6}{0.01 \times 10^{-6}}}$$

$$= 10 \,(24494.89)$$

$$\therefore \quad V = 245 \text{ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= \frac{1}{2}\sqrt{\frac{6}{0.01 \times 10^{-6}}}$$

$$= \frac{1}{2}(24494.89)$$

$$\therefore \quad R = 12.24 \text{ k}\Omega$$

Example 69 : *A 50 cycles, 3 phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit breaker. The capacitance to earth between the alternator and circuit breaker is 0.003 μF per phase. The circuit breaker opens when rms value of current is 7500 A. Determine the following:*

i) Maximum rate of rise of restriking voltage.

ii) Time for maximum rate of rise of restriking voltage.

iii) Frequency of oscillations

Neglect first pole to clear factor.

Solution :

$i = 7500$ A, $\quad L = 1.6$ mH, $\quad C = 0.003$ μF

$$X_L = 2\pi f L = 2\pi \times 50 \times 1.6 \times 10^{-3} = 0.50265\ \Omega$$

Peak value of active recovery voltage (Phase to neutral) i.e.

$$E_m = (i \times X_L) \times \sqrt{2} = (7500 \times 0.50265) \times \sqrt{2}$$

$$= 5331.4083 \text{ V}$$

$$f_n = \text{frequency of oscillations} = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{1.6 \times 10^{-3} \times 0.003 \times 10^{-6}}}$$

$$= 72643.96 \text{ Hz}$$

$$\text{Maximum RRRV} = 2\pi f_n E_m = 2\pi \times 72643.96 \times 5331.4083$$

$$= 2433443822 \text{ V/sec}$$

$$= 2433.4438 \text{ V/μsec}$$

Time for maximum RRRV

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

$$= 3.4414 \text{ μsec}$$

Example : *In a short circuit test on a 132 kV, 3-phase system the breaker gave the following results p.f. of the fault 0.4, recovery voltage 0.95 of full line value, breaking current is symmetrical and the restriking transient had a natural frequency of 16 kHz. Determine RRRV assuming that the fault is grounded.*

Solution :

$$E_m = \frac{\sqrt{2} \times 132}{\sqrt{3}} = 107.77 \text{ kV}$$

$$V_{ar} = K_1 K_2 K_3 E_m, \quad \text{where } K_1 = \sin\phi$$

$$\text{Here } \phi = \cos^{-1} 0.4 = 66.42°$$

$$\therefore \quad K_1 = \sin(66.42°) = 0.9165$$

$$K_2 = 0.95$$

$$K_3 = 1$$

$$\therefore \quad V_{ar} = (0.9165)(0.95)(1)(107.77) = 93.83 \text{ kV}$$

$$\therefore \quad \text{Maximum } e = 2V_{ar} = 2(93.83) = 187.66 \text{ kV}$$

$$\text{Maximum time} = \pi\sqrt{LC}, \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum } t = \frac{1}{2f_n} = \frac{1}{2 \times 16 \times 10^3} = 3.125 \times 10^{-5} \text{ sec}$$

$$\text{Average RRRV} = \frac{\text{Maximum } e}{\text{Maximum } t} = \frac{187.66}{3.125 \times 10^{-5}} = 6.0051 \approx 6 \text{ kV/μsec.}$$

Circuit Breakers

Introduction to Circuit Breakers, Requirement and Classification of CB

A circuit breaker is defined as, switching device which interrupts the faulty current and performs the function of a switch thus protecting the electrical system from damage. Under normal conditions, a circuit breaker can make, carry or break currents and under abnormal conditions, it can make or carry for a specific time and break the currents.

The characteristics of a Circuit Breaker are as follows:

- It can make or break a circuit under normal operating conditions either manually or using a remote control.
- Under abnormal or fault conditions, it can break the circuit automatically.
- It can make the circuit under fault conditions either manually or using a remote control.

These characteristics of a Circuit Breaker makes it a very useful device for switching and protection in a power system.

Duties of Circuit Breaker

➢ It must be capable of closing, breaking and carrying full load rated current of the circuit without any excessive temperature rise (not more than 35℃).

➢ It must be capable of breaking the heavy currents which flow when a short circuit occurred in the circuit in which it is connected.

➢ It must be capable of closing on to the circuit when it carries fault currents and re-opens immediately to clear the fault from the system.

➢ It must be capable of carrying current of short circuit magnitude until the fault is cleared by another breaker nearest to the point of fault.

➢ Lastly, but not the least it must be capable of withstanding the effects of arcing at its contacts and the severe electromagnetic forces and thermal conditions which arise due to the flow of heavy currents in the circuit under the fault conditions.

➢ Interruption of small inductive currents.

➢ Switching of capacitors banks.

➢ Interruption of terminal faults.

➢ Asynchronous switching.

Classification of Circuit Breakers

There are several ways of classifying different circuit breakers. Some of the common criteria used for classification of circuit breakers are:

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

Even though there are several ways to classify circuit breakers, the classification based on the medium and method of current interruption is most general and significant in the industry as well. For now, we will briefly about all these classifications and in the later section, we will discuss the main classification (i.e. based on method of arc extinction) more thoroughly.

A) Based on Voltage Level

Firstly we classify the circuit breakers according to the voltage levels they can operate on. So there are three most used types of circuit breakers in this category. These are:

- Low Voltage Circuit Breakers (< 1 kV)
- Medium Voltage Circuit Breakers (1-72 kV)
- High Voltage Circuit Breakers (> 72 kV)

Low Voltage Circuit Breakers: A low – voltage circuit breaker is one which is suited for circuits rated at 1000 volts or lower. Low-voltage circuit breakers are common in domestic, commercial and industrial applications. Most commonly used low-voltage circuit breakers are, miniature circuit breaker, molded case circuit breaker, earth leakage circuit breaker, and Residual current protective devices.

- MCB (Miniature Circuit Breaker)—rated current not more than 100 A.
- MCCB (Molded Case Circuit Breaker)—normal rated current is up to 2,500A with the thermal or thermal-magnetic operation.

Medium Voltage Circuit Breaker: Medium-voltage circuit breakers rated between 1 and 72 kV may be assembled into metal-enclosed switchgear lineups for indoor use, or maybe individual components installed outdoors in a substation. Medium-voltage circuit breakers nearly always use separate current sensors and protective relays, instead of relying on built-in thermal or magnetic overcurrent sensors. Medium-voltage circuit breakers can also be classified by the medium used to extinguish the arc as Vaccum, SF6, Airblast, and oil circuit breaker.

High Voltage Circuit Breaker: Electrical power transmission networks are protected and controlled by high-voltage breakers**.** The definition of high voltage varies but in power transmission work is usually thought to be 72.5 kV. High-voltage circuit breakers are broadly classified by the medium used to extinguish the arc:

1. Bulk Oil Circuit Breaker
2. Minimum Oil Circuit Breaker
3. Airblast Circuit Breaker
4. Vacuum Circuit Breaker
5. SF6 Circuit Breaker
6. CO2 Circuit Breaker

B) Based on Installation

Circuit breakers are also classified based on the location of installation

- Outdoor Circuit Breaker

- Indoor Circuit Breaker

- Indoor Circuit breakers are designed for use only inside buildings or weather-resistant enclosures. Generally, indoor circuit breakers are operated at a medium voltage with a metal clad switchgear enclosure.
- Outdoor Circuit breakers are designed to use at outside without any roof. So these breakers external enclosure arrangement will be strong compared to indoor breakers to withstand wear and tear.

C) Based on Actuating Mechanism

There is another category which is based on the mechanism used to actuate the circuit breaker, which specifies the mechanism of operation of the breaker, there are three further types:

- Spring Operated Circuit Breaker
- Pneumatic Circuit Breaker
- Hydraulic Circuit Breaker

- A spring-operated mechanism is one driven by the mechanical energy stored in springs. Typically, the "closing spring" is mechanically charged by a motor and is held in its compressed position by a closing latch.
- A hydraulic-operated mechanism uses pressurized gas to direct the flow of oil, thus actuating the linkage(s) connected to the interrupter(s).
- A pneumatic-operated mechanism uses compressed air as the energy source for closing and tripping.

D) Based on Type of External Design

The classification of circuit breakers is also done based on the physical structural design and it is usually done in two ways. They are:

- Dead Tank Type Circuit Breakers
- Live Tank Type Circuit Breakers

- In Dead Tank Type Circuit Breakers, the switching device is placed in a vessel at ground potential and it is surrounded by interrupters and insulating medium.
- In a Live Tank Type Circuit Breaker, the vessel containing the interrupters and insulating medium is at higher potential than ground.

E) Based on Interrupting Medium

Now considering the medium in which a circuit breaker can operate. The most general way of classification is on the basis of the medium used for arc extinction. The medium used for arc extinction is usually oil, air, sulfur hexafluoride (SF6) or vacuum, CB may be classified into:

- Oil Circuit Breaker which employs some insulating oil (eg, transformer oil) for arc extinction
- Air Blast Circuit Breaker in which high-pressure air-blast is used for extinguishing arc.
- SF6 Circuit Breaker in which sulfur hexafluoride (SF6) gas is used for arc extinction.
- Vacuum Circuit Breaker in which vacuum is used for arc extinction.

Air Circuit Breaker

Air Circuit Breaker (ACB) is an electrical protection device used for short circuit and overcurrent protection up to 15kV with amperes rating of 800A to 10kA. It operates in air (where air-blast as an arc quenching medium) at atmospheric pressure to protect the connected electric circuits.

The working principle of **Air Circuit breaker** is rather different from other types of circuit breaker. The main aim of circuit breaker is to prevent reestablishment of arcing after current zero where the contact gap will withstand the system recovery voltage. It does it same work, but in a different manner. The air circuit breaker employs a high resistance interruption method for arc extinction.

During interruption of arc, it creates an arc voltage instead of supply voltage. Arc voltage is defined as the minimum voltage required for maintaining arc .The circuit breaker increases the voltage in three different ways:

- Arc voltage can be increased by cooling arc plasma. As soon as the temperature of arc plasma motion of particle in arc plasma is reduced, more voltage gradient will be required to maintain the arc.
- By splitting the arc into a number of series will increases the arc voltage.
- Arc voltage can be increased by lengthening the arc path. As soon length of arc path is increased the resistance path will increase more arc voltage is applied across the arc path hence arc voltage is increased.

Types of Air Circuit Breaker

There are four **types of ACBs** used in the control and protection to maintain and stable operation of switch gears and indoor medium voltage.

- **Plain Break Type Air Break Circuit Breaker** or **Cross-Blast ACB**
- **Magnetic Blowout Type** Air Break Circuit Breaker
- **Air Chute Air Break** Circuit Breaker
- **Air Blast Circuit Breaker**

Air Blast Circuit Breaker

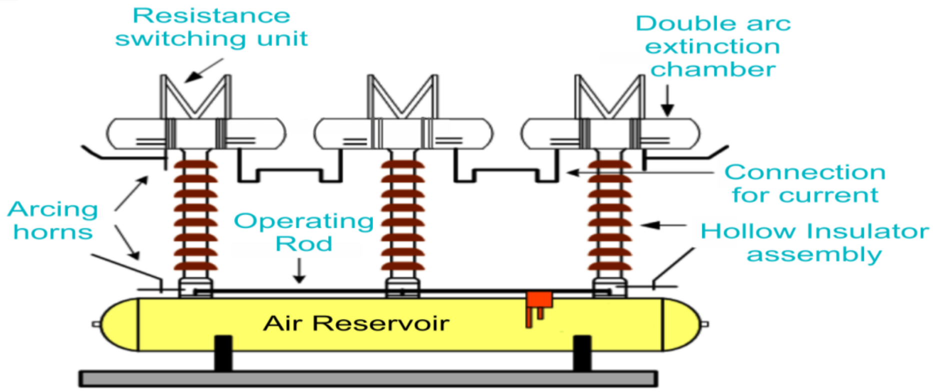
The Air Blast Circuit breaker is a type of circuit breaker where at high pressure (at a pressure of 30 kg/cm^2) the air blast is used for arc extinction in the electrical circuit. So they seek applications in the high voltage (132 kV and above) transmission system and interconnected networks with breaking capacity up to 7500 MVA. The main principle behind it is that it has a fixed contact and a moving contact, where high pressure is applied for arc extinction in a circuit breaker. This is done to avoid the overflow of the electric current.

Construction of Air Blast Circuit Breaker

The major components of the air blast circuit breaker are,

- Air reservoir
- Hallow insulator assembly

- Arc extinction chamber
- Valves
- Current carrying conductors.



Air Blast Circuit Breaker

Air Reservoir

- It is a tank that stores air, at high pressure, around 20-30 atm.
- It is connected to an auxiliary system which supplies high-pressure air to the reservoir.

Hollow Insulator Assembly

- These insulators **connect** the **air reservoirs** to the **arc extinction chamber**.
- They supply high-pressure air from the reservoir to the arc extinction chamber.
- Values at the base of the hollow insulators enable us to control the flow of high-pressure air into the system.
- They also insulate the other equipment, protecting them from high-voltage lines.

Arc Extinction Chamber

- The arc extinction chamber is mounted on the hollow insulator assembly.
- Here, the circuit moves and breaks, within the arc extinction chamber, which consists of **fixed** and **moving contacts**.
- The movement of contacts is dependent upon the air pressure.

Valves

- They are at the base of insulators which **regulate** the **flow** of **high-pressure** air.
- It generally flows in the direction: from the air reservoir to the arc extinction chamber.
- If upon a faulty circuit, the valves open with the help of an iron rod via a pneumatic operating system.

Current Carrying Conductors

- The sole purpose of current-carrying conductors is to link all the neighbouring equipment with the arc extinction chambers in series.

Operation

In the air blast circuit breaker compressed air is stored in a tank. The air blast circuit breaker consists of a fixed contact and a moving contact, enclosed in an arc extinction chamber.

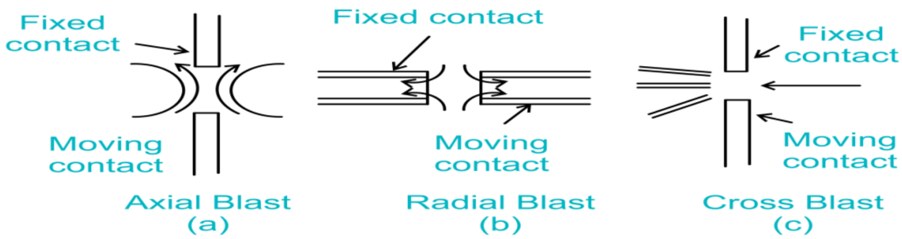
Under normal conditions, the breaker contacts present in the arc extinction chamber are in touch with each other.

When a fault occurs, the contacts are opened and an arc is struck between them. The opening of contacts is done by a flow of air blast established by the opening of the blast valve (located between air reservoir and arcing chamber). The air blast cools the arc and sweeps away the arching products into the atmosphere. Thus the dielectric strength of the medium is increased, prevents from re-establishing the arc. The arc gets extinguished and the flow of current is interrupted.

Types of air blast circuit breakers

The air blast circuit breakers are classified on the basis of direction of flow of air blast with respect to arc. These are classified into

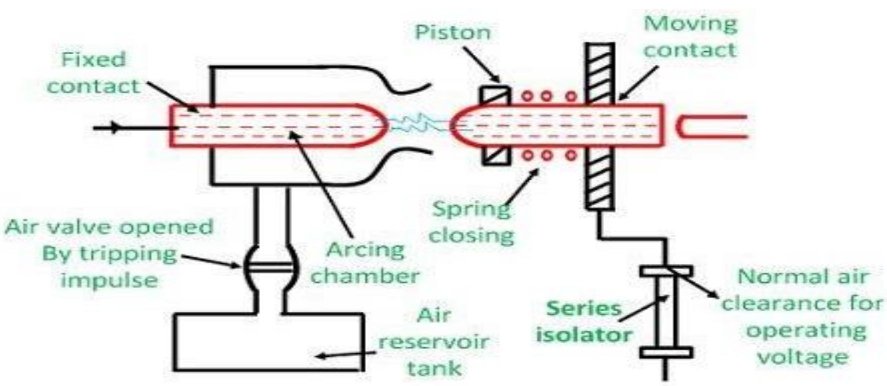
– **Axial blast type:** In which the flow of air blast is directed along the arc path.
– **Cross blast type:** In which the flow of air blast is perpendicular with respect to arc.
– **Radial blast type:** In which the air blast is directed radially.



Air Blast Circuit Breakers

Axial Blast Circuit Breaker

Under Normal Condition, The fixed and moving contacts are held in a closed position with the help of spring pressure. There is an air reservoir connected to the arcing chamber through an air valve.



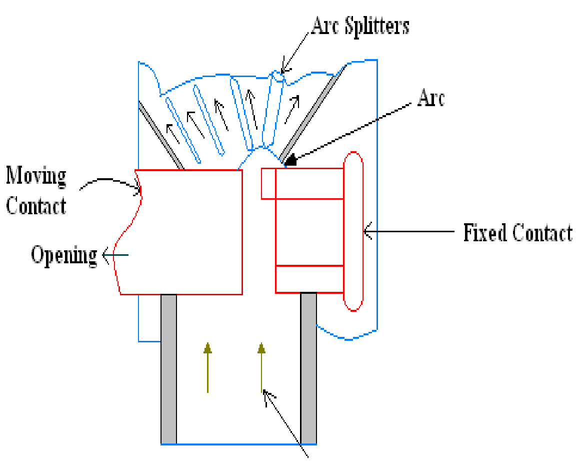
Axial Blast Air Circuit Breaker

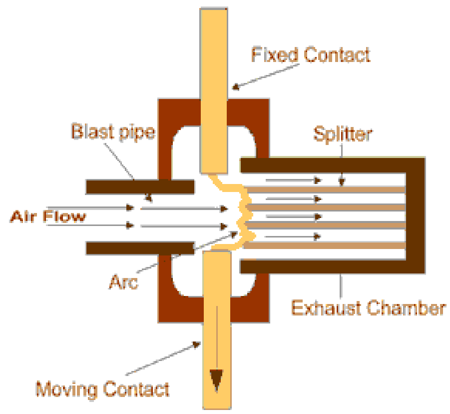
The air valve controls the flow of air into the arcing chamber. The valve is closed under normal conditions.

Under Faulty Condition, when a fault occurs a tripping impulse is produced which causes the opening of the air valve. Since the air valve connects the air reservoir and the arcing chamber, a high-pressure air enters the arcing chamber. This air pushes away the moving contact against the spring pressure.
The moving contact is separated and an arc is struck. At the same time, high-pressure air blast flows along the arc and takes away the ionized gases along with it. Consequently, the arc is extinguished and the current flow is interrupted.

Cross Blast Circuit Breaker

In this type of breaker, an air-blast is directed at right angles to the arc. The cross blast lengthens and forces the arc into a suitable chute for arc extinction.
The figure shows the essential components of a typical cross-blast air circuit breaker.





Principle of Cross Blast Air Circuit Breaker

When the moving contact is withdrawn, an arc is struck between the fixed and moving contacts. The high-pressure cross-blast forces the arc into a chute consisting of arc splitters and baffles. The splitters serve to increase the length of the arc and baffles give improved cooling.
The result is that arc is extinguished and the flow of current is interrupted. Since blast pressure is the same for all currents, the inefficiency at low currents is eliminated.
The final gap for interruption is great enough to give normal insulation clearance so that a series isolating switch is not necessary.

Application of air blast circuit breakers

Air blast circuit breakers finding their best application in system operating at 132 kV to 400 kV and above, especially where fast breaker operation requires. These are the high capacity circuit breakers and suitable for all EHV applications.

Advantages

1. There is no risk of fire and explosion caused by oil.
2. The arc extinguished very quickly.
3. As the duration of arc is smaller, therefore burning of contacts is less.
4. Much less maintenance is required as compared to oil circuit breaker.
5. It has a relatively small size.

Drawbacks of air blast circuit breakers

1. Compressor plant is required for compressing air.
2. They are very sensitive to variation in the rate of rise of restriking voltage.
3. Leakage of air at the pipe line fitting.
4. Due to poor dielectric strength of air it has relatively interior arc extinguishing property.
5. Cost of operation is high.

Air Break Circuit Breakers

Air break circuit breaker uses atmospheric pressure in air as an air quenching medium. This type of circuit breaker employs a **high resistance interruption principle**. In this circuit breaker arc is expanded by the mean of arc runners, arc chutes, and arc resistance is increased by splitting, cooling and lengthening.

The arc resistance is increased to such an extent that the voltage drop across the arc becomes more than the system voltage, and the arc gets extinguished at the current zero of AC wave.

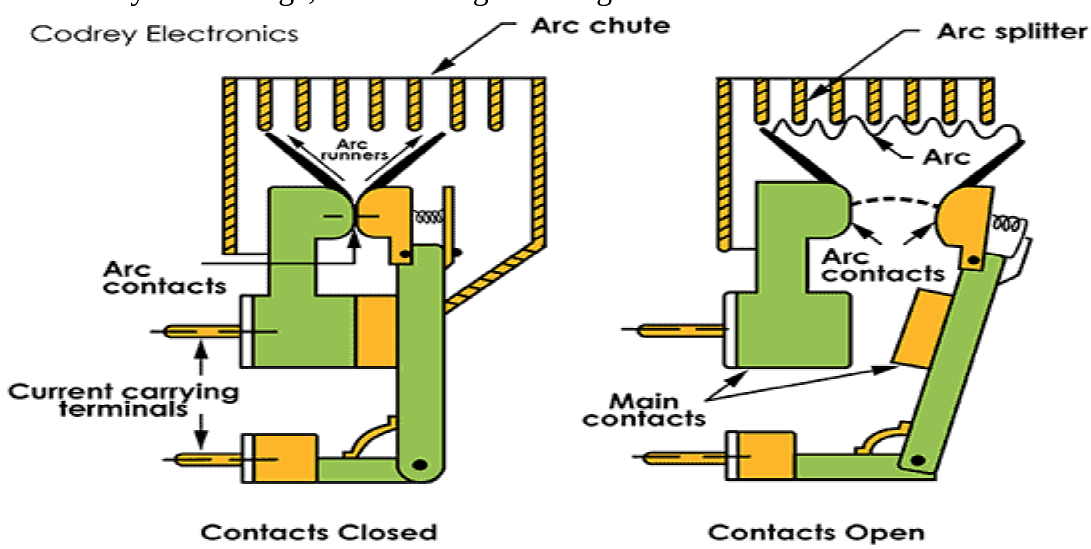


Fig: Air Break Circuit Breaker diagram

The breaker has two contacts: main contact and arc contact. The main contacts are silver plated and have low contact resistance. The current conduct when the mains contacts are in a closed position. The arcing contacts are made of copper alloy and they are heat resistant.

Working

When the breaker is in close condition, the current flows in the main contact. When the contacts are open, the main contact is separated first and the arcing contact remains closed.

Therefore, the current in the main contact moves to the arcing contact. Now the arcing contacts are separated and an arc is formed between them. Here, the high resistance is used for arc interruption.

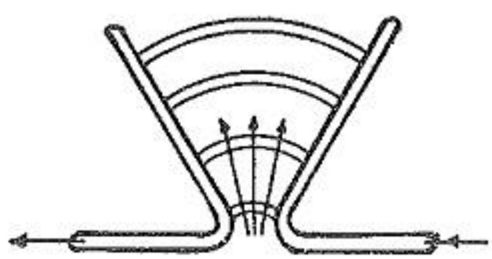
The following methods are employed for increasing arc resistance. The lengthening, splitting, and cooling the arc increases the resistance.

- **Arc lengthening:** Resistance is approximately proportional to length of the arc.
- **Arc cooling:** The voltage required to maintain ionization increases with a decrease of temperature so that cooling effectively increases the
- **Arc splitting:** An appreciable voltage is absorbed at the two contact surfaces so that if the arc can be split into a number of small arcs in series the voltage available for the actual arc column is reduced.
- **Arc constraining:** If the are can be constrained into a very narrow channel the voltage necessary to maintain it is increased.

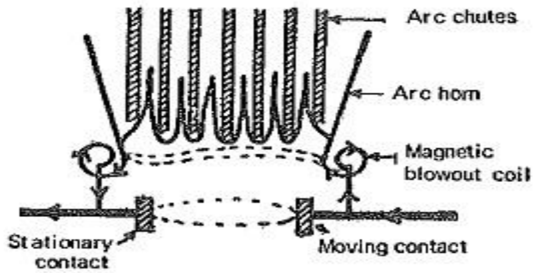
The two chambers called arc runner (Arcing horns) and arc chutes increases the length of the arc. The arc moves along the arc runner and forced to move upwards into the arc chute. The arc is split in this way by arc splitters and thus it extinguishes.
Low and medium voltage systems use ACB in electric furnaces and in large motors. They are available in the range of 400V to 12kV.

<u>Types of Air Break Circuit Breaker.</u>

Plain Break Types:
This is the simplest type of Air Break Circuit Breaker where contacts are made in the shape of two horns. The arc initially strikes across the shortest distance between the horns, but it is then driven steadily upwards by the convection currents set up due to heating of air during arcing and the interaction of magnetic and electric fields. The arc extends from one tip to the other when the horns are fully separated resulting in arc lengthening and cooling. The relative slowness of the process and the possibility of the arc spreading to adjacent metal work limit the application to about 500 V and to low power circuits. Figure shows such a breaker.



Magnetic Blow-Out Type:
In a number of Air Break Circuit Breaker used in circuits up to 11 KV the extinction of the arc is carried out by means of a magnetic blast. . To achieve this arc is subjected to the action of magnetic field set up by coils connected in series with the circuit being interrupted. Such coils are called blow out coils, because they help in the arc being magnetically **blown out**. Figure shows the principal scheme of a magnetic-blast circuit breaker. The arc is blown magnetically into arc chutes where the arc is lengthened, cooled and extinguished. The arc shields prevent spreading of the arc to adjacent metal work. As the breaking action becomes more effective with heavy currents, this principle has resulted in increasing the breaking capacities of these breakers to higher values.

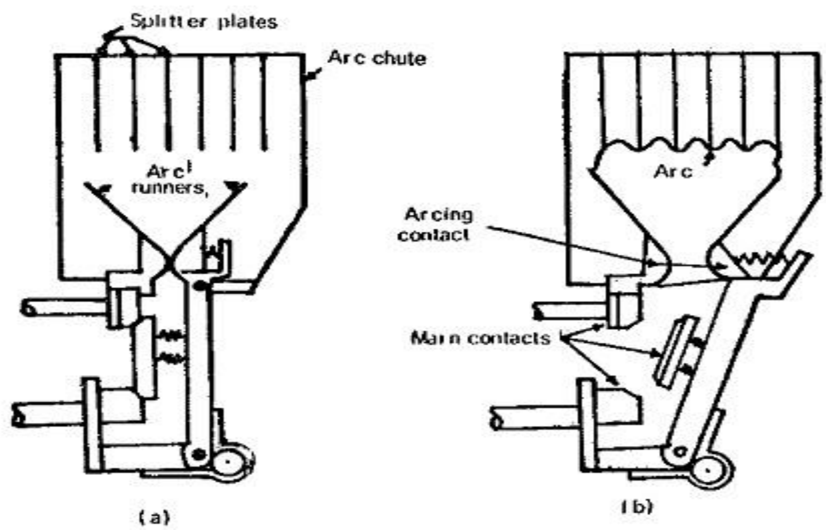


Arc chute is an efficient device for quenching an arc in air, which performs three interrelated functions:

- It confines the arc within a restricted space.
- It provides magnetic control of the movement of the arc, so that extinction occurs within the device.
- It provides for the rapid cooling of the arc gases to ensure extinction by deionization.

Arc Splitter Type:

Here the blow-outs consist of steel inserts in the arcing chutes. These are so arranged that the magnetic field induced in them by the current in the arc moves it upwards still faster. The steel plates divide the arc into a number of short arcs in series. The distribution of voltage along the length of an arc. is not linear but is accompanied by a rather large anode and cathode drops. If the total sum of anode and cathode drops of all short arcs in series is more than the voltage of the circuit to be interrupted, conditions for quick extinction of the arc are automatically established.



When the arc comes into contact with the relatively cool surfaces of the steel plates, it gets rapidly and effectively cooled. The movement of the arc may be natural or assisted by a magnetic blow-out, the latter is used for heavy duties up to 500 MVA at 16 KV. This type of breaker becomes more bulky, the arc chutes more complex and the initial cost higher as the voltage and MVA increase. Further the time of operation is not small enough to make this breaker suitable for modern power systems.

Application:

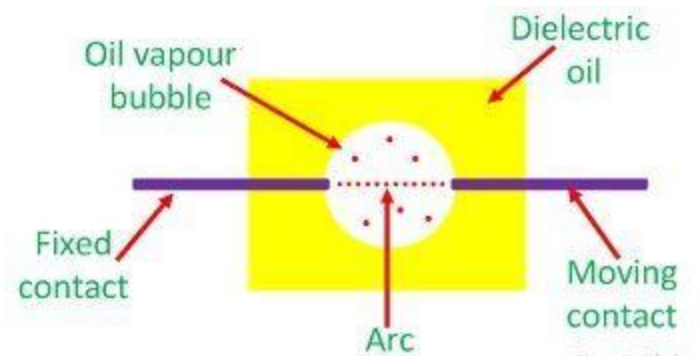
Air Break Circuit Breaker are, therefore, generally suitable for the control of power station auxiliaries and industrial plants. When they are chosen for such service, it is generally on the ground that they combine a high degree of safety with minimum maintenance.

Oil Circuit Breaker

Oil circuit breaker is such type of circuit breaker which used oil as a dielectric or insulating medium for arc extinction. In oil circuit breaker the contacts of the breaker are made to separate within an insulating oil. When the fault occurs in the system the contacts of the circuit breaker are open under the insulating oil, and an arc is developed between them and the heat of the arc is evaporated in the surrounding oil. The heat generated due arc will dissociates the oil into a substantial volume of gaseous hydrogen at a high pressure.

Mainly hydrogen gas is produced as a result of decomposition but a small amount of methane, ethylene and acetylene is also produced.

This hydrogen gas will form a bubble surrounding the arc and the parting contacts (fixed and moving) as shown in the figure below.



The arc extinction is done mainly by two processes.

1. The hydrogen gas has high heat conductivity and it cools the arc, thus de-ionization of the medium between contacts occurs.
2. The gas sets up turbulence (fast movement) of oil and thus it force the oil to pass through the space between contacts and the arcing products are eliminated from the path of arc.

The oil circuit breaker is divided into two categories

- Bulk Oil Circuit Breaker
- Low Oil Circuit Breaker

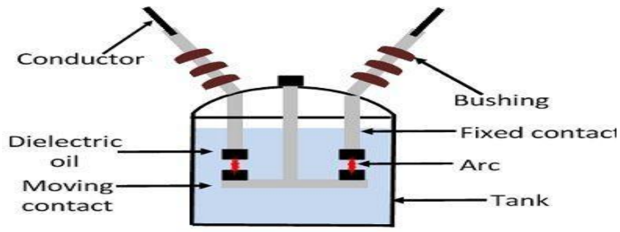
Bulk Oil Circuit Breaker (BOCB)

Bulk oil circuit breaker uses a large quantity of oil. The oil used serves two purposes. It extinguishes the arc when the contacts separate and it also insulates the live current-carrying parts from the earthed parts of the circuit breaker.

The quantity of oil requires for arc extinction is only about **one-tenth of the total** and the rest being used for the insulation. These are of two types,

a) ***Plain break oil circuit breaker*** : these have simple construction and normal operation, they do not have any special mechanism to quench the arc.
b) ***Arc control oil circuit breakers***: they employ special arc control methods.

a) Plain Break Oil Circuit Breaker



It consists of current-carrying contacts immersed in transformer oil and enclosed in a strong earthed metal tank. The oil acts as an insulator between live parts and earthed tank as well as arc extinguishing medium. The oil tank is not fully filled with oil, but some space is left for air at the top. Air serves as a cushion and provides space for the displaced oil on formation of gas around the arc. It also absorbs the mechanical shock produced due to the upward movement of oil.
The breaker tank is tightly bolted to a foundation to bear out vibrations produced at the time of operation of the circuit breaker. A sufficient head of oil above the arcing contacts is necessary to provide enough oil pressure at the arc and to prevent the occurrence of the chimney effect. A chimney of gas from the arc to the oil surface is produced. It comes in contact with the earthed tank. If this gas is of low dielectric strength, an arc will strike between contacts and earthed tank. It will result in severe consequences.
Hence a sufficient amount of oil should always exist between the live parts and the tank. A gas outlet from the tank is essential, and some form of the vent is made in the tank cover. There is a double break plain oil circuit breaker in the fig., it has two breaks in series.
In normal condition the contacts of circuit breaker are closed but When there is a fault occurred, the contacts of the breaker opened under the oil and an arc is struck between them, the arc extinction is done by following ways

- Due to the heat of arc, ionisation of oil occurs and hydrogen gas is produced which will form a bubble and finally the arc gets extincted due to good heat conductivity of gas and it cools the arc and it also aids the de-ionisation process.
- The gas sets up a turbulence in a oil which helps in eliminating arcing products from arc path.
- The moving contact of breaker will start moving in downward direction and arc length gets increased, hence the dielectric strength of medium is increased and arc will be extinguished.

DISADVANTAGES

- No special arrangement for arc extinction.
- The only way is to increase the gap length of between contacts which is not feasible when it has to deal with large value of current.
- It do not have a high speed interruption.

b) Arc Control Oil Circuit Breaker

Such BOCB includes a special system designed to control the arc to efficiently quench it. These designs enable the CB to extinguish the arc even if the contact gap is small. Unlike plain-break OCB, these CBs can be used in high voltage circuits.

The arc control Oil circuit breaker can be classified into the following two types.

- Self-Blast Oil Circuit Breaker
- Forced Blast Oil Circuit Breaker

Self-Blast Oil Circuit Breaker- In such OCB, the arc is controlled by internal means such as the energy of the arc is used for its own extinction.

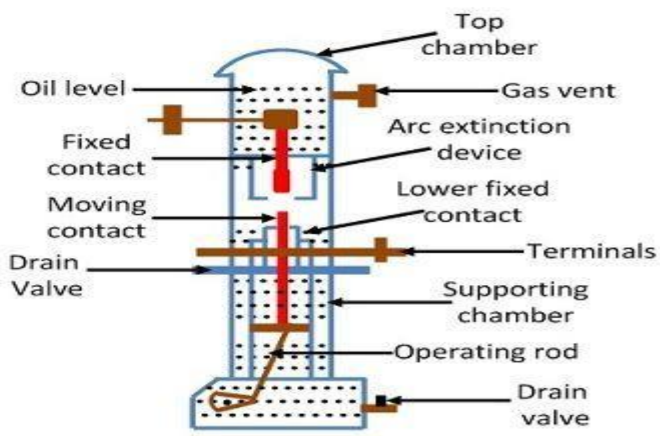
Forced Blast Oil Circuit Breaker- In such OCB, the arc control is provided by external means.

Minimum Oil Circuit Breaker

In this type of circuit breaker minimum oil is used as an arc quenching medium and it is mounted on a porcelain insulator to insulate it from the earth. The arc chamber of such type of circuit breaker is enclosed in a bakelised paper. The lower portion of this breaker is supported by the **porcelain** and the upper porcelain **enclosed the contacts**.

This circuit breaker is of the single breaker type in which a moving contact tube moves in a vertical line to make or break contact with the upper fixed contacts mounted within the arc control devices.

A lower ring of fixed contacts is in permanent contact with the moving arm to provide the other terminal of the phase unit. Within the moving contact, the tube is a fixed piston. When the moving contact moves downwards, it forces the insulating oil to enter into the arc control devices . Thus, the arc gets extinguished.



Minimum Oil Circuit Breaker

Minimum oil circuit breaker requires less space as compared to bulk oil circuit breaker which is an important feature in large installations. But it is **less suitable** in places where the **frequent operation is required** because the degree of carbonisation produced in the small volume of oil is far more dangerous than in the conventional bulk oil circuit breakers and this also decreases the dielectric strength of the material.

The low oil circuit breakers have the advantages of a requirement of the lesser quantity of oil, smaller space requirement, smaller tank size, smaller weight, low cost, reduced risk of fire and reduced maintenance problems. Minimum oil circuit breaker suffers from the following drawbacks when compared with the bulk oil circuit breakers

- Increased degree of carbonisation due to a smaller quantity of oil.
- The dielectric strength of oil decreases due to a high degree of carbonisation.
- Difficulty in removal of gases from the contact space-time.

Vacuum Circuit Breaker

A vacuum circuit breaker is a kind of circuit breaker where the arc quenching takes place in a vacuum medium in the order of range from 10^{-7} to 10^{-5} torr.. The operation of switching on and closing of current carrying contacts and interrelated arc interruption takes place in a vacuum chamber in the breaker which is called a vacuum interrupter.

Vacuum offers the highest insulating strength. So it has **far superior arc quenching properties** than any other medium (oil in oil CB, SF6 in SF6 circuit breaker). For example, when contacts of a breaker are opened in the vacuum, the **interruption occurs at first current zero with dielectric strength between the contacts building up at a rate thousands of times higher than that obtained with other types of circuit breakers.**

The material used for current carrying contacts plays an important role in the performance of the **vacuum circuit breaker**. Cu/Cr is the ideal material to make VCB contacts.

It is mainly used for medium voltage ranging from **11 KV to 33 KV.**

Construction

It consists of three contacts.

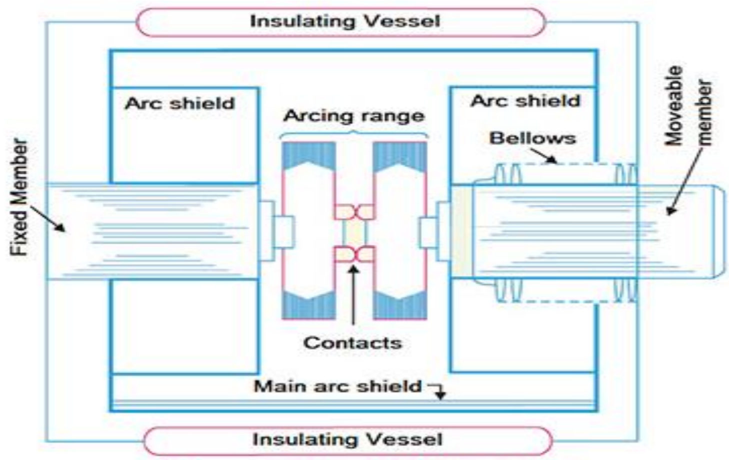
- Fixed contact
- Moving contact
- Arc shield inside the vacuum chamber.

The moving member is connected to the control mechanism by Stainless steel bellows.

The stainless steel bellows enable the permanent sealing of the vacuum chamber so as to avoid the likelihood of leakages.

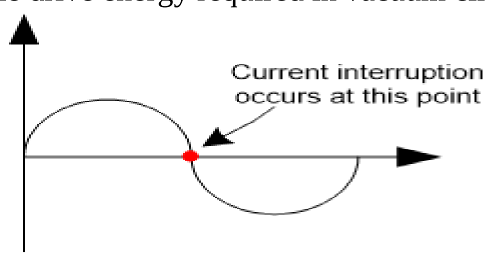
Ceramic envelop is used as the outer insulating body.

The spring mechanism is connected to the lower bottom of the breaker to move the metallic bellows.

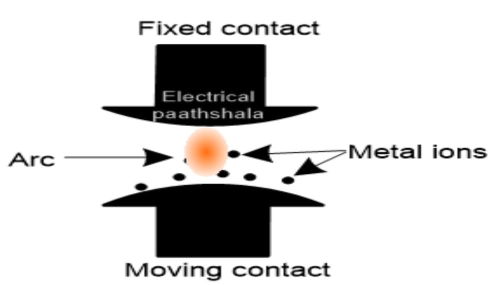


Operation of Vacuum Circuit Breaker

The main aim of any circuit breaker is to quench arc during current zero crossing, by establishing high dielectric strength in between the contacts so that reestablishment of arc after current zero becomes impossible. The dielectric strength of vacuum is eight times greater than that of air and four times greater than that of SF_6 gas. This high dielectric strength makes it possible to quench a vacuum arc within very small contact gap. For short contact gap, low contact mass and no compression of the medium the drive energy required in vacuum circuit breaker is minimum.



Initially, the fixed contact and moving contact both are connected to each other and the current flows through them. But as soon as any fault occurs in the system, the moving contact start separating from the fixed contact and arc phenomenon occurs between them. When two face to face contact areas are just being separated to each other, they do not be separated instantly, the **contact area on the contact face is being reduced and ultimately comes to a point and then they are finally de-touched.** Although this happens in a fraction of microsecond, it is a fact.



At this instant of de-touching of contacts in a vacuum, the **current through the contacts concentrated on that last contact point on the contact surface and makes a hot spot and the temperature of their connecting parts is very high due to which ionization occurs. Due to the ionization, the contact space is filled with vapour of positive ions which is discharged from the contact material.**

As it is a vacuum, the metal on the contact surface is easily vaporized due to that hotspot and create a conducting media for arc path. Then the arc will be initiated and continued until the next current zero.

After the current zero, the medium regains its dielectric strength provided vapour density around the contacts reduced. Hence, the arc does not restrike again because the metal vapour is quickly removed from the contact zone.

Thus, **At current zero this vacuum arc is extinguished and the conducting metal vapor is re-condensed on the contact surface. At this point, the contacts are already separated hence there is no question of re-vaporization of the contact surface, for the next cycle of current. That means, the arc cannot be reestablished again**. In this way **vacuum circuit breaker** prevents the reestablishment of arc by producing high dielectric strength in the contact gap after current zero.

Advantages

- There is no fire hazards or risk of fire.
- These breakers are compact in size.
- Very high chances to perform arc extinction process successfully every time i.e. can interrupt any fault current.
- Silent and less vibrational operation.
- Arc energy is low as compared to other circuit breakers.
- They can also withstand lightning surges.
- Quick operation (interrupts current at its first half cycle
- Reliable, require less maintenance and have longer service life than other types of circuit breakers.
- The vacuum has high dielectric strength.
- No generation of gas after the operation.
- It is much environmentally friendly than the SF6 Circuit breaker.
- Replacement of vacuum interrupter is much convenient

Disadvantages

- Their voltage range is limited and they can’t be used for higher voltage levels above 36kV like SF6 circuit breaker.
- If they are used for voltage level more than 36kV, then some units are to be connected in series which increases complexity and cost.
- Extra care for leakage should be done.
- The high technology used in the generation of vacuum.

Applications

- These circuit breakers are used both for indoor and outdoor applications.
- They are very useful for remote areas like hilly areas or rural areas because of less maintenance and longer life.
- Vacuum circuit breakers are employed for Reactor switching, capacitor bank switching and Transformer switching.

SF6 Circuit Breaker (Sulfur Hexafluoride Circuit Breaker)

A circuit breaker in which SF_6 under pressure gas is used to extinguish the arc is called SF_6 circuit breaker. SF_6 (sulphur hexafluoride) gas has excellent dielectric, arc quenching, chemical and other physical properties which have proved its superiority over other arc quenching mediums such as oil or air. It is used for arc quenching in high voltage circuit breakers up to 800 kV in power stations, electrical grids etc.

Properties of SF6 Gas

SF6 gas has very **high electronegativity**. It has a strong tendency to **absorb free electrons.** When an arc is struck between the contacts, it absorbs the free electrons from it. It converts into **negative ions which are heavier than electrons**. **Due to its heavyweight, its mobility is reduced**. Therefore, the mobility of the charges in SF6 gas has low mobility which enhances the dielectric strength of the medium since the movement of charges is responsible for current flow.
The fact that makes the SF6 better arc quenching medium is due to its physical and chemical properties that are given below.

Physical Properties

Physical properties of SF6 gas

- It is non-flammable gas.
- It is colorless and odorless gas.
- It has excellent thermal conductivity.
- It has high density and heavier than air.
- It liquefies at low temperature which is pressure-dependent.

Chemical Properties

Chemical properties of SF6 gas

- SF6 gas is stable and inert.
- It is non-toxic in its pure form but its products are.
- It has high electronegativity meaning it has a strong affinity for free electrons.
- It recombines very easily after arc quenching for re-utilization.
- They are non-corrosive.

Electrical Properties

- It has superior dielectric strength which is directly proportional to the pressure.

- Its arc quenching capabilities is almost 100 times better than air.
- The frequency of the voltage does not affect its dielectric strength.

Production of SF6

SF6 gas is an electronegative gas, it means that it has high tendency to absorb the free electrons. When there is a fault in the system, then the current carrying contacts starts separating and an arc struck between them due to ionization of the surrounding medium. Huge number of free electrons generated due this ionization.

When the SF6 gas molecule reacts with the free electrons, then they **form negative immobile ions** which is shown by the reaction below.

$$SF6 + e^{-} \rightarrow SF6^{-}$$

$$SF6 + e^{-} \rightarrow SF5^{-} + F$$

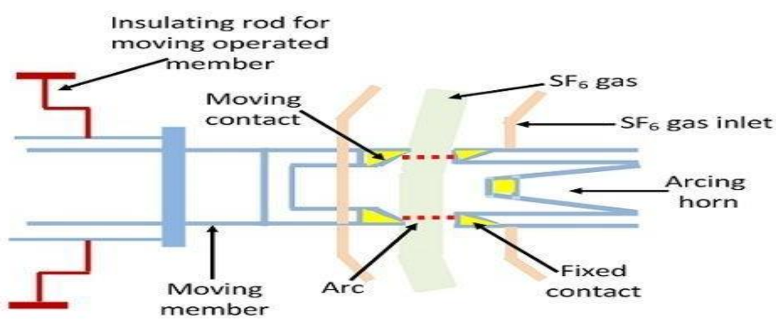
These **negative immobile ions are heavier as compared to free electrons and they do not get sufficient energy to lead cumulative ionization in the gas under a given electric field.**

This process makes dielectric strength of the medium very high and the arc gets extinguished. SF6 gas cools the arc much effectively

Construction of SF_6 Circuit Breakers

SF_6 circuit breakers mainly consist of two parts, namely (a) the interrupter unit and (b) the gas system.

Interrupter Unit – This unit consists of moving and fixed contacts comprising a set of current-carrying parts and an arcing probe. It is connected to the SF_6 gas reservoir. This unit consists slide vents in the moving contacts which permit the high-pressure gas into the main tank.

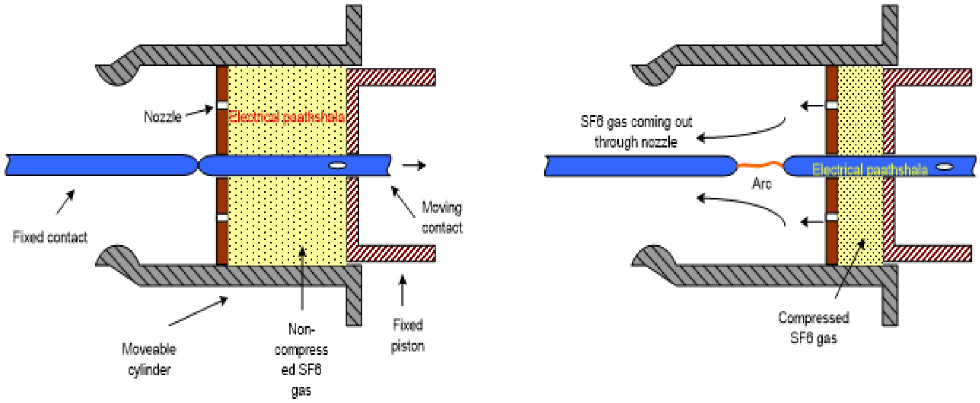


Interrupter Unit of SF6 Circuit Breaker

Gas System – The closed circuit gas system is employed in SF_6 circuit breakers. The SF_6 gas is costly, so it is reclaimed after each operation. This unit consists low and high-pressure chambers with a low-pressure alarm along with warning switches. When the pressure of the gas is very low due to which the dielectric strength of gases decrease and an arc quenching ability of the breakers is endangered, then this system gives the warning alarm.

Working Principle of SF_6 Circuit Breaker

In the normal operating conditions, the contacts of the breaker are closed. When the fault occurs in the system, the contacts are pulled apart, and an arc is struck between them. The displacement of the moving contacts is synchronised with the valve which enters the high-pressure SF_6 gas in the arc interrupting chamber at a pressure of about 16kg/cm^2.



The SF_6 gas absorbs the free electrons in the arc path and forms ions which do not act as a charge carrier. These ions increase the dielectric strength of the gas and hence the arc is extinguished. This process reduces the pressure of the SF_6 gas up to 3kg/cm^2 thus; it is stored in the low-pressure reservoir. This low-pressure gas is pulled back to the high-pressure reservoir for re-use.

Now a day puffer piston pressure is used for generating arc quenching pressure during an opening operation by mean of a piston attached to the moving contacts.

Advantages

- SF6 gas has a superior arc quenching property that is 100 times more effective than air.
- The arcing time is very short.
- SF6 has high dielectric strength due to electronegativity. It increases with an increase in pressure.
- Due to high dielectric strength, required contact separation is small to prevent arc restriking.
- Due to High dielectric strength, it can interrupt large current.
- It has a compact design. Thus requires small space and cost for installation.
- SF6 gas can handle all kinds of switching phenomena.
- SF6 CB has a closed circuit gas system with no leakage. Therefore, it can be installed in any kind of extreme environment.
- Due to the closed-circuit gas system, there is no problem of moisture.
- The dielectric strength does not reduce because no carbon particles are formed with arcing.
- It does not require an expensive and bulky air compressing system except for the 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

- Leakage of byproduct gases formed by SF6 gas during arcing are toxic for the environment
- 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 and maintaining the quality of gas.
- The SF6 is heavier than oxygen and can cause difficulty in breathing.
- Recombination and reconditioning of the SF6 gas requires additional equipment.

Application of SF6 Circuit Breaker

SF6 circuit breakers are mainly used for the protection of very high voltage circuits up to 800 kV from fault current. it can safely break and depower a high voltage circuit for any kind of inspection or maintenance.

Each interrupter unit is capable of handling 60 kA in the range of 80 kV. Multiple interrupter units are connected in series to increase their voltage handling capacity according to the system. They are used for the protection of power transmission and distribution systems. They are installed in power generation plants and power grids.

Difference between VCB and SF6 Circuit Breaker

The function of both vacuum circuit breaker (VCB) and SF6 circuit breaker is the same. However, there are several differences between VCB and SF6 circuit breaker that are listed in the following table −

Basis of Point	VCB	SF6 CB
Definition	A circuit breaker which uses vacuum as the arc quenching medium is called vacuum circuit breaker or VCB.	A circuit breaker that uses SF_6 (Sulphur Hexafluoride) gas as the arc quenching medium is known as SF_6 circuit breaker.
Voltage range	VCB is used for medium voltage range from 11 kV to 33 kV.	SF6 CB are used for high voltage range from 11 kV to 800 kV.
Arc quenching medium	Vacuum acts as the arc quenching medium in VCB.	SF_6 circuit breaker has Sulphur hexafluoride (SF_6) gas as the arc quenching medium.
Pressure of quenching medium	Pressure of vacuum in VCB is maintained at 10-2 torr to 10-6 torr in a vacuum chamber.	The pressure of SF_6 gas is maintained at 1500 torr to 1875 torr. Which is very high as compared to pressure of vacuum in VCB.
Development of arc	A very low arc is developed in a VCB while the circuit is opened.	The arc developed in SF_6 circuit breaker is slightly higher than VCB.
Refilling cost	There is no refilling cost of quenching medium because vacuum in vacuum chamber stay intact for long duration.	SF_6 circuit breaker involves very high refilling cost of SF_6 gas.

Suitability	Vacuum circuit breakers are largely suitable for indoor applications.	SF_6 CB are mainly suitable for outdoor applications as well for indoor applications
Maintenance	Vacuum CB require rare maintenance.	SF_6 CB require periodic maintenance.
Short circuit breaking capacity	Short circuit breaking capacity of vacuum CB is extremely high.	Short circuit breaking capacity of SF_6 circuit breakers is high but less than that of a VCB.
Installation	Installation of vacuum breakers is relatively less difficult.	SF_6 CB involve extremely complicated installation.
Cost	Cost of VCB is comparatively low.	SF_6 CB are comparatively expensive.
Applications	Used in medium voltage range circuits for switching and protection such as in high voltage induction motor circuits, primary distribution stations, etc.	Used in high voltage applications like high tension (HT) power control centers (PCC), transmission substations, etc.

Comparison of insulating methods for CBs

Property	Air	Oil	SF6	Vacuum
Number of operations	Medium	Low	Medium	High
'Soft' break ability	Good	Good	Good	Fair
Monitoring of medium	N/A	Manual test	Automatic	Not possible
Fire hazard risk	None	High	None	None
Health hazard risk	None	Low	Low	None
Economical voltage range	Up to 1 kV	3.3–22 kV	3.3–800 kV	3.3–36 kV

The following table highlights the features for different types of circuit breakers.

Factor	Oil Breakers	Air Breakers	Vacuum/SF6
Safety	Risk of explosion and fire due to increase in pressure during multiple operations	Emission of hot air and ionized gas to the surroundings	No risk of explosion
Size	Quite large	Medium	Smaller
Maintenance	Regular oil replacement	Replacement of arcing contacts	Minimum lubrication for control devices
Environmental factors	Humidity and dust in the atmosphere can change the internal properties and affect the dielectric		Since sealed, no effect due to environment
Endurance	Below average	Average	Excellent

Transformer Protection

Introduction

Transformer which are the costliest protection system of the electrical system. Due to the long lead time for repair of and replacement of transformers, a major goal of transformer protection is limiting the damage to a faulted transformer. Since transformer working under several voltage levels, it's also required to have better protection in the transformers. Hence the protection of power transformer against possible fault is very important.

The electrical windings and the magnetic core in a transformer are subject to a number of different forces during operation:

- Expansion and contraction due to thermal cycling
- Vibration
- Local heating due to magnetic flux
- Impact forces due to through-fault current
- Excessive heating due to overloading or inadequate cooling

So, due to these failure on transformer occurs.

Transformer Failures

Failures in transformers can be classified into

- **Winding failures** due to short circuits (turn-turn faults, phase-phase faults, phase-ground, open winding)
- **Core faults** (core insulation failure, shorted laminations, Open ground strap, Core overheating)
- **Terminal failures** (open leads, loose connections, short circuits)
- **On-Load tap changer failures** (mechanical, electrical, short circuit, overheating)
- Abnormal operating conditions (over fluxing, overloading, overvoltage)
- **Incipient faults** (inter-lamination short circuit due to insulation failure between core lamination, lowering the oil level due to oil leakage, blockage of oil flow paths)
- **External faults**

Transformer Protection for Different Types of Transformers

The protection system used for a power transformer depends on the transformer's categories. A table below shows that,

Category	Transformer Rating - KVA	
	1 Phase	3 Phase
I	5 - 500	15 - 500
II	501 - 1667	501 - 5000
III	1668 - 10,000	5001 - 30,000
IV	> 10,000	>30,000

- Transformers below **5000 KVA** (Category I & II) are protected using **Fuses. Fuses and MV circuit breakers** are often used to protect **transformers up to 1000 kVA** (distribution transformers for 11kV and 33kV).
- For transformers **10 MVA and above** (Category III & IV), **differential relay** are commonly used to protect them. Current differential relays are applied for transformers as main protection. For backup protection, distance protection or overcurrent (phase current, zero sequence current) protection or both are mainly applied.

  In addition to above, mechanical relays such as Buchholz relays and sudden pressure relays are widely applied to transformer protection, and are particular to application to transformer protection. Mechanical relays are intended to detect faults which the main relay could not detect. In addition to these relays, thermal overload protection is often applied for the purpose of extending a transformer's life time rather than for detecting faults.

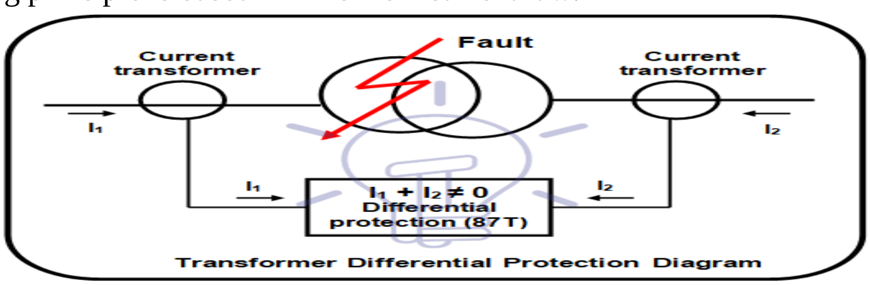
Main Electrical Protection

Differential Protection of Transformer

The percentage differential protection or Merz-Price protection based on the circulating current principle can also be used for the transformers. This system gives protection against phase-to-phase faults and phase to ground faults to the power transformers.

The ideal way of *protecting any piece of power system equipment* is to compare the current entering that piece of equipment, with the current leaving it." *Under normal healthy conditions* the two are equal. If the *two currents are not equal*, then a fault must exist.

This is done through *"*differential protection*"* which diagram is shown in Fig. and the functioning principle is based in Kirchhoff current law.



If there is no earthing / grounding connection *at the transformer location point, this protection* can also be used to protect against earth faults. If the *earth fault current* is limited by impedance, it is generally not possible to set the *current threshold* to a value less than the limiting current.

This protection is connected to *current transformers CT (Current Transformers*) at both side of the transformer *(primary and secondary).*

Compared to the differential protection used in generators, there are certain important points which must be taken care of while using such protection for the power transformers. These points are,

1. In a power transformer, the voltage rating of the two winding is different. The high voltage winding is low current winding while low voltage winding is high current winding. Thus there always exists difference in current on the primary and secondary sides of the power transformer. Hence if C.T.s of same ratio are used on two sides, then relay may get operated through there is no fault existing.

To compensate this difficulty, current ratios of C.T.s on each side are different. These ratios depend on the line currents of the power transformer and connection of C.T.s. Due to different turns ratio, the currents fed into the pilot wires from each end are same under normal conditions so the relay remains inoperative. For example if K is the turns ratio of a power transformer then the ratio of C.T.s on low voltage side is made K times greater than C.T.s on high voltage side.

2. In case of power transformers, there is an inherent phase difference between the voltages induced in high voltage winding and low voltage winding. Due to this, there exists a phase difference between the line currents on primary and secondary sides of a power transformer. This introduces the phase difference between the C.T. secondary currents, on the two sides of a power transformer. Through the turns ratio of C.T.s are selected to compensate for turns ratio of transformer, a differential current may result due to the phase difference between the currents on two sides. Such a different current may operate the relay though there is no fault. Hence it is necessary to correct the phase difference.

To compensate for this, the C.T. connections should be such that the resultant currents fed into the pilot wires from either sides are displaced in phase by an angle equal to the phase shift between the primary and secondary currents. To achieve this, secondaries of C.T.s on star connected side of a power transformer are connected in delta while the secondaries of C.T.s on delta connected side of a power transformer are connected in star.

The table gives way of connecting C.T. secondaries for various power transformer connections.

Power Transformer Connections		C. T. Connections	
Primary	Secondary	Primary	Secondary
Star	Delta	Delta	Star
Delta	Delta	Star	Star
Star	Star	Delta	Delta
Delta	Star	Star	Delta

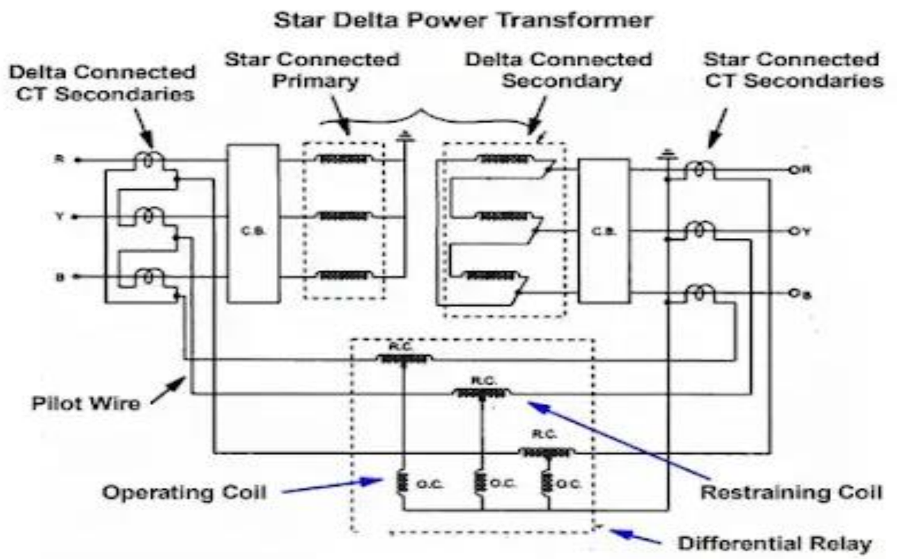
With such an arrangement, the phase displacement between the currents gets compensated with the oppositely connected C.T. secondaries. Hence currents fed to the pilot wires from both the sides are in phase under normal running conditions and the relay is ensured to be inoperative.
3. The neutrals of C.T. star and power transformer stars are grounded.

4. Many transformers have tap changing arrangement due to which there is a possibility of flow of differential current. For this, the turns ratio of C.T.s on both sides of the power transformer are provided with tap for of C.T.s on both sides of the power transformer are provided with tap for their adjustment.

Connection for Differential Protection for Transformer

A) Merz-Price Protection for Star-Delta Transformer

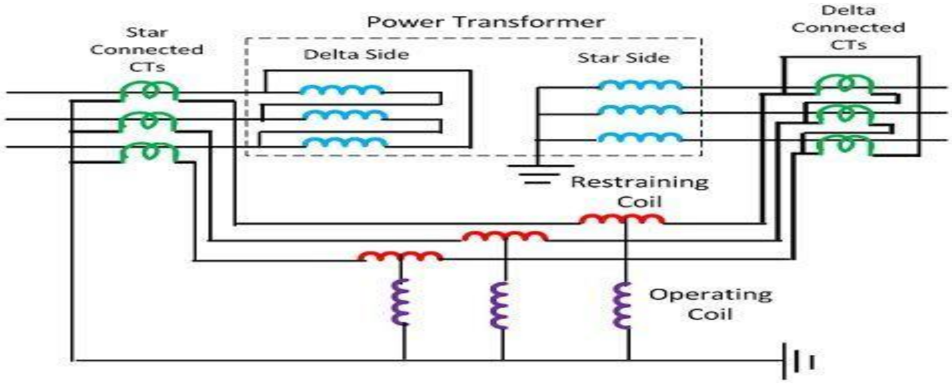
The diagram shows the connection of differential protection for star delta power transformer



- The primary of power transformer is connected in star while the secondary is connected in delta. Hence to compensate the phase difference, the CT secondaries on the primary side I.e the star side of the transformer must be connected in delta and the CT secondaries of the secondary side I.e the delta side of the transformer must be connected in star.
- The star point of the transformer primary and star point of star-connected secondaries of CT must be grounded.
- The restraining coils are connected across the secondaries of CT while operating coils are connected between Tapping point on restraining coils and star point of CT secondaries.
- During normal operation, the CT secondaries carry an equal current which is in phase under normal operating conditions. Therefore the current entering and leaving the pilot wire at both ends are the same and no current flows through the operating coil of the relay and the relay is inoperative.
- When an internal fault occurs in power transformer winding the balance in CTs gets disturbed and the current in secondaries of CTs will no longer be the same and the differential current starts flowing through the operating coil and the relay circuit will trip the breaker on both sides of the transformer.
- The protection provided by differential protection scheme is limited to the region between CTs on the high voltage side and CTs on low voltage side of the power transformer.

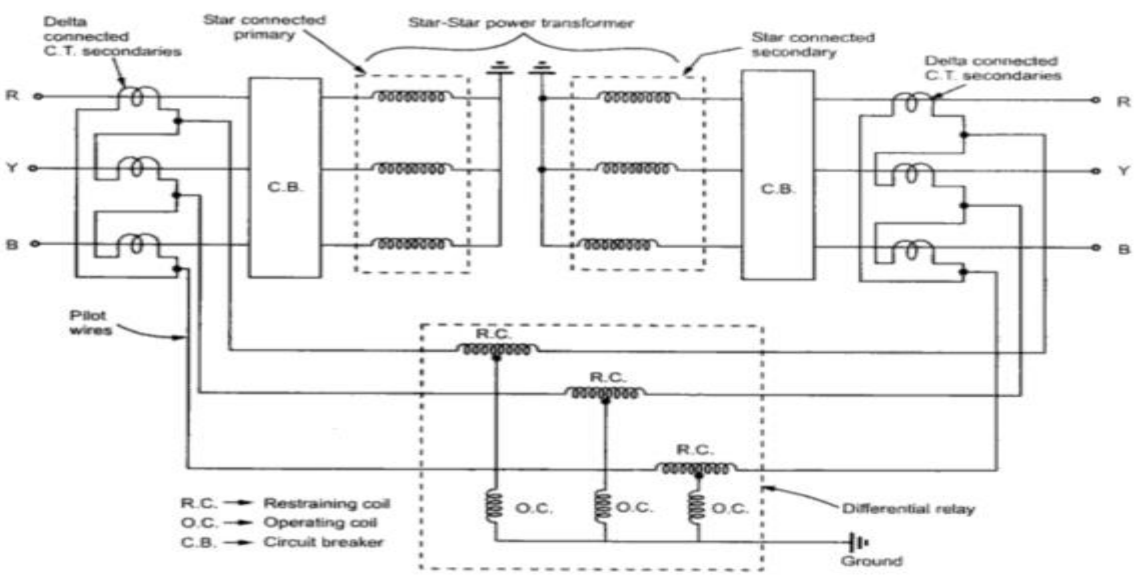
B) Merz-Price Protection for Delta- Star Transformer

- Let, the transformer is star connected on one side and delta connected the other side.
- The CTs on the star side are delta-connected and those on the delta-connected side are star-connected. The neutral of both the transformers are grounded.
- The transformer has two coils, one is the **operating coil** and the other is the **restraining coil**. As the name implies, the restraining-coil is used to produce the restraining force, and the operating-coil is used to produce the operating force. The restraining-coil is connected with the secondary winding of the current transformers, and the operating coil is connected in between the equipotential point of the CT.

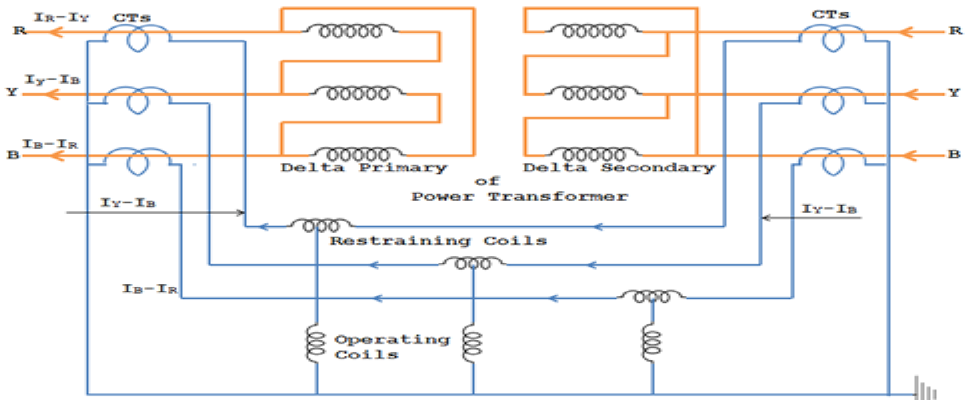


- Normally, the operating coil carries no current as the current is matched on both sides of the power transformers, when an internal fault occurs in the windings, the balance is altered and the operating coils of the **differential relay** start producing differential current among the two sides of the transformer. Thus, the relay trips the circuit breakers and protects the main transformer.

C) Merz-Price Protection for Star-Star Transformer



D) Merz-Price Protection for Delta-Delta Transformer



Merz price differential protection of delta-delta power transformer
(CTs are connected in star)

Problems Associated with the Application of Differential Protection

Simple differential protection system is inadequate because of its following inherent drawbacks:

1. Difference in Length of Pilot Wires on Either Side of Relays: This difficulty is overcome by inserting balancing resistances in series with the pilot wires. These are adjusted on site to get equipotential points on pilot wires.

2. Different CT Characteristics: Unless saturation is avoided, the difference in CT characteristics due to different ratios being required in circuits of different voltages may cause appreciable difference in the respective secondary currents on occurrence of through faults. This problem is aggravated in the case of power transformers due to unequal ratio CTs being used on either side of the power transformer. A source of ratio error which results in circulating currents under through-fault condition is the unequal burden imposed on CTs due to unequal lead length.

3. Tap Changing: In most of the transformers there is provision for tap changing so that the voltage can be varied as per requirement to keep the system voltage within limits. During tap changing voltage ratio differs from the original one and affects the operation of the differential relay. This problem is overcome by using biasing coil (i.e., percentage differential protection).

4. Magnetising Inrush Current: Under normal operating conditions, the magnetising current is very small. However, when a transformer is energized after it has been taken out of service, the magnetising inrush current can be extremely large (as large as 10 times full-load current) for a short period (5 to 10 cycles, sometimes as large as 4 to 6 seconds). Since magnetising current flows only through primary winding, it causes difference in CTs output and makes the relay to operate, which is not desirable.

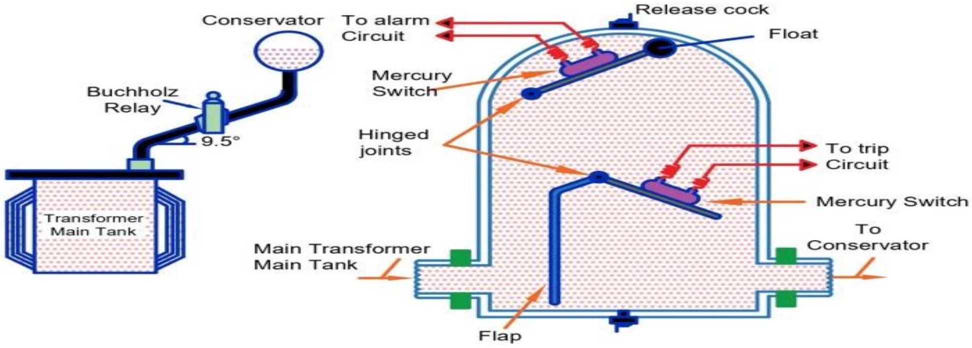
There are a number of ways of overcoming the above problem. Firstly, the relay may be provided with a setting larger than the maximum inrush current; secondly, the time setting may be made long enough for the magnetising current to subside (fall below the primary operating current) before the relay operates. But for EHV transformers these simple remedies are not incompatible. The third alternative is the use of second harmonic restraint relay.

Buchholz Relay

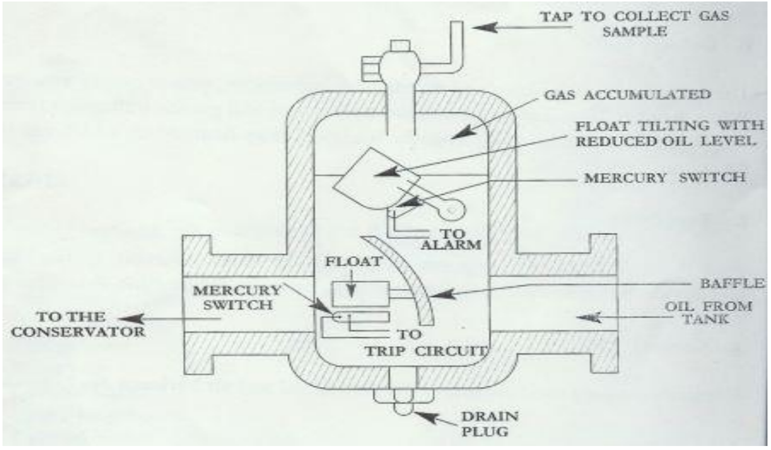
Buchholz relay is a safety device which is generally used in large oil immersed transformers (rated more than 500 kVA). It is a type of oil and gas actuated protection relay.
It is used for the protection of a transformer from the faults occurring inside the transformer, such as impulse breakdown of the insulating oil, insulation failure of turns etc.

Construction of Buchholz Relay

Buchholz relay has two hinged which is placed in the metallic chamber which is connected through the pipe between the conservator and main tank.



Buchholz relays have two main elements. The upper element consists of a float. The float is attached to a hinge in such a way that it can move up and down depending upon the oil level in the Buchholz relay container. A mercury switch is fixed on the float. The alignment of the mercury switch hence depends upon the position of the float.
The lower element consists of a baffle plate and a mercury switch. This plate is fitted on a hinge just in front of the inlet (main tank side) of the **Buchholz relay in a transformer** in such a way that when oil enters in the relay from that inlet in high pressure the alignment of the baffle plate along with the mercury switch attached to it, will change. In addition to these main elements, a **Buchholz relay** has gas release pockets on top. The electrical leads from both mercury switches are taken out through a molded terminal block.



Operation of Buchholz Relay

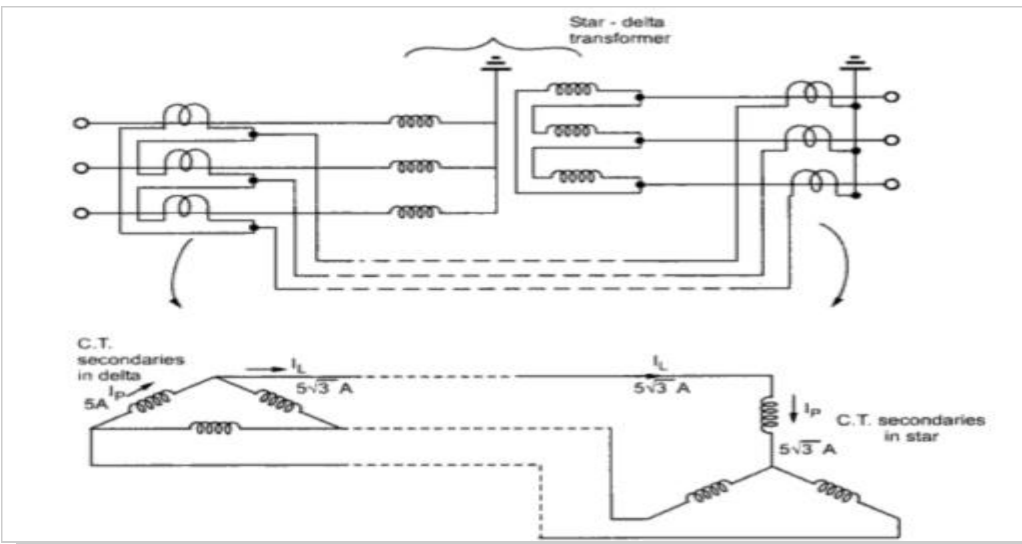
Whenever a minor fault occurs inside the transformer, heat is produced by the fault currents. The produced heat causes decomposition of transformer oil and gas bubbles are produced. These gas bubbles flow in upward direction and get collected in the buchholz relay. The collected gas displaces the oil in buchholz relay and the displacement is equivalent to the volume of gas collected. The displacement of oil causes the upper float to close the upper mercury switch which is connected to an alarm circuit. Hence, when minor fault occurs, the connected alarm gets activated. The collected amount of gas indicates the severity of the fault occurred. During minor faults the production of gas is not enough to move the lower float. Hence, during minor faults, the lower float is unaffected.

During major faults, like phase to earth short circuit, the heat generated is high and a large amount of gas is produced. This large amount of gas will similarly flow upwards, but its motion is high enough to tilt the lower float in the buccholz relay. In this case, the lower float will cause the lower mercury switch which will trip the transformer from the supply, i.e. transformer is isolated from the supply.

Numerical

Example 1: A three phase power transformer having a line voltage ratio of 400 V to 33 kV is connected in star-delta. The C.T.s on 400 V side have current ratio as 1000/5. What must be the C.T. ratio on 33 kV side.

Assume current on 400 V side of transformer to be 1000 A.



Solution:

The arrangement is shown in the Fig.

On the primary side, which is 400 V side of transformer the current is 1000 A.

Hence C.T.s primary will carry current of 1000 A.

The C.T. ratio is 1000/5 on the primary side hence the current in C.T. Secondary's which is phase current of delta connected C.T.s is,

$$I_p = 1000 \times (5/1000) = 5 \text{ A}$$

This is shown in the Fig.

$$I_L = \sqrt{3}\, I_p = 5\sqrt{3} \text{ A}$$

This is balance the C.T. secondaries are connected in delta.

The same current flows through the star connected C.T. secondaries. Hence each secondaries of C.T. on the secondary side of transformer carries a current of $5\sqrt{3}$ A.
For the power transformer the apparent power on both sides must be same.

Primary apparent power = Secondary apparent power

$$\sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$
$$\sqrt{3} \times 400 \times 1000 = \sqrt{3} \times 33000 \times I_{L2}$$
$$I_{L2} = (400 \times 1000)/33000 = 12.12 \text{ A}$$

Thus each primary of C.T.s connected in star carries a current of 12.12 A. while each secondary of C.T.s connected in star carries a current of $5\sqrt{3}$ A.
Hence the C.T. Ratio on 33 kV side is,

C.T. ratio = Primary current/Secondary current = $12.12/5\sqrt{3} = 1.4 : 1$

This is the required C.T. Ratio on 33 kV side.

2) A 3-phase 33000/6600 V transformer is connected in star/delta and the protecting current transformers on low voltage side have a ratio of 300/5. What will be the ratio of the current transformer on the high voltage side.

Here;

On low voltage side of transformer, the main Tr. winding are connected in delta So,

voltage per phase = Line voltage = 6600V

CT on Low voltage i.e. 6600V side are connected in star and the ratio is 300/5 i.e. 60

on high voltage side of Tr. The main Tr. Winding are connected in star

So, phase voltage = $33000/\sqrt{3}$ = 19050 V

The turn ratio of main Tr. = 19050/6600 =2887

HV side CT ratio = 60*1/2887 = 20.8:1

3) A 3-phase, 200MVA, 11/0,4 KV transformer is connected in delta /star. The protection transformer on the o.4 KV side has the turn ratio of 500/5. What will be the CT ratio on HV side?

Here;

On low voltage side of transformer, the main Tr. winding are connected in star

So voltage per phase = Line voltage/$\sqrt{3}$ =o.4/$\sqrt{3}$ = 0.231 KV

CT on Low voltage i.e. 0.4kV side are connected in delta and the ratio is 500/5 i.e. 100

On high voltage side of Tr. The main Tr. Winding are connected in delta

So, phase voltage = Line voltage= 11KV

The turn ratio of main Tr. = 11/0.231 = 47.63

HV side CT ratio = 100*1/47.63 =2.1:1

4) A three phase transformer rated for 33kV/6.6Kv is connected star/delta and the protecting current transformer on the low voltage side have the ratio of 400/5A. Determine the ratio of current transformer on the HV side. Draw the connection diagram showing the how relay operates under the faults conditions.

Solution : C.T.s on delta connected side are star connected. Hence the secondary phase currents are equal to currents in pilot wires.

C.T.s on star connected side are delta connected hence current in secondary is equal to current in pilot wires divided by $\sqrt{3}$.

Assume 400 A is flowing in the lines on low voltage side i.e. 6.6 kV side.

Now primary apparent power = secondary apparent power

$$\therefore \quad \sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$

$$\therefore \quad \sqrt{3} \times 33 \times 10^3 \times I_{L1} = \sqrt{3} \times 6.6 \times 10^3 \times 400$$

$$\therefore \quad I_{L1} = 80 \text{ A}$$

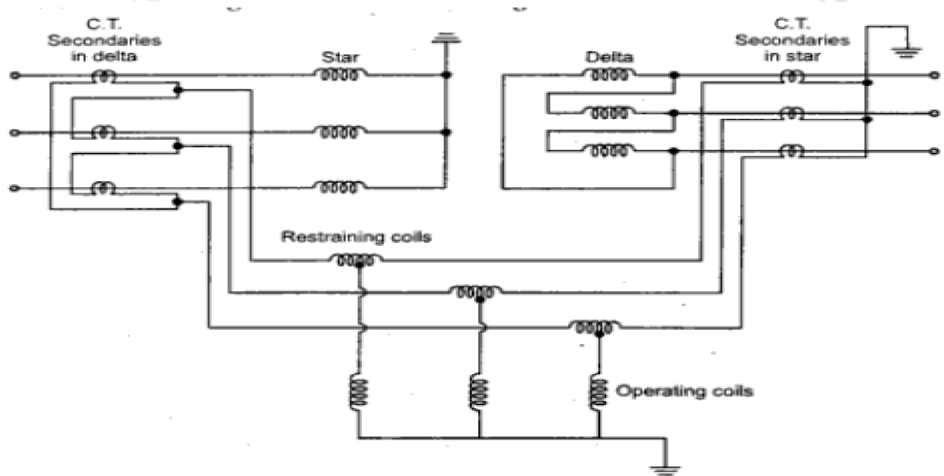
This is primary current of C.T. on high voltage side.

On the delta side of transformers the C.T. secondaries are star connected. Their secondary current is 5 A. Hence current fed in pilot wires from low voltage side is 5 A. Same current is fed from C.T. connections on high voltage side which are delta connected.

Hence secondary current of C.T.s on high voltage side is $5/\sqrt{3}$ A.

Thus C.T. ratio on H.T. side is $80 : 5/\sqrt{3}$ i.e. 27.712:1.

The connection diagram is shown in the Fig.



Example : *A 11 kV/132 kV power transformer is connected in delta-star. The C.T.s on the low voltage side have turns ratio of 600/5. Find the suitable turns ratio for the C.T.s on high voltage side.*

Solution : The connections are shown in the Fig.

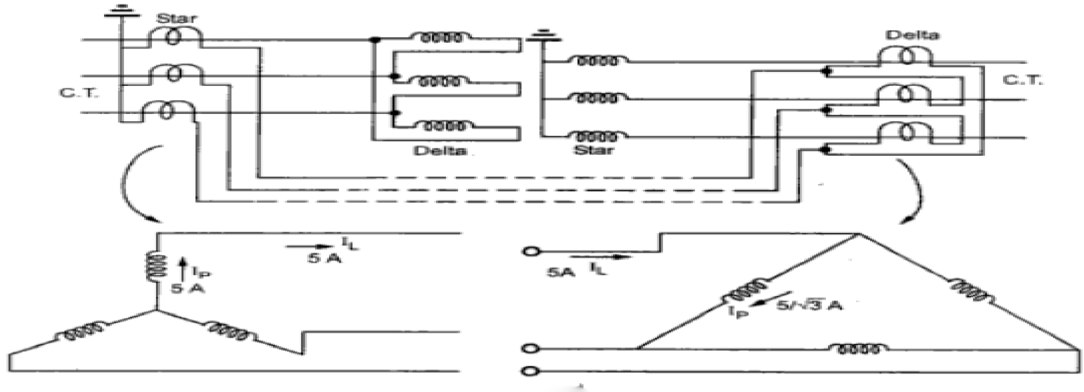


Fig. Fig

5A

Let the current on the primary i.e. low voltage side of power transformer be 600 A. This current will flow through each line on primary of transformer.

Hence current in each secondary of star connected C.T. on primary is the phase current I_P as shown in the Fig. 7.10.

$$\therefore \quad I_P = 600 \times \frac{5}{600} = 5 \text{ A}$$

The same in line current I_L which is line current for the C.T.s connected in delta on secondary of transformer.

Hence current in each secondary of C.T. which is phase current of C.T. is $\frac{1}{\sqrt{3}}$ times the line value.

$$\therefore \quad I_P = \frac{5}{\sqrt{3}} \text{ A} \qquad \text{for C. T. secondary connected in delta}$$

Now apparent power on both sides is same,

$$\sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$

$$\therefore \quad \sqrt{3} \times 11000 \times 600 = \sqrt{3} \times 132000 \times I_{L2}$$

$$\therefore \quad I_{L2} = \frac{11000 \times 600}{132000}$$

$$= 50 \text{ A}$$

This is the current flowing through each primary of delta connected C.T.

$$\therefore \quad \text{C.T. ratio on high voltage side} = \frac{50}{(5/\sqrt{3})}$$

$$= 17.32 : 1$$

Generator Protection

Introduction

The generator is the prime equipment and one of the most important in the power system. Generator protection is different and complex as compared to other equipment and machines due to the reason that it is connected with 3 other systems simultaneously, a DC exciter circuitry for providing DC to field winding, a prime mover for rotating rotor and is synchronized with the grid. Also, generating systems consist of auxiliaries like heat water pumps and exhaust fans, etc. which are supplied power through the generator itself that is why it is never preferred to completely turn off the generator as it would be a time taking task to start the generator again. Unlike other apparatus only isolating the circuit breaker is not enough to prevent further damage as the generator would still supply power to its stator windings until the excitation is suppressed. So, for isolation it is needed to open the field to avoid any excitation, and to minimize the fuel supply to the prime mover.

Generator faults

Generator faults can be considered as follows.

(a) Stator faults

These types of faults occur due to the insulation breakdown of the stator coils. The stator is prone to maximum number of faults in the system with phase to earth fault being the most common. The interturn faults and phase faults are less common but develop into an earth fault in the long run. These include the following stator faults:

1. Phase to earth faults.
2. Phase to phase faults
3. Inter turn faults

Phase to earth fault are limited by resistance of the neutral grounding resistor. There are fewer chances for the occurrence of the phase to phase and interturn faults. The insulation between the two phases is at least twice as thick as the insulation between one coil and the iron core, so phase to phase fault is less likely to occur. Inter turn fault occurs due the incoming current surges with steep wave front.

(b) Rotor faults / Field Winding

- The faults that exist in the rotor can be either earth fault or an interturn fault, Winding short-circuit (*wound rotor*), Overheating. These faults are mainly caused by the mechanical and thermal stress acting upon the winding insulation.
- The field system is normally not grounded (i.e., remains isolated from the earth) and, therefore, a single fault between field winding and rotor body due to insulation breakdown does not give rise to any fault current. However, a second earth fault will short circuit some part of the rotor winding and may thereby develop an unsymmetrical field system, giving unbalanced force on the rotor. This can cause severe vibration of the

rotor with possible damage to the bearings. Thus a single earth fault can be tolerated for a while but it should not be allowed to continue. Rotor earth fault protection is provided in case of large generators.

- Owing to a fault, there may be an unbalance in the three-phase stator currents. According to the theory of symmetrical components, unbalance three-phase currents have a negative sequence component, which rotates at synchronous speed in a direction opposite to the direction of rotation of rotor. So, double frequency currents are induced in the rotor.
- This causes overheating of rotor and possible damage to the rotor. Unbalanced currents may also cause severe vibration, but the overheating problem is more acute. Rotor temperature indicators are used with large generators for detecting rotor overheating due to unbalanced loading of generator.
- Rotor open-circuit faults, though rare, can cause arcing and thus result on serious conditions.
- Reduced excitation may occur due to open circuit or short circuit in the field or exciter circuits or a fault in automatic voltage regulator. When a generator loses its field excitation it speeds up slightly and continues to run as an induction generator deriving excitation from the system and supplying power at a leading power factor.
- A fall in voltage will also occur due to loss to excitation which may result in loss of synchronism and system stability. There is also the possibility of overheating of the rotor due to induced currents in the rotor and damper windings. This can be avoided by using a tripping scheme which is so arranged that opening of field circuit breaker causes the tripping of generator unit breaker.

Abnormal Conditions in Generator

The abnormal conditions that can occur are

1. Loss of excitation,
2. Unbalance loading,
3. Overloading,
4. Ventilation failure
5. Failure of prime mover
6. Current leakage in the body of generator,
7. Over speeding, and
8. Overvoltage.

Loss of Excitation: Field failure may occur due to a faulty field breaker. When a generator loses its excitation, the amount of reactive power supplied to the system is lost. Instead, it would draw excitation from the system while delivering real power at leading power factor. This leads to an operation of an induction generator where the speed is slightly increased. Also due to loss of excitation there would be a voltage fall which would lead to loss of synchronism. The situation may also lead to overheating in rotor and damper winding

Unbalance loading: If there is any unbalance in the system due to a phase fault or due to the unbalance loading, it gives rise to negative sequence currents. It produces an armature reaction field which rotates in a direction opposite to that of the rotor and hence produces a flux which is twice the frequency. Due to this eddy current and hysteresis loss are increased resulting in high amount of heating in the generator.

Over speeding: Whenever the generator is disconnected from the grid, it tends to run at no load with much higher speed than rated speed known as runaway speed. Over speeding caused increased in frictional losses. Governor which can vary the speed by changing the frequency and fuel supply is used to overcome this scenario.

Failure of prime mover: If the prime mover stops rotating and is not supplying active power to the generator then the generator will act as synchronous condenser. In this condition the generator the generator tries to compensate the losses causing a lot of heat. The machine start drawing small active power from the grid but continues to supply reactive power. In this condition a reverse power relay is used.

Overloading: Overloading can cause overheating in the stator winding of the generator. Failure of cooling systems and insulation failure of stator laminations also cause overheating of the stator winding. The overheating is detected by embedded temperature detectors at various points in the stator winding.

Protection Scheme of Generator

A. STATOR PROTECTION:

1. Differential Protection Scheme

For the protection of phase and ground fault, a differential protection scheme is employed. This protection scheme differs from the transformer differential protection scheme as:

- There is no interposing CT involvement
- No turn ratio problem
- No tap changer requirement

This type of protection scheme is known as a **longitudinal differential protection scheme**.

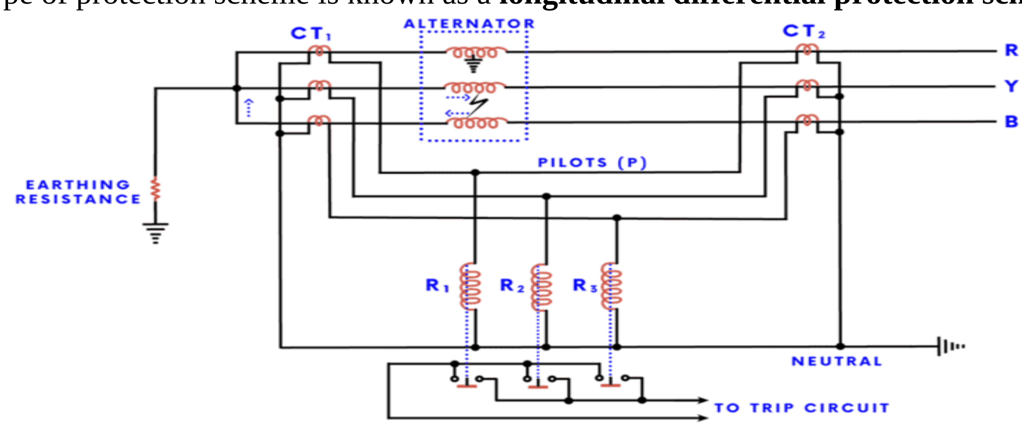


Figure: Connection Diagram of the Longitudinal Differential Protection Scheme

The connection diagram of longitudinal protection is such that, for each phase red (R), yellow (Y), and blue (B) there are two current transformers (CT). One of the CT connected at the neutral point (at generator) and the other at phase (switchgear). There are 4 pilot cables available, which is used for the connection of CTs with the relay coil (R1, R2, and R3).
The differential protection scheme works on the current matching principle that is when there is no fault, the current flowing through CT1 and CT2 will be the same, in this case, no current flows through relay coil and there is no tripping. In case of phase or ground fault, the relay coil gets energize and the difference of current is non-zero. Thus, relay issues a trip signal.

Differential Protection Scheme Using a Balance Resistor

There is a certain limitation in the above-mentioned protection scheme that is for the efficient working of this scheme, the relay coil should be placed in mid of the pilot cable (at an equipotential point) otherwise there could be a mal-operation of the relay.
But in some cases, generator and switch gears are placed at a certain distance and as the relays are placed in switchgear, the relay coil is placed at an uneven distance. The relay might give a trip signal in normal condition as well (due to unequal impedance).
A balancing resistor is connected with phase point CT for the reliable working at the time of fault and no-fault. It is known as **differential protection using a balancing resistor.**

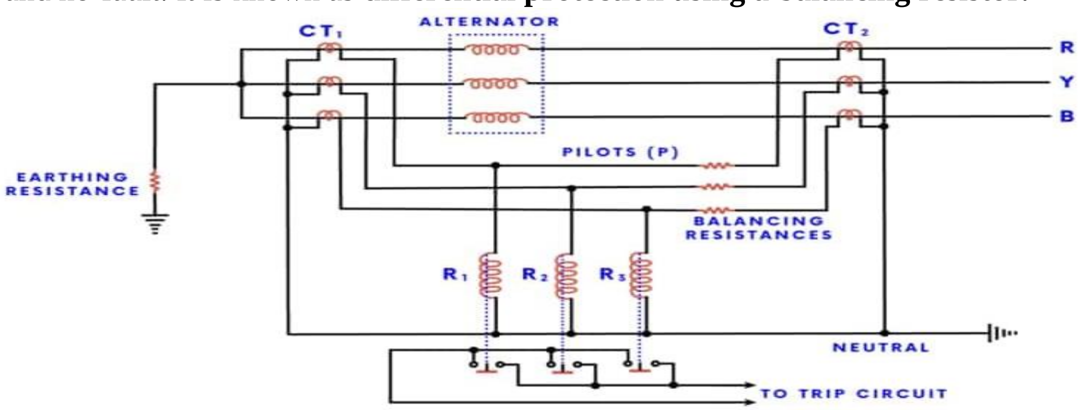
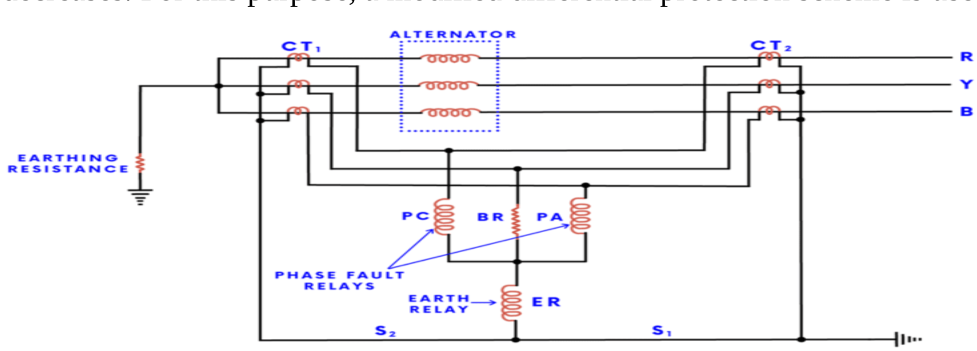


Fig: Connection Diagram of Differential Protection Using Balancing Resistor

Modified Differential Protection

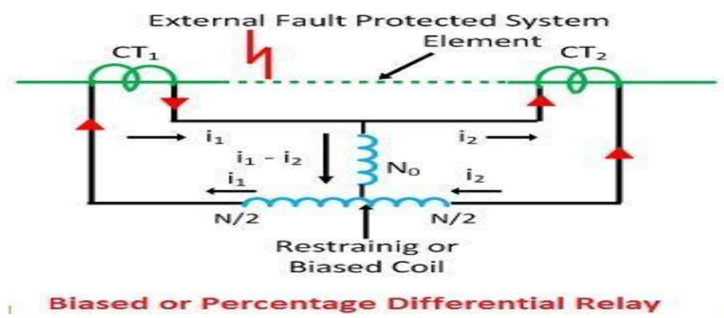
As the star point of the stator, the winding is grounded using some earthing resistance to reduce the effect of an earth fault. The fault which occurs close to the neutral point is not detected by relay. So, it is usually in practice to protect 85% of the stator winding,
Due to the presence of earthing resistance, the sensitivity of detecting an earth fault by the above schemes decreases. For this purpose, a modified differential protection scheme is used.



2. Biased Differential scheme (Merz-Price Scheme)

Percentage differential relay consists restraining coil for overcoming the trouble arising out of differences in the current ratio for the high value of an external short circuit current. Percentage differential system consists of a restraining coil connected in the pilot wire as shown in the figure below and the current induced in both the CTs flows through it. The operating coil places between the midpoint of the restraining coil.

The restraining coil controls the sensitive characteristic of the relay. It restricts the unwanted tripping of the transformer due to the imbalance current. The restraining coil also restrains the harmonics in the inrush current.



Biased Differential scheme (Merz-Price Scheme) for protection of Generators

This is most commonly used protection scheme for the alternator stator windings. The scheme is also called biased differential protection and percentage differential protection. The figure below shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator

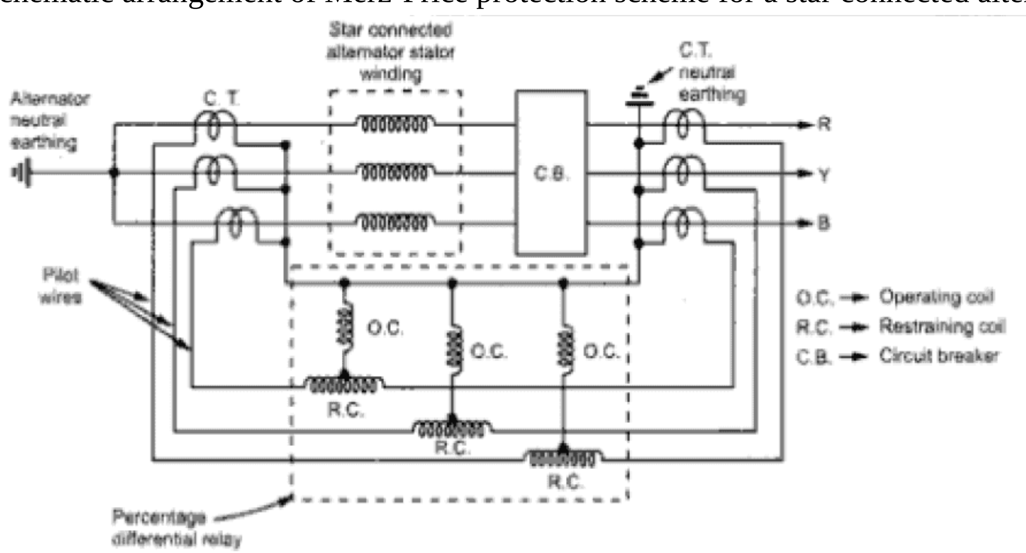


Fig: Merz-Price Protection Scheme for a Star Connected Alternator

The differential relay gives protection against short circuit fault in the stator winding of a generator. When the neutral point of the windings is available then, the C.T.s may be connected in star on both the phase outgoing side and the neutral earth side, as shown in the above figure. But, if the neutral point is not available, then the phase side CTs are connected in a residual connection, so that it can be made suitable for comparing the current with the generator ground

point CT secondary current. The restraining coils are energized from the secondary connection of C.T.s in each phase, through pilot wires. The operating coils are energized by the tappings from restraining coils and the C.T. neutral earthing connection.
The similar arrangement is used for delta connected alternator stator winding, as shown below.

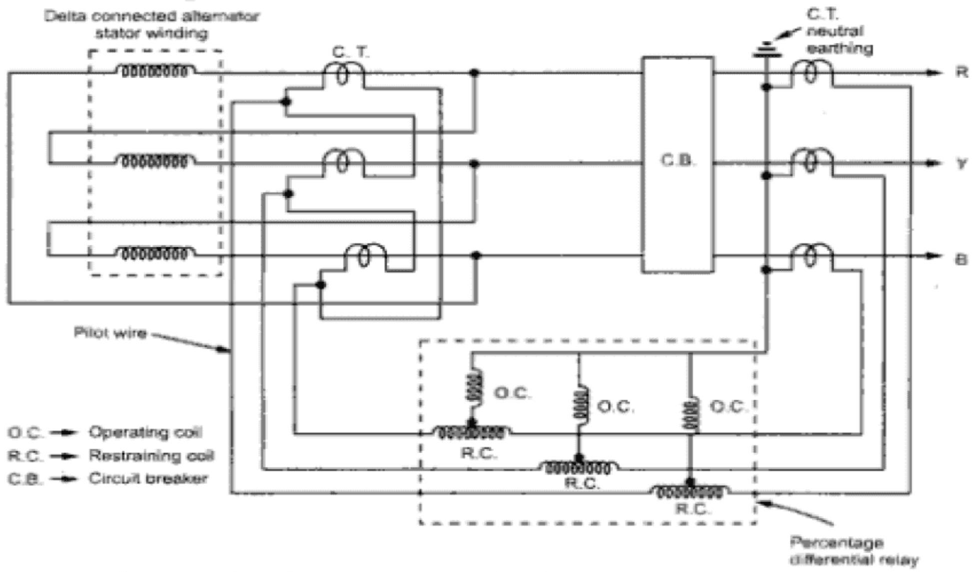


Fig: Merz-Price Protection Scheme for a Delta Connected Alternator

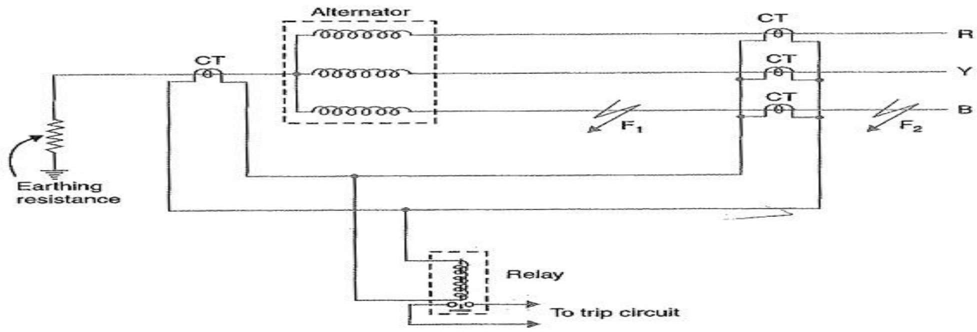
This scheme provides very fast protection to the stator winding against phase-to-phase faults and phase to ground faults. If the neutral is not grounded or grounded through resistance, then additional sensitive earth fault relay should be provided.

The advantages of this scheme are,

- Very high-speed operation with operating time of about 15 msec.
- It allows low fault setting which ensures maximum protection of machine windings.
- It ensures complete stability under most severe through and external faults.
- It does not require current transformers with air gaps or special balancing features.

Balanced 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.



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 transformers secondaries. The protection against earth faults is limited to the region between the neutral and the line current transformers.

Working

When there is normal operating condition, the currents flowing in the alternators leads and hence the current flowing in the secondary of neutral current transformer supplies no current to 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** occurs at F_2 outside to the protection zone, the sum of the currents at the terminals of the alternators is exactly equal to the current in the neutral connection and hence no current flows through the relay coil.

When an earth-fault occurs at F_1 or within the protected zone, the currents are no longer equal and the differential current flows through the operating coil of the relay. The relay is thus energised and closes the trip coil circuit and our system is protected..

Methods of Ground fault protection

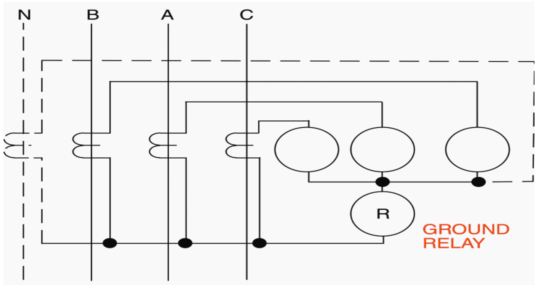
Ground-fault protection to prevent excessive damage to electrical equipment with current sensitivity in the order of amperes to hundreds of amperes. Faults involving just one of the phase conductor and ground are called Ground Faults. Faults involving two or more phase conductors, with or without ground, are called Phase Faults.

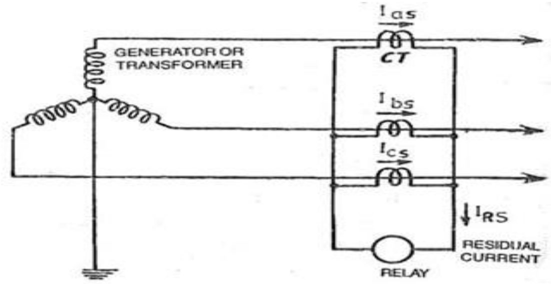
Methods of ground-fault detection:

a) Residually connected overcurrent relays
b) Core balance
c) Ground-return

1. Residually connected overcurrent relays

The actual ground current is measured by CTs that are interconnected in such a way that the ground relay responds to a current proportional to the ground-fault current. Each phase relay is connected in the output circuit of its respective CT, while a ground relay connected in the common or residual circuit measures the ground-fault current.





In three-phase three-wire systems, no current flows in the residual leg under normal conditions **because the resultant current of the three CTs is zero**. This situation is true for phase-to-phase short circuits also.

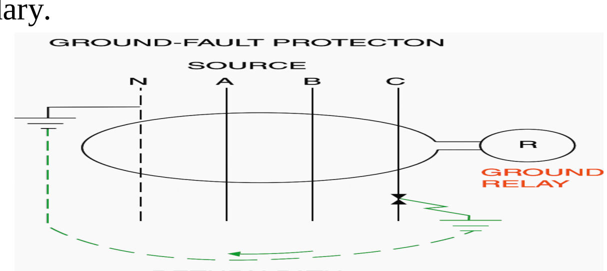
When a ground-fault occurs, the short-circuit current, returning through earth, bypasses the phase conductors and their CTs, and the resultant current flows in the residual leg and operates its relay. On four-wire circuits, a fourth CT should be connected in the neutral circuit as shown in the dashed portion of the current.

The selectivity is determined by the CT ratio and the relay pickup setting in which CT ratio must be high enough for normal load circuits. Also, the unbalanced primary currents in each phase, the sum of which may contain sufficient asymmetrical current to cause a trip during a motor start. For this reason, **sensitive ground-fault protection schemes do not use instantaneous trips when a residually connected circuit is involved**.

If ground-fault protection with greater sensitivity is needed, core-balance method should be considered.

2. **Core balance**

All load-carrying conductors pass through the same opening in the CT and are surrounded by the same magnetic core. Core-balance method is based on primary current phasor addition or flux summation. The remaining zero-sequence component, if any, is then transformed to the secondary.



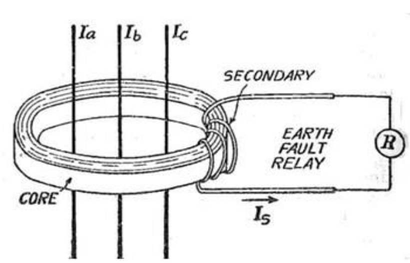


Figure – Core-balance CT encircling all phase and neutral conductors

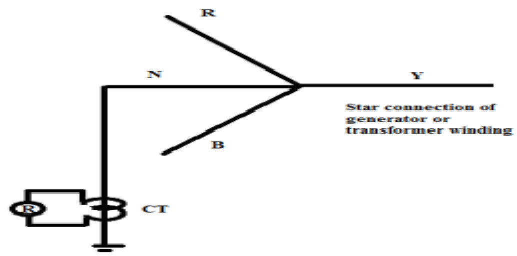
This method can be more sensitive than the residual method because the sensor rating is large enough for the possible imbalance, not for the individual conductor load current.

Under normal condition, all current flows out and returns through the CT. The net flux produced in the CT core is zero, and no current flows in the ground relay.

When a ground fault occurs, the ground-fault current returns through the equipment grounding circuit and bypasses the CT. The flux produced in the CT core is proportional to the ground-fault current, and a proportional current flows from the CT secondary to the relay circuit.

3. **Earth Lead Methods/Ground Return**

In this method, single current transformer is inserted in the neutral earth connection of a generator or transformer. Relay 'R' is connected to the secondary of the CT. In normal condition without any earth fault there will not be any flow of current in the neutral earth connection line, so that the relay will not operate. Whenever the earth fault occurs, a high fault current will flow in the ground through neutral earth connection and the grounded line. This will energize the relay to operate and subsequently operation of the breaker to isolate the fault.



Restricted and Unrestricted Earth Fault Protection

Ground fault protection for a power system network provides in two ways. They are

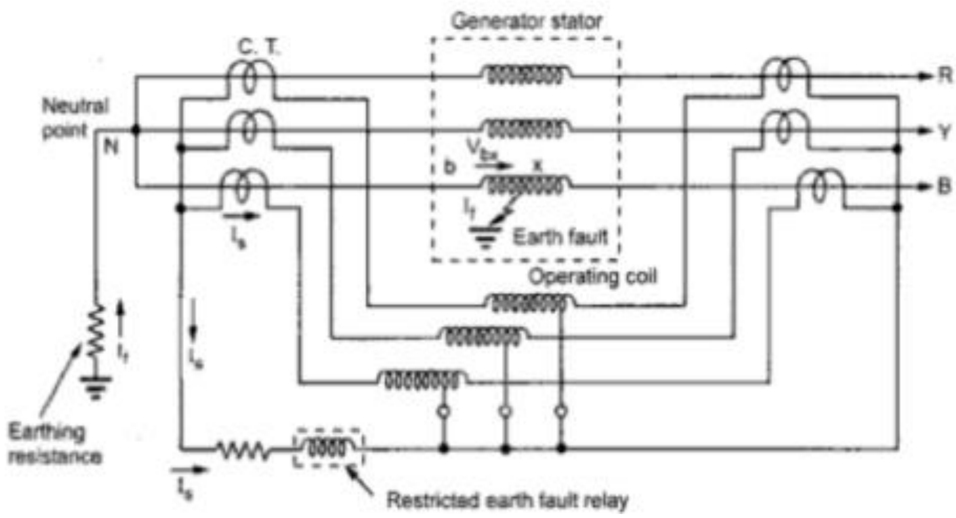
- Restricted Ground fault and
- Unrestricted Ground Fault Protection methods.

1. Restricted Earth Fault Protection of Generator

Generally, Merz-Price protection based on circulating current principle provides the protection against internal earth faults. But for large generators, as there are costly, an additional protection scheme called restricted earth fault protection is provided.

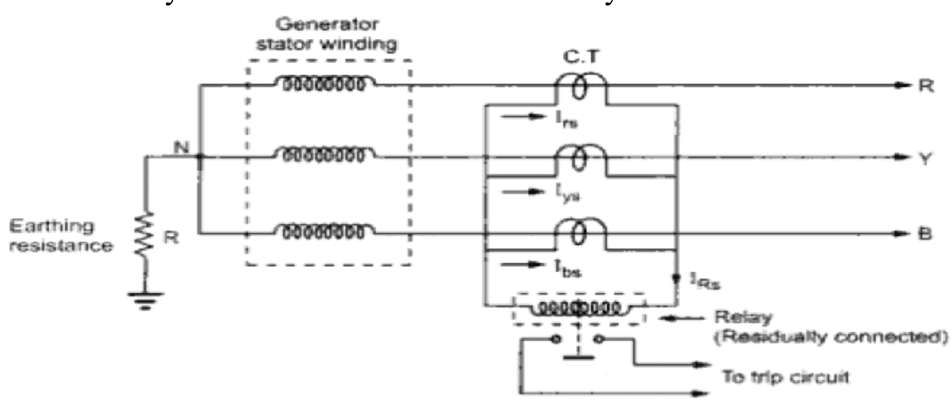
When the neutral is solidly grounded then theets completely protected against earth faults. But when neutral grounded through earth resistance, then the stator windings get partly protected against earth faults. The percentage of windings protected depends on the earthing resistance and the relay setting. In this scheme, the value of earth resistance, relay setting, current rating of earth resistance must carefully selected. The earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less. But when earth fault occurs near the neutral point then the insufficient voltage across the fault drivers very low fault current than the pick up current of relay coil. Hence the relay coil remains unprotected in this scheme. Hence it is called restricted earth fault protection. It is usual practice to protect 85% of the winding. The restricted earth fault protection scheme is shown in the Fig.

Consider earth fault occurs on phase B due to breakdown of its insulationto earth, as shown in Fig. The fault current If will flow through the core, frame of machine to earth and complete the path through the earthing resistance. The C.T. secondary current Is flows through operating coil and restricted earth fault relay coil of the differential protection.



Unrestricted Earth Fault Relay:

Unrestricted earth fault protection is used to protect alternator winding from internal earth fault. It uses a residual connected earth fault relay. Unrestricted earth fault relay consists of three Current Transformer one in each phase. The primary of the current transformer is considered as line. The earth fault relay is connected across the secondary's which carries a residual current.



Principle of Unrestricted earth fault relay:

The vector sum of three-line current is equal to zero under normal condition. If the fault occurs in the generator, the relay reads the unbalance current in the system.

Under normal conditions the vector sum of the all current $\bar{I}rs + \bar{I}ys + \bar{I}bs = 0$. The earth fault relay is connected in such a way that the residual current flows through the relay operating coil. Under normal condition, residual current is zero so relay does not carry any current and is inoperative. However, in presence of earth fault condition, the balance gets disturbed and the residual current IRs is no more zero. If this current is more than the pickup value of the earth fault relay, the relay operates and opens the circuit breaker through tripping of the trip circuit. In the scheme shown in the figure, the earth fault at any location near or away from the location of C.T.s can cause the residual current. Hence the protected zone is not definite. Such a scheme is hence called unrestricted earth fault protection.

Numerical

1) **A generator is provided by restricted earth fault protection. The generator rating are 13.2kV, 10MVA. The percentage of winding protected against phase to ground fault is 85%. The relay setting is such that it trips for 20% out of balance. Calculate the resistance to be added in the neutral to ground connection.**

Solution,

Given, V_L = 13.2kV   Rating= 10MVA

From rating, calculating full load current,

$$I = \frac{Rating\ in\ VA}{\sqrt{3}\ VL} = \frac{10*10^6}{\sqrt{3}*13.2*10^3} = 437.386A$$

Relay setting is 20% out of balance i.e. 20% of the rated current activates the relay

Io = 4387.386 * 20/100 = 87.477 A

= Minimum operating current

Vph = $13.2*10^3/\sqrt{3}$ = 7621.02V

% of winding unprotected = 15% as 85% is protected

$$15 = \frac{R\ Io}{V} * 100$$

$$15 = \frac{R*87.477}{7621.02} * 100$$

R = 13.068 ohms

2) **A star connected 3 phase 12MVA 11kV alternator has a phase reactance of 10%. It is protected by Merz-Price circulating current scheme which is set to operate for fault current not less than 200A. Calculate the value of earthing resistance to be provided in order to ensure that only 15% of the alternator winding remains unprotected.**

Given, V_L = 11 kV   Rating= 12MVA

From rating, calculating full load current,

$$I_L = \frac{Rating\ in\ VA}{\sqrt{3}\ VL} = \frac{12*10^6}{\sqrt{3}*11*10^3} = 629.8366A$$

Vph = $11*10^3/\sqrt{3}$ = 6350.8529V

$$\%\ reactance = \frac{X\ I}{V} * 100$$

$$10 = \frac{X*629.8366}{6350.8529} * 100$$

X = 1.0083 ohms

So, reactance of unprotected winding = (% of unprotected winding) * X

= (15/100)*1.083 = 0.1512 ohms

V = voltage induced in unprotected winding = (15/100)*V = 0.15*6350.8529 = 952.6279

I = fault current = 200A

Z = impedance offered to the fault = (v/i) = 952.6279/200 = 4.7631 ohm …………….i)

Now, Z = r+j (reactance of unprotected winding)

Z= r+ j(0.1512) ohm ………………ii)

Equating i) and ii)

4.7631 = r+ j(0.1512

Squaring

$22.6875 = r^2 + 0.02286$

r = 4.7607 ohms

This is resistance required.

3) **The neutral point of a 11kV alternator is earthed through a resistance of 12 ohms, the relay is set to operate when there is out of a balance current of 0.8A. The CTs have the ratio of 200/5. What percentage of winding is protected against earth faults? What must be the minimum value of earthing resistance required to give 90% of protection to each phase?**

Soln,

Given, V_L = 11kV R=12 ohms CT ratio = 2000/5

io= relay current = 0.8A

Io = minimum operating line current (CT primary)

= io*200/5 = 0.8*2000/5 = 320A

Vph = Vph = $11*10^3/\sqrt{3}$ = 6350.8529V

% winding unprotected = $\frac{R\ Io}{V} * 100$

$= \frac{12 * 320}{6350.8529} * 100$ = 60.46%

% winding protected = 100-60.46% = 39.53%

Thus, with R= 12ohms only 39.53% winding is protected

It is necessary to give 90% protection

% winding unprotected = 100-90% = 10%

10% = $\frac{R\ Io}{V} * 100$

10 = $\frac{R*320}{6350.8529} * 100$ = 1.9846 ohms

This is the minimum value of resistance to give 90% protection to the largest machine

4) **A 50 MVA 3 phase 33kV synchronous generator is protected by merz price differential protection using 100/5 ratio CTs. It is provided with restricted earth fault protection with earthing resistance of 7.5 ohms. Calculate the percentage of winding unprotected in each phase against earth faults if the minimum operating time of relay is 0.5A.**

Soln,

Given, V_L= 33kV CT ratio=100/5 R=7.5ohms

Io = 0.5 A = relay current

Io = minimum operating current (primary) = ia * 1000/5 = (0.5*1000)/5 = 100A

Vph = $33*10^3/\sqrt{3}$ = 19052.55V

% winding unprotected = $\frac{R\ Io}{V} * 100$

$= \frac{7.5 * 100}{19052.55} * 100$ = 3.936%

5) A 13.2 kV 3 phase 100MW at 0.8 pf lag, alternator has reactance of 0.2pu. if it is equipped with a circulating current differential protection set to operate at least at 500A fault current, determine the magnitude of neutral grounding resistance that leaves the 10% of the winding unprotected.

Solution : The given values are,

$$V_L = 13.2 \text{ kV} \quad \cos\phi = 0.8 \quad P = 100 \text{ MW} \quad X = 0.2 \text{ p.u.}$$

Now $$P = \sqrt{3}\, V_L I_L \cos\phi$$

$\therefore$ $$100\times10^6 = \sqrt{3}\times 13.2\times 10^3 \times I_L \times 0.8$$

$\therefore$ $$I_L = 5467.33 \text{ A} = I = \text{full load current}$$

The p.u. reactance is given by,

$$\text{p.u. } X = \frac{IX}{V} \quad \text{where } X = \text{reactance per phase}$$

$\therefore$ $$0.2 = \frac{5467.33\,X}{\left(\frac{13.2\times10^3}{\sqrt{3}}\right)} \quad \text{where } V = \frac{V_L}{\sqrt{3}}$$

$\therefore$ $$X = 0.2787\ \Omega \text{ per phase}$$

% of unprotected winding = 10%

$\therefore$ Reactance of unprotected winding $= \frac{10}{100}\times 0.2787$

$$= 0.02787\ \Omega$$

Voltage induced in 10% of unprotected winding

$$= \frac{10}{100}\times V = \frac{10}{100}\times\frac{13.2\times10^3}{\sqrt{3}} = 762.1023 \text{ V}$$

Let this voltage be $v = 762.1023$ V

$$Z = \sqrt{r^2 + x^2}$$

where Z = Impedance offered to the fault

r = Resistance in neutral

x = Reactance of 10% of winding

Now $$Z = \frac{v}{i}$$

where v = Voltage induced in 10% winding

$= 762.1023$ V

i = Fault current = 500 A

$\therefore$ $$\sqrt{r^2 + x^2} = \frac{762.1023}{500}$$

$\therefore$ $$\sqrt{r^2 + (0.02787)^2} = 1.5242$$

$\therefore$ $$r^2 + (0.02787)^2 = 2.3232$$

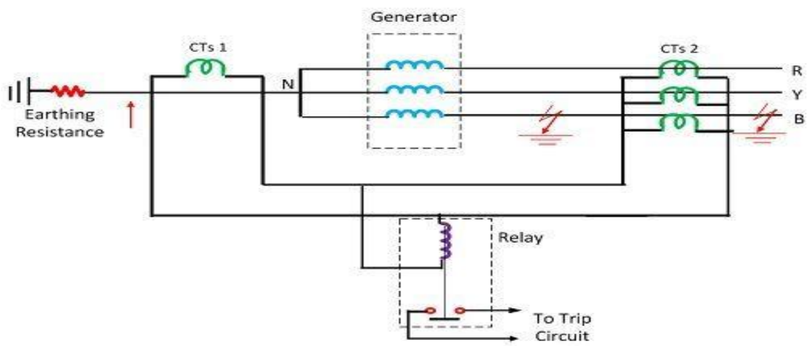
$\therefore$ $$r^2 = 2.3224$$

$\therefore$ $$r = 1.524\ \Omega$$

This is the required resistance in neutral earthing.

Balanced Earth Fault Protection

The balanced earth fault protection scheme is mainly used for protection of small generator where differential and self-balanced protection systems are not applicable. In a small generator, the neutral end of the three phase windings is connected internally to a single terminal. So the neutral end is not available, and protection against earth fault is provided by using the balanced earth protection scheme. Such scheme does not provide protection against phase-to-phase fault until and unless they develop into earth faults.



The balanced protection schemes provide protection against earth fault in the limited region between the neutral and line CTs (current transformers). It provides protection against the stator winding of the earth fault in the stator and does not operate in case of an external earth fault. This scheme is also called restricted earth fault protection scheme. Such type of protection is provided in the large generator as an additional protection scheme.

Working of Balanced Earth Fault Protection Scheme

When the generator is in a normal operating condition the sum of the currents flow in the secondary of the current transformers is zero and the current flow into secondary to neutral is also zero. Thus the relay remains de-energized.

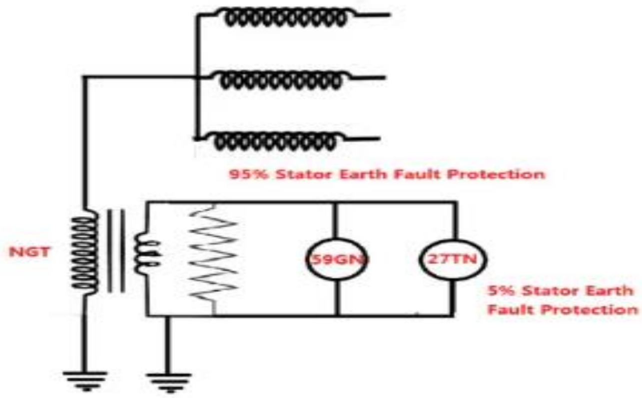
When the fault occurs in the protected zone (left of the line) the fault current flow through the primary of current transformers and the corresponding secondary current flow through the relay which trips the circuit breaker.

When the fault develops external of the protective zone (right of the current transformer) the sum of the currents at the terminal of the generator is exactly equal to the current in the neutral connection. Hence, no current flows through the relay operating coil.

100% stator Earth Fault protection

100% stator earth fault protection work as back up protection of the alternator. Most commonly the generator neutral is earthen with the NGR Neutral grounding resistor. Here during normal condition, The current through the NGR will normally be 5 – 10 A (depending upon rating and resistance value) when subjected to the rated phase to earth voltage. Here the generators with step-up transformer, a neutral point voltage relay (27TN/59N) with typical setting 5 % of generator phase voltage will provide earth-fault protection for 95 % of the stator winding.

If the earth-fault nearer to the neutral point of the generator will not give sufficient neutral point voltage to activate the neutral point voltage (95 %) relay. Therefore, additional protection methods are used to provide a 100% stator ground fault protection. Special protection systems based on the third harmonic analysis and on the sub harmonic voltage injection can detect stator ground faults close to the neutral. These protection methods are strongly recommended for large generators since the entire stator winding must be protected.



Remaining 5% Stator Earth fault protection:

Normally, the Generator produces about 1 % or more third harmonic voltage under all service conditions, can have the entire stator winding, including the neutral point, protected using a scheme which combines the neutral point voltage function (95 % relay) and a third harmonic under voltage function. Under normal condition, typically 40 – 60 % of the generated third harmonic phase voltage will appear across the neutral point resistor and will activate the third harmonic voltage relay. If an earth-fault occurs close to the neutral point, the third harmonic voltage drops to a low value and the under voltage relay operates. Hence the remaining position of the generator windings is being covered.

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. The inter-turn faults i.e., the fault between the turns of the same winding of the stator cause to flow of a circulating current through the winding turns undergoing the fault. So, it does not produce any imbalance between the currents entering and leaving the winding where the two CTs are located. Hence, the differential protection scheme does not respond to the inter-turn faults.

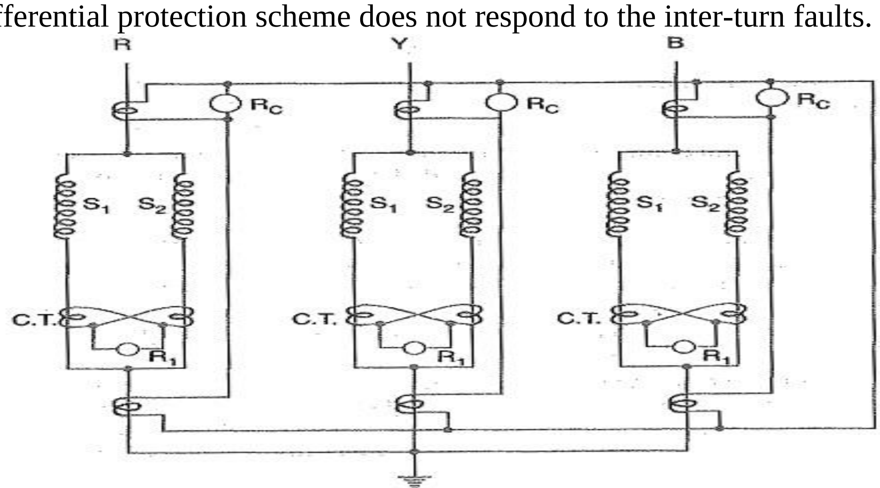


Fig shows the schematic arrangement of circulating-current and inter-turn protection of a 3-phase double wound generator. The relays R_C provide protection against phase-to-ground and phase-to-phase faults whereas relays R_1 provide protection against inter-turn faults.
Under normal conditions, the currents in the stator windings S_1 and S_2 are equal and so will be the currents in the secondary's of the two CTs. The secondary current round the loop then is the same at all points and no current flows through the relay R_1.
If a short-circuit develops between adjacent turns, say on S_1, the currents in the stator windings S_1 and S_2 will no longer be equal. Therefore, unequal currents will be induced in the secondary's of CTs and the difference of these two currents flows through the relay R_1. The relay then closes its contacts to clear the generator from the system.

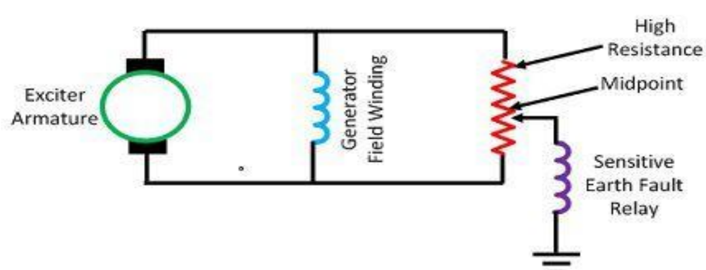
Rotor Earth Fault

Rotor earth fault relay 64R which is used to protect the generator or alternator rotor against earth fault (the short circuit between rotor's winding to ground). It senses the alternator's rotor earth leakage current.

Methods of Rotor Earth Fault Protection

- **Rotor Earth Fault Protection By Using High Resistance**

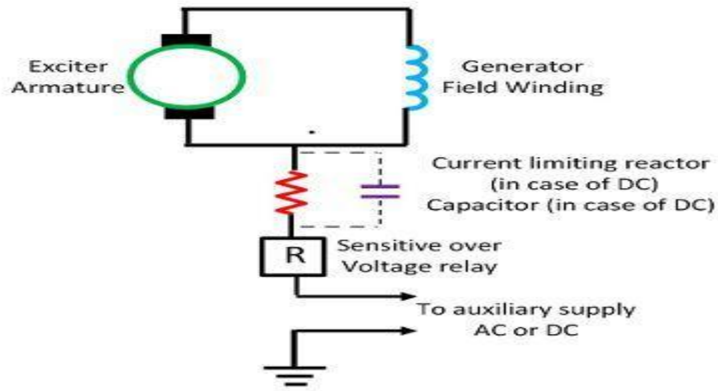
In this method, a high resistance is connected across the field winding of the rotor. The midpoint of the resistor is grounded through a sensitive relay. When the fault occurs the relay detect the fault and send the tripping command to the breaker.
The major disadvantage of such type of system it that it can detect the fault for most of the rotor circuit except the rotor centre point. This difficulty can be overcome by shifting the tap on the resistor from centre to somewhere else. Thus, the relay can detect the midpoint fault of the rotor.



- **AC and DC Injection Methods for Rotor Earth Fault Protection**

In this method, alternating current is injected into the field winding circuit and ground along with a sensitive overvoltage relay and a current limiting capacitor. A single earth fault in the rotor will complete the circuit comprises the alternating current source, sensitive relay and earth fault. Thus, the earth fault is sensed by the relay.
In normal conditions, the system is in a floating state, the device has a high resistance, and the current flowing through the device is zero. A single earth fault in the rotor circuit completes the circuit comprising the voltage source, sensitive overvoltage relay, and the earth fault and thus the earth fault will be sensed by the relay.

The major disadvantage of such type of system is the leakage current that flows through the capacitor. This current unbalanced the magnetic field and increases the stress on the magnetic bearing. Another disadvantage of alternating current is that the relay cannot pick up the current that normally flow through the capacitance to the ground. Thus, the care must be taken to avoid resonance between the capacitance and the relay inductance.



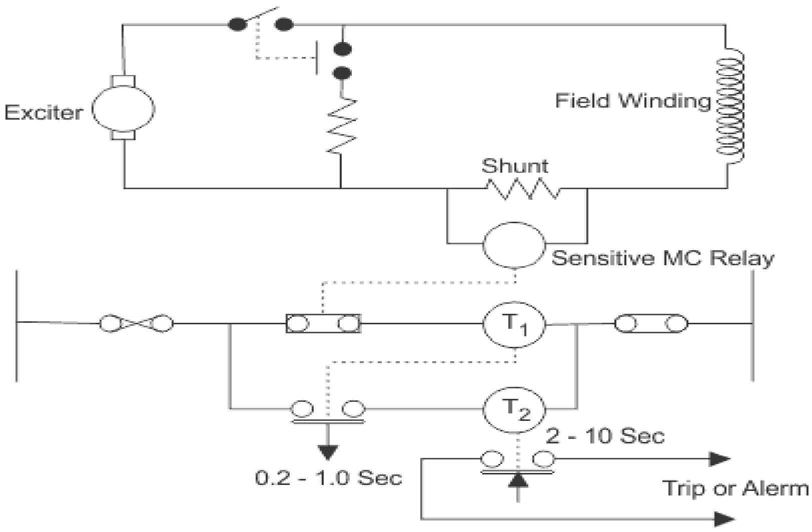
The problem of the AC injection system can be overcome by using the DC injection method. This method is simple and has no problem of leakage currents. The one terminal of the sensitive relay is connected to the exciter, and the other terminal is connected to the negative terminal of the DC source. The positive terminal of the DC source is grounded. When the earth fault occurs, the fault current will complete the circuit path, and the fault is sensed by the relay.

Loss of Excitation Protection

Loss of field or excitation can be caused in the generator due to excitation failure. Failure of excitation that is failure of field system in the generator makes the generator run at a speed above the synchronous speed and results in loss of synchronism between rotor flux & stator flux (the generator still in online with the grid). In that situation the generator or alternator becomes an induction machine which draws magnetizing current from the system. The generator works as an induction motor at higher speed and draws reactive power from the grid. This will result in the flow of slip frequency currents in the rotor body as well as severe torque oscillations in the rotor shaft. As the rotor is not designed to sustain such currents or to withstand the high alternating torques which results in rotor overheating, coupling slippage and even rotor failure.

The schemes available for protection against loss of field or excitation of a generator,

we use an undercurrent relay connected in shunt with main field winding circuit. This relay will operate if the excitation current comes below its predetermined value. If the relay is to operate for complete loss of field along, it must have a setting lies well below the minimum excitation current value which can be 8% of the rated full load current. Again when loss of field occurs due to failure of exciter but not due to problem in the field circuit (field circuit remains intact) there will be an induced current at slip frequency in the field circuit. This situation makes the relay to pick up and drop off as per slip frequency of the induced current in the field. This problem can be overcome in the following manner.



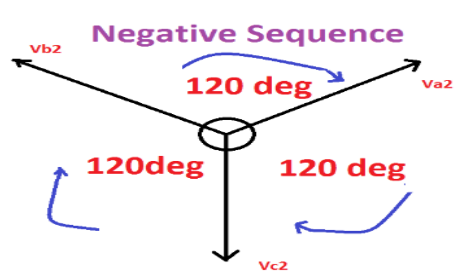
In this case a setting of 5% of normal of full load current is recommended. There is a normally closed contact attached with the undercurrent relay. This normally closed contact remains open as the relay coil is energized by shunted excitation current during normal operation of the excitation system. As soon as there is any failure of excitation system, the relay coil becomes de-energized and the normally closed contact closes the supply across the coil of timing relay T_1.

Negative Sequence Relay

A relay which protects the electrical system from negative sequence component is called a negative sequence relay or unbalance phase relay. The negative sequence relay protects the generator and motor from the unbalanced load which mainly occurs because of the phase-to-phase faults.

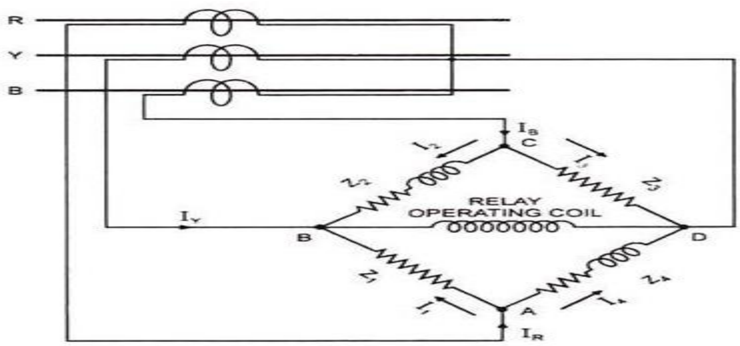
Negative Sequence Relay Operation:

What is negative sequence. Negative sequence is a balanced 3-phase system with the opposite phase sequence as the original sequence which means the set of the three pharos are equal in magnitude, spaced 120° apart from each other & having the phase sequence opposite to that of the original pharos.



Symmetrical Components Negative Sequence

Under the balanced condition, the generator gives equal currents in all the 3-phase either star connected or delta connected loads. Here the vector sum of the negative sequence current is 0, hence net unbalance current is 0 here, The unbalance may occur due to the circuit breaker operation, circuit breaker failures or system faults. Hence the negative sequence current starts flowing through the stator winding, which creates additional flux in the air gap which rotates in the opposite direction to that of the rotor synchronous speed. This flux induces currents in the rotor body, retaining rings at twice the line frequency. Due to this, the rotor body temperature starts increasing. But if the magnitude of these negative sequence current is high, then this opposite direction potentially affects the normal operating direction of turbine. It leads to significant damage to the generator set.



Negative Phase Sequence Relay

Generally, negative sequence relays are having two stage of tripping. The first stage tripping is given to the grid circuit breaker as the grid is infinite loads, the second stage of tripping will be given to the generator circuit breaker.

Problems

Q) The neutral of the three phase 20 MVA, 11kV alternator is earthed through a resistance of 5 ohms, the relay is set to operate when there is an out of balance current of 1.5 A. The CTs have a ratio of 100/5. What percentage of the winding is protected against earth faults?

Soln, The primary CT current for the relay operation = 1.5*1000/5 = 300 A

% winding unprotected = (Is*RV* 100%)

$$= \frac{300 * 5\sqrt{3}}{11000} * 100$$

$$= 23.6\ \%$$

% winding protected = 100-23.6 = 76.4 %

Q) The neutral of the three phase 20 MVA, 11kV alternator is earthed through a resistance of 5 ohms, the relay is set to operate when there is an out of balance current of 1.5 A. The CTs have a ratio of 100/5. What percentage of the winding is protected against L-G faults?

Soln, The primary CT current for the relay operation = 1.5*1000/5 = 300 A

% winding unprotected = (Is*RV*100%)

= (300*5√3)/11000*100

= 23.6 %.

Q) The neutral of the three phase 20 MVA, 11kV alternator is earthed through a resistance of 5 ohms, the relay is set to operate when there is an out of balance current of 1.5 A. The CTs have a ratio of 100/5. What should be the minimum value of the earthing resistance to protect 90% of winding?

SOLN, % winding protected = 76.4 %

resistance required to protect 90% of the winding

10 = Is*RV*100

R = 2.12 Ω.

➡ **Example** : *An alternator stator winding protected by a percentage differential relay is shown in the Fig. – . The relay has 15% slope of characteristics ($I_1 - I_2$) against ($I_1 + I_2/2$). The high resistance ground fault has occurred near the grounded neutral end of the generator winding while the generator is carrying load. The currents flowing at each end of the generator winding are also shown. Assuming C.T. ratio to be 500/5 A, will the relay operate to trip the circuit breaker ?*

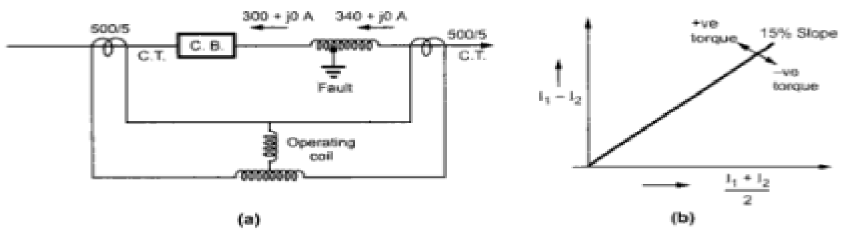


Fig.

Solution : From the given current at two ends, let us calculate C.T. secondary currents at two ends,

$$\therefore \qquad i_1 = (300 + j\,0) \times \frac{5}{500} = 3 \text{ A}$$

and

$$i_2 = (340 + j\,0) \times \frac{5}{500} = 3.4 \text{ A}$$

The directions of currents are shown in the Fig.

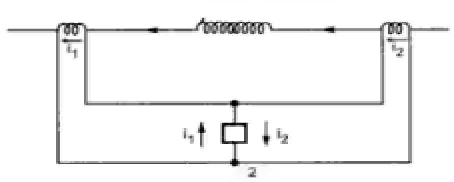


Fig.

The current flowing through the relay coil is $i_1 - i_2$.

$$\therefore \qquad i_1 - i_2 = 3 - 3.4 = -0.4 \text{ A}$$

While

$$\frac{i_1 + i_2}{2} = \frac{3 + 3.4}{2} = 3.2 \text{ A}$$

From the characteristics of 15 % slope, corresponding to $\frac{i_1 + i_2}{2}$ the out of balance current required is,

$$i_1 - i_2 = \text{Slope} \times \left(\frac{i_1 + i_2}{2}\right)$$

$$= 0.15 \times 3.2$$

$$= 0.48 \text{ A}$$

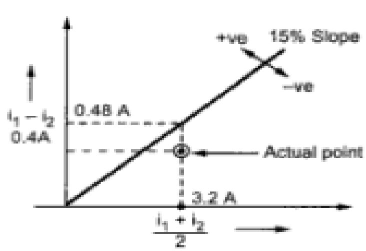


Fig. 5.

This is shown in the Fig. 5.29.

Thus $i_1 - i_2$ must be more than 0.48 A i.e. above the line to operate the relay but actual point is located below the line in negative torque region.

Hence the **relay will not operate.**

Bus-Bar Protection

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.

Desirable Features of Busbar Protection :

The following are the desirable features for a bus bar protection scheme.

Stability: Even for high faults, the bus bar protection should be stable i.e., during the faulty period, the faulty section must be disconnected or it should not operate.

Speed: Whenever high faults or external faults occur then the protection system should get tripped quickly. Typically, the maximum fault clearing time is 100 ms. But with the help of fast breakers, the clearing time is reduced to 20 to 30 ms.

Trip circuit: Each circuit breaker should have a separate trip circuit, so that, if a fault occurs at or nearer to any of the circuit breakers then that particular circuit breaker is only tripped.

In case, if there occurs any mal-operation due to power swings or due to current transformer saturation then, during this period there should not be any operation.

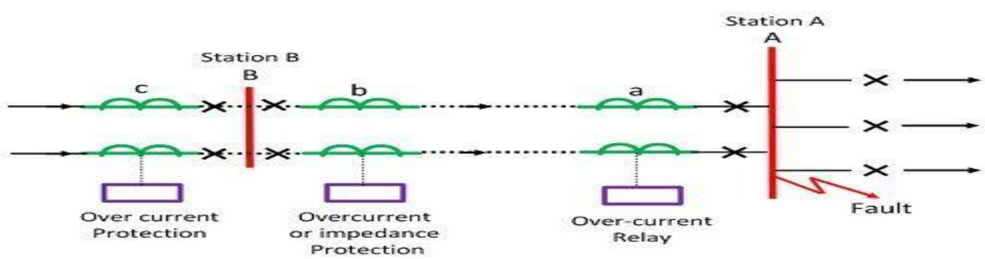
Reduce the interruption of supply: The protection system should correctly identify the area of faults and should be able to open only necessary & minimum number of circuit breakers.

The most commonly used schemes for bus zone protection are:

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

Backup Protection for Bus-Bars

The backup protection is provided to the supply system. The figure below shows the simple arrangement for the protection of bus-bar. The bus A is protected by the distance protection of the bus B. If the fault occurs on A, then the B will operate. The operating times of the relay will be 0.4 seconds.

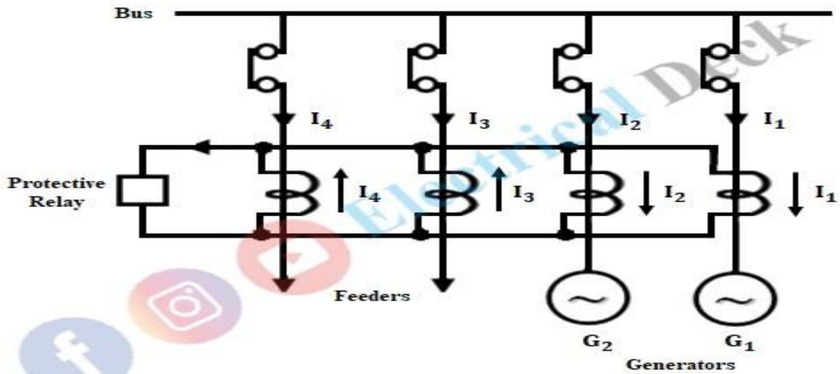


The bus-bar protection system has few disadvantages likes the protection system is slow. Such system is mainly used for the protection of the transmission lines. But as the protection system is very economical, thereby it is also used for the bus-bar protection.
This protective scheme is not used for small switchgear system. The backup protection system has many disadvantages likes delayed in action, disconnections of more circuits for two or more transmission line requires etc.

Differential Overcurrent Protection

- **Current Differential Protection** :

The differential scheme of busbar protection is based on principle of Kirchhoff's current law. According to the principle, under normal working conditions or external fault conditions, the vector sum of currents entering and leaving the bus zone will be equal to zero *i.e.,* $I_1 + I_2 + I_3 + I_4 = 0$. Thus no current flows through the protective relay and will remain inoperative.



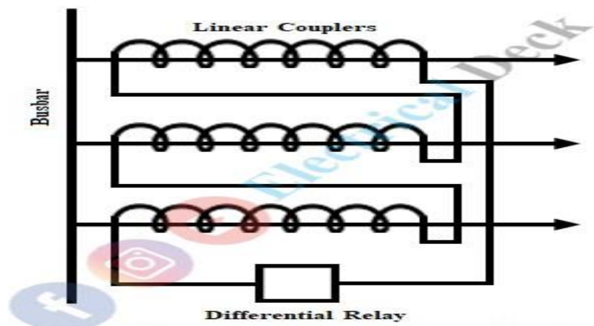
Current Differential Protection of Busbar

A current in the relay indicates a fault i.e. when a fault occurs in the protected zone, the currents entering and leaving the busbar will no longer be the same. Therefore, the difference between the currents entering and leaving will flow through the protective relay and initiate the opening of the circuit breaker of each generator and feeder. When there is a fault in the protected section, the vector sum of currents in the circuit connected to the busbar is equal to the fault current.
i.e., $I_1 + I_2 + I_3 + I_4 = I_f$
The **main disadvantage** of this type of protection is that there will be chances of relay operation during external fault conditions also. This is due to the saturation of one of the CT of the faulted feeder which causes a differential current to flow through the relay. This flow of current initiates the operation of the relay.
There are certain methods available to overcome the drawbacks of current differential protection.

- Using identical current transformers having large iron cores to avoid saturation with maximum fault currents. This method is not applicable because the dc transient component presents difficulties due to its slow decaying nature.
- Using high impedance relay in place of normal low impedance relay. Because a high impedance relay has the capability to discriminate between the internal and external faults better than the low impedance relay. The ratio of relay current during internal fault to relay current during external fault is proportional to the value of the impedance of the relay. For relays of higher impedance value, the ratio is higher.

- Using current transformers with no iron cores are known as linear couplers. This method of protection is known as voltage differential protection which is discussed below.

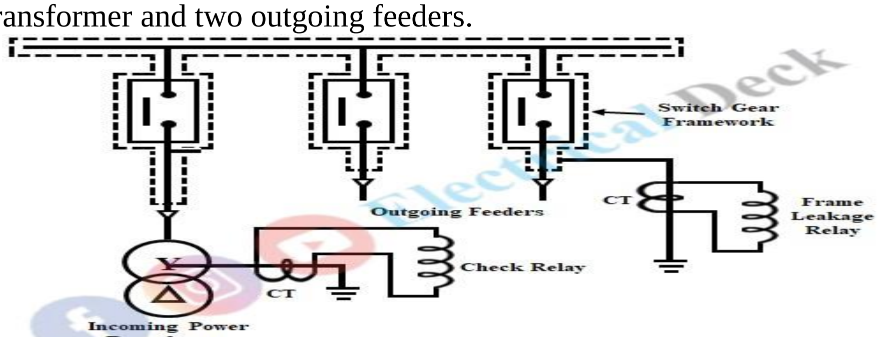
Voltage Differential Protection:
Voltage differential protection is a high-speed form of protection employed to overcome the drawbacks of current differential protection. A special type of current transformers known as linear couplers is used. In linear couplers, there is no iron core and the number of secondary windings is much greater than in the iron core current transformer. The secondary voltage in a linear coupler is proportional to the primary current. The schematic diagram of voltage differential protection for busbars is shown below.



Under normal operating conditions or under the conditions of an external fault, the voltages in the secondary windings add up to zero. Hence, no current flows through the secondary windings and the operating relay.
Under the condition of occurrence of a fault within the busbar zone, there is a resultant voltage in the secondary circuit which results in the flow of current through the secondary winding and the operating relay initiating the operation of the relay to isolate the fault.

Frame Leakage Protection :

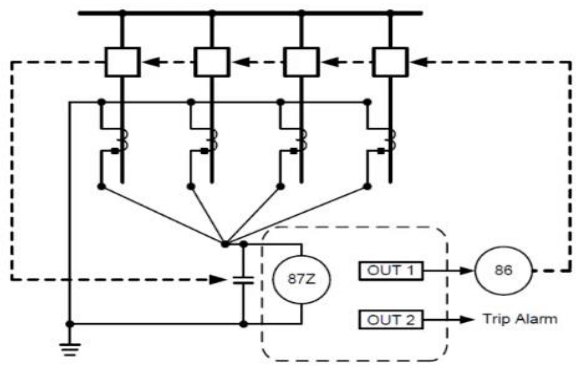
Almost all the protection schemes employed for the busbars are designed such that the faults occurred will result in an earth fault. This can be achieved by providing an earthed metal barrier surrounding each bus supporting structure and switchgear from the earth. So that the faults that occur must involve a connection between a conductor and an earthed metal part.
Frame leakage protection is normally applied to small-sized metal-clad switchgear units. The switchgear frame is lightly insulated from its adjacent earthed structural steelwork for this scheme of protection. The below shows the schematic arrangement in the case of a station having an incoming transformer and two outgoing feeders.



As seen from the figure, the switchgear framework is connected to the station main earth through the primary of a CT The secondary of the CT is connected to a sensitive frame leakage relay. In the event of an earth fault, currents flowing in the switchgear framework and relay will operate. The check relay is an earth-fault relay energized from a CT mounted in the incoming transformer neutral earth connection. The contacts of the check relay and frame earth leakage relay are in series so that two independent relays must operate before the trip circuit is completed.

High Impedance Bus Differential

Where the differential protection relay coil operates in high voltage with low current such relay is called high impedance differential protection relay.



High-impedance bus differential relays are applied to the paralleled output of all CTs from each phase connected to a common bus. As the name implies, the high-impedance bus differential relay presents very high impedance to the flow of current.

To establish high impedance differential protection, we should satisfy some important conditions. Let see..

- The parallel CT must have same CT ratio
- The CTs must be connected in same polarity
- Burden of the all parallel CTs should be same to avoid the voltage, drop across the CT
- CT accuracy should be same
- CT should not be shared with other circuit's equipments
- The connection configuration should be as follow.

From the circuit Any current difference is forced through the high impedance of the bus differential relay causing a voltage drop across the relay. The high-impedance relay, which is calibrated and set to trip based on the voltage across the relay, is extremely sensitive to CT difference current. For this reason, not only must the CT ratios match, but the CT accuracy ratings must also match to minimize the CT performance differences that could create CT difference current.

FEEDER AND TRANSMISSION LINE PROTECTION

The word FEEDER may be referred as the connecting link between the two circuits. The feeder could be in the form of transmission line that is short, medium, or long or this could be a distribution circuit. ¬ Feeders form the integral part of power system, as power is transferred through feeders from source to load. Hence it is important to protect feeders from faults for continuous supply of power to consumers.

The main requirement of the feeder protection are;

1. During the short circuit, the circuit breaker nearest to the fault should open and all other circuit breakers remain in a closed position.
2. If the breaker nearest to the fault fails to open then, backup protection should be provided by the adjacent circuit breaker.
3. The relay operating time should be small to maintain the system stability without necessary tripping of a circuit.

Methods of protection of feeder

1. Non-Unit Type Protection:

i. Time-graded over-current protection

ii. Current-graded over current protection

iii. Distance protection

2. Unit Type Protection:

i. Pilot-Wire Differential protection

ii. Carrier-current protection based on phase comparison method etc

Separate protection systems are necessary for ground faults because ground faults are more frequent on overhead transmission lines than phase fault, and ground fault current is different from phase fault current in magnitude.

The selection of a particular scheme of protection depends upon the following factors:

1. Economic justifiability of the scheme to ensure 100% continuity of supply.
2. Types of feeders-radial or ring mains.
3. Availability of pilot wires.
4. Number of switching stations in series between supply end and the far end of the system.
5. System earthing-whether the neutral is grounded or insulated.

i. Time Graded Protection

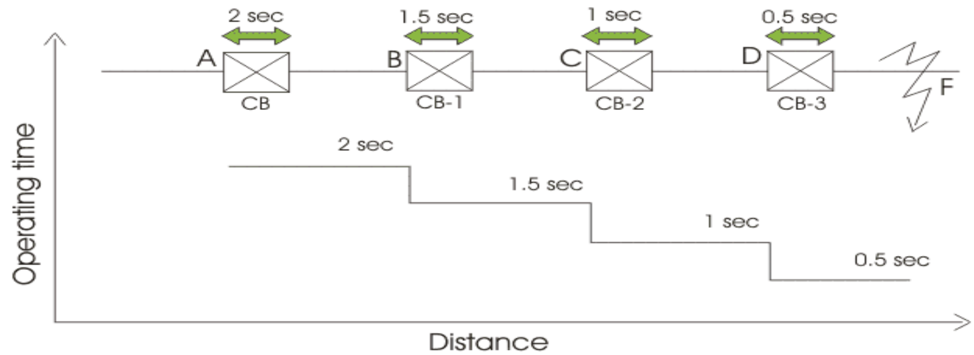
This may also be referred simply as over-current protection of electrical power transmission line. This is a scheme in which the time setting of relays is so consecutive that in the event of a fault, the smallest possible part of the system is isolated. The applications of time graded are explained below.

a. Protection of Radial Feeder

In radial feeder, the power flows in one direction only, which is from source to load. This type of feeders can easily be protected by using either **definite time relays or inverse time relays.**

Line Protection by Definite Time Relay

This protection scheme is very simple. Here total line is divided into different sections and each section is provided with definite time relay. The relay nearest to the end of the line has minimum time setting while time setting of other relays successively increased, towards the source.
For example, suppose there is a source at point A, in the figure below



- At point D the circuit breaker CB-3 is installed with definite time of relay operation 0.5 sec. Successively, at point C another circuit breaker CB-2 is installed with definite time of relay operation 1 sec. The next circuit breaker CB-1 is installed at point B which is nearest of the point A. At point B, the relay is set at time of operation 1.5 sec.
- Now, assume a fault occurs at point F. Due to this fault, the faulty current flow through all the current transformers or CTs connected in the line. But as the time of operation of relay at point D is minimum the CB-3, associated with this relay will trip first to isolate the faulty zone from rest part of the line.
- In case due to any reason, CB-3 fails to trip, then next higher timed relay will operate to initiate the associated CB to trip. In this case, CB-2 will trip. If CB-2 also fails to trip, then next circuit breaker i.e. CB-1 will trip to isolate major portion of the line.

Advantages of Definite Time Line Protection

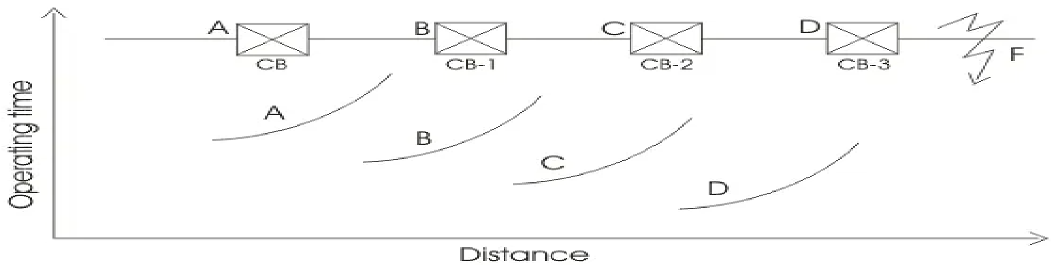
The main advantage of this scheme is simplicity. The second major advantage is, during fault, only nearest CB towards the source from fault point will operate to isolate the specific position of the line.

Disadvantage of Definite Time Line Protection

If the number of sections in the line is quite large, the time setting of relay nearest to the source would be very long. So during any fault nearer to the source will take much time to be isolated. This may cause severe destructive effect on the system.

Over Current Line Protection by Inverse Relay

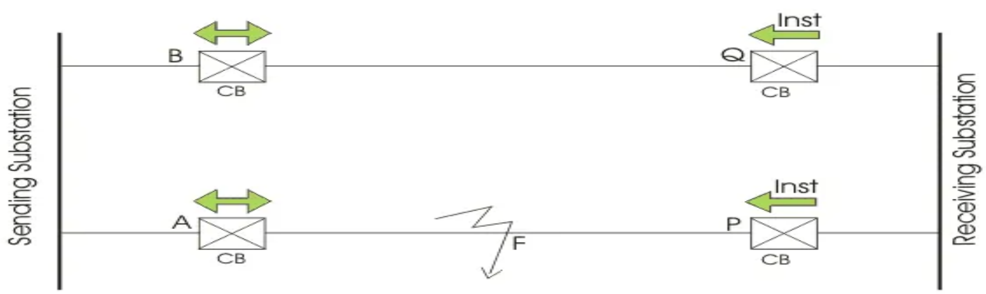
The drawback as we discussed just in definite time over current protection of transmission line, can easily be overcome by using inverse time relays. In inverse relay the time of operation is inversely proportional to fault current.



In the above figure, overall time setting of relay at point D is minimum and successively this time setting is increased for the relays associated with the points towards the point A. In case of any fault at point F will obviously trip CB-3 at point D. In failure of opening CB-3, CB-2 will be operated as overall time setting is higher in that relay at point C. Although, the time setting of relay nearest to the source is maximum but still it will trip in shorter period, if major fault occurs near the source, as the time of operation of relay is inversely proportional to faulty current.

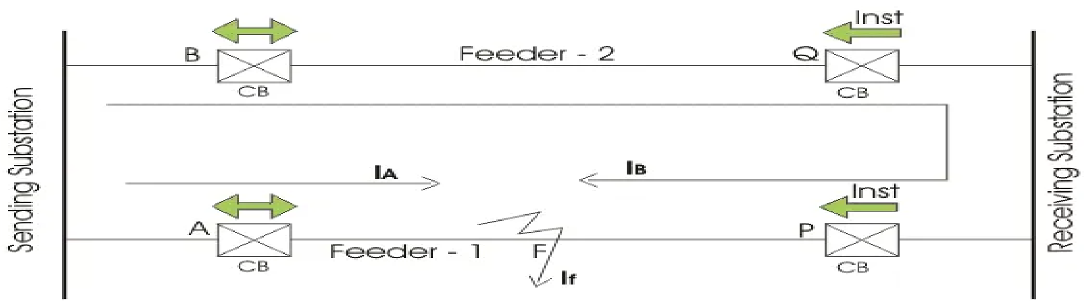
b. Protection of Parallel Feeders

For maintaining stability of the system, it is required to feed a load from source by two or more than two feeders in parallel. If fault occurs in any of the feeders, only that faulty feeder should be isolated from the system in order to maintain continuity of supply from source to load. This requirement makes the protection of parallel feeders' little bit more complex than simple non direction over current protection of line as in the case of radial feeders. The protection of parallel feeder requires to use directional relays and to grade the time setting of relay for selective tripping.



There are two feeders connected in parallel from source to load. Both of the feeders have non-directional over current relay at source end. These relays should be inverse time relay. Also, both of the feeders have directional relay or reverse power relay at their load end. The reverse power relays used here should be instantaneous type. That means these relays should be operated as soon as flow of power in the feeder is reversed. The normal direction of power is from source to load.

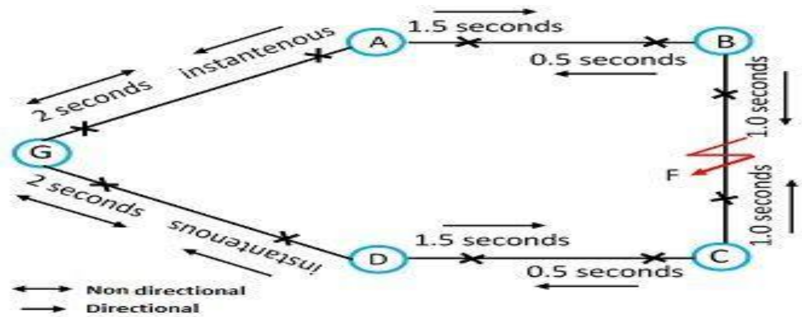
Now, suppose a fault occurs at point F, say the fault current is I_f. This fault will get two parallel paths from source, one through circuit breaker. A only and other via CB-B, feeder-2, CB-Q, load bus and CB-P. This is clearly shown in figure below, where I_A and I_B are current of fault shared by feeder-1 and feeder-2 respectively.



As per Kirchhoff's current law, $I_A + I_B = I_f$.
Now, I_A is flowing through CB-A, I_B is flowing through CB-P. As the direction of flow of CB-P is reversed it will trip instantly. But CB-Q will not trip as flow of current (power) in this circuit breaker is not reversed. As soon as CB-P is tripped, the fault current I_B stops flowing through feeder and hence there is no question of further operating of inverse time over current relay. I_A still continues to flow even CB-P is tripped. Then because of over current I_A, CB-A will trip. In this way the faulty feeder is isolated from system.

c. Protection of Ring Main System

The ring main is a system of interconnection between a series of the power station by a different route. In the main ring system, the direction of power can be changed at will, particularly when the interconnection is used.
The elementary diagram of such a system is shown in the figure below where G is the generating station, and A, B, C, and D are substation. At the generating station, the power flow only in one direction and hence no time lag overload relays is used. The time grade overload relay is placed at the end of the substation, and it will trip only when overload flows away from the substation which they protect.



Protection of Ring System

Going round the ring in the direction GABCD the relay on the further side of each station are set with decreasing time lags. At generating station 2 seconds at station A, B, C and 1.5 seconds, 1.0 second, 0.5 second and instantaneous respectively. Similarly going round the ring in the opposite direction the relay on the outgoing sides would be set as follows.
If the fault occurs at point F, the power F is fed into the fault through two paths ABF and DCF. The relay to operate is that between substation B and fault point F and substation C and fault point F. Thus, the fault on any section will cause the relay on that section to operate, and the healthy section will be operating uninterruptedly.

Drawbacks of time graded protection

- ➢ Time lag is provided which is not desirable on short circuits.
- ➢ Suitable for radial feeders with supply at one end only
- ➢ Difficult to coordinate and requires changes with addition of load.

ii. Current-Graded Protection of Transmission Lines:

As time graded system provides delay which is not required at high faulty currents, we use current graded system. ¬It cannot differentiate the zone in which fault occurred due to low difference in their magnitudes. ¬So, time graded IDMT relays are used along with current grading scheme to overcome the limitations.

An alternative to time grading or in addition to time grading current grading protection can be applied when the impedance between two substations is sufficient. It is based on the fact that the short-circuit current along the length of the protected circuit decreases with the increase in distance between the supply end and the fault point. If the relays are set to operate at a progressively higher current towards the supply end then the drawback of long time delays occurring in graded time lag system can be partially overcome. This is known as current grading. Current-graded systems normally employ high-speed high-set overcurrent relays.

A simple current-graded protection scheme applied to a radial feeder is shown in Fig. It consists of high-set overcurrent relays at A, B and C with settings such that relay at A would operate for faults between A and B, the relay at B for faults between B and C and the relay at C for faults beyond C. The current setting diminishes progressively from the supply end to the remote end of the line.

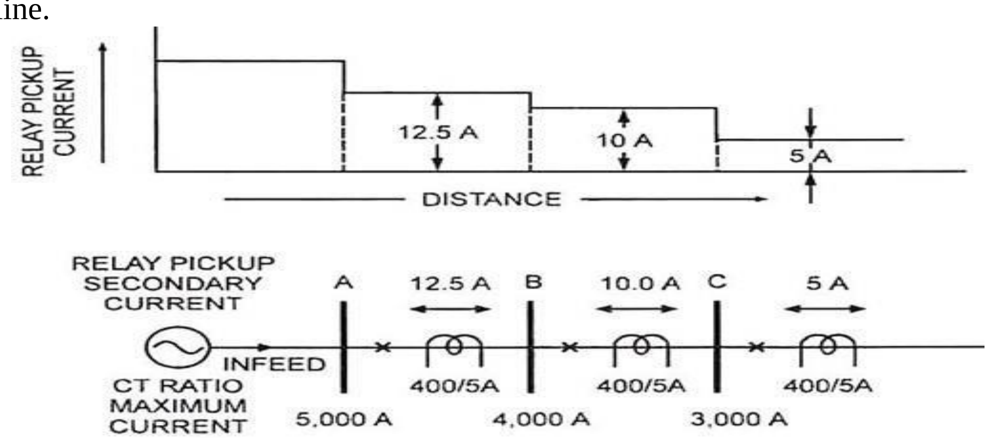


Fig. 5.8. ***Current-Graded Protection Applied To a Radial Feeder***

In practice, however, this protection scheme poses some difficulties which are given below:

- The relay cannot differentiate between faults which are very close to, but are on each side of B i.e., if a fault is very near to station B in section BC, the relay at A may feel that it is in section AB because there may be very little difference in the fault currents and the relays do not discriminate between the fault in the next section and the end of first section.

This is because:

(i) The difference in the fault currents would be extremely small,
(ii) The magnitude of fault currents cannot be accurately determined, and
(iii) The accuracy of the relays under transient conditions is likely to be different.
Hence for discrimination the relays are set to protect only part of the line, usually 80%. For this reason current grading alone cannot be employed and this protection system should be supplemented by time-graded inverse definite minimum time (IDMT) relay system.

- The fault currents are different for different types of faults and so a certain difficulty is experienced in relay setting.
- For ring mains, parallel feeders, interconnected systems, where power can flow to the fault from either direction, a system without directional control is not suited.

Schemes where speed of fault clearance is proportional to the current are usually preferred, i.e. the higher the current the faster the relay operates. The schemes that follow have this characteristic.

iii. Distance or Impedance Protection of Transmission Lines:

The distance protection provides discrimination protection without making use of pilot wires. Distance protection is widely employed for protection of high voltage ac transmission lines because of its inherent advantages.

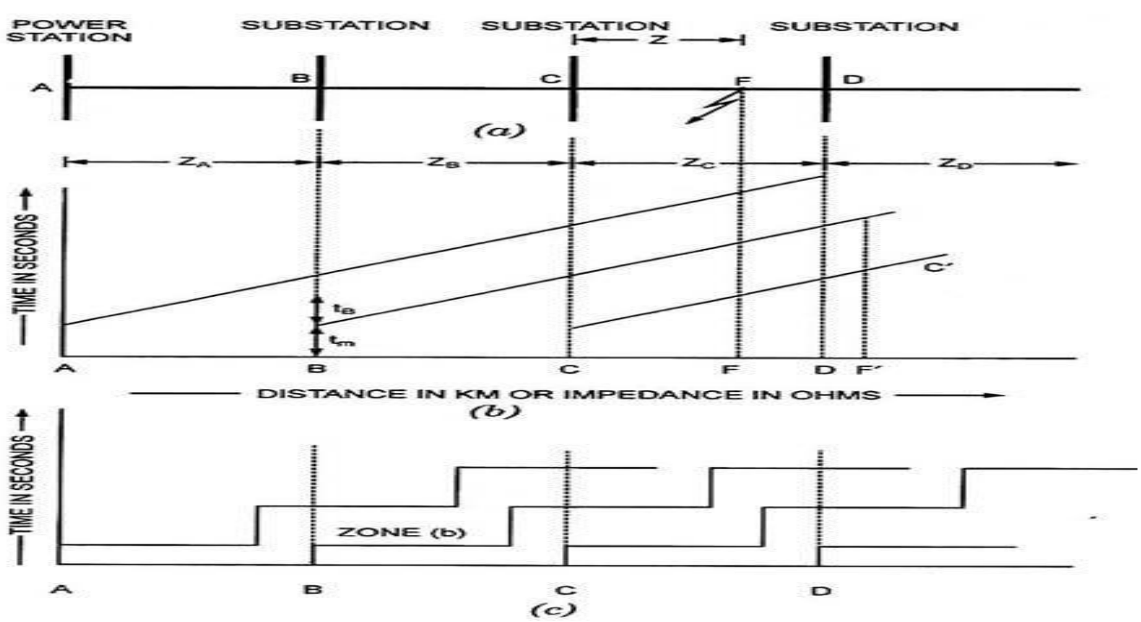


Fig. 5.22. *Distance or Impedance Protection*

Figure shows the simplest system consisting of feeders in series such that the power can flow only from left to right. The relays at A, B, C and D are set to operate with impedances less than Z_A, Z_B, Z_C and Z_D respectively. For a short-circuit fault at point F between substations C and D, the fault loop impedances at power station A and substations B and C are ($Z_A + Z_B + Z$), ($Z_B +$

Z), and Z respectively. It is obvious that only relay at substation C will operate. Similarly for short-circuit faults between substations B and C, and power station and substation B only relays at substation B and power station A respectively will operate.
A system with instantaneous impedance relays, set to act on impedances less than or equal to the impedance of a section, as illustrated in Fig. 5 (a), would be difficult to adjust; a fault near the junction of two sections is likely to cause the operation of two relays. Furthermore, if a fault of finite resistance occurs near the end of a section, it is possible that total impedance is greater than that for relay operation. For these reasons it is advantageous to use impedance time relays, the characteristics of which are illustrated in Fig. 5 (b), for the power system illustrated in Fig. 5(a).

If a fault occurs on right hand side of a substation B, say, relay at substation B operates in the minimum time t_m and the breaker at substation B operates t_B second later. If t_B is made less than the time difference between consecutive relays, only one relay will operate. Assume that the fault at F has a resistance causing total impedance at substation C represented by the point F' (the fault resistance being FF'). Relay as substation C operates in time F'C', whereas in the previous system it would not operate at all.
An impedance-time relay is a delicate mechanism and it is considered worthwhile to replace it by three simple impedance relays with a definite time of operation. The series combination can be arranged to provide a 3-step-time characteristic, as illustrated in Fig. 5.22 (c), which does the same thing as the previous linear characteristic.

Modern practice is to employ definite distance method of protection applied in 3 zones (steps). A number of distance relays are used in association with timing relays so that the power system is divided into a number of zones with varying tripping times associated with each zone. The first zone tripping which is instantaneous is normally set to 80% of the protected section. The zone 2 protection with a time delay sufficient for circuit breaker operating time and discriminating time margins covers the remaining 20% portion of the protected section plus 25 to 50 per cent of the next section. Zone 2 also provides backup protection for the relay in the next section for fault close to the bus. Zone 3 with still more time delay provides complete backup protection for all faults at all locations.

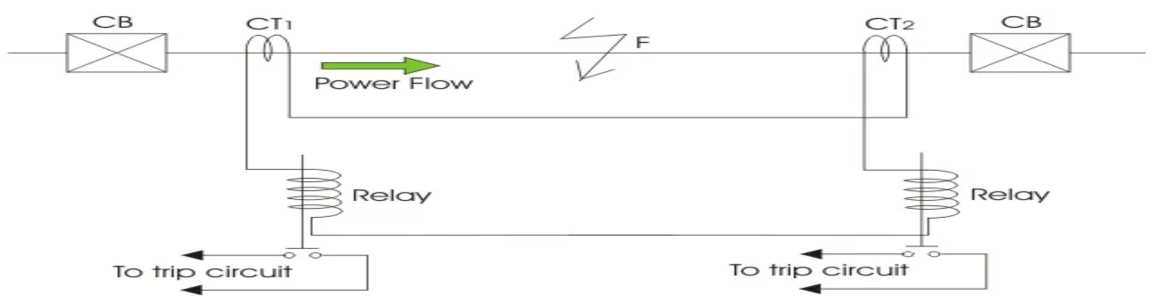
Thus the distance protection provided for line AB (section 1) serves as backup protection for sections 2 and 3, because in case of occurrence of faults in line BC (section 2) or line CD (section 3) it will clear those in their respective zone time from tripping the circuit breaker at end A.

Differential Pilot Wire Protection

This is simply a differential protection scheme applied to feeders. Several differential schemes are applied for protection of line but Mess Price Voltage balance system and Translay Scheme are most popularly used.

Merz Price Balance System

The working principle of Merz Price Balance system is quite simple. In this scheme of line protection, identical CT is connected to each of the both ends of the line. The polarity of the CTs is same. The secondary of these current transformer and operating coil of two instantaneous relays are formed a closed loop as shown in the figure below. In the loop pilot wire is used to connect both CT secondary and both relay coil as shown.



Now, from the figure it is quite clear that when the system is under normal condition, there would not be any current flowing through the loop as the secondary current of one CT will cancel out secondary current of other CT.

Now, if any fault occurs in the portion of the line between these two CTs, the secondary current of one CT will no longer equal and opposite of secondary current of other CT. Hence there would be a resultant circulating current in the loop.

Due to this circulating current, the coil of both relays will close the trip circuit of associate circuit breaker. Hence, the faulty line will be isolated from both ends.

Advantages of Differential Pilot Wire Protection:

- 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 of Differential Pilot Wire Protection:

- 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.

Digital Protection Device And Protection Scheme

Static Relay

The relay which does not contain any moving parts is known as the static relay. In such type of relays, the output is obtained by the static components like magnetic and electronic circuit etc. The relay which consists static and electromagnetic relay is also called static relay because the static units obtain the response and the electromagnetic relay is only used for switching operation.

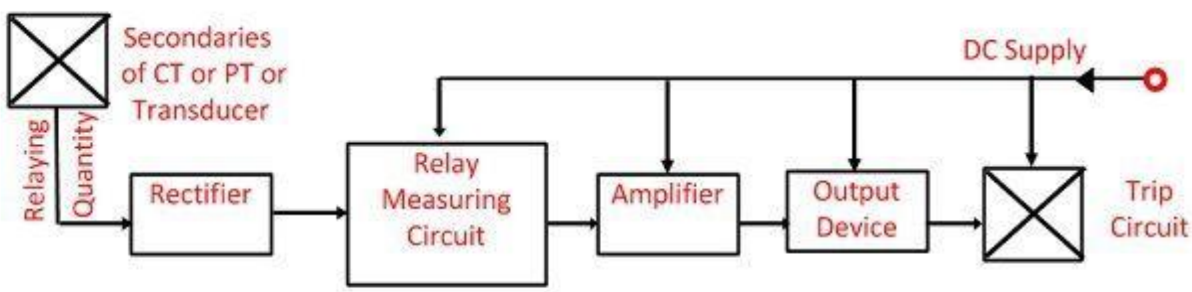
The static relay works on the comparison or measurement of electrical quantities. It uses comparators, level detectors, zero-crossing detector, etc that uses static electronic circuits for the comparison, and gives an output signal for tripping of the circuit breaker.

Components Of Static Relays.

The static relay works on the comparison or measurement of electrical quantities. It uses comparators, level detectors, zero-crossing detector, etc that uses static electronic circuits for the comparison, and gives an output signal for tripping of the circuit breaker.

The static relay doesn't use any moving parts such as armature in an electromagnetic relay. But the tripping circuit used to disconnect breaker contacts can be either electronic or electromagnetic.

Let us see the basic components of static relays.



- The input of the current transformer is connected to the transmission line, and their output is given to the rectifier. The rectifier was rectifying the input signal and pass it to the relaying measuring unit.
- The rectifying measuring unit has the comparators, level detector and the logic circuit. The output signal from relaying unit obtains only when the signal reaches the threshold value. The output of the relaying measuring unit acts as an input to the amplifier.
- The amplifier amplifies the signal and gives the output to the output devices. The output device activates the trip coil only when the relay operates. The output is obtained from the output devices only when the measurand has the well-defined value. The output device is activated and gives the tripping command to the trip circuit.

- The static relay only gives the response to the electrical signal. The other physical quantities like heat temperature etc. is first converted into the analogue and digital electrical signal and then act as an input for the relay.

Advantages of Static Relays :

- In static relays moving parts and contacts are greatly reduced as the designed response is being developed by incorporating solid-state components like transistors and diodes, without mechanical motion. Hence, friction or contact losses are absent as a result of minimum. maintenance is required.
- Static relays have a high speed of operation.
- They have greater sensitivity as amplification of signals can be obtained very easily by the use of semiconductor devices.
- Resetting time and overshoots can be reduced.
- The use of printed circuits avoids wiring errors and facilitates the rationalization of batch production.
- Several functions can be accommodated in a static relay.
- Static relays have superior characteristics and accuracy.
- Static relays consume less power compared to conventional electromechanical relays and provide less burden on the CTs and PTs.
- By making use of the linear couplers in place of CTs reduces the cost and solves the difficulty of the DC component of the fault current.
- Simplified testing and servicing are possible.
- They have excellent mechanical stability which is not possible with the electromechanical relays.
- They are not affected by the vibrations as they are compact in size.
- They have a long life.

Limitations of Static Relays:

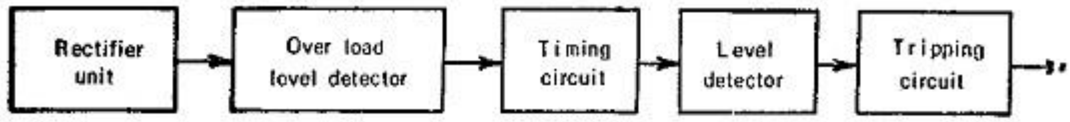
- The characteristics of semiconductors devices (such as transistors, diodes, etc.) used in static relays vary with temperature and aging.
- They are sensitive to voltage transients.
- They are not robust in construction.
- The reliability of static relays depends upon a large number of small components and their electrical connections.
- Easily affected by surrounding interference.
- Static relays have low short-time overload capacity compared with electromechanical relays.
- These relays could not meet practical requirements and hence are never used for commercial purposes.

Difference Between Static and Electromagnetic Relays :

Static Relays	Electromagnetic Relays
Static relays have no moving parts. All the components are static.	Electromagnetic relays possess moving parts which lead to problems such as contact bounce, arcing, contact erosion, spring restraint, etc.
Static relays possess a reduced burden on protective current transformers and potential transformers due to lower VA requirements of the static circuits.	In electromagnetic relays, the burden on the CTs and PTs is high due to higher VA.
Static relays have a very small operating time, hence it gives a faster response.	The response is comparatively slow.
Relaying characteristics could be controlled more precisely. But these characteristics vary with temperature and aging.	Relaying characteristics are lesser precise due to the moving core in the electromagnetic relays.
In this type of relays, the sensitivity attained is more due to the amplification.	Less sensitive due to higher VA.
Compact size due to small-sized ICs.	Bulky in size due to the presence of armature disc etc.
Comparatively less robust.	Comparatively robust.
This type of relay requires lesser maintenance.	Maintenance required is more due to the bearing friction, contact trouble, etc.
Static relays are reliable.	Electromechanical relays have high reliability due to the smaller number of components and experience gained in manufacturing practices.
Overload capacity is comparatively less.	Good overload capacity.
Comparatively lesser manufacturing difficulties.	Manufacturing difficulties are more.

Static Time Current Relays:

The static Overcurrent Protection Relay in Power System consists of a rectifier unit which converts the a.c. signals to d.c. levels, followed by overload level detector timing circuit, level detector and a trip. Figure below represents the block schematic of a time-current relay.



The current from the line CT is reduced to 1/1000th by an auxiliary CT, the auxiliary CT has taps on the primary for selecting the desired pickup and current range and its rectified output is supplied to an overload level detector and an RC timing circuit. When the voltage on the timing capacitor has reached the value for triggering the level detector, tripping occurs.

Several methods for timing and curve shaping are available. The timing capacitor is generally charged by a voltage derived from the CT current, e.g. from the voltage across a nonlinear resistor through which the rectified current flows. This also facilitates the shaping of the time-current characteristic to a desired curve by nonlinear resistors and RC networks.

Types of Static Overcurrent Relays:

Static Instantaneous and Definite Time Overcurrent Relays:

The block diagram of an instantaneous overcurrent relay is shown in Fig. The same construction may be used for under-voltage, overvoltage or earth fault relays too.

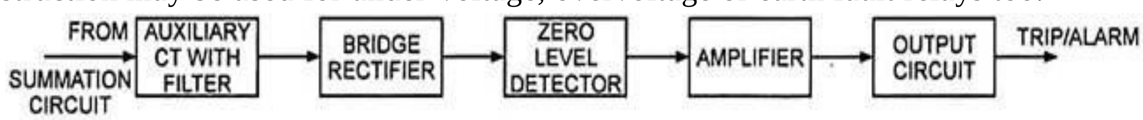


Fig. 4.9. ***Simplified Block Diagram of Static Overcurrent Relay***

The secondaries of the line CTs are connected to a summation circuit. The output of this summation CT is fed to an auxiliary CT, whose output is rectified, smoothened and supplied to the measuring unit (level detector). The measuring unit determines whether the quantity has attained the threshold value (set value) or not. When the input to measuring unit is less than the threshold value, the output of the level detector is zero. For an overcurrent relay-

For $I_{input} < I_{threshold}$; $I_{output} = 0$

For $I_{input} \geq I_{threshold}$; I_{output} = Present

In an actual relay, $I_{threshold}$ can be adjusted.

After operation of the measuring unit, the output is amplified by the amplifier. The amplified output is given to the output circuit to cause trip/alarm.

If time delay is desired, a timing circuit is introduced before the level detector.

Smoothening circuit and filters are introduced in the output of the bridge rectifier.

Static overcurrent relay is made in the form of a single unit in which diodes, transistors, resistors, capacitors etc., are arranged on printed board and are bolted with epoxy resin.

The general equation for time characteristic is given as –

$$I^n t = K$$

Where, I is the relay current, t is the time of operation and n is the characteristic index of relay and K is constant.

In conventional electromagnetic relays, n may vary between 2 and 8.

- The characteristic becomes a straight line parallel to current axis for n = 0. Such a characteristic is known as definite time characteristic of overcurrent relay.
- With n = 1; I_t = K. The characteristic becomes inverse characteristic.
- With higher value of n, the characteristic becomes more and more inverse. With n = 7 or 8, the characteristic becomes extremely inverse.

The general expression for the operating time of a static time-current relays may be given as

$$t = K\ M/I^n - I^n_p$$

where M is time-multiple setting, I is multiple of tap current; I_p is the multiple of tap current at which pick-up occurs, n is characteristic index of relay, t is time of operation in seconds and K is design constant of the relay.

If the relay picks up at top value current i.e., I_p = 1. then $t = K\ M/I^n - 1$.

Directional Static Overcurrent Relay

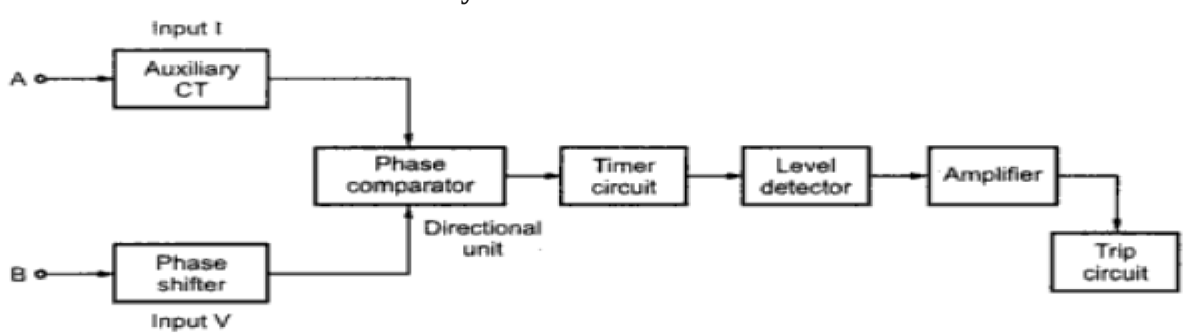


Fig: Directional static overcurrent relay

Directional relay is nothing but a directional power relay which operates when the power in the circuit flows in a particular direction. Thus it requires to serve the system voltage as well as system current. Fig. shows block diagram of the directional static overcurrent relay.

The input A is proportional to the system current supplied to a directional unit through auxiliary transformer. The input B is proportional to the system voltage, supplied to a directional unit through phase shifter.

The phase comparator compares the phase angle between the two inputs. Let this angle is Φ while the relay characteristics angle is θ. Let I_p be the current setting magnitude. Then, relay operates when,

$$I_p \leq I\cos(\phi - \theta)$$

The output of the phase comparator is applied to a level detector through timer if time delay is required. The output of the level detector is amplified and given to the trip circuit.

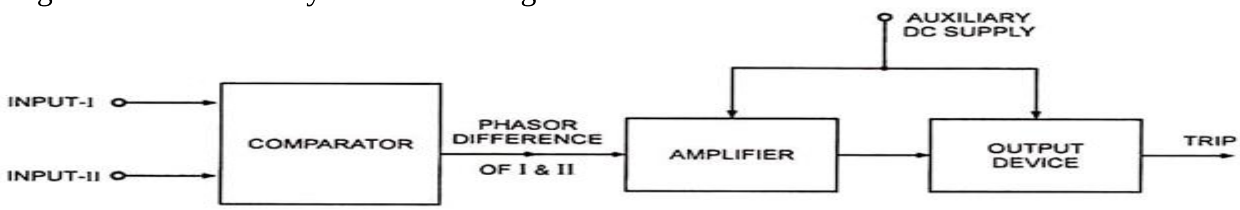
The phase comparator is generally of two types:

1. Hall effect generator which is popularly used in Russian countries.
2. Rectifier bridge type comparator which is popularly used in European countries.

The static directional overcurrent relays are very sensitive and directional unit can be made reliable down to 1% of the system voltage

Static Differential Relays

The differential relay measures the phasor difference between two similar electrical quantities (voltage-voltage or current-current). The rectifier bridge amplitude comparator is the most common static form for applications as a differential relay element. The block diagram for such a relay is shown in Fig.

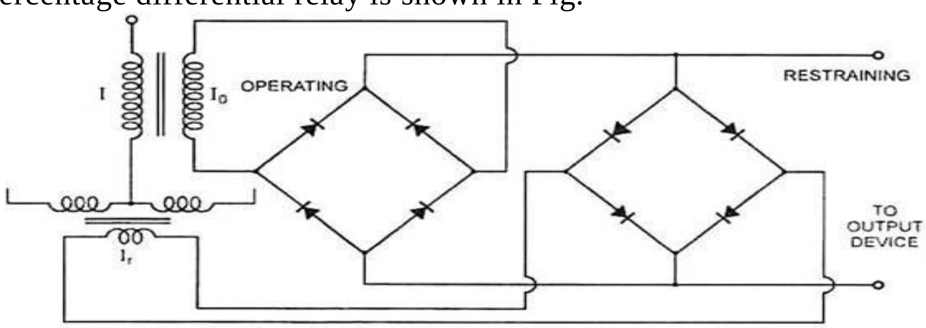


Inputs I and II are supplied to the comparator. The output of the comparator (phasor difference of inputs I and II) is amplified and used to operate the relay.

Advantageous of static differential relay over electromagnetic differential relays

- Very compact, highly sensitive for internal faults and have absolute stability for heavy through faults,
- Extremely short tripping times (20-50 ms) regardless magnitude of auxiliary voltage, accurate and absolutely stable tripping characteristic even for asymmetrical faults as each phase can have its own relay,
- Low VA burden, inrush current proof characteristic even during high starting currents, inrush currents.

Static type percentage differential relay is shown in Fig.



The difference of the currents in the operating coil and restraining coil is fed to the output element for the relay operation. The relay operates when-

$$K_0n_0I_0 > K_rn_rI_r + K'$$

Where, n_0 and n_r are the number of turns on the operating and restraining coils respectively and K_0 and K_r the design constants and K' the spring control torque constant.

At the threshold of operation $K' = K_0n_0\ I_{0min}$

Now equation under threshold condition becomes –

$$K_0n_0I_0 > K_rn_rI_r + K_0n_0\ I_{0min}$$

or $\quad I_0 = [(K_rn_r/K_0n_0)\ I_r] + I_{0min} = K''\ I_r + I_{0min}$ where $K'' = (K_rn_r/K_0n_0)$

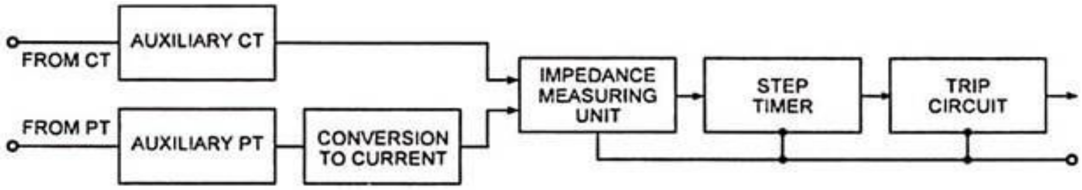
The above equation is an equation of a straight line of the form y = mx + c, the intercept c = I_{0min} and the slop m = K''.

The differential current schemes do not react to the peak currents caused by overloads or swings, also due to dissimilarity in CTs, inrush magnetizing current in transformer protection.

Static Distance Protection Relay:

Static Distance Protection Relay are characterized by having two input quantities respectively proportional to voltage & current at a particular point, referred to as the relaying point.

A block diagram of a distance relay based on current comparison principle is given in Fig



Such relays have characteristics which are not dependent on actual values of voltage and current, but on their ratio and phase angle between them. The distance relays includes impedance relays, reactance relays and mho relays. The measurement of impedance, reactance or admittance is done by comparing input current and voltage.

i) Impedance Relay:

Amplitude Comparison:

Impedance relay is inherently an amplitude comparator and the inputs are I Z_R and V.

For operation of relay –

$|I Z_R| > |V|$

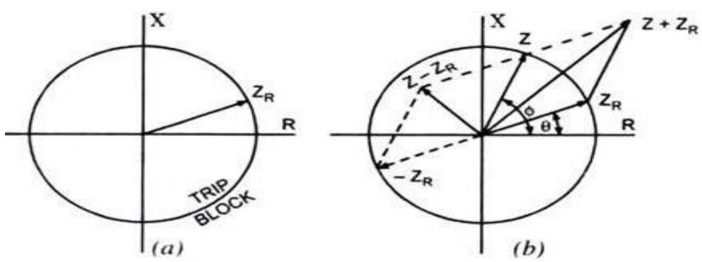
Or $|Z| < |Z_R|$

Or $R + jX < Z_R$

For threshold condition $R + jX = Z_R$ which is an equation of a circle on impedance (R-X) diagram. The circle having radius equal to Z_R and centre at the origin, as illustrated in Fig (a), is the characteristic of the impedance relay.

Phase Comparison:

The inputs are $(V + I Z_R)$ and $(V – I Z_R)$. The characteristic is given in Fig. (b). It can be seen that as long as Z_R lies along the circumference of the circle with radius Z_R, the two quantities $(Z + Z_R)$ and $(Z – Z_R)$ make an angle of ± 90°. This gives the same characteristic as shown in Fig (a).



ii) Reactance Relay:

Amplitude Comparison:

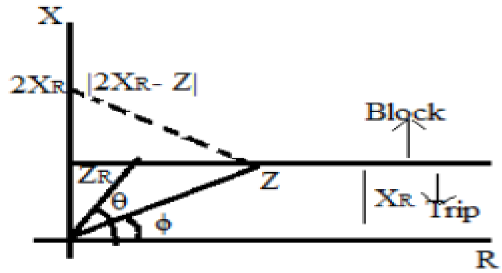
This relay is a particular case of an angle impedance relay in which the reactance component of the impedance is measured and, therefore, for operation of relay –

$|2X_r – Z| > |Z|$

The two inputs are V and $(2 I Z_R – 2 I R_r – V)$ where R_R is made equal to resistance of Z_R, thus leaving only its reactive component X_R.

<u>Phase Comparison</u>:

The two inputs are I Z_R and (I Z_R – V) as in case of an angle impedance relay. The relay will trip when Z is below the characteristic i.e., when $(\Psi + \theta) < 180°$. For Z to be purely reactive Ψ would be 90° under threshold condition and the relay would trip when Z sin ϕ is less than X_R on the R-X diagram.



iii) **Mho or Angle Admittance Relay:**

This is the inverse of the angle impedance relay. The two relays are dual of each other. The equation of one type on an impedance diagram corresponds to the equation of other type on admittance diagram and vice versa. The characteristic for mho or admittance relay is a straight line offset from the origin on G-B diagram while on R-X diagram it will be a circle passing through the origin.

<u>Amplitude Comparison</u>:

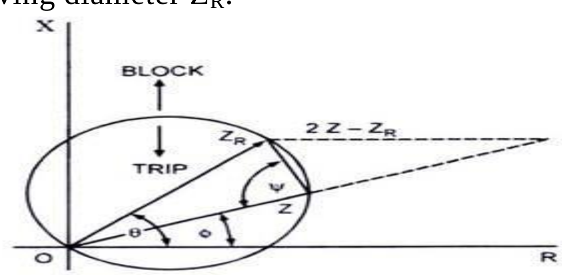
The two inputs are $|I Z_R|$ and $|2V – I Z_R|$.

For relay operation-

$|2 V – I Z_R| < |I Z_R|$

or $|2 Z – Z_R| < |Z_R|$

The characteristic is illustrated in Fig. The relay will operate as long as the fault impedance Z lies within the circle having diameter Z_R.



Phase Comparison:

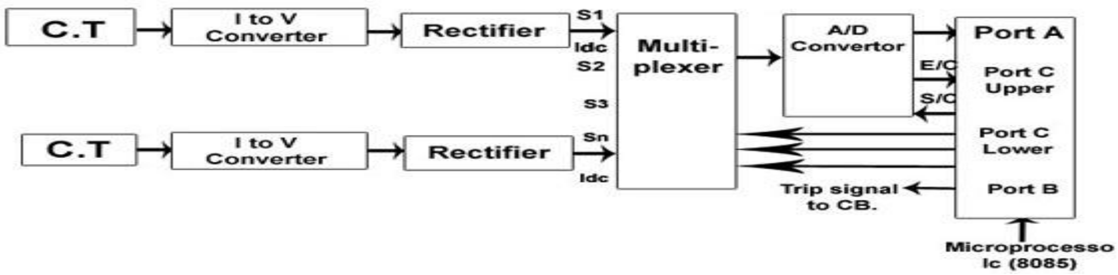
The two inputs are $|I Z_R – V|$ and V and the relay will operate when the phase angle between them is less than 90° i.e., when $90° > \Psi > – 90°$.

Since mho relay is inherently directional relay, phase comparator is the more convenient construction.

Microprocessor Based Overcurrent Relay

Microprocessor relays provide many functions that were not available in electromechanical or solid-state designs. Relay logic is very important to understand the microprocessor-based relay. The relay can be ON or OFF, that is, it has two stable states.

Figure shows the block diagram of the microprocessor-based relay.



Working principle

The output of the CT line is given to the input receiver block where the signal is processed. Signal processing includes overvoltage protector, rectifier, smoothing filters, auxiliary CT, etc., depending on the requirements. This signal is an analog signal. The A / D converter converts this into a digital signal that is accepted by the microprocessor. The microprocessor is a block of decision making. The received digital signal is compared with the reference to generate the appropriate trigger signal. This is a digital signal that is converted back to analog to operate the trip coil. This is achieved by the D / A converter. The data logger captures the data and sends it to the microprocessor when there is a request from the microprocessor. The information can be displayed with a suitable display device when taking the signal from the microprocessor.

The main advantage of this relay is that it is programmable. The program can handle the online calculations and make the decision accordingly. Another important advantage of the microprocessor-based relay is that a microprocessor unit can perform the retransmission operation of several systems.

Advantages of microprocesser based relay:

Thus various advantages of microprocessor based relay are:

1. Very efficient and reliable.
2. Highly accurate.
3. Very fast in operation.
4. Programmable in nature.
5. A unit can perform retransmission of several systems.
6. economical for large systems.
7. Useful for centrally coordinated backup protection.

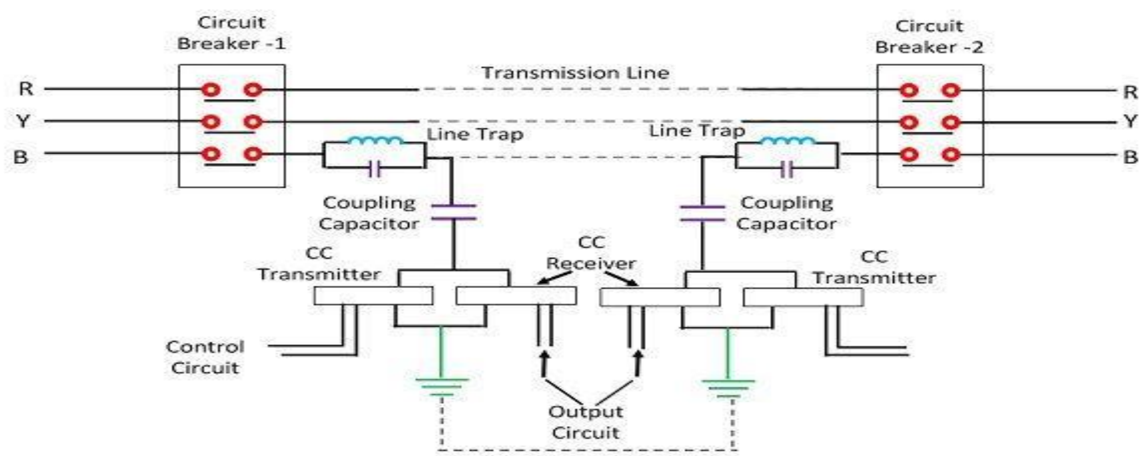
Only care that must be taken is that the microprocessor unit must be properly shielded as it gets affected by external interferences and environment Proper care of earthing must also be taken.

Carrier Aided Protection

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

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

Different methods of current carrier protection and basic form of 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 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

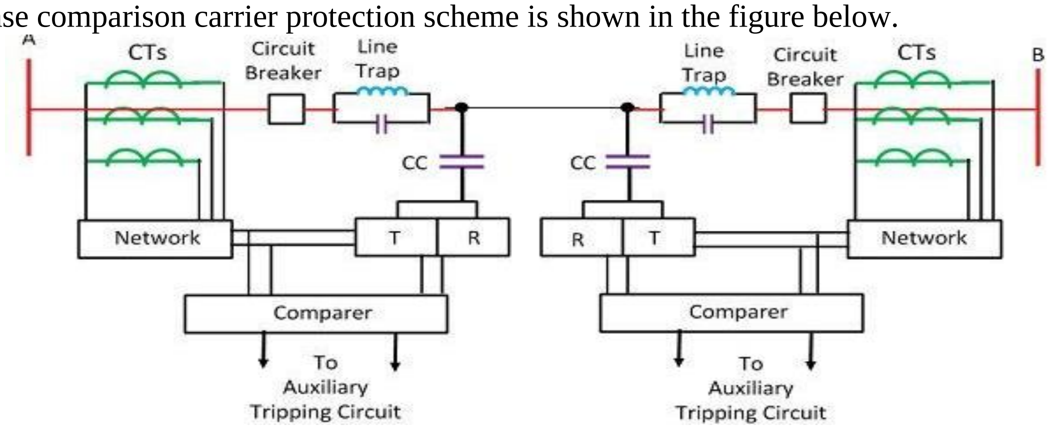
end of the line is on the bus to a line direction. After the direction comparison, the carrier pilot relay informs the equipment how a directional relay behaves at the other end to a short circuit.
The relay at both the end removes the fault from the bus. If the fault is in protection section the power 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: Carrier blocking protection scheme restrict 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.