UNIT - I

Power System Protection and Switchgear – SEE1401
UNIT 1- INTRODUCTION

I. Introduction

Essential requirements of protection - nature and causes of faults - types of faults - effects of faults - zones of protection - protection schemes - CTs and PTs and their applications - Basic relay terminology.

1.1 NEED FOR PROTECTIVE SYSTEMS

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

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

A protective system includes circuit breakers, transducers (CTs and VTs), and protective relays to isolate the faulty section of the power system from the healthy sections. A circuit breaker can disconnect the faulty element of the system when it is called upon to do so by the protective relay. Transducers (CTs and VTs) are used to reduce currents and voltages to lower values and to isolate protective relays from the high voltages of the power system. The function of a protective relay is to detect and locate a fault and issue a command to the circuit breaker to disconnect the faulty element. It is a device which senses abnormal conditions on a power system by con- stantly monitoring electrical quantities of the systems, which differ under normal and abnormal conditions. The basic electrical quantities which are likely to change dur- ing abnormal conditions are current, voltage, phase-angle (direction) and frequency. Protective relays utilise one or more of these quantities to detect abnormal conditions on a power system.

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

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

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

1.2 NATURE AND CAUSES OF FAULTS

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

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

1.3 TYPES OF FAULTS

Two broad classifications of faults are

(i) Symmetrical faults

(ii) Unsymmetrical faults

Symmetrical Faults

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

Unsymmetrical Faults

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

Single-phase to Ground (L-G) Fault

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

Two-phase to Ground (2L-G) Fault

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

Phase-to-Phase (L-L) Fault

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

Open-circuited Phases

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

Winding Faults

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

Simultaneous Faults

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

1.4 EFFECTS OF FAULTS

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

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

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

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

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

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

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

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

1.5 FAULT STATISTICS

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

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

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

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

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

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

Types of Faults	**Fault Symbol**	**% of Total Faults**
Line to Ground	L-G	85
Line to Line	L-L	8
Double Line to Ground	2L-G	5
Three Phase	3-f	2

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

1.6 ZONES OF PROTECTION

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

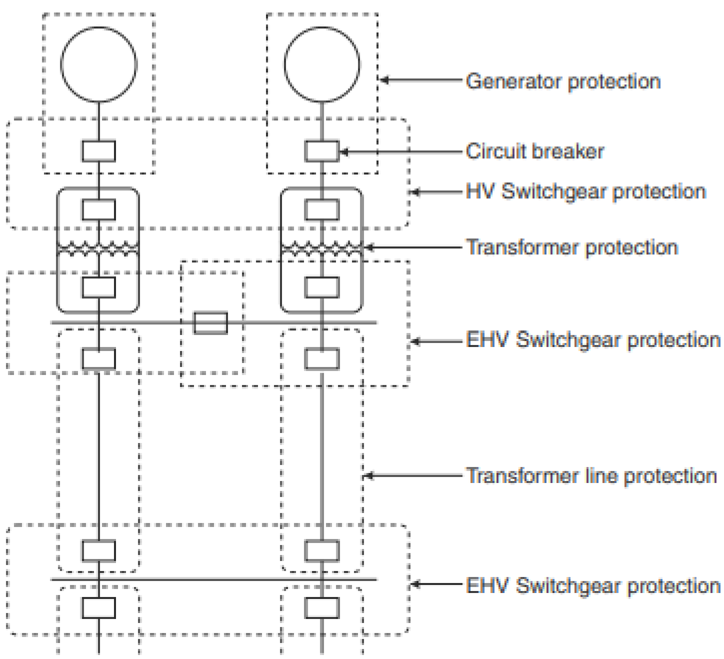

Fig. 1.1 Zone of Protection

1.7 PRIMARY AND BACK-UP PROTECTION

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

The causes of failures of protective scheme may be due to the failure of various elements,asmentionedinTable1.3.Theprobabilityoffailuresisshownagainsteach item.

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

The back-up relays are made independent of those factors which might cause primaryrelaystofail.Aback-uprelayoperatesafteratimedelaytogivetheprimary relay sufficient time to operate. When a back-up relay operates, a larger part of the power system is disconnected from the power source, but this is unavoidable. As far as possible, a back-up relay should be placed at a different station. Sometimes, a local back-up is also used. It should be located in such a way that it does notemploy components (VT, CT, measuring unit, etc.) common with the primary relays which are to be backed up. There are three types of back-uprelays:

(i) Remoteback-up

(ii) Relayback-up

(iii) Breakerback-up

Table 1.3 Percentage failure rate of various equipment

Name of Equipment	*% of Total Failures*
Relays	44
Circuit breaker interrupters	14
AC wiring	12
Breaker trip mechanisms	8
Current transformers	7
DC wiring	5
VT	3
Breaker auxiliary switches	3
Breaker tripcoils	3
DC supply	1

1.7.1 RemoteBack-up

When back-up relays are located at a neighbouring station, they back-up the entire primaryprotectiveschemewhichincludestherelay,circuitbreaker,VT,CTandother elements,incaseofafailureoftheprimaryprotectivescheme.Itisthecheapestandthe simplest form of back-up protection and is a widely used back-up protection for transmission lines. It is most desirable because of the fact that it will not fail due to the factors causing the failure of the primary protection.

1.7.2 RelayBack-up

Thisisakindofalocalback-upinwhichanadditionalrelayisprovidedforback-up protection. It trips the same circuit breaker if the primary relay fails and this opera- tion takes place without delay. Though such a back-up is costly, it can be recom- mended where a remote back-up is not possible. For back-up relays, principles of operation that are different from those of the primary protection as desirable. They should be supplied from separate current and potential transformers.

1.7.3 BreakerBack-up

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

1.8 ESSENTIAL QUALITIES OF PROTECTION

The basic requirements of a protective system are as follows:

(i) Selectivity ordiscrimination
(ii) Reliability
(iii) Sensitivity
(iv) Stability
(v) Speed and time
(vi) Adequateness
(vii) Simplicity and economy

1.8.1 Selectivity orDiscrimination

Selectivity, is the quality of protective relay by which it is able to discriminate between a fault in the protected section and the normal condition. Also, it should be able to distinguish whether a fault lies within its zone of protection or outside the zone. Sometimes, this quality of the relay is also called discrimination. When afault occurs on a power system, only the faulty part of the system should be isolated. No healthypartofthesystemshouldbedeprivedofelectricsupplyandhenceshouldbe leftintact.Therelayshouldalsobeabletodiscriminatebetweenafaultandtransient conditions like power surges or inrush of a transformer's magnetising current. The magnetising current of a large transformer is comparable to a fault current, which may be 5 to 7 times the full load current. When generators of two interconnected powerplantslosesynchronismbecauseofdisturbances,heavycurrentsflowthrough theequipmentandlines.Thisconditionislikeashortcircuit.Theflowofheavycur- rents is known as a power surge. The protective relay should be able to distinguish betweenafaultorpowersurgeeitherbyitsinherentcharacteristicorwiththehelp ofan auxiliary relay. Thus, we see that a protective relay must be able to discriminate between those conditions for which instantaneous tripping is required and those for which no operation or a time-delay operation is required.

1.8.2 Reliability

Aprotectivesystemmustoperatereliablywhenafaultoccursinitszoneofprotection. The failure of a protective system may be due to the failure of any one or more ele- mentsoftheprotectivesystem.Itsimportantelementsaretheprotectiverelay,circuit breaker, VT, CT, wiring, battery, etc. To achieve a high degree of reliability, greater attention should be given to the design, installation, maintenance and testing of the various elements of the protective system. Robustness and simplicity of therelaying equipmentalsocontributetoreliability.Thecontactpressure,thecontactmaterialof the relay, and the prevention of contact contamination are also very important from the reliability point of view. A typical value of reliability of a protective scheme is 95%.

1.8.3 Sensitivity

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

1.8.4 Stability

Aprotectivesystemshouldremainstableevenwhenalargecurrentisflowingthrough its protective zone due to an external fault, which does not lie in its zone. The con- cerned circuit breaker is supposed to clear the fault. But the protective system will notwaitindefinitelyiftheprotectiveschemeofthezoneinwhichfaulthasoccurred fails to operate. After a preset delay the relay will operate to trip the circuitbreaker.

1.8.5 Speed and Time

Aprotectivesystemshouldbefastenoughtoisolatethefaultyelementofthesystem as quickly as possible to minimise damage to the equipment and to maintain the systemstability.Foramodernpowersystem,thestabilitycriterionisveryimportant and hence, the operating time of the protective system should not exceed the criti- cal clearing time to avoid the loss of synchronism. Other points under consideration for quick operation are protection of the equipment from burning due to heavy fault currents, interruption of supply to consumers and the fall in system voltage which may result in the loss of industrial loads. The operating time of a protective relay is usually one cycle. Half-cycle relays are also available. For distribution systems the operating time may be more than onecycle.

1.8.6 Adequateness

It is impossible to provide protection against each and every fault and in each equipment. But the protective system should provide adequate (sufficient) protection for all the elements in the system. The adequateness is assessed by Ratings, cost, Location of the equipments, probability of abnormal condition due to internal and external faults, Discontinuity of the supply due to failure of the equipment

1.8.7 Simplicity and Economy

In addition to all important qualities, it is necessary that the cost of the system should be well within the limits. As a rule, the protection cost should not be more than 5% of the total cost. If the equipment to be protected is more important, then Economic considerations are relaxed. The protective system should be as simple as possible so that it can be easily maintained. The simpler systems are always more reliable

1.9 CLASSIFICATION OF PROTECTIVE SCHEMES

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

(i) Overcurrentprotection

(ii) Distanceprotection

(iii) Carrier-currentprotection

(iv) Differentialprotection

1.9.1 OvercurrentProtection

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

1.9.2 DistanceProtection

Distance protection is used for the protection of transmission or sub-transmission lines; usually 33 kV, 66 kV and l32 kV lines. It includes a number of distance relays of the same or different types. A distance relay measures the distance between the relay location and the point of fault in terms of impedance, reactance, etc. The relay operates if the point of fault lies within the protected section of the line. There are various kinds of distance relays. The important types are impedance, reactance and mho type. An impedance relay measure the line impedance between the fault point and relay location; a reactance relay measures reactance, and a mho relay measures a component of admittance.

1.9.3 Carrier-CurrentProtection

This scheme of protection is used for the protection of EHV and UHV lines, gener- ally 132 kV and above. A carrier signal in the range of 50-500 kc/s is generated for thepurpose.Atransmitterandreceiverareinstalledateachendofatransmissionline tobeprotected.Informationregardingthedirectionofthefaultcurrentistransmitted from one end of the line section to the other. Depending on the information, relays placed at each end trip if the fault lies within their protected section. Relays do not tripincaseofexternalfaults.Therelaysareofdistancetypeandtheirtrippingopera- tion is controlled by the carrier signal.

1.9.4 DifferentialProtection

This scheme of protection is used for the protection of generators, transformers, motors of very large size, bus zones, etc. CTs are placed on both sides of eachwindingofamachine.Theoutputsoftheirsecondariesareappliedtotherelay coils. The relay compares the current entering a machine winding and leaving the same. Under normal conditions or during any external fault, the current entering the wind- ing is equal to the current leaving the winding. But in the case of an internal fault on the winding, these are not equal. This difference in the current actuates the relay. Thus, the relay operates for internal faults and remains inoperative under normal conditions or during external faults. In case of bus zone protection, CTs are placed on the both sides of the busbar.

1.10 BASIC RELAY TERMINOLOGY

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

Protective relay: A protective relay is an automatic device which detects an abnor- mal condition in an electrical circuit and causes a circuit breaker to isolate thefaulty element of the system. In some cases it may give an alarm or visible indication to alertoperator.

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

Restraining force or torque: A force or torque which opposes the operatingforce/ torque.

Actuating quantity: An electrical quantity (current, voltage, etc) to which relay responds.

Pick-up(level): Thethresholdvalueoftheactuatingquantity(current,voltage,etc.) above which the relayoperates.

Reset on drop-out (level): The threshold value of the actuating quantity (current, voltage,etc.)belowwhichtherelayisde-energisedandreturnstoitsnormalposition or state. Consider a situation where a relay has closed its contacts and the actuating currentisstillflowing.Now,duetosomereason,theabnormalconditionisoverand thecurrentstartsdecreasing.Atsomemaximumvalueofthecurrentthecontactswill start opening. This condition is called reset or drop-out. The maximum value of the actuating quantity below which contacts are opened is called the reset or drop-out value.

Operatingtime: Itisthetimewhichelapsesfromtheinstantatwhichtheactuating quantity exceeds the relays pick-up value to the instant at which the relay closes its contacts.

Resettime: Itisthetimewhichelapsesfromthemomenttheactuatingquantityfalls below its reset value to the instant when the relay comes back to its normal (initial) position.

Setting: The value of the actuating quantity at which the relay is set to operate.
Seal-in relay: This is a kind of an auxiliary relay. It is energised by the contacts of the main relay. Its contacts are placed in parallel with those of the main relay and is designed to relieve the contacts of the main relay from their current carrying duty.It remains in the circuit until the circuit breaker trips. The seal-in contacts are

usually heavier than those of the main relay.

Back-up relay: A back-up relay operates after a slight delay, if the main relay fails to operate.

Back-up protection: The back-up protection is designed to clear the fault if the primary protection fails. It acts as a second line of defence.

Primaryprotection: Ifafaultoccurs,itisthedutyoftheprimaryprotectivescheme to clear the fault. It acts as a first line of defence. If it fails, the back-up protection clears thefault.

Auxiliary relays: Auxiliary relays assist protective relays. They repeat the operations of protective relays, control switches, etc. They relieve the protective relays of dutiesliketripping,timelag,soundingandalarm,etc.Theymaybeinstantaneousor may have a timedelay.

Electromagnetic relay: A relay which operates on the electromagnetic principle, i.e., an electromagnet attracts magnetic moving parts (e.g.,) plunger type moving iron type, attracted armature type). Such a relay operates principally by action of an electromagnetic element which is energized by the input quantity.

Electromechanical relay: An electrical relay in which the designed response is developed by the relative movement of mechanical elements under the action of a currentintheinputcircuit.Suchrelayoperatesbyphysicalmovementofmechanical parts resulting from electromagnetic or electrothermic forces created by the input quantities.

Static relays: These are solid state relays and employ semiconductor diodes, transistors, thyristors, logic gates, ICs, etc. The measuring circuit is a static circuit and therearenomovingparts.Insomestaticrelays,aslaverelaywhichisadcpotarised relay is used as the trippingdevice.

Analog relay: An analog relay is that in which the measured quantities are con- verted into lower voltage but similar signals, which are then combined or compared directly to reference values in level detectors to produce the desired output.

Digitalrelay: Adigitalrelayisthatinwhichthemeasuredacquantitiesaremanipulated in analog form and subsequently converted into either square-wave voltagesor digital form. Logic circuits or microprocessors compare either the phase relation- ships of the square waves or the magnitudes of the quantities in digital form tomake a trip decision.

Numerical relay: A numerical relay is that in which the measured ac quantities are sequentially sampled and converted into numerical (digital) data form. A microprocessor or a microcontroller processes the data numerically (i.e., performs mathematical and/or logical operations on the data) using an algorithm to calculate the fault discriminants and make tripdecisions.

Microprocessor-based relay: A microprocessor is used to perform all functions of a relay. It measures electrical quantities, makes comparisons, performs computa- tions, and sends tripping signals. It can realise all sorts of relaying characteristics, even irregular curves which cannot be reslised by electromechanical or static relays easily.

Microcontroller-based relay: A microcontroller is used for performing all the functionoftherelay.Itmeasurestheelectricalquantitiesbyacquiringthemindigital form through a data acquisition system, makes comparisons, processes the digital data to calculate the fault discriminants and make trip decisions. It can realise all sorts of relaying characteristics.

DSP-basedrelay:ADigitalSignalProcessor(DSP)isusedtoperformallthefunc- tions of a relay.

Undervoltage relay: A relay which operates when the system voltage falls below a certain preset value.

Directional or reverse power relay: A directional relay is able to detect whether thepointoffaultliesintheforwardorreversedirectionwithrespecttotherelayloca- tion. It is able to sense the direction of power flow, i.e. whether the power is flowing in the normal direction or the reversedirection.

Polarised relay: A relay whose operation depends on the direction of current or voltage.

Time-lag relay: A time-lag relay operates after a certain preset time lag. The time lagmaybeduetoitsinherentdesignfeatureormaybeduetothepresenceofatime- delay component. Such relays are used in protection schemes as a means of time discrimination. They are frequently used in control and alarm schemes.

Inverse time relay: A relay in which the operating time is inversely proportionalto the magnitude of the operating current.

Definitetimerelay: Arelayinwhichtheoperatingtimeisindependentofthemag- nitude of the actuating current.

Inverse Definite Minimum Time (IDMT) Relay: A relay which gives an inverse time characteristic at lower values of the operating current and definite time charac- teristic at higher values of the operating current.

Induction relay: A relay which operates on the principle of induction. Examples are induction disc relays, induction cup relays etc.

Thermal relay: This relay utilises the electrothermal effect of the actuating current for its operation.

Distance relay: A relay which measures impedance or a component of the imped- anceattherelaylocationisknownasadistancerelay.Itisusedfortheprotectionofa transmissionline.Astheimpedanceofalineisproportionaltothelengthoftheline, a relay which measures impedance or its component is called a distancerelay.

Impedancerelay: Arelaywhichmeasuresimpedanceattherelaylocationiscalled an impedance relay. It is a kind of a distancerelay.

Pickup

A relay is said to be picked up when it **moves from 'OFF' position to ' ON' position**.

Pickup Value

It is the minimum value of an actuating quantity at which relay starts operating. In most of the Relays the actuating quantity is current in the relay coil and pickup value of current is indicated along with the Relay.

Dropout or Reset

A relay is said to 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 the relay to operate after it has sensed the fault** is called time delay of relay

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 **(Note : Auxillary relay contact bypasses the relay contact)**

Current Settings

The pick up value of current can be adjusted to the required level in the relays – current setting of that relay.It is achieved by use of tapings on the relay coil – Plug bridge.Tap values - % full load ratings of C.T with which the relay is associated. Fig 1.2 shows the current setting.

The value of pickup current is obtained as

$$\text{pickup current} = \%\,\text{current setting X rated secondary current of CT}$$

The rating of CT = 500 / 10 A
Current setting = 150 %
Pickup current = 1.5 X 10 = 15A
When the relay coil current is greater than
or equal to15A, the relay operates

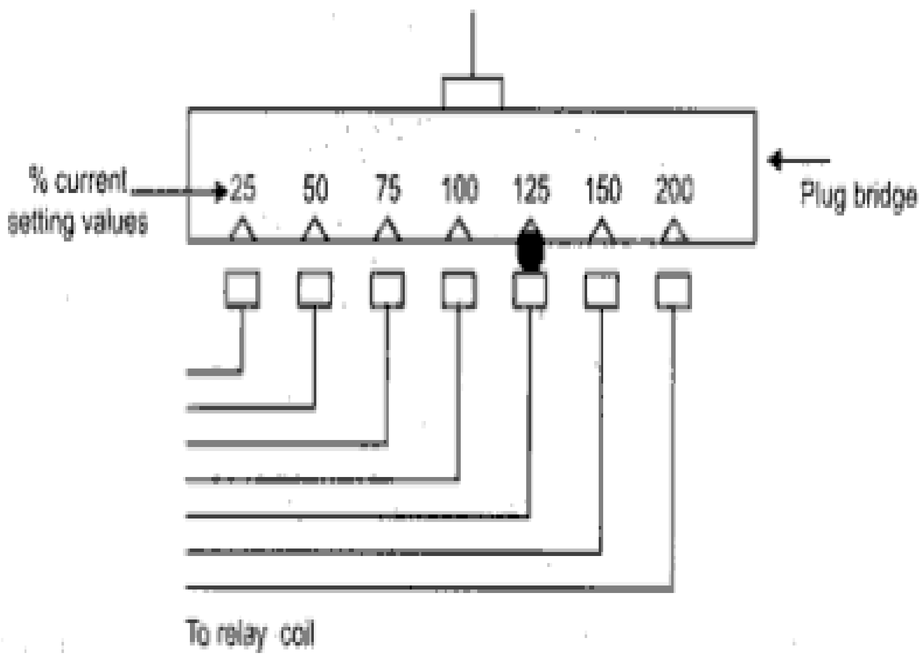

Fig. 1.2 Current Settings

Plug Setting Multiplier (P.S.M)

Fih 1.3 shows the graph of PSM vs Time.

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

$$P.S.M = \frac{fault\ current\ in\ Relay\ coil}{\%\ Current\ setting\ x\ rated\ secondary\ current\ of\ C.T}$$

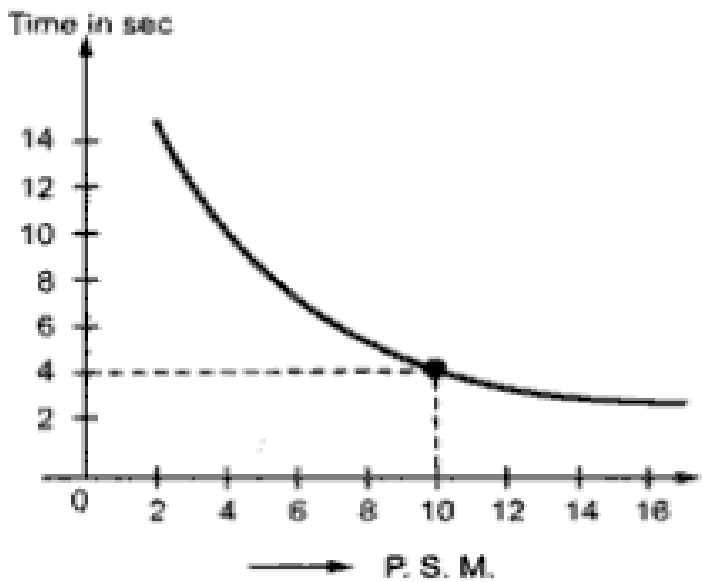

Fig. 1.3 PSM vs Time

Time Setting Multiplier

A relay is provided with a feature with which its time of operation can be controlled. Its dial is calibrated from 0 to 1 in steps of 0.05. Fig.1.4 shows the TSM.

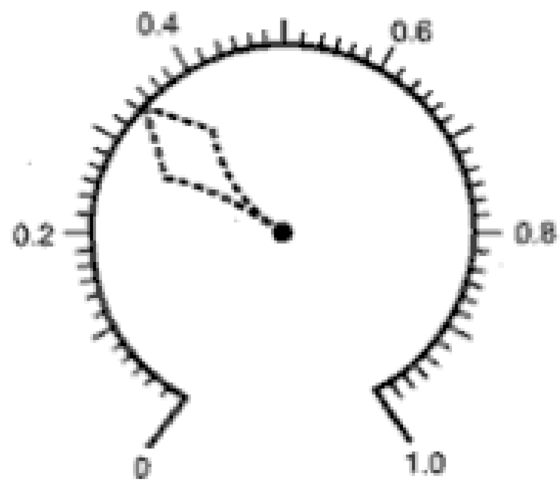

Fig.1.4 Time Setting Multiplier

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

Actual Time of operation = time in seconds X time setting multiplier

Time setting multiplier = 0.2

Time Corresponding to P.S.M of 10 =4 sec

Actual Time of operation = 4 X 0.2 = 0.8 sec

Trip Circuit

The opening operation of C.B is controlled by a circuit which consists of trip coil, relay contacts, auxiliary switch, battery supply etc.,

Protective Scheme

The combination of various protective systems covering a particular protective zone for a particular equipment

Protective System

The combination of C.B's, trip circuits, C.T and other protective relaying equipments

Unit Protection

A protective system in which the protection zone is early defined by the C.T boundaries. Such systems work for internal faults only

Reach

The limiting distance in which protective system responds to the faults

Over Reach

The operation beyond the set distance

Under Reach

Failure of distance relay within set distance

Earth Fault

The fault involving earth. SLG fault, DLG fault

Phase Fault

The fault which does not involve earth. LL fault

1.11 Current Transformer

- ✓ A large alternating currents which cannot be sensed by or passed through normal ammeters, current coils of watt meters, energy meters can be easily measured by use of C.T along with normal low range instruments.

- ✓ CT also **provides isolation from high current and high voltage ac circuits**.

Primary coil -one or more turns of **heavy cross sectional area**(or) a bar carrying high current

Secondary Coil– large number of turns of fine wire having **small cross sectional area**. This is connected to the coil of normal range ammeter

$$\frac{I1}{I2} = \frac{N2}{N1}$$

1.11.1 Wound Type C.T

- Primary is wound for more than one full turn on the core
- In L.V wound type C.T, the secondary winding is wound on a Bakelite former and heavy primary winding is directly wound on the top of the secondary winding with suitable insulation in between the two.
- The C.T's can be ring type or window type. Fig 1.5 and 1.6 shows the wound type CT. Fig.1.7 shows the stampings of core
- Core material – **Nickel Iron Alloy or an oriented electrical steel**
- Before installing the Secondary winding on core it is insulated with the help of end collars and circumferential wraps of pressboards. These provides additional insulation and protection to the winding from damage due to sharp corners

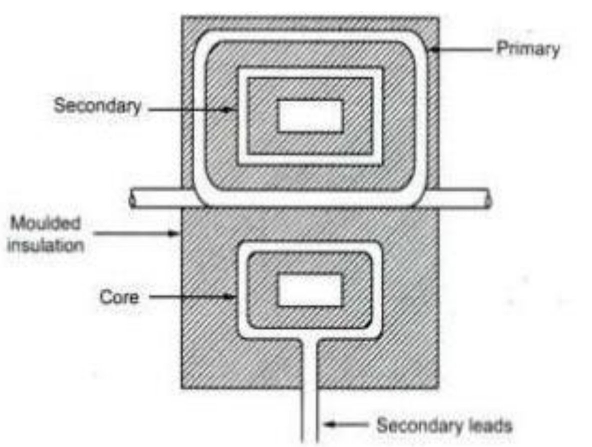

Fig. 1.5 Wond type CT

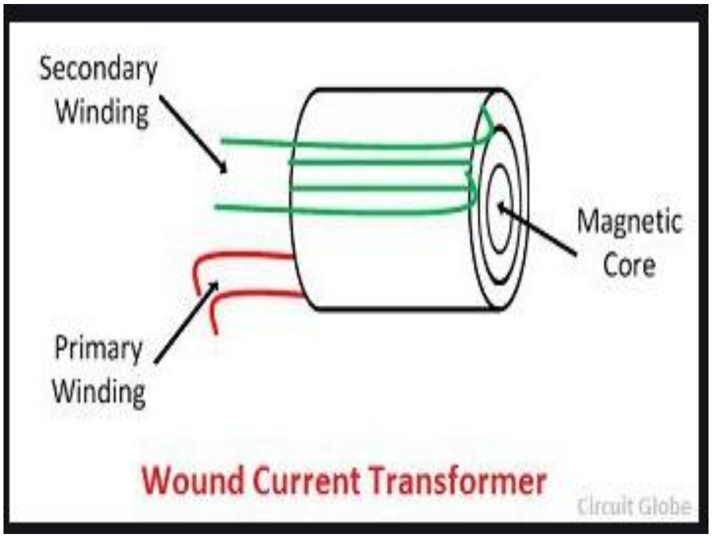

Fig. 1.6 Wonund type CT

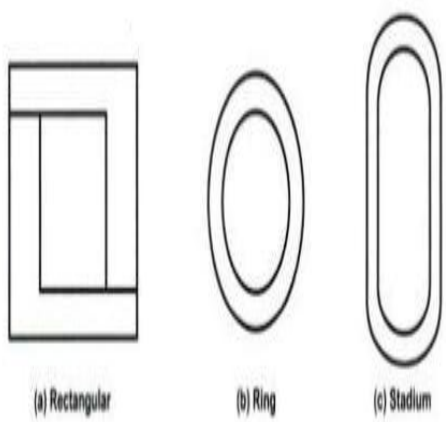

Fig.1.7 Stampings

1.11.2 Bar Type C.T

- The primary winding is a bar of suitable size
- Insulation on bar type primary is bakelized paper tube or a resin directly moulded on the bar
- Bar type primary is the integral part of C.T
- Core and secondary windings are same

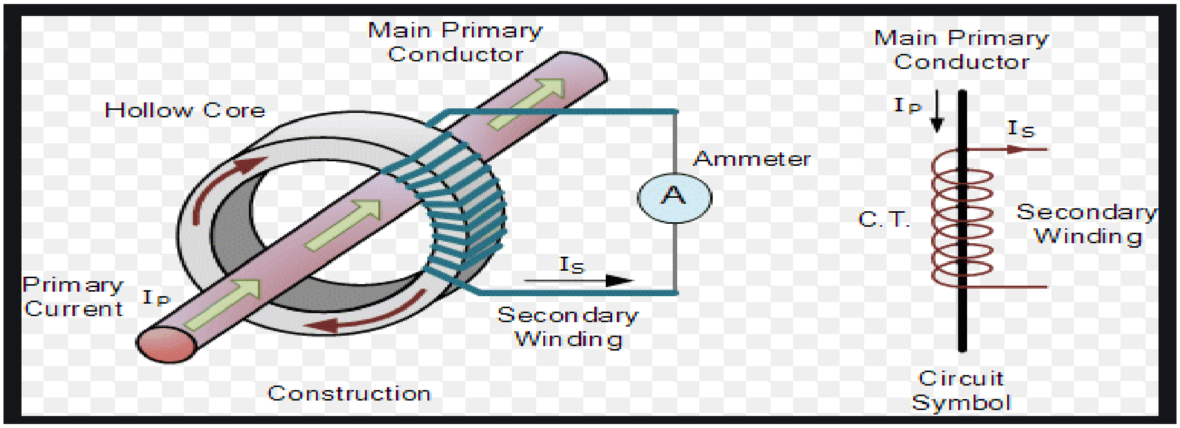

Fig.1.8 Bar type CT

- The stampings used for the laminations in C.T's must have high cross sectional area than the ordinary transformers. Due to it, magnetising current is small. Fig.1.8 shows the bar type CT.
- Windings are placed very close to each other to reduce leakage reactance.
- The external diameter of the tube is large to avoid the corona effect.
- Windings are so designed such that it can withstand S.C currents.
- For small line voltages – Tape and varnish - Insulation
- For voltages > 7KV – oil immersed or compound filled C.T's are used

1.12 Why Secondary of C.T should not be open?

- Secondary of C.T should not be kept open
- Either it should be **shorted or must be connected in series with a low resistance coil** such as current coils of wattmeter, coil of ammeter etc.
- If it left **open**, the **currentthrough secondary becomes zero** hence the ampere turns produced by **secondary** which generally oppose **primary** ampere turns becomes zero (Note: mmf= NI)
- As there is **no counter m.m.f**, unopposed primary m.m.f produce **high flux in the core**
- This produces **excessive core losses , heating the core** beyond limits
- Heavy e.m.f's will be induced on the primary and secondary side. This **damages the insulation** of the winding. Danger from the operator point of view as well
- It is usual to ground the C.T on the secondary side to avoid a danger of shock to the operator. Thus most of the **C.T have a S.C link or switch at secondary terminals**
- When the primary is to be energized, the S.C link must be closed so that there is no

danger of O.C secondary.

1.13 Potential Transformer

- The high alternating voltage are reduced in a fixed proportion for the measurement purpose with the help of potential transformers
- Construction is similar to the normal transformer
- Extremely accurate ratio step down transformer
- Windings are low power rating windings
- **Primary windings - large number of turns**
- **Secondary windings – less number of turns – usually 110V ratings**
- Primary is connected to high voltage line
- Secondary is connected to low range voltmeter coil
- One end of the secondary is always grounded for safety purpose. Fig 1.9 shows the circuit diagram of potential transformer.

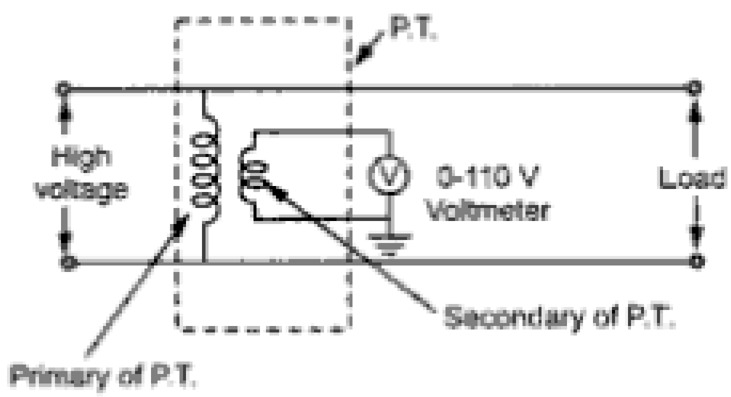

Fig.1.9 Potential Transformer Circuit Diagram

1.13.1 Construction of Potential Transformer

- P.T use larger core and conductor sizes
- At time of design, Economy is not important consideration but accuracy is important
- **Shell type or core type construction** is preferred
- Special core is used to reduce the effect of air gap at the joints at the time of assembly
- **Coaxial primary and secondary windings – to reduce the leakage reactance**

- Secondary winding – low voltage winding is always next to the core
- Primary winding - single coil - LV P.T.
- For HV, Primary winding – Small sections of short coils – HV P.T – to reduce the need of insulation between the layers

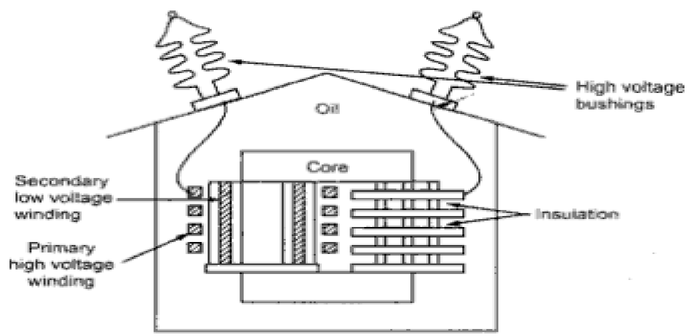

Fig.1.10 Potential Transformer

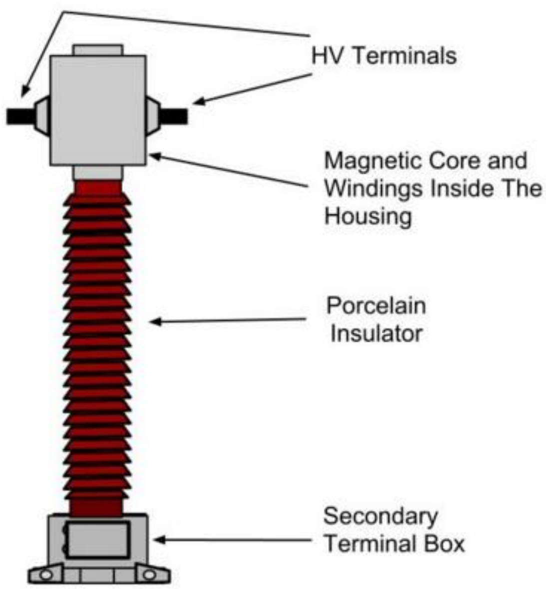

Fig.1.11 Potential Transformer

- Insulation for windings – **Cotton tape and varnished cambric**
- Insulation between coils – Hard fiber separators
- Voltage levels > 7KV – Oil immersed PT – Oil filled bushings\
- Fig. 1.10 and 1.11 shows the potential transformer.

Table 1.4 Comparison of C.T & P.T.

	Current Transformer	Potential Transformer
1	It can be treated as series transformer under virtual short circuit conditions	It can be treated as parallel transformer under open circuit secondary
2	Secondary must be always be shorted	Secondary is nearly under open circuit conditions
3	A small voltage exists across its terminal as connected in series	Full line voltage appears across its terminals
4	The winding carries full line current	The winding is impressed with full line voltage
5	The primary current and excitation varies over a wide range	The line voltage is almost constant hence exciting current and flux density varies over a limited range
6	The primary current is independent of the secondary circuit conditions	The primary current depends on the secondary circuit conditions
7	Needs only one bushing as the two ends of primary winding are brought out through the same insulator. Hence there is saving in cost.	Two bushings are required when neither side of the line is at ground potential

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Question Bank

PART – A

Q.No.	Question
1.	What are the essential requirements of protective relay?
2.	Define the function of protective relay.
3.	List the different types of faults, Which type of fault is most dangerous?
4.	Explain about zones of protection.
5.	Define seal-in relay?
6.	Define operating time and reset time.
7.	Explain about Auxiliary relay.
8.	Discuss about IDMT.
9.	What is back up protection?
10.	What is measuring relay?

PART – B

Q.No.	Question
1.	Explain the nature and cause of faults.
2.	Classify the types of faults and explain the effects of them.
3.	Explain the essential qualities of protection relay.
4.	Explain the classification of protective schemes.
5.	Discuss about the current transformer and potential transformer and their applications.
6.	Discuss briefly the role of protective relays in a modern power system

UNIT - II

Power System Protection and Switchgear – SEE1401
UNIT II- PROTECTIVE RELAY

II. Protective Relay

Electromagnetic relays - operating principle - torque equation - relay characteristics - over current relay, directional relay, distance relay, differential relay, negative sequence relay, amplitude and phase comparator of over current static relays, duality between comparators. Microprocessor based over current relay

2.1 Torque

- **Operating torque or Driving torque(T_d)**

Driving torque created on the relay coil. When any fault occurred, the current through the operating coil, crosses its pick up value, and hence the mmf of operating coil increases and crosses its pick-up value.

- **Restraining torque(T_r)**

Provided with the help of springs

- **Resultant torque(T_R)**

T_R= T_d-Tr When operating torque is greater than restraining torque, the relay operates

2.2 ELECTROMECHANICAL RELAYS

- Electromechanical relays operate by mechanical forces generated on moving parts due to electromagnetic or electrothermic forces created by the input quantities.
- The mechanical force results in physical movement of the moving part which closes the contacts of the relay for its operation.
- The operation of the contact arrangement is used for relaying the operated condition to the desired circuit in order to achieve the required function. Since the mechanical force is generated due to the flow of an electric current, the term 'electromechanical relay' is used.
- Most electromechanical relays use either **electromagnetic attraction or electromagnetic induction principle** for their operation. Such relays are called electromagnetic relays.
- Depending on the principle of operation, the **electromagnetic relays** are of two types
  - (i) attraction type relays, and
  - (ii) induction relays.

2.2.1 (a) Attracted Armature type

- Respond to ac as well as dc.
- Laminated electromagnet carries a coil.
- The coil is energized by the operating quantity which is proportional circuit voltage or current.

- The armature is subjected to the magnetic force produced by the operating quantity.
- The force produced is proportional square of current .
- The spring is used to produce restraining force.

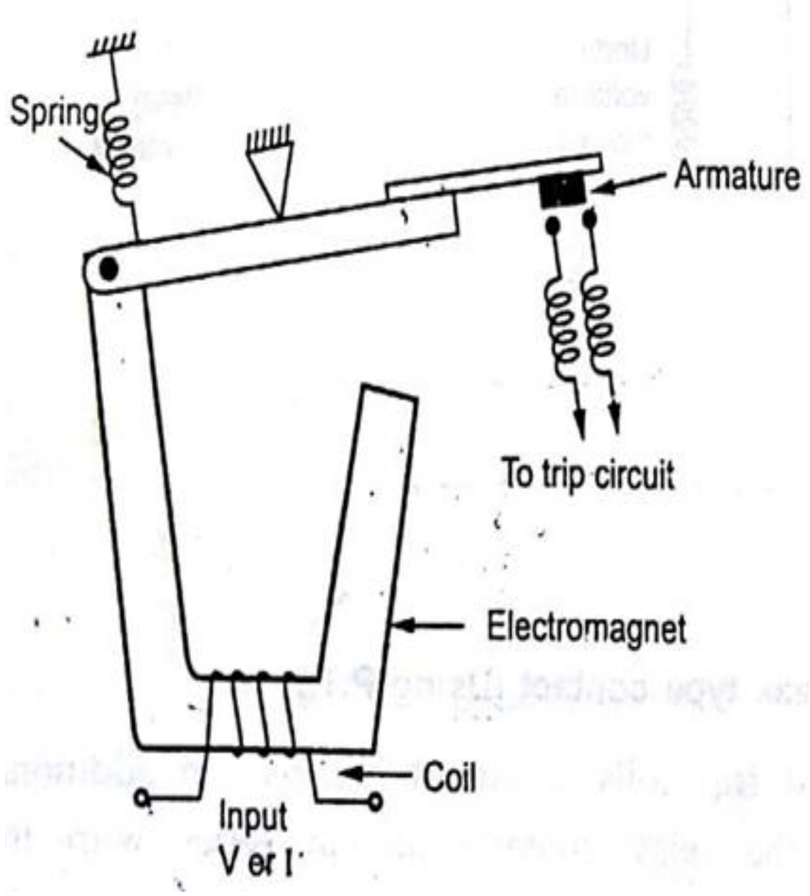


Fig. 2.1 Hinged armature type relay

- Armature gets attracted, when current through the coil increases beyond the limit under fault conditions.
- Due to this it makes contact with contacts of a trip circuit, which results in the opening of circuit breaker.

2.2.1(b) Solenoid and Plunger type

- In this type of a relay, there is **a solenoid and an iron plunger** which moves in and out of the solenoid to make and break the contact.

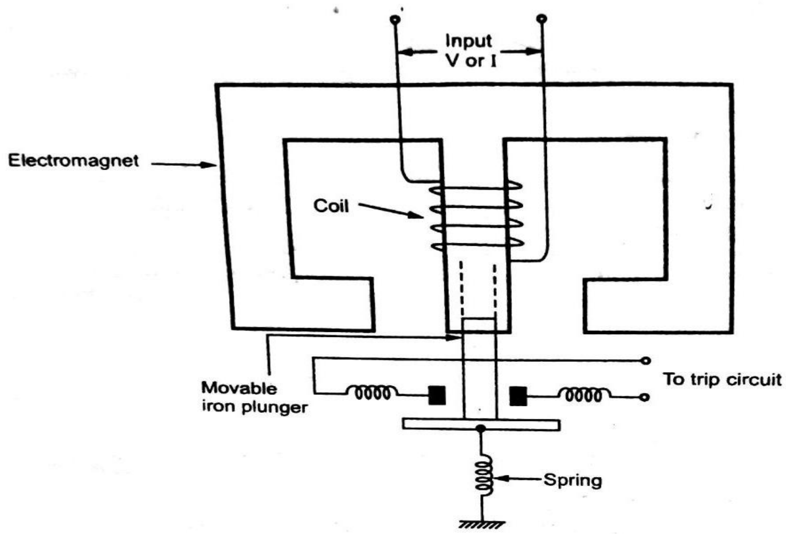


Fig.2.2 Solenoid and Plunger type

- The movement of the plunger is controlled by a spring.
- Under fault condition, current through the relay coil increases, hence the solenoid draws the
  plunger upwards and closes the trip Circuit.

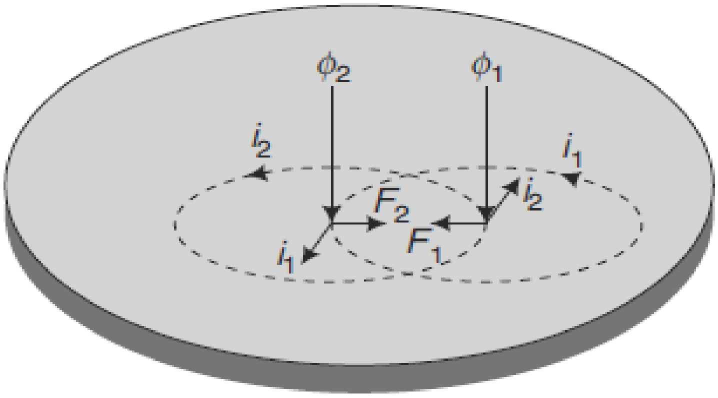
2.3Induction Relay

- Also called magnitude relay.
- Works on the principle of the induction motor or an energy meter.
- Metallic disc is allowed to rotate between two electromagnets.
- The coil of the electromagnets are energized with the help of alternating currents.
- The torque produced in the relay is due to the interaction of one alternating flux with eddy currents induced in the rotor by another alternating flux.
- As the interaction of alternating quantity is the base of operation of the relay , these are not used for d.c quantities.

Types of Induction Relay

- Watt hour meter type
- Induction cup type
- Shaded pole type

Torque equation for Induction Relay



ϕ_1 is produced by the upper magnet

ϕ_2 by the lower magnet

$$\phi_1 = \phi_{1m} \sin \omega t$$

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

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

Voltages induced in the rotor are:

$$e_1 \propto \frac{d\phi_1}{dt}$$

$$\propto \phi_{1m} \cos \omega t$$

$$e_2 \propto \frac{d\phi_2}{dt}$$

$$\propto \phi_{2m} \cos (\omega t + \theta)$$

induced eddy currents in the rotor

$$i_1 \propto \phi_{1m} \cos \omega t$$

$$i_2 \propto \phi_{2m} \cos (\omega t + \theta)$$

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

The forces produced are:

$$F_1 \propto \phi_1 \, i_2$$
$$\propto \phi_{1m} \sin \omega t \cdot \phi_{2m} \cos(\omega t + \theta)$$
$$\propto \phi_{1m} \, \phi_{2m} \cos(\omega t + \theta) \cdot \sin \omega t$$

$$F_2 \propto \phi_2 \, i_1$$
$$\propto \phi_{2m} \sin(\omega t + \theta) \cdot \phi_{1m} \cos \omega t$$
$$\propto \phi_{1m} \, \phi_{2m} \sin(\omega t + \theta) \cdot \cos \omega t$$

As these forces are in opposition, the resultant force is

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

$$F = K\phi_1 \, \phi_2 \sin \theta.$$

ϕ_1 and ϕ_2 are rms values

If the same current produces ϕ_1 and ϕ_2

the force produced is given by

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

where θ is the angle between ϕ_1 and ϕ_2.

2.3.1Watthour Meter Type Induction relay

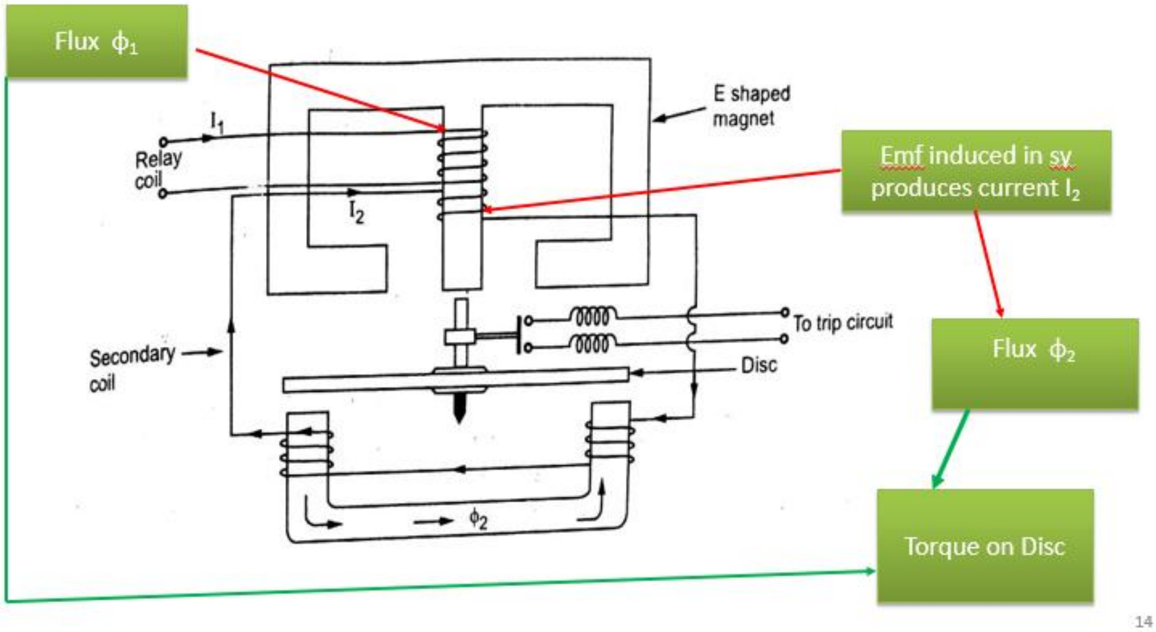


Fig 2.3 Watthour meter type induction relay

- The construction of **Watthour Meter Type Induction relay** is similar to the watthour meter which is very popularly used everywhere.Thus relay has double winding structure.
- It consists of two magnets, one E shaped magnet and other U shaped magnet.
- The disc is free to rotate in between these two magnets.
- The upper E shaped magnet carries both primary winding which is relay coil and the secondary winding.
- The primary carries the relay current I_1 which produces the flux φ_1.The e.m.f gets induced in the secondary due to this flux.This drives current I_2 through secondary.
- Due to this current I_2, flux φ_2 gets produced in the lower magnet.**This flux lags behind the main flux φ_1 by an angle $\propto$**.Due to the interaction of these two fluxes, the torque is exerted on the disc and disc rotates.
- Assuming that the entire flux φ_1 enters the disc from upper magnet and entire Flux φ_2 enters the disc from lower magnet, we can Write, $T \propto \varphi_1 \varphi_2 \sin \propto$
- In **Watthour Meter Type Induction relay**, the tapping can be provided on the primary. With the help of this suitable number of primary turns can be selected and hence current setting can be adjusted. Most of the **induction relays** are of this type.
- An important feature of **Watthour Meter Type Induction relay** is that its operation can be controlled by opening or closing of the secondary winding. It is opened, no current can flow through secondary hence flux φ_2 cannot be produced and hence no torque can be produced.Thus relay can be made inoperative opening the secondary winding.

2.3.2 Induction Cup Type Relay

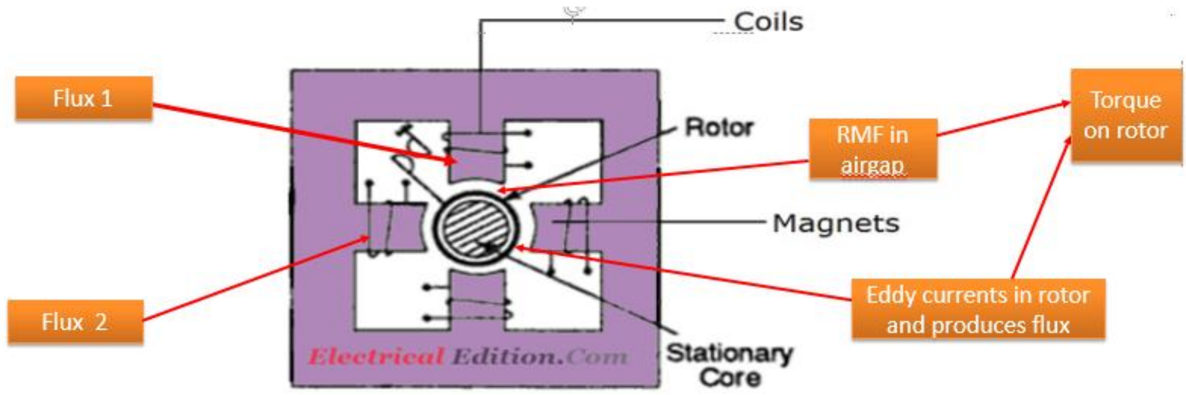


Fig. 2.4 Induction cup relay

- The currents and respective fluxes produced by the two pairs of coils are displaced from each other by angle ∝.
- Thus the resultant flux in the air gap is rotating.So rotating magnetic field is produced by two pairs of coils. Due to this, eddy currents are induced in the cup type rotor.
- These currents produce the flux. The interaction of the two fluxes produce the torque and the rotor rotates in the same direction as that of rotating magnetic field.
- A control spring and the back stop carried on an arm attached to the spindle of the cup, are responsible to prevent continuous rotation.
- Induction cup relay is very fast in operation.The operating time of the order of 10 milliseconds is possible with this type. This is because the rotor is light having very low moment of (induction loop) inertia

2.3.3 Shaded Pole type induction relay

- It consists of an aluminium disc which is free to rotate in an air gap of an electromagnet.

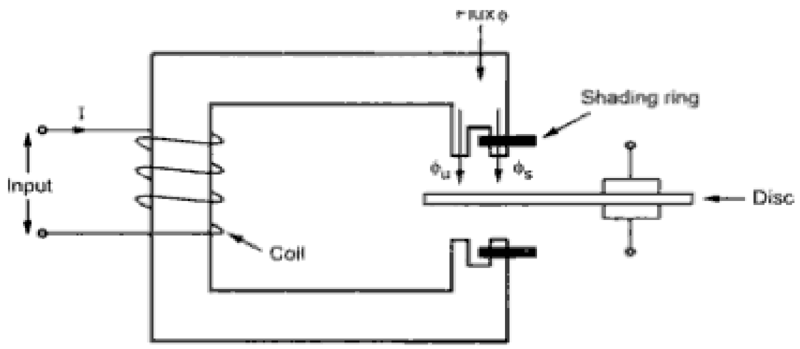


Fig. 2.5 Shaded pole type induction relay

- The part of pole face of each pole is shaded with the help of copper band or ring. This is called shading ring.
- The total flux φ produced due to the alternating current split into two fluxes displaced in time and space due to the shading ring.
- Due to the alternating flux, e.m.f gets induced in the shading ring .This e.m.f drives the currents causing the flux to exist in shaded portion.This flux lags behind the flux in the unshaded portion by angle $\propto$.

$T \propto \varphi_s \varphi_u \sin \propto$

- Assuming fluxes φ_s and φ_u to be proportional to the current I in the relay coil we can write, $T \propto I^2 \sin \propto$
- $\therefore \quad T = kI^2$

2.4 Non Directional Induction Type Over Current Relay

- Also called earth leakage induction type relay
- 2 magnets – upper E and lower U
- Aluminium disc free rotate between 2 magnets
- Spindle of the disc- carries moving contact– get contact with fixed contact of trip circuit.
- Upper magent – py & sy
- Py- connected to sy of CT

-wdg tapped at regular intervals

-tapping connected to plug setting bridge.

- Plug setting bridge- no. of turns of py wdg adjusted- thus desired current setting obtained.
- 7 section-50,75,100,125,150,175,200%

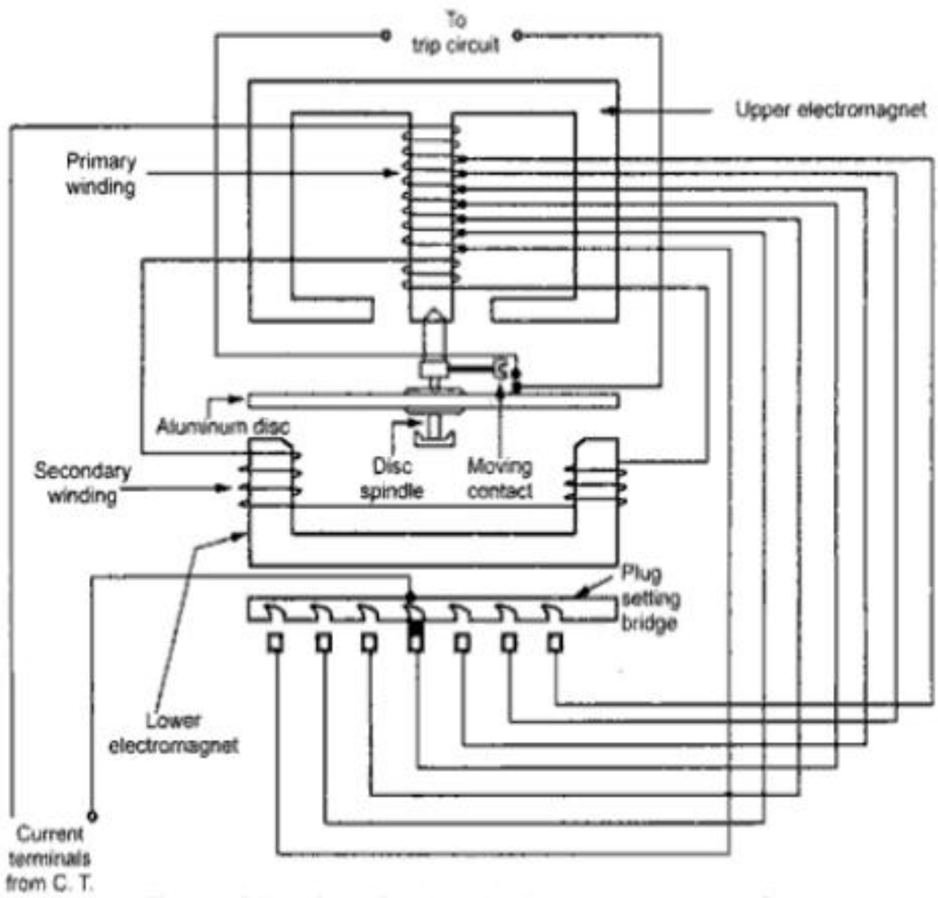


Fig.2.6 Non directional over current relay

IDMT-Inverse definite min time

Fig. 2.7 Time current characteristics

Example 2.1 : *An I.D.M.T. 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 C.T. having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 5000 A. The time-current characteristics of the relay is shown in the Fig. 2.17.*

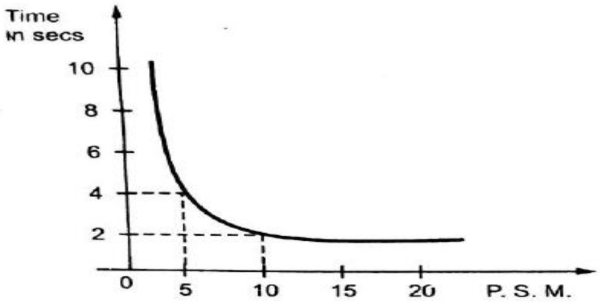


Fig. 2.17

lution : Let us calculate P.S.M. first.

Fault current in relay coil = actual fault current × C.T. ratio

$$= 5000 \times \frac{5}{400}$$

$$= 62.5 \text{ A}$$

Rated secondary of C.T. = 5 A

Current setting = 150% = 1.5

$$\text{P.S.M.} = \frac{62.5}{5 \times 1.5} = 8.333$$

From Fig. 2.17, approximate time for P.S.M. of 8.33 is 1.8 sec.

Actual operation time = 1.8 × time setting multiplier

$$= 1.8 \times 0.6$$

$$= 1.08 \text{ seconds}$$

2.5 Directional power relay

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.

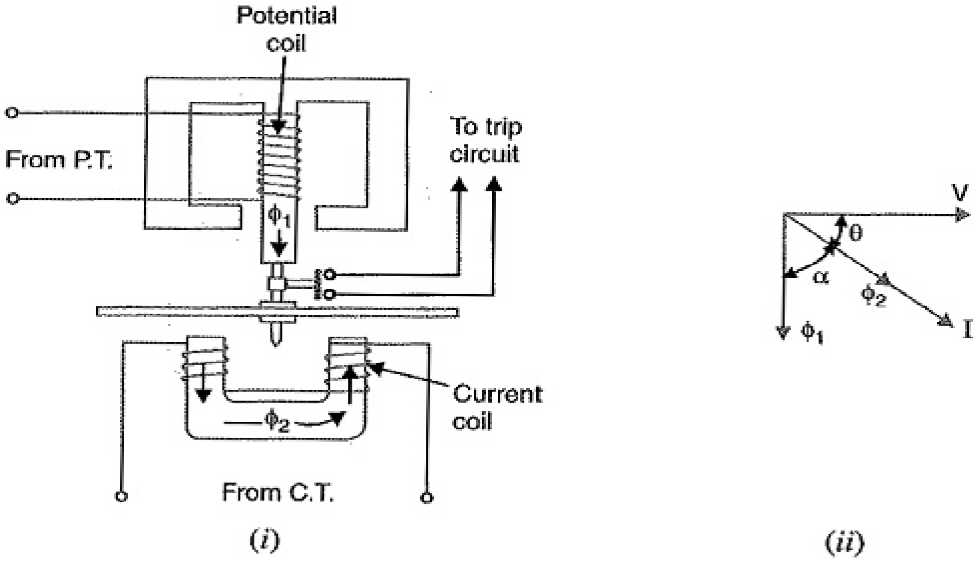


Fig.2.8 Directional power relay

Constructional details: Fig. 21.18 shows the essential parts of a typical induction type directional power relay. It consists of an aluminum disc which is free to rotate in between the poles of two electromagnets. The upper electromagnet carries a winding (called potential coil) on the central limb which is connected through a potential transformer (P.T.) to the circuit voltage source. The lower electromagnet has a separate winding (called current coil) connected to the secondary of C.T. in the line to be protected. The current coil is provided with a number of tappings connected to the plug-setting Midge (not shown for clarity). This permits to have any desired current setting. The restraining torque is provided by a spiral spring.

The spindle of the disc carries a moving contact which bridges two fixed contacts when the disc has rotated through a pre-set angle. By adjusting this angle, the travel of the moving disc can be adjusted and hence any desired time-setting can be given to the relay.

Operation: The flux Φ_1 due to current in the potential coil will be nearly 90° lagging behind the applied voltage V. The flux Φ_2 due to current coil will be nearly in phase with the operating current I.

- [See vector diagram in Fig. 21.18 (ii)]. The interaction of fluxes Φ_1 and Φ_2 with the eddy currents induced in the disc produces a driving torque given by :

$$T \propto \phi_1 \phi_2 \sin \alpha \qquad \text{[See Art. 21.5]}$$

$$\text{Since} \quad \phi_1 \propto V, \quad \phi_2 \propto I \quad \text{and} \quad \alpha = 90 - \theta$$

$$T \propto VI \sin(90 - \theta)$$

$$\propto VI \cos \theta$$

$$\propto \text{power in the circuit}$$

-

It is clear that the direction of driving torque on the disc depends upon the direction of power flow in the circuit to which the relay is associated. When the power in the circuit flows in the normal direction, the driving torque and the restraining torque (due to spring) help each other to turn away the moving contact from the fixed contacts. Consequently, the relay remains inoperative. However, the reversal of current in the circuit reverses the direction of driving torque on the disc. When the reversed driving torque is large enough, the disc rotates in the reverse direction and the moving contact closes the trip circuit. This causes the operation of the circuit breaker which disconnects the faulty section.

2.6 Directional Induction Type Over current relay

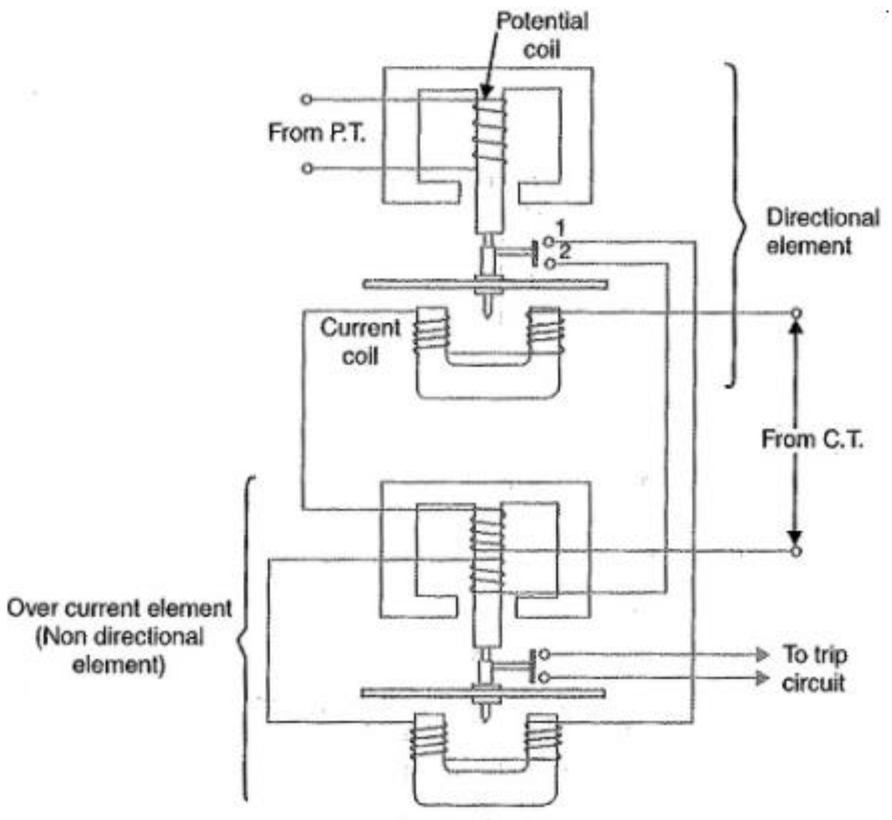


Fig. 2.9 Directional induction type over current relay

- Directional power relay – not suitable for SC. Under SC, V reduced, therefore not sufficient to produce the driving torque. Thus, directional Ind type relay is used
- Operated independent of Vsys and CosΦ
- Two relay element- Directional and non directional element
- **Directional Element**
- Operates when power in the ckt flows in a particular direction
- Voltage coil energised by Vsys of potential transformer

- I coil energised by Isys of CT
- Trip contact of this relay (1-1') connected in series with sy wdg of non directional element

Non directional element

- I coil of directional element is connected in series with Py wdg of non directional element.
- Plug setting bridge- to adjust I setting as per requirement.
- Trip contact 1-1' are in series with winding on lower magnet of non directional element
- Until trip contacts 1-1' are closed by the movement of disc of directional element, the non-directional element cannot operate.

- **Operation**

- Power flows in proper direction
    - relay inoperative - contacts of directional element open- secondary of non directional element are open
- Under SC condition- power reversal takes place
    - I thro I coil of directional element – produce flux
    - I thro V coil of directional element- produce flux
    - Interaction of 2 flux cause torque , therefore 1-1' closed.

- **Directional Characteristics**

V = Relay voltage through PT

I= Relay coil current through CT

θ=Angle between V and I

Note : The system current is generally lagging the voltage but with suitable connection the relay current is made to lead the voltage by an angle θ.

Due to this correct operation of relay at all types of faults under all system conditions is ensured.

I lead V by θ,

ϕ_v lags V by angle ϕ

ϕ_1 is in phase with current I

$$T \propto \phi_V \phi_I \sin(\phi_V \wedge \phi_I)$$

$$\propto \phi_V \phi_I \sin(\theta + \phi)$$

$$\phi_V \propto V \quad \text{and} \quad \phi_I \propto I$$

$$\boxed{T = KVI \sin(\theta + \phi)}$$

For maximum torque , $\theta + \phi = 90^0$

Torques is zero, $\theta + \phi = 0$ or 180^0

$$\phi = 90^\circ - \tau$$

Substituting in the torque equation,

$$T = KVI \sin(\theta + 90^\circ - \tau)$$

$$T = KVI \cos(\theta - \tau)$$

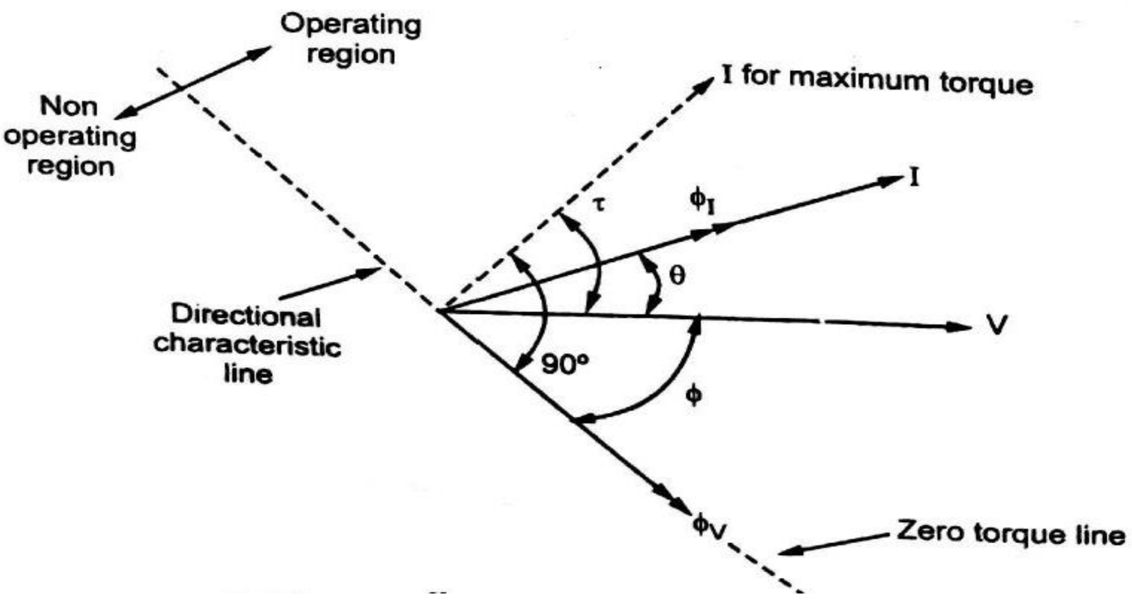


Fig.2.10 Directional characteristics

2.7 Differential Relay

- Difference in current > preset value- relay operates- CB open
- Normal condition – Two currents are equal in magnitude and phase, therefore relay is inoperative.
- Fault condition- there is difference in current, relay operates
- **Types** :
  - Current differential relay
  - Biased beam relay or percentage differential relay
  - Voltage balance differential relay

2.7.1 Current Differential Relay

- ✓ 2CT of same CT ratio on either side of the section to be protected
- ✓ Sy of CT are connected in series, so carry current in same direction.
- ✓ I be external fault current
- ✓ Sy of CT carries same current
- ✓ Therefore no current flows thro operating coil. Hence relay inoperative

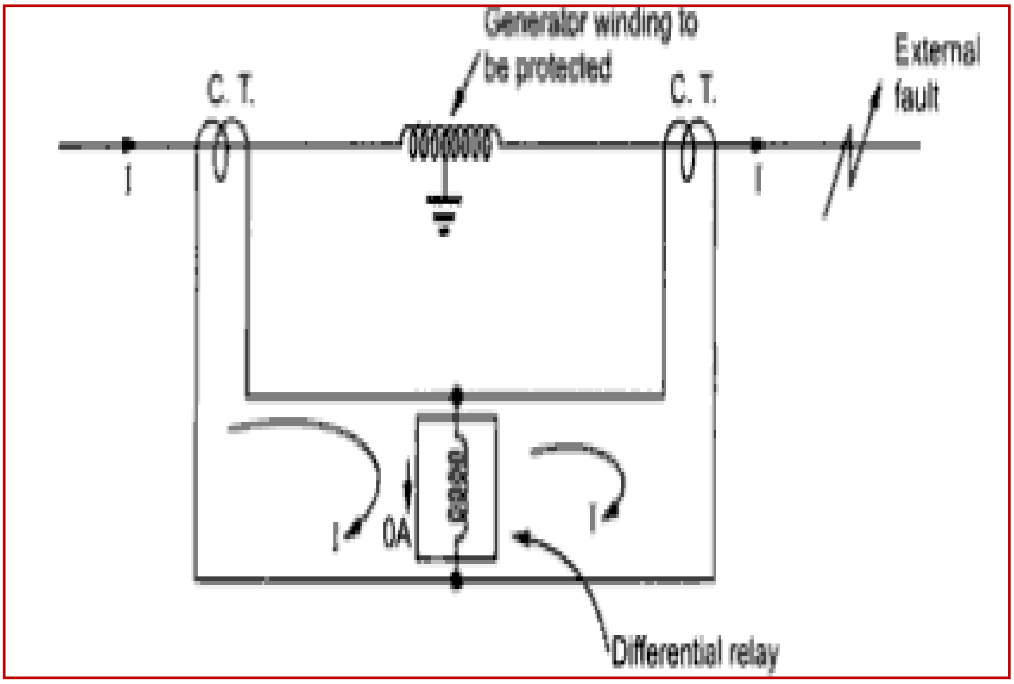


Fig.2.11 Current differential relay

- ✓ Internal fault
- ✓ Current flows thro fault from both sides
- ✓ Sy I of CT's are not equal.
- ✓ I thro operating coil is I_1+I_2.
- ✓ High current relay operates

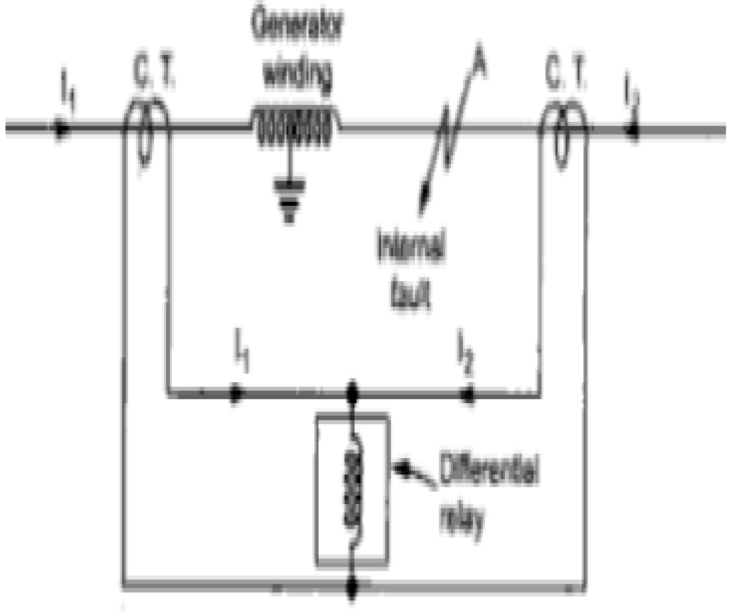


Fig.2.12 Action of differential relay

2.7.2 Biased Beam Relay or Percentage Differential relay

- Operating coil O carries--- I_2-I_1
- Restraining coil R carries--- $(I_1+I_2)/2$
- N=no.of turns of restraining coil
- I_1 flows thro N/2 turns, I_2 flows thro N/2 turns..

Therefore effective AT $=(NI_1+NI_2)/2$

$= N(I_1+I_2)/2$

- Under normal condition, $F_{res}>F_{op}$
- Under internal fault condition $F_{op}> F_{res}$

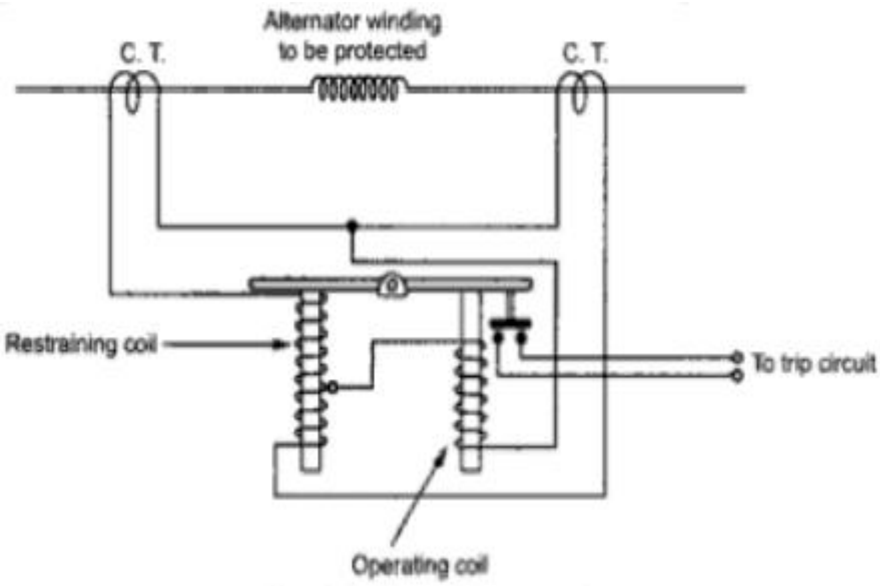


Fig.2.13 Biased beam relay

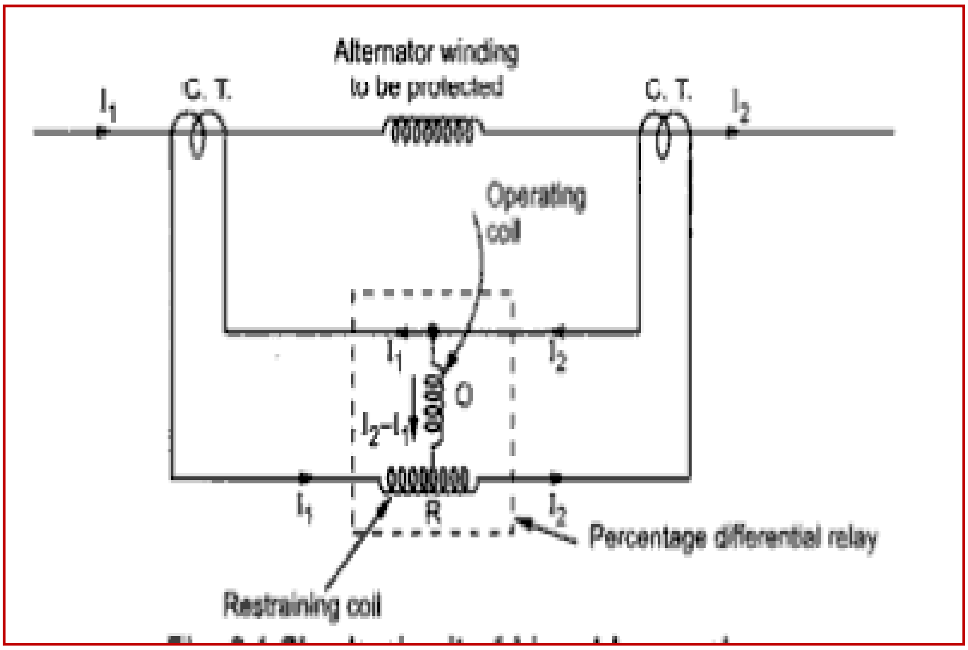


Fig.2.14 Simple circuit of biased beam relay

2.7.3 Voltage balance differential relay

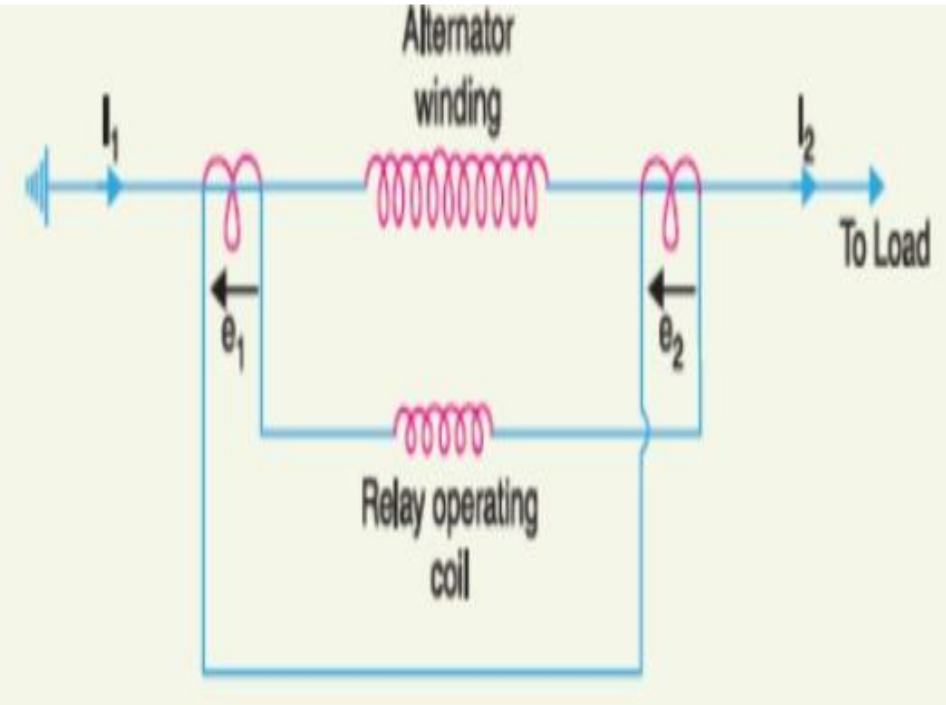


Fig. 2.15 Voltage balance differential relay

- ✓ Also called opposed voltage method
- ✓ Over current relay connected in series with sy of CT
- ✓ Under normal condition, current @ends of section are to be protected are same. Therefore no voltage drop across the relay to cause the current to flow
- ✓ Under fault – I in two sy of CT are diff. This causes a large voltage drop across relay. Thus the voltage balance of the ckt gets disturbed.
- ✓ Hence large current thro relay due to which the relay operate to open the CB.

2.8 Distance Relay

- Dependent on V/I ratio or Z
- Also called impedance relay or ratio relay
- Z--- is a measure of distance along a transmission line
- Relay operates when Fault impedance<predetermined value ($Z_f < Z_{line}$)
- Three types
  - – Impedance relay
  - – Reactance relay
  - – Admittance or mho relay

2.8.1 Impedance relay

- ✓ Current element fed by CT
- ✓ Voltage element fed by PT
- ✓ I element– T_{op}(+ve) or pickup torque
- ✓ V element- T_{res}(-ve) or reset torque
- ✓ Two element T α I, T α V
- ✓ AB – line to be protected
- ✓ Under normal condition
  - ✓ V/I = Z_L (impedance of the line)
  - ✓ Relay inoperative
- ✓ Fault occurred @ F
  - ✓ V decreases I increases
  - ✓ V/I = Z_f decreases
  - ✓ $Z_f < Z_L$
  - ✓ Trips the ckt

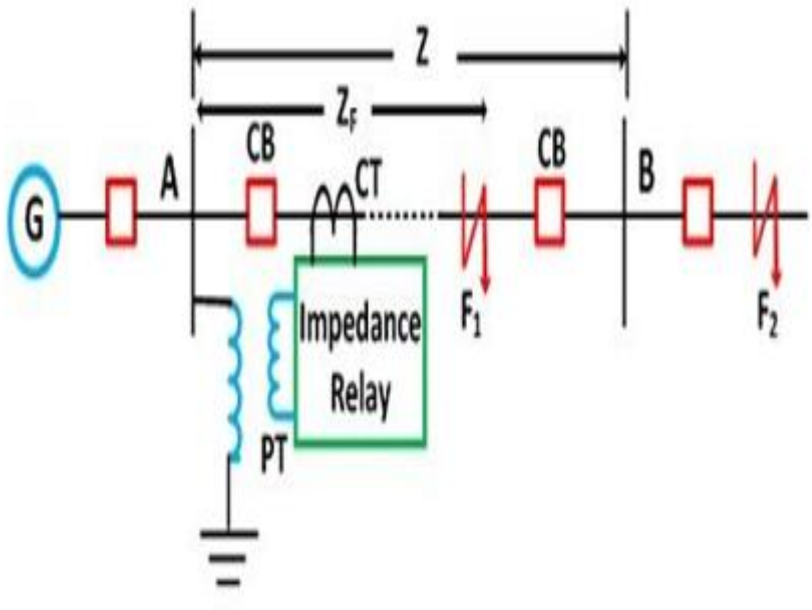


Fig.2.16 Principle of operation of impedance relay

- Universal torque equation is

$$T= K_1I^2+K_2V^2+K_3VI\cos(\theta-\tau)+K_4$$

Restraining torque, operating torque, spring effect

For restraining and spring effect ----- negative

4.2.1 Torque Equation

The positive torque produced by the current element is proportional to I^2 while the negative torque produced by the voltage element is proportional to V^2.

Let control spring effect produces a constant torque of $-K_3$.

Hence the torque equation becomes,

$$T = K_1 I^2 - K_2 V^2 - K_3 \qquad \dots (1)$$

where K_1, K_2 are the constants, while V and I are r.m.s. values.

At the balance point, when the relay is on the verge of operating, the net torque is zero hence we can write,

$$0 = K_1 I^2 - K_2 V^2 - K_3$$

$$\therefore \quad K_2 V^2 = K_1 I^2 - K_3 \qquad \dots (2)$$

Dividing both sides by $K_2 I^2$,

$$\frac{V^2}{I^2} = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$

$$\therefore \quad Z^2 = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$

$$\therefore \quad Z = \sqrt{\frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}} \qquad \dots (3)$$

Generally the spring effect is neglected as its effect is dominant at low currents which generally do not occur in practice. So with $K_3 = 0$,

$$Z = \sqrt{\frac{K_1}{K_2}}$$

$$= \frac{V}{I} = \text{constant} \qquad \dots (4)$$

Operating characteristics of R-X diagram

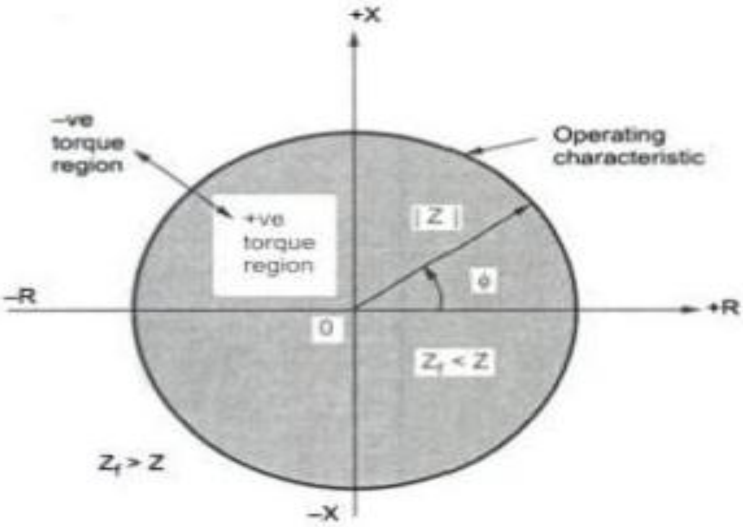


Fig.2.17 Characteristics of impedance relay on R-X diagram

$$Z = R + jX$$
$$|Z| = \sqrt{R^2 + X^2}$$
$$Z^2 = R^2 + X^2 \quad \ldots (1)$$

$$(x - x_1)^2 + (y - y_1)^2 = r^2$$

x_1, y_1 center

r = radius

Z_f = Impedance between relay and fault point

Z = Set value for impedance = Radius of circle

$Z_f < Z$ … relay operates

$Z_f > Z$ … relay is inoperative

2..8.1.1 Directional impedance relay

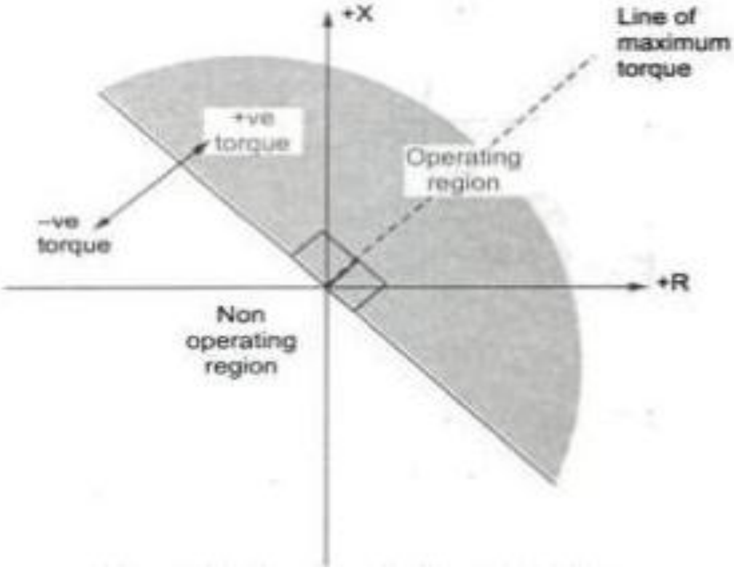


Fig.2.18 Directional characteristics

$$T \propto \phi_V \phi_I \sin(\phi_V \wedge \phi_I)$$

$$\propto \phi_V \phi_I \sin(\theta + \phi)$$

$$\phi_V \propto V \quad \text{and} \quad \phi_I \propto I$$

$$\boxed{T = KVI \sin(\theta + \phi)}$$

$$\phi = 90^\circ - \tau$$

Substituting in the torque equation,

$$T = KVI \sin(\theta + 90^\circ - \tau)$$

$$T = KVI \cos(\theta - \tau)$$

2.8.2 Reactance relay

- ✓ T_{op}– current
- ✓ T_{res}– I-V directional relay
- ✓ Induction cup type
- ✓ 4 pole --- operating coil, polarising coil and restaining coil
- ✓ I flows from pole 1 to 3.
- ✓ Top– produced by interaction of fluxes due to pole 1,2,3 (operating and polarizing)
- ✓ T_{res}– due to pole 1,3,4 (polarizing and restraining)
- ✓ $T_{op} \alpha I^2$
- ✓ $T_{res} \alpha$ VI
- ✓ Desired max torque angle is obtained with help of RC circuit

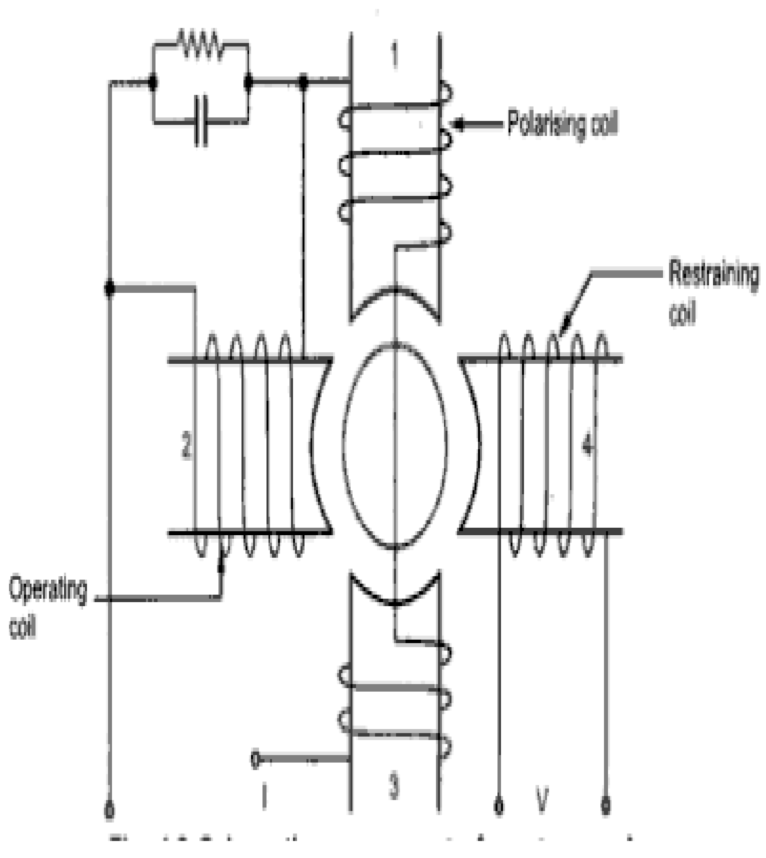


Fig.2.19 Reactance relay

Torque equation

The driving torque is proportional to the square of the current while the restraining torque is proportional to the product of V and I.

Hence the net torque neglecting the effect of spring is given by,

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

At the balance point net torque is zero,

$$\therefore \quad 0 = K_1 I^2 - K_2 V I \cos(\theta - \tau)$$

$$\therefore \quad K_1 I^2 = K_2 V I \cos(\theta - \tau)$$

$$\therefore \quad K_1 = K_2 \frac{V}{I} \cos(\theta - \tau)$$

$$\therefore \quad K_1 = K_2 Z \cos(\theta - \tau)$$

Adding capacitor, the torque angle is adjusted as 90°,

$$\therefore \quad K_1 = K_2 Z \cos(\theta - 90^\circ)$$

$$\therefore \quad K_1 = K_2 Z \sin\theta$$

$$\therefore \quad Z \sin\theta = \frac{K_1}{K_2}$$

Consider an impedance triangle shown in the Fig. 1.44.

$$Z \sin\theta = X = \text{reactance}$$

$$Z \cos\theta = R = \text{resistance}$$

$$X = \frac{K_1}{K_2}$$

$$= \text{constant}$$

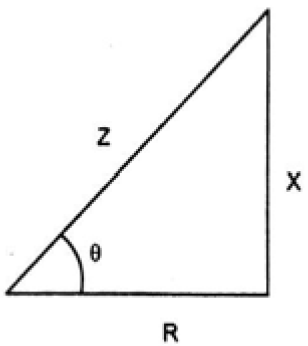


Fig.2.20 Impedance Triangle

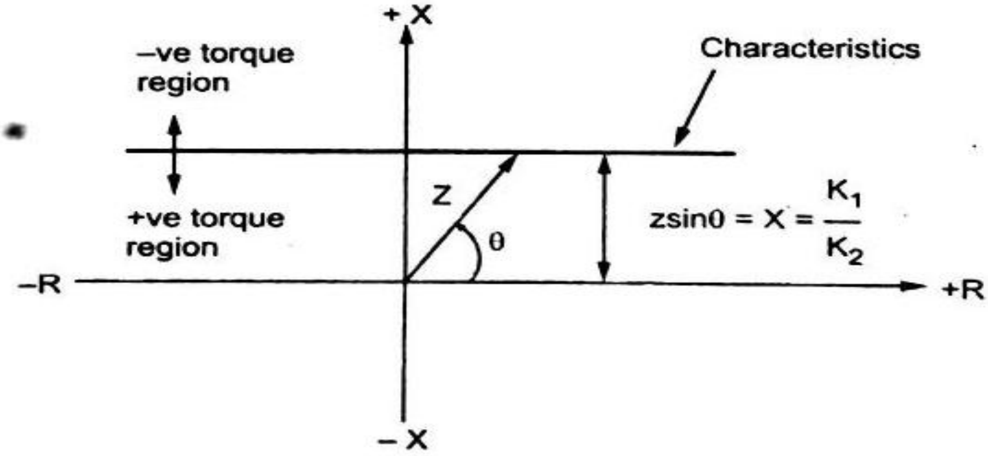


Fig.2.21 Operating characteristics of reactance relay

2.8.3 Mho relay or admittance relay

- Top– interaction of fluxes of pole 1,2,3(voltage & current element)
- T_{res}– interaction of fluxes of pole 1,3,4 (Voltage element)
- $T_{res} \alpha V^2$
- $T_{op} \alpha VI$
- Torque angle adjusted using series tuning circuit.

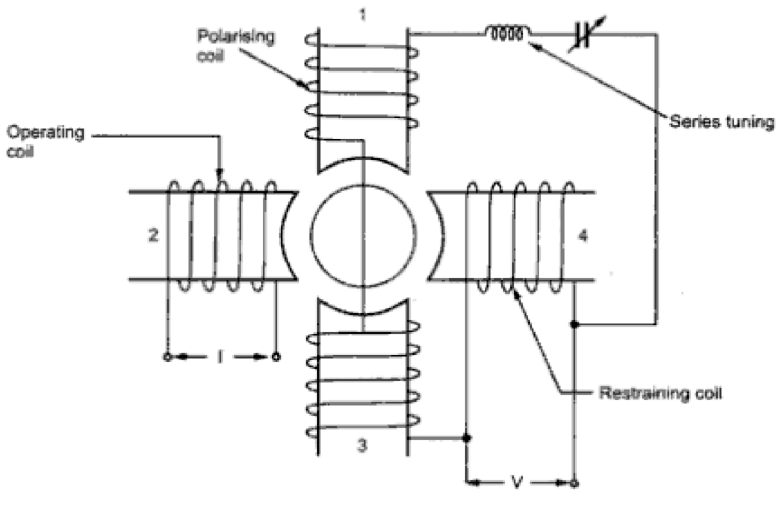


Fig.2.22 Mho relay

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

where K_3 = control spring effect

Generally control spring effect is neglected ($K_3 = 0$).

And at balance net torque is also zero.

$$\therefore \quad 0 = K_1 V I \cos(\theta - \tau) - K_2 V^2$$

$$\therefore \quad K_1 V I \cos(\theta - \tau) = K_2 V^2$$

$$\therefore \quad K_1 \cos(\theta - \tau) = K_2 \frac{V^2}{VI}$$

$$\therefore \quad K_1 \cos(\theta - \tau) = K_2 \frac{V}{I}$$

$$\therefore \quad Z = \frac{K_1}{K_2} \cos(\theta - \tau)$$

- $\tau = 45^o, 60^o, 75^o$
- $\tau = 45^o$ used for HV (33kV or 11kV distribution line)
- $\tau = 60^o$ used for 66kV or132kV
- $\tau = 75^o$ used for 275kV and 400kV line

Operating characteristics

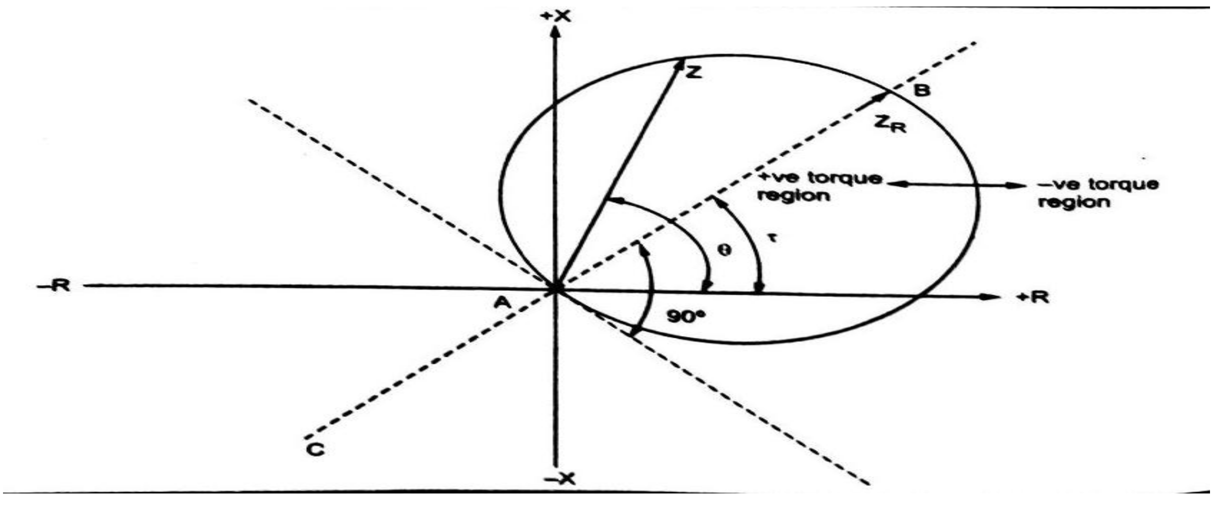


Fig.2.23 Operating characteristics of mho relay

2.9 Classification distance relay

- 1) Definite Distance relay
- Can be Z, X,Y type
- Operates instantaneously for the faults upto certain predetermined distance.
- 2) Distance Time Relay
- Can be Z,X,Y type
- Time of operation α distance of fault from pt where relay installed.
- Fault nearer to relay –operates faster
- Fault far from relay– operates slower

2.9.1 Definite distance Type Impedance relay

- Balanced beam pivoted at central point
- Beam carries armature of two electromagnet
- $T_{res} \alpha V^2$ $T_{res}=k_1V^2$
- $T_{op} \alpha I^2$ $T_{op}=k_2I^2$
- Normal condition $T_{res}>T_{op}$---relay inoperative
- @Fault - - $Z_f=V/I$…. I increase … Z_f decreases… $Z_f<Z_L$…..Top> Tres …Therefore Beam experience a pull on I coil side…closes the trip ckt…CB open

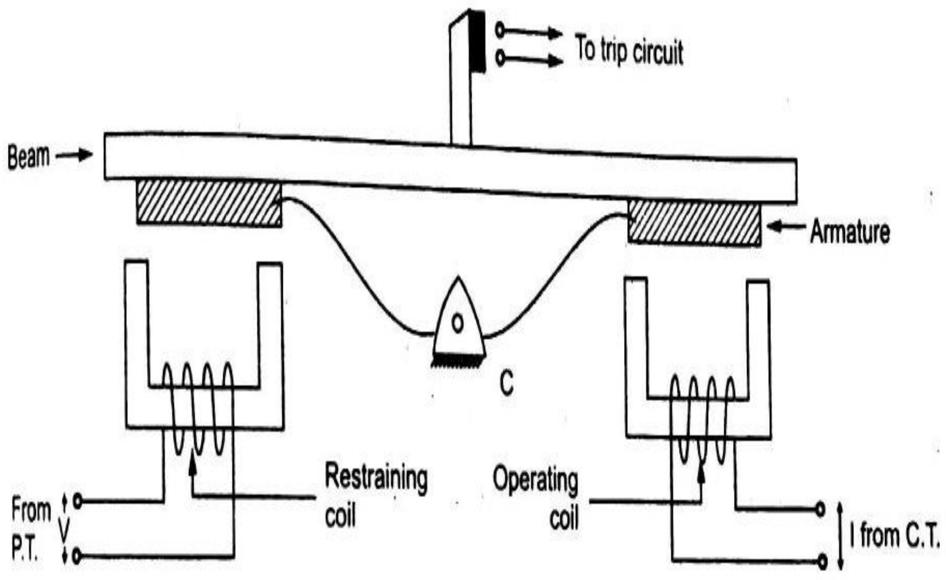


Fig.2.24 Definite distance Type Impedance relay

$T_{res}<T_{op}$

$$K_1 V^2 < K_2 I^2 \quad \ldots \text{ relay operates}$$

$$K_1, K_2 = \text{constants}$$

$$\frac{V^2}{I^2} < \frac{K_2}{K_1}$$

$$\frac{V}{I} < \sqrt{\frac{K_2}{K_1}}$$

$$Z < \sqrt{\frac{K_2}{K_1}}$$

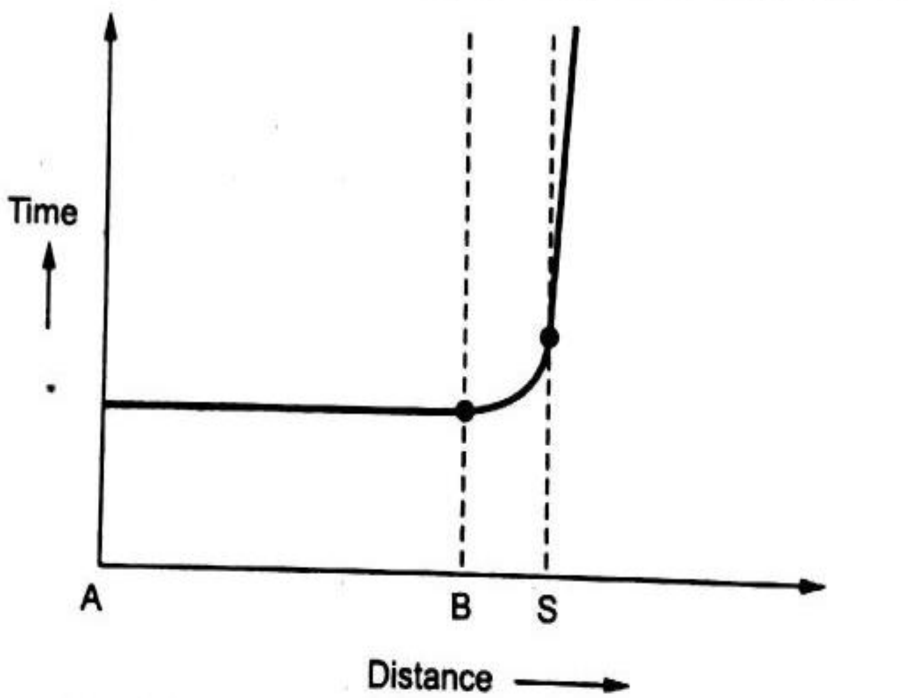


Fig.2.25 characteristics of Definite distance Type Impedance relay

K_1 and K_2 dependent on ampere turns of the 2 electromagnet

AB length– time of operation remains constant irrespective of distance

For unprotected line , if fault occurs then time suddenly reaches infinite

2.9.2 Distance Time Impedance Relay

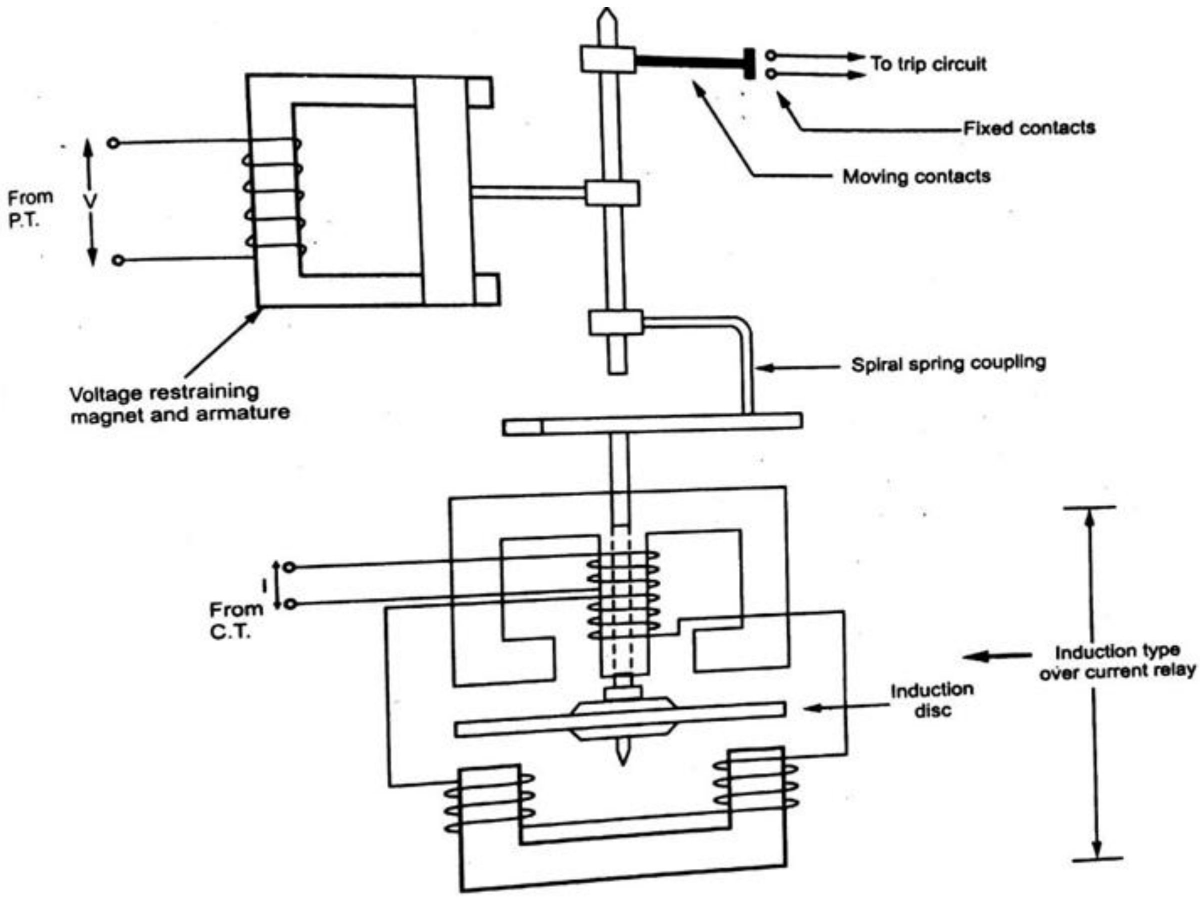


Fig.2.26 Distance Time Impedance Relay

- Consists of Induction type Over Current relay driven by current element.
- Spindle carrying disc is also connected to a 2^{nd} spindle with help of spiral spring coupling.
- 2^{nd} spindle carries moving contacts which can bridge the trip contacts
- Normal condition– contacts are open- $F_{res}>F_{oc}$ induction element.
- Under fault– induction disc rotates--$N_{disc}\alpha\ I_{op}$ (no spring effect)- spiral spring wound exerts force on armature—to pull it away from V restrained magnet
- Disc rotates continuously, till tension of spring is sufficient to overcome Fres

2.10 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.(causes overheating)

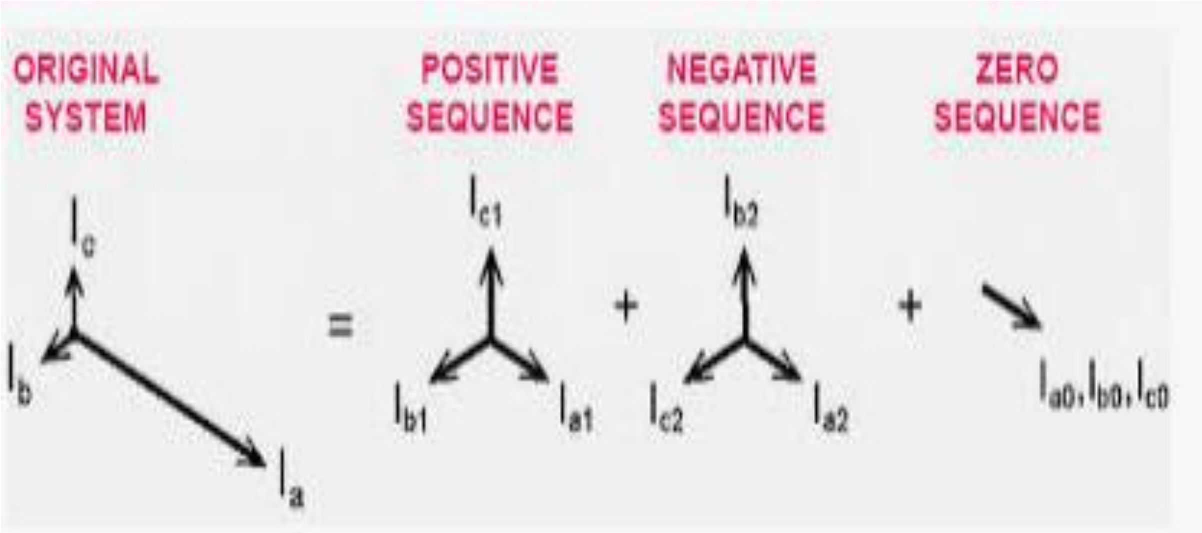


Fig.2.27 symmetrical components

Negative Sequence Relay

- During fault, Phase sequence is reversed RYB to RBY
- Phase unbalance relay
- Protection against negative sequence component of unbalanced currents due to unbalance load, 3 ph faults
- Unbalanced currents – dangerous-Generator and Motor—over heating
- Negative sequence relay- has filter ckt – operates only for –ve seq component

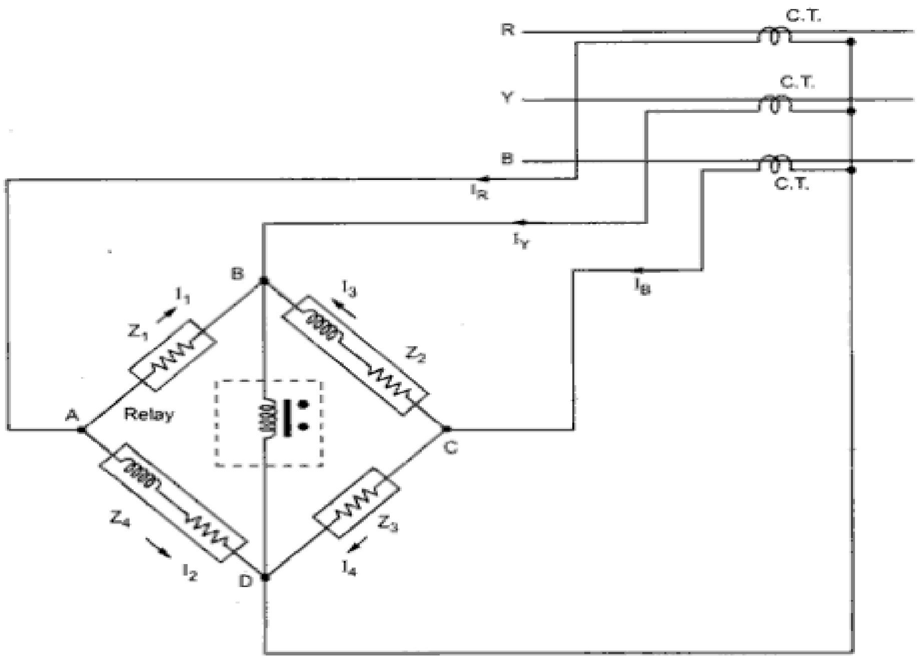


Fig.2.28 Negative sequence relay

Current entering relay at junction B of the bridge is $I_{relay}=I_1+I_3+I_Y$

- Low order of over current also can cause dangerous situations hence a negative sequence relay has low current settings.
- Provides protection against phase to phase faults.
- It consists of resistance bridge network.
- The magnitude of all the branches of the network are equal.
- The impedances Z_1 and Z_3 are purely resistive.
- Branch Z_2 and Z_4 are the combination of resistance and reactance.
- The currents in the branches Z_2 and Z_4 lag by 60^0 from the currents in the branches Z_1 and Z_3.

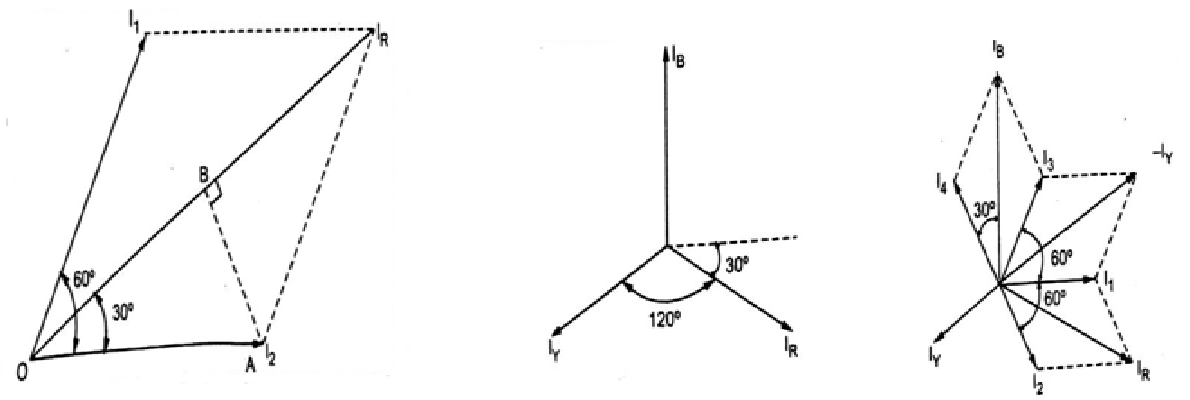


Fig.2.29 vector diagram

Balanced load

$I_1+I_3=-I_y$ (from the vector diagram)

$I_1+I_3+I_y=0$

During balanced Condition, Current entering the relay at junction B of the bridge is zero. Therefore the relay is inoperative.

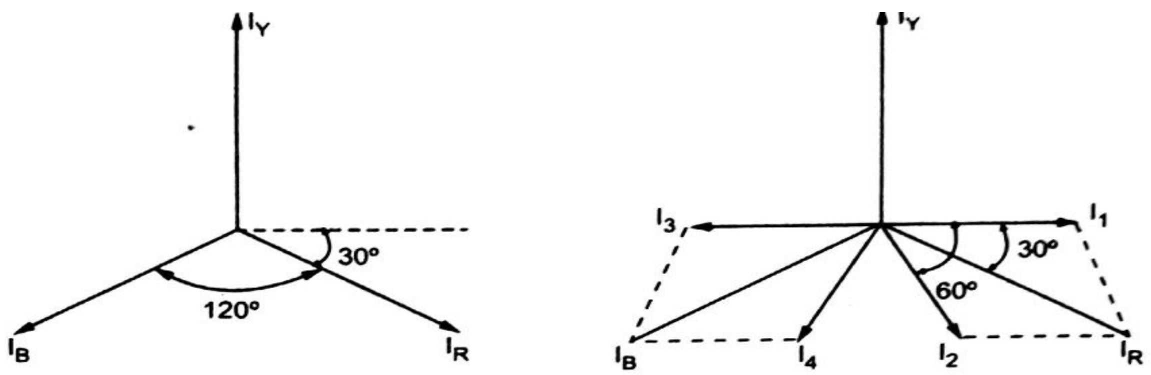


Fig.2.30 Secondary CT currents and vector sum

Unbalanced load

During unbalanced load on generator or motor, negative sequence current exist. Thus phase sequence changes from RYB to RBR with 120^o phase shift.

From vector diagram, I_1 and I_3 are equal and opposite. Therefore cancel each other.

Hence $I_{relay}= I_Y$. This current $I_Y> I_{set}$

Thus the relay operates.

Delta connection of CTs

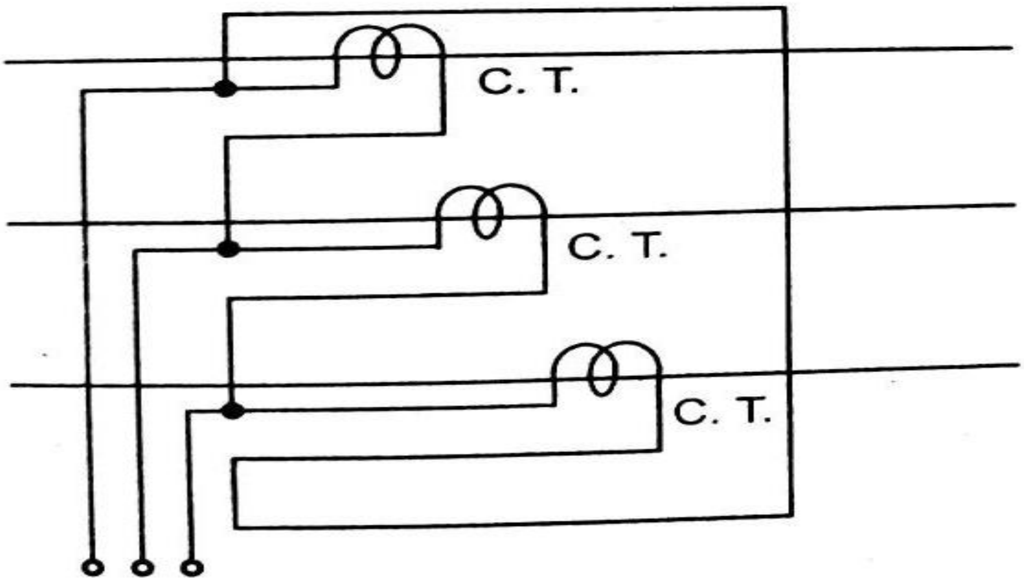


Fig.2.31Delta connection of CTs

To make the relay sensitive to only negative sequence currents by making it inoperative under the influence of zero sequence currents is possible by connecting the current transformers in delta connection

2.11 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.

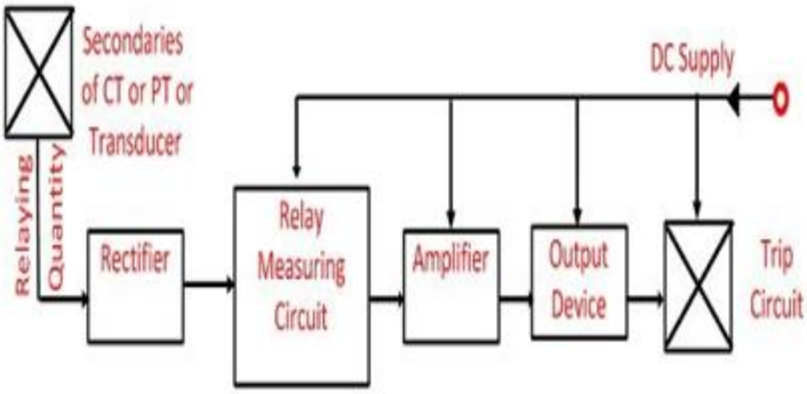
- 

Fig.2.32 Block diagram of static relay

- 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 relay 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 Relay
- The static relay consumes very less power because of which the burden on the measuring instruments decreases and their accuracy increases.
- The static relay gives the quick response, long life, high reliability and accuracy and it is shockproof.
- The reset time of the relay is very less.
- It does not have any thermal storage problems.
- The relay amplifies the input signal which increases their sensitivity.
- The chance of unwanted tripping is less in this relay.

- The static relay can easily operate in earthquake-prone areas because they have high resistance to shock.
- **Limitations of Static Relay**
- The components used by the static relay are very sensitive to the electrostatic discharges. The electrostatic discharges mean sudden flows of electrons between the charged objects. Thus special maintenance is provided to the components so that it does not affect by the electrostatic discharges.
- The relay is easily affected by the high voltage surges. Thus, precaution should be taken for avoiding the damages through voltage spikes.
- The working of the relay depends on the electrical components.
- The relay has less overloading capacity.
- The static relay is more costly as compared to the electromagnetic relay.
- The construction of the relay is easily affected by the surrounding interference.

2.12 Comparator

- When fault occurs, the magnitude of voltage and current , phase angle between V and I may change.
- These quantities are different from faulty to health conditions .
- Static relay is used to distinguish it and gives a trip signal to CB.

Types of comparator

- **Amplitude comparator**
  - Compares magnitude of two input quantities, irrespective of the angle between them.
  - Two inputs are--- (M)operating and (N)restraining quantity
  - Operating qty> restraining qty--- relay should operate
- **Phase Comparator**
  - Compares phase angle of 2 quantities, irrespective of their magnitudes and operates if the phase angle between them is <=90

2.13 Duality between Amplitude and Phase Comparator

2.13.1Amplitude comparator used for phase comparison

An amplitude comparator can be converted to a phase comparator and vice versa if the input quantities to the comparator are modified. The modified input quantities are the sum and difference of the original two input quantities. To understand this fact, consider the operation of an amplitude comparator which has two input signals M and N as shown in Fig. 2.33(a). It operates when $|M| > |N|$. Now change the input quantities to $(M + N)$ and $(M – N)$ as shown in

Fig. 2.19(b). As its circuit is designed for amplitude comparison, now with the changed input, it will operate when $|M + N|$

> $|M – N|$. This condition will be satisfied only when the phase angle between *M* and

N is less than 90°. This has been illustrated with the phasor diagram shown in Fig.

2.34. It means that the comparator with the modified inputs has now become a phase comparator for the original input signals *M* and *N*.

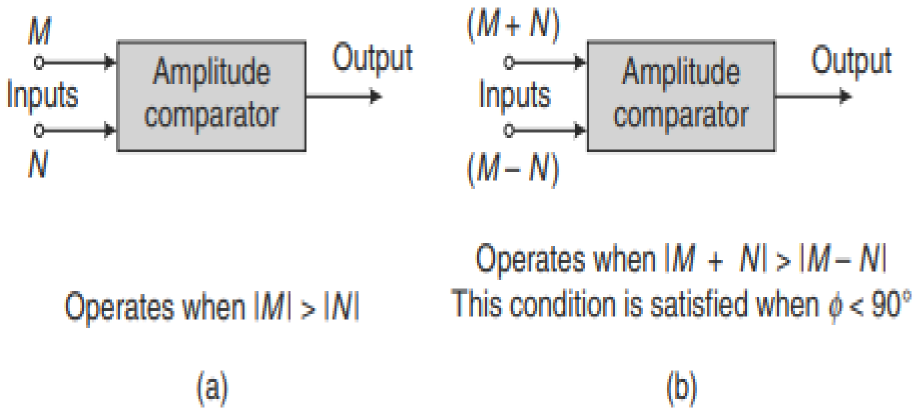


Fig.2.33 (a) Amplitude comparator (b) Amplitude comparator for phase comparison

- The modified input quantities are the sum and difference of the original two input quantities.
- Amplitude comparator which has two input signals M and N. It operates when |M| > |N|.
- Now change the input quantities to (M + N) and (M – N). As its circuit is designed for amplitude comparison, now with the changed input, it will operate when |M + N| > |M – N|. This condition will be satisfied only when the phase angle between M and N is less than 90°.

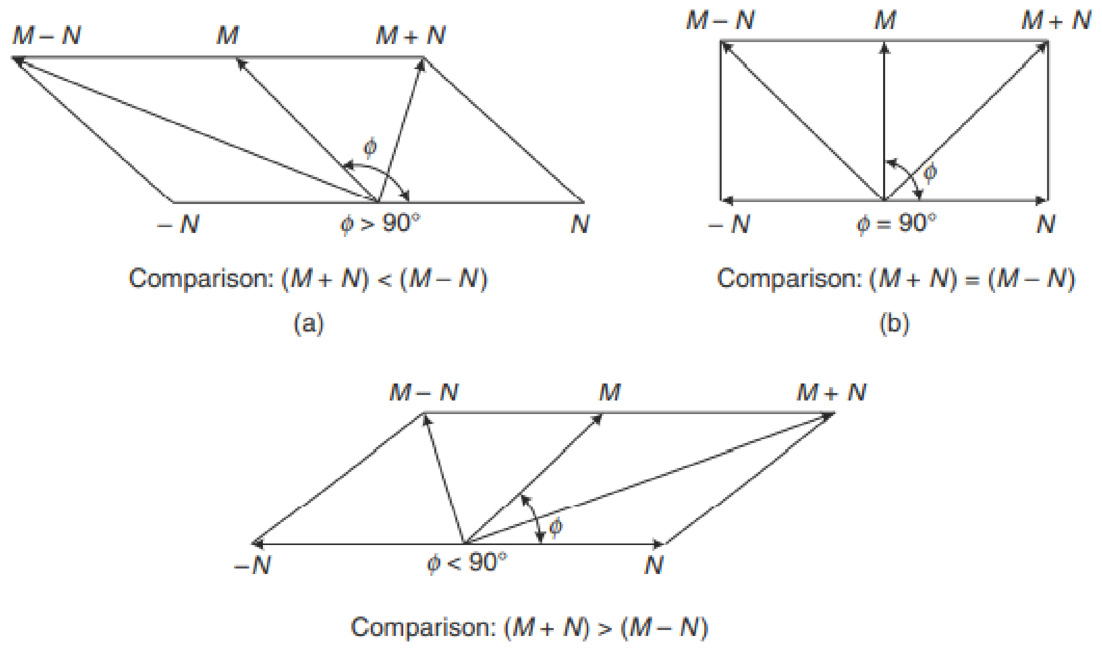


Fig.2.34 phasor diagram for amplitude comparator used for phase comparison

2.13.2 Phase comparator used for amplitude comparison

Similarly, consider a phase comparator shown in Fig. 2.35(a). It compares the phases of input signals *M* and *N*. If the phase angle between *M* and *N*, i.e. angle f is less than 90°, the comparator operates. Now change the input, signals to ($M + N$) and ($M - N$), as in Fig. 2.35(b). With these changed inputs the comparator will operate when phase angle between ($M + N$) and ($M - N$), i.e. angle l is less than 90°. This condition will be satisfied only when $|M| > |N|$. In other words, the phase comparator with changed inputs has now become an amplitude comparator for the original input signals *M* and *N*. This has been illustrated with phasor diagrams as shown in Fig. 2.36.

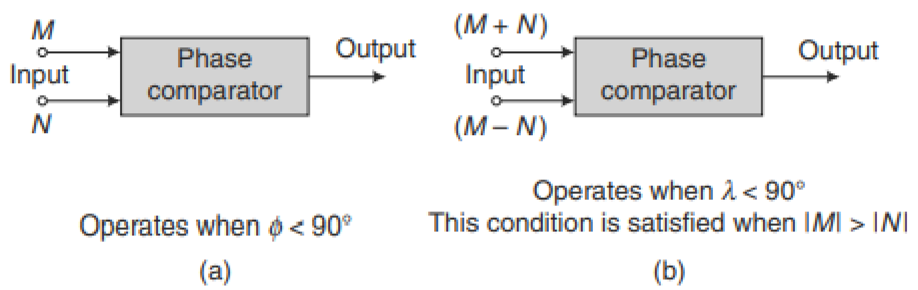


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Fig.2.35 (a) Phase comparator (b) Phase comparator used for amplitude comparison

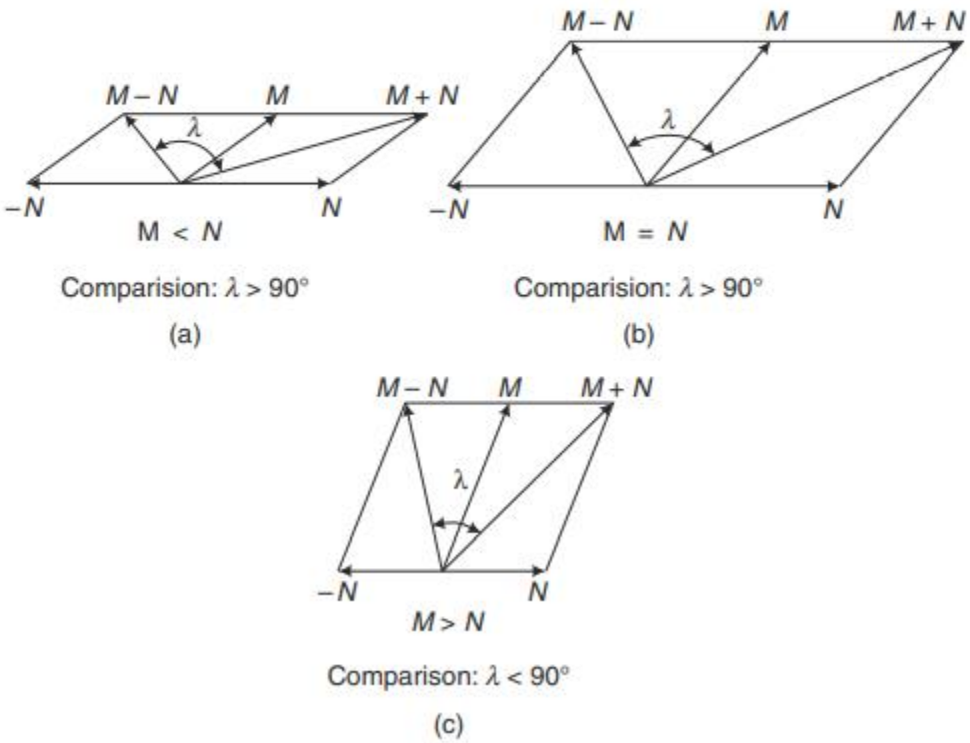


Fig.2.36 Phase comparator used for amplitude comparison

Figure 2.34 shows three phasor diagrams for an amplitude comparator. The phase angle between the original inputs *M* and *N* is f. Now the inputs to the amplitude com- parator are changed to (*M* + *N*) and (*M* – *N*) and its behaviour is examined with the help of three phasor diagrams. The three phasor diagrams are with phase angle f (*i*) greater than 90°, (ii) equal to 90° and (iii) less than 90°, respectively. When f is less than 90°, |*M* + *N*| become greater than |*M* – *N*| and the relay operates with the modi- fied inputs. When f is equal to 90° or greater than 90°, the relay does not operate.

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

Figure 2.36 shows three phasor diagrams for a phase comparator. The original inputs are *M* and *N*. Now the inputs of the phase comparators are changed to (*M* + *N*) and (*M* – *N*), and its behavior is examined with the help of three phasor diagrams drawn for (i) |*M*| < |*N*|, (ii) |*M*| = |*N*| and (iii) |*M*| > |*N*|. The angle between (*M* + *N*) and (*M* – *N*) is l. The angle l becomes less than 90° only when |*M*| > |*N*|. As the comparator under consideration is a phase comparator, the relay will trip. But for the original inputs *M* and *N*, the comparator behaves as an amplitude comparator. This will be true irrespective of the phase angle f between *M* and *N*. The figure has been drawn with f less than 90°. The reader can check it by drawing phasors with f = 90° or f > 90°. The result will remain the same.

2.14 Types of AmplitudeComparators

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

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

(i) Circulating current type rectifier bridge comparators

(ii) Phase splitting type comparators

(iii) Sampling comparators

2.14.1 Rectifier Bridge Type Amplitude Comparator

The rectifier bridge type comparators are widely used for the realisation of overcur- rent and distance relay characteristics. The operating and restraining quantities are rectified and then applied to a slave relay or thyristor circuit. Figure 2.37(a) shown a rectifier bridge type amplitude comparator. There are two full wave rectifiers, one for the operating quantity and the other for the restraining quantity. The outputs of these bridges are applied to a dc polarised relay. When the operating quantity exceeds the restraining quantity, the relay operates. Figure 2.37(b) shows a rectifier bridge type amplitude comparator with the thyristor circuit as an output device.

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

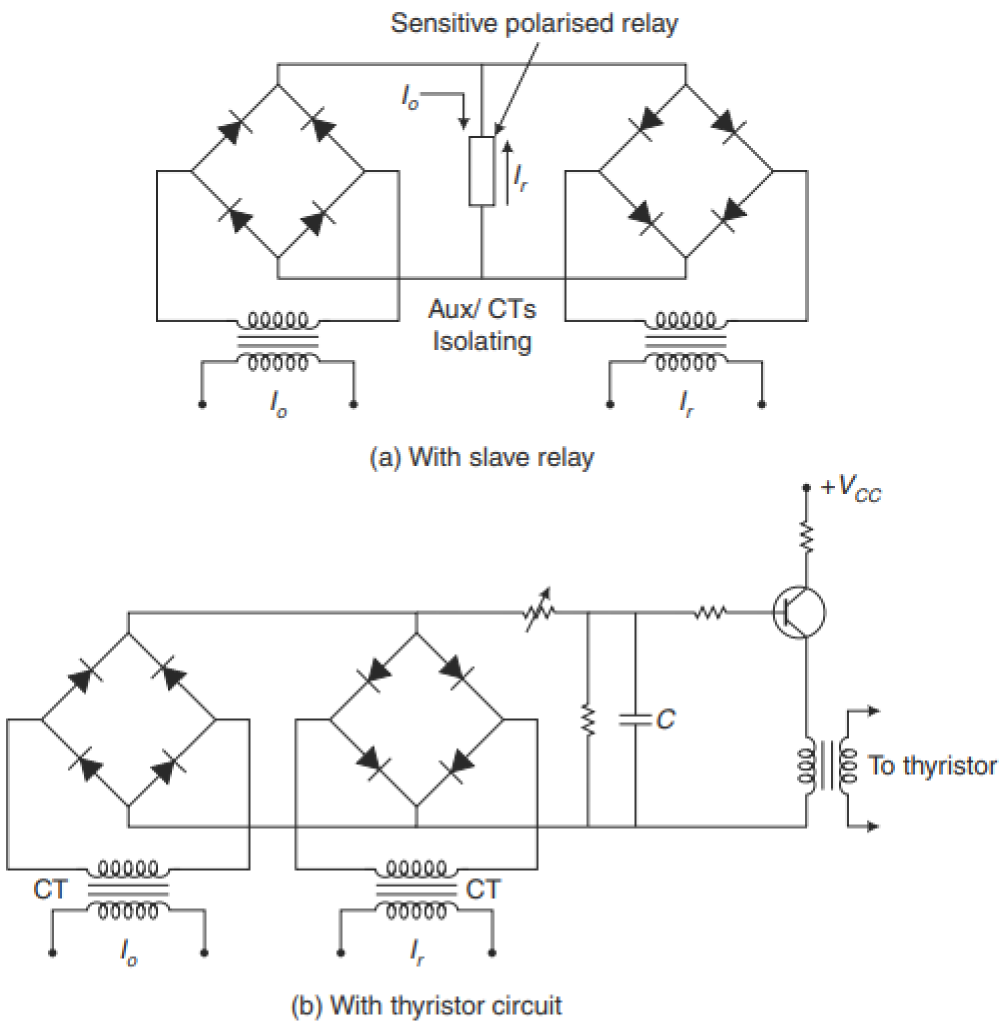


Fig.2.37 Rectifier bridge type amplitude comparator

2.14.2 Phase Splitting Type Amplitude Comparators

Figure 2.38 shows a phase splitting of inputs before rectification. The input is split into six components 60° apart, so that output after rectification is smoothed within 5%.

As both input signals to the relay are smoothed out before they are compared, a con- tinuous output signal is obtained. The operating time depends on the time constant of the slowest arm of the phase-splitting circuit and the speed of the output device.

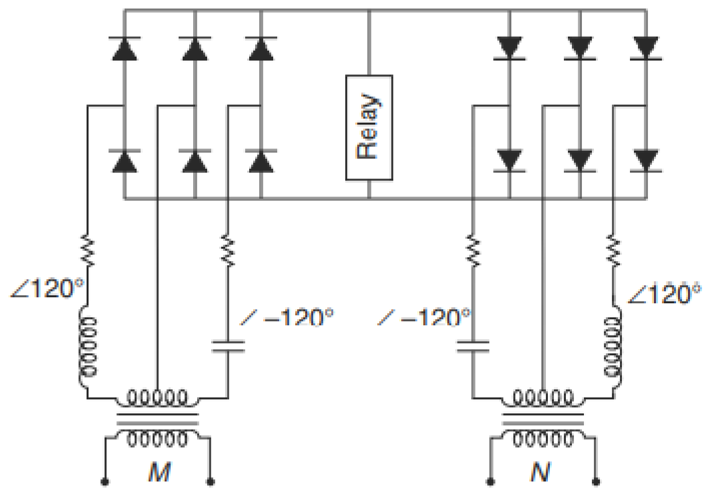


Fig.2.38 Phase splitting type amplitude comparator

2.14.3 Sampling Comparators

In sampling comparators, one of the inputs is rectified and it is compared with the other input at a particular moment. The instantaneous value of the other input is sampled at a particular desired moment.

2.15 Types of Phase Comparators

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

(iv)Vector product phase comparators

(v) Coincidence type phase comparators.

2.15.1 Vector Product Phase Comparators

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

Hall effect phase comparator

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

Magneto-resistivitys

Some semiconductors exhibit a resistance variation property when subjected to a magnetic field. Suppose two input signals are $V1$ and $V2$. $V1$ is applied to produce a magnetic field through a semiconductor disc. $V2$ sends a current through the disc at a right angle to the magnetic filed. The current flowing through the disc is proportional to $V1$ $V2$ cos f, where f is the phase angle between the two voltages. Therefore, this can be used as a phase comparator. This device is considered to be better than the Hall effect type comparator because it gives a higher output, its construction and circuitry are simpler and no polarising current is required. This device is also used only in the USSR.

2.15.2 Coincidence Circuit Type Phase Comparators

In a coincidence circuit type phase comparator, the period of coincidence of positive polarity of two input signals is measured and compared with a predetermined angle, usually 90°. Figure 2.39 shows the period of coincidence represented by an angle y. If the two input signals have a phase difference of f, the period of coincidence y = 180 – f. If f is less than 90°, y will be greater than 90°. The relay is required to trip when f is less than 90°, i.e. y > 90°. Thus, the phase comparator circuit is designed to trip signal when y exceeds 90°.

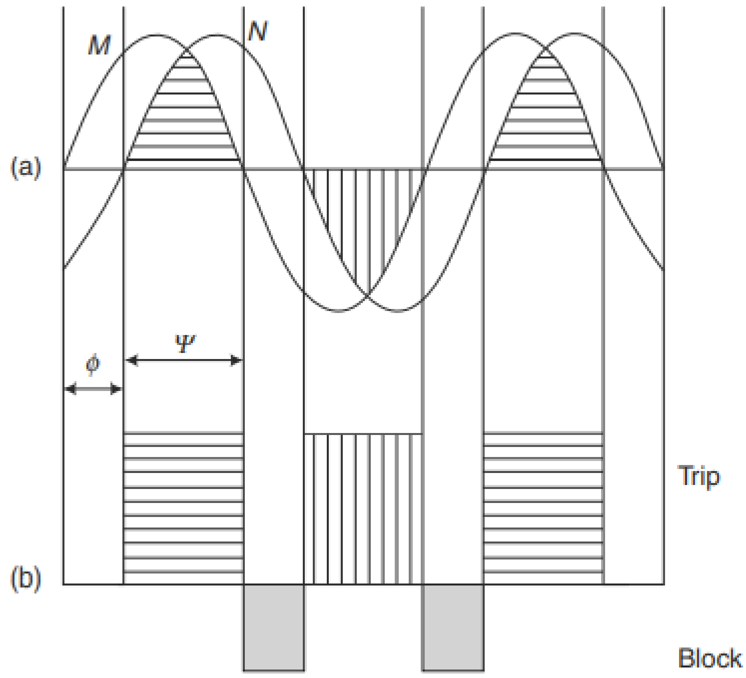


Fig.2.39 Period of coincidence of sine wave inputs

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

(a) Phase-splitting type phase comparator

(b) Integrating type phase comparator

(c) Rectifier bridge type phase comparator

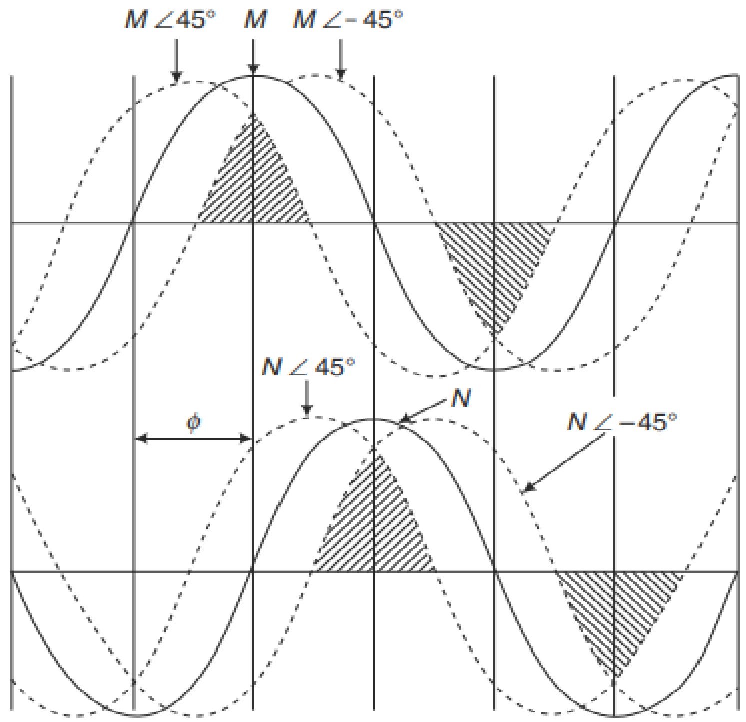
(d) Time-bias type phase comparator.

Phase-splitting Type Phase Comparator

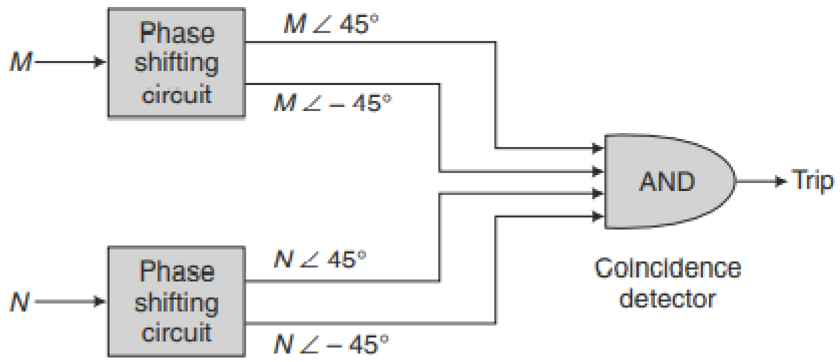
In this technique, both inputs are split into two components shifted ± 45° from the original wave, as shown in Fig. 2.40(a). All the four components, which are now available, are fed into an AND gate as shown in Fig. 2.40(b). The tripping occurs when all the four signals become simultaneously positive at any time during the cycle. An AND gate is used as a coincidence detector. The coincidence of all the four signals occurs only when f is less than 90°. The full range of operation is

– 90° < f < 90°

It is a technique of direct comparison.



(a)



(b)

Fig. 2.40 Phase comparator with phase split inputs…

2.16 Microprocessor based over current relay

An overcurrent relay is the simplest form of protective relay which operates when the current in any circuit exceeds a certain predetermined value, i.e. the pick-up value. It is extensively used for the protection of distribution lines, industrial motors and equip- ment. Using a multiplexer, the mircoprocessor can sense the fault currents of a num- ber of circuits. If the fault current in any circuit exceeds the pick-up value, the micro- processor sends a tripping signal to the circuit breaker of the faulty circuit breaker of the faulty circuit. As the microprocessor accepts signals in voltage form, the current signal derived from the current transformer is converted into a proportional volt- age signal using a current to voltage converter. The ac voltage proportional to the load current is converted into dc using a precision rectifier. Thus, the microprocessor accepts dc voltage proportional to load current.

The block schematic diagram of the relay is shown in Fig. 2.41. The output of the rectifier is fed to the multiplexer. The microcomputer sends a command to switch on the desired channel of the multiplexer to obtain the rectified voltage pro- portional to the current in a particular circuit. The output of the multiplexer is fed to the A/D converter to obtain the signal in digital form. The A/D converter ADC0800 has been used for this purpose. The microcomputer sends a signal to the ADC for starting the conversion. The microcomputer reads the end of conversion signal to examine whether the conversion is over or not. As soon as the conversion is over, the

microcomputer reads the current signal in digital form and then compares it with the pick-up value.

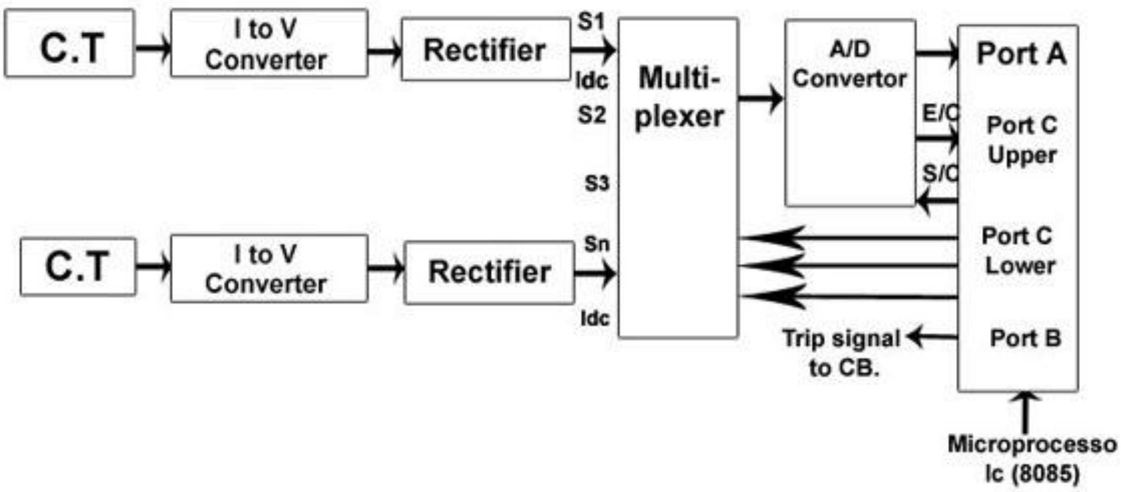


Fig.2.41Schematic diagram of Microprocessor based over current relay

- ✓ C.T - (Current Transformer) -Current is taken from here to the circuit
- ✓ Current is taken from C.T. and given to I to V converter because many electronics circuit require voltage signal for operation.
- ✓ The A.C. voltage is converted into D.C. voltage by using rectifier.

- ✓ The output of rectifier is given to Multiplexer
- ✓ The Multiplexer gives output to A/D Converter
- ✓ Analog DC voltage is converted to Digital form (in form of O and 1 i.e. binary form).
- ✓ Compares the set value with the input value
- ✓ If the input value is more than set value , then it sends signal to circuit breaker

- **Advantages of microprocessor relays**
  - reliability
  - functional flexibility
  - self-checking and self- adaptability.
- **Disadvantages of microprocessor relay**
  - High price
  - reliable operating current required
  - needs electromagnetic compatibility
  - needs information security
  - narrow operating temperature range

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Question Bank

Part-A

Q.No.	Question
1.	Define electromagnetic relay?
2.	Compare operating torque and restraining torque.
3.	Illustrate the purpose of Distance relay.
4.	Classify the types of differential relay
5.	List the advantages of Microprocessors based relay
6.	Why microprocessor based relays have more flexibility than static relays?
7.	Explain about static relay.
8.	Justify static relay better than electromagnet relay.
9.	Define comparator and their types.
10.	List the types of phase comparator

PART – B

Q.No.	Question
1.	Elaborate the Construction, principle of operation and applications of a directional over current relay.
2.	Build and explain the scheme of protecting transmission line using an impedance relay and its operating characteristics on R-X diagram.
3.	Construct with a suitable sketch and explain about principle of operation and applications of a over current relay.
4.	Build the schematic diagram of a phase comparator and explain the various techniques applied in phase comparator.
5.	Construct a suitable sketch and explain the operation of induction type negative phase sequence relay?
6.	Analyze the realisation of a over current relay using a

	microprocessor.
7.	(a) Explain the operation of various building blocks that constitute the static relay. (b) Explain the following terms applied to protective relaying: (i) Plug setting multiplier. (ii) Time setting multiplier.
8.	Discuss the characteristics of the following distance relays in the R- X diagrams and explain. (i) Mho – relay (ii) Reactance relay

UNIT - III

Power System Protection and Switchgear – SEE1401
UNIT III- APPARATUS PROTECTION

III. Apparatus Protection

Protection of Generator- stator & rotor protection - Large Motor protection. Transformer protection - Bus bar Protection - Transmission line protection

3.1 Rotating Machine Protection

- Rotating machines include synchronous generators, synchronous motors, synchronous condensers and induction motors.
- The protection scheme for any machine is influenced by the size of the machine and its importance in the system.
- The failures involving short circuits are usually detected by some type of overcurrent or differential relay.
- Electromechanical, static or microprocessor-based relays can be used stand-alone or in combination with one another to achieve the desired degree of security and dependability.

3.2 GENERATOR PROTECTION

- **Stator faults**

faults associated with 3 ph winding of generator.(insulation failure)

- phase to earth
  - Occur in armature slots
  - Faults are dangerous and cause severe damage to expensive machine.
  - Fault current<20A– less burning of core
  - High fault current– severe burning of core. (Earth fault protection required)
- Phase to phase
  - SC between to phase winding
  - This is uncommon because insulation used between the coils of different phases in a slot is large.
  - Phase-earth fault occurs ------ overheating takes place----- phase to phase fault occurs (occurs at the end connections of the armature winding which are overheating parts outside the slots)
  - This fault causes sever arching with high temperature. This may lead to melting of copper and fire the insulation.

- Inter turn faults
    - Coils used in alternators are multi turn coils
    - SC between the turns of one coil may occur which is called inter turn fault.
    - This fault is due to current surges with high value of Ldi/dt voltage across the turns.

- **Rotor faults**
  - Rotor--- field winding
    - SC between the turns of winding
    - conductor to earth fault
  - Above faults due to severe mechanical and thermal stresses acting on field winding insulation

- **Abnormal running conditions**

  Following are the some of the abnormal conditions

- Overloading
  - Overloaded– overheating of stator—increases winding temp—insulation fails(over current protection)
- Over speeding
  - Hydraulic generators –loss of load—over speeding.
  - This is because water flow cannot be stopped instantly.
  - Turbo governor is provided to prevent over speeding
- Unbalanced Loading
  - Circulation of negative sequence currents.
- Overvoltage
  - This is due to…
    - over speeding of generator
    - Faulty operation of voltage regulator
    - Atmospheric surge voltage caused by direct lightning stroke.(this voltage is transferred to the generator . Thus to protect generator, surge arrester or surge capacitors are used)
- Failure of prime mover
  - This results in motoring operation of synchronous generator

- Generator draws active power from the network and continues to run at synchronous speed as a synchronous motor.
- This leads to dangerous mechanical conditions if allowed to persists for more than 20secs(directional power relay)

- Loss of excitation
  - Opening of field wdg
  - SC in field
  - Fault in exciter system

Should not persist long--- disconnection of alternator

- Cooling system failure

3.2.1 Merz-Price Protection of Stator Windings(Star connected)

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.

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.

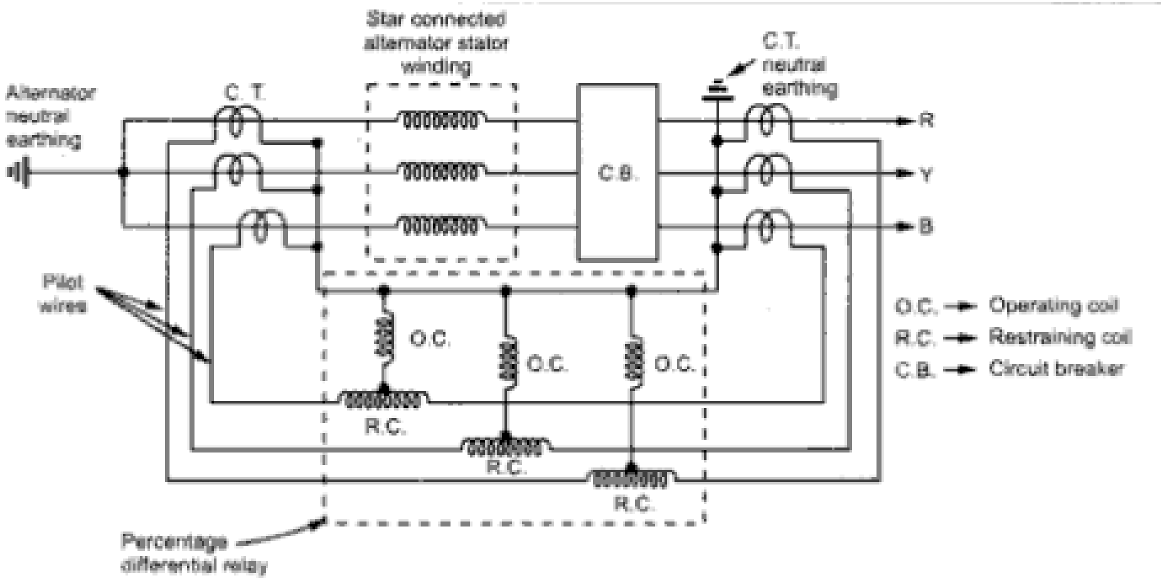

Fig. 3.1 Merz-Price Protection of Stator Windings (Star connected)

The similar arrangement is used for the delta connected alternator stator winding, as shown below.

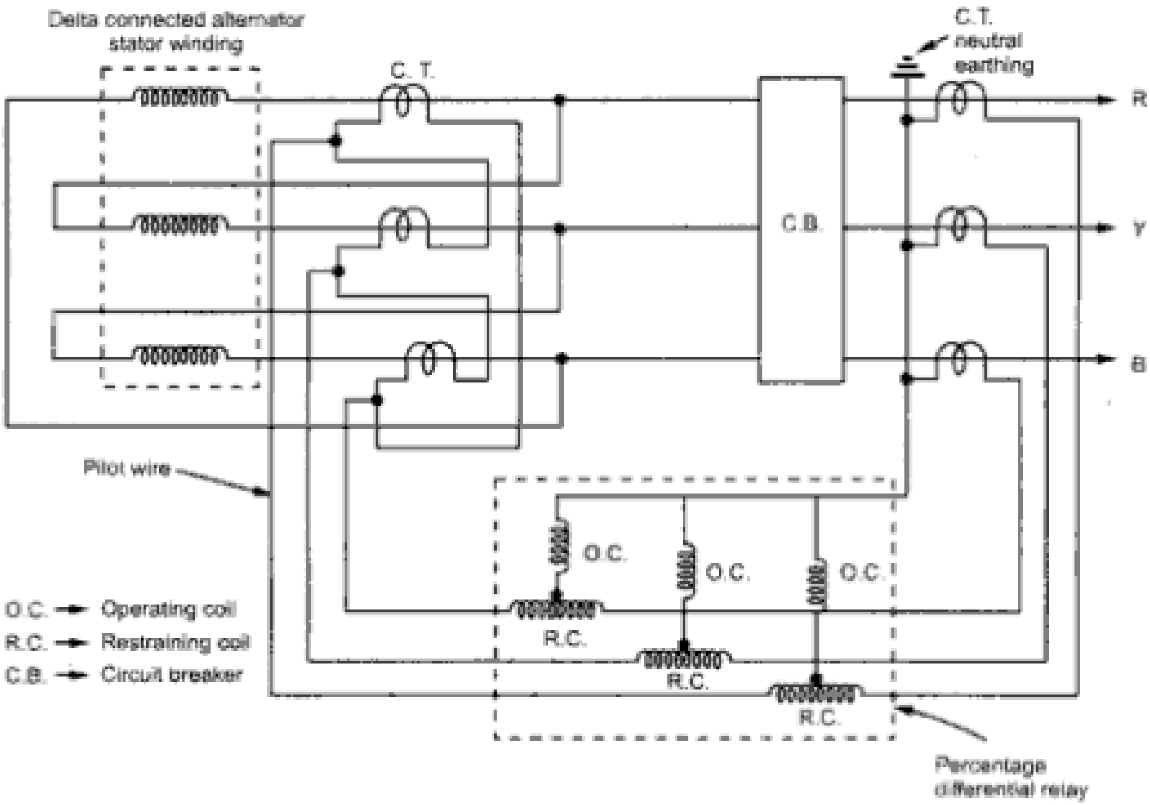

Fig. 3.2 Merz-Price Protection of Stator Windings (Delta connected)

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.

3.2.2 Restricted Earth Fault Protection

Merz price is used for internal faults. Restricted earth fault protection is required for large generators which are costly.

- For solidly grounded,
  - the generator gets completely protected against earth faults.
- But when neutral is grounded through resistance,
  - then stator winding gets partly protected against the earth faults.

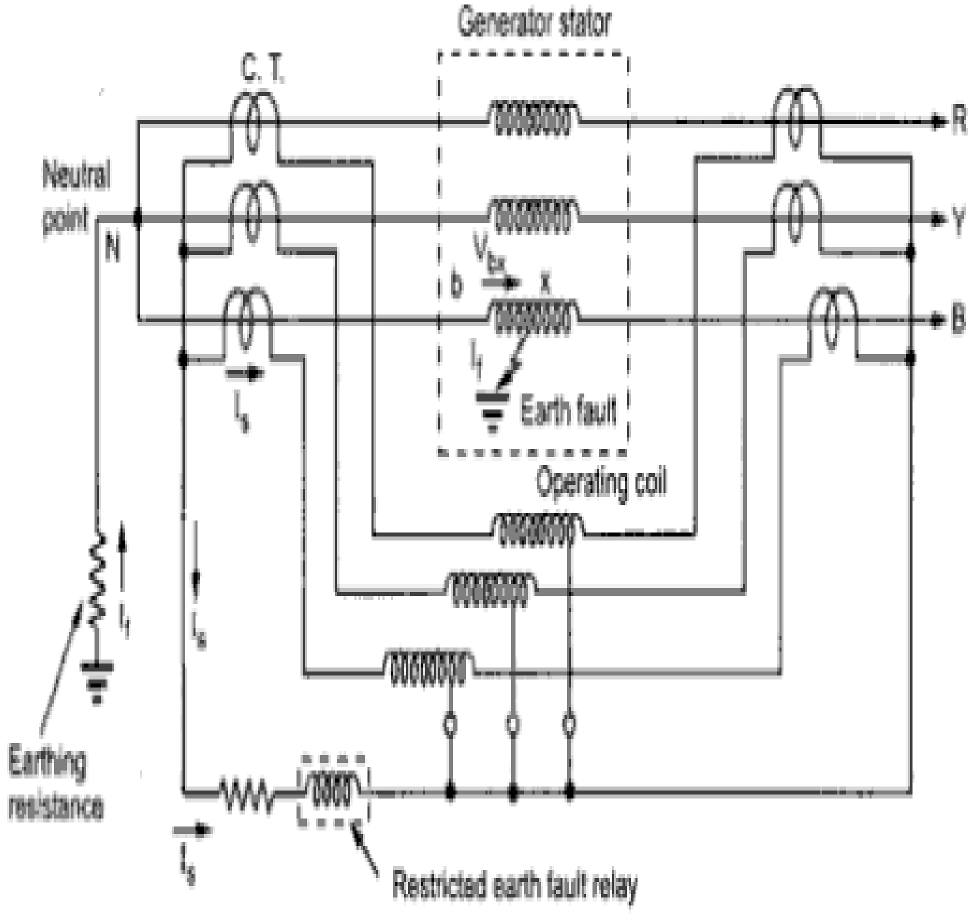

Fig. 3.3 Restricted Earth fault relay

- The percentage of winding protected depends on the value of earth resistance and relay setting.
- Earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less.
- But when earth occurs near neutral point insufficient voltage across the fault drives very low fault current than the pick up current of the relay coil. Hence relay coil is inoperative.
- Thus 15% to 20% of the winding from the neutral side is unprotected. Hence called restricted earth fault relay.
- Fault occurs on phase B- breakdown of insulation to earth
- Fault current I_f flows thro- core, frame of machine to earth and earth resistance.
- CT secondary current I_s flows thro the operating coil and restricted earth fault relay coil of the differential protection.
- As the current I_s flows, the relay operates to trip the CB. The voltage V_{bx} is sufficient to drive the enough fault current I_f when the fault point is x is away from the neutral point.

- If the fault point x is nearer to the neutral point then the voltage V_{bx} is small and not sufficient to drive enough fault current I_f. Thus relay does not operate and part of the winding from the neutral point is unprotected.

3.2.3Unrestricted Earth Fault Protection

The unrestricted earth fault protection is used to protect the 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.

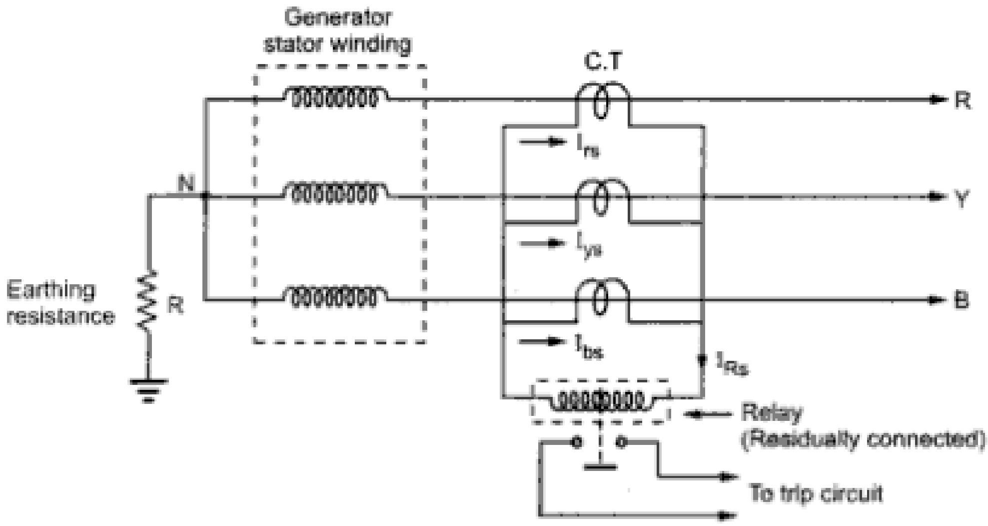

Fig.3.4 Unrestricted Earth Fault Protection

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.

3.2.4 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.

Connection of Balanced Earth Fault Protection Scheme

In this scheme, the current transformers are mounted on each phase. Their secondary is connected in parallel with that of CT mounted on a conductor joining the star point of the generator to earth. A relay is connected across the secondaries of the CTs.

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.

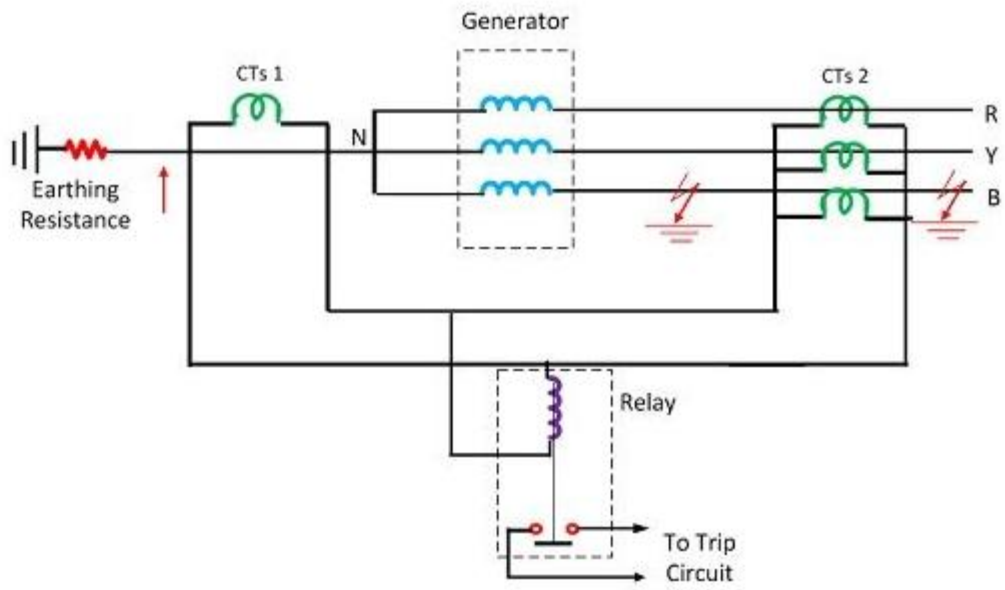

Fig. 3.5 Balanced earth fault protection

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.

3.2.6 100 % Earth Fault Protection

- Maximum protection achieved by other schemes is up to 85% to 90%.
- 100% earth fault protection to the stator of the generator.
- It uses a coupling transformer and coded signal current.

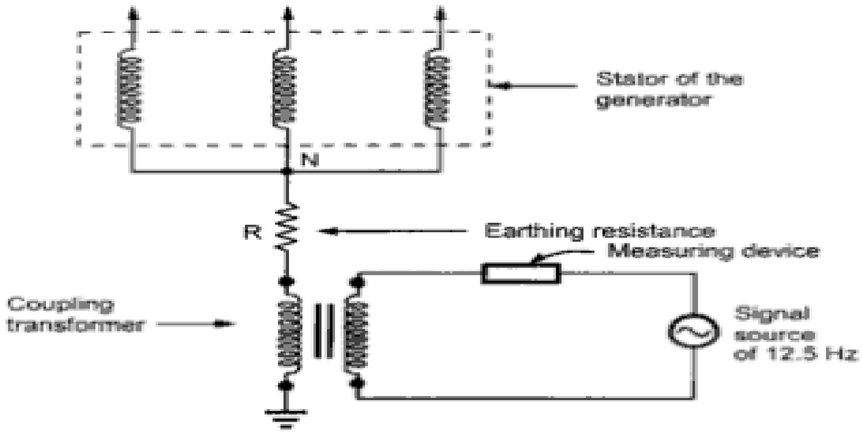

Fig.3.6 100% Earth fault protection

- A coupling transformer is connected between the earth and the earthing resistance R in neutral to ground circuit.
- Primary of coupling transformer is excited by coded signal current source.
- This coded signal current has a frequency of 12.5Hz.
- This current is continuously injected into a generator stator winding through the secondary of the coupling transformer.
- Under normal condition
  - Signal current injected into stator flows through stray capacitance of the generator and directly connected system.
- During fault condition
  - Stay capacitance is bypassed which increases the monitoring current.

– This current is measured and corrective action is taken

- This scheme gives protection of 15% to 20% of stator winding from neutral side which is unprotected by Merz- Price protection.

- The remaining portion is protected by Merz-Price protection.

- Thus overall 100% stator windings gets protected against earth faults.

3.2.7 Stator Interturn Protection

- Merz price protection system gives protection against phase- phase faults and earth faults. It does not give protection for interturn faults.
- Interturn fault is short circuit between the turns of the same phase winding.

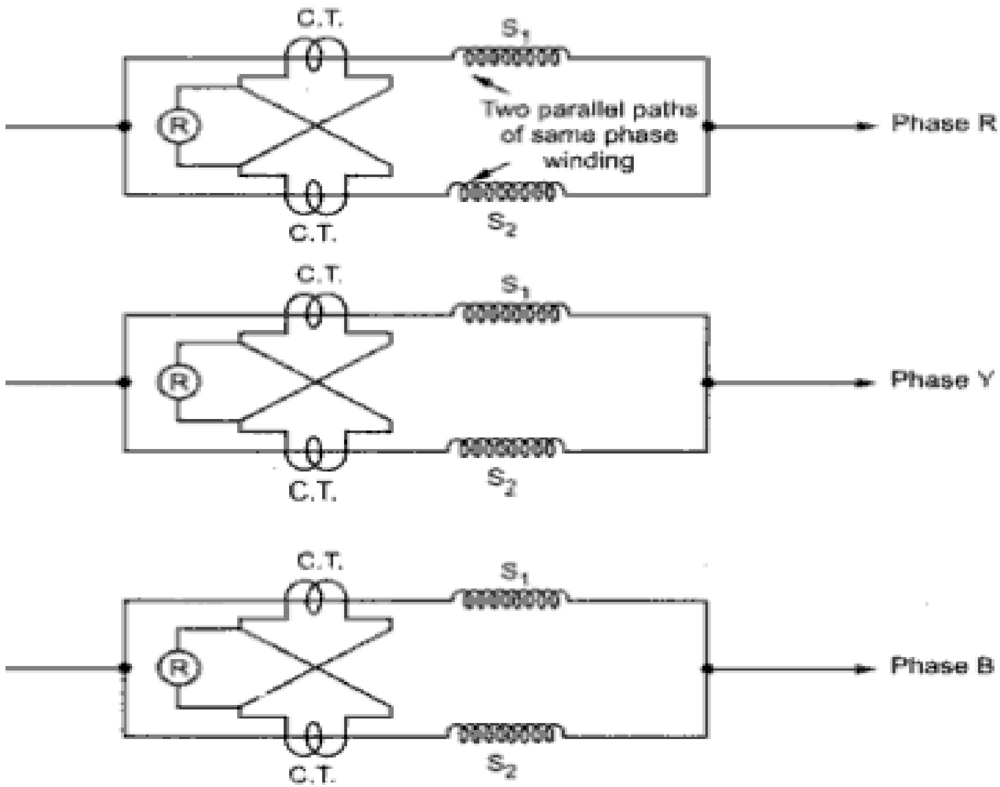

Fig.3.7 Stator inter turn fault protection

- Thus the current produced due to such fault is a local circuit current and it does not affect the currents entering and leaving the winding at the two ends, where CT are located. Hence Merz Price protection cannot give protection against interturn faults.
- In single turn generator – No interturn fault.
- Multi turn generator- interturn fault exist.
- Each winding is divided into two halves, due to the heavy currents which they have to carry.

- This splitting of single phase winding into two is advantageous in providing interturn fault protection to such hydroelectric generators.
- The scheme uses cross differential principle.
- Each phase of the generator is doubly wound and split into two phases S_1 and S_2.
- The current transformers are connected in parallel paths of the each winding.
- The secondaries of the CT are cross connected.
- Under Normal Condition
  - Current in two parallel paths S_1 and S_2 are equal
  - Hence current in secondaries of CT are equal
  - Secondary current flows round the loop and its same at all points.
  - Hence no current through the relay and relay is inoperative.
- Under fault condition
  - If short circuit is developed between the adjacent turns of S_1 winding, then current thro S_1 and S_2 are no longer same.
  - Thus unequal currents will be induced in the secondaries of the CT.
  - The difference of these currents flows through the relay. Hence relay operated and CB made open.
- This scheme is applied to Generator having Doubly wound armature.

3.2.8 Generator Rotor Earth Fault Protection

The rotor of an alternator is wound by field winding. Any single earth fault occurring on the field winding or in the exciter circuit is not a big problem for the machine. But if more than one earth fault occur, there may be a chance of short circuiting between the faulty points on the winding. This short circuited portion of the winding may cause unbalance magnetic field and subsequently mechanical damage may occur in the bearing of the machine due to unbalanced rotation.

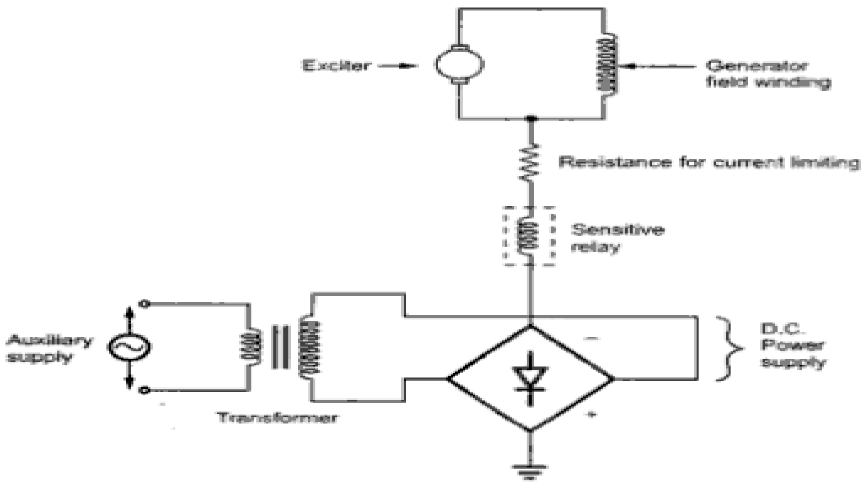

Fig. 3.8 Rotor earth fault protection

Hence it is always essential to detect the earth fault occurred on the rotor field winding circuit and to rectify it for normal operation of the machine. There are various methods available for detecting rotor earth fault of alternator or generator. But basic principle of all the methods is same and that is closing a relay circuit through the earth fault path.

AC Injection Method

Here, one voltage sensitive relay is connected at any point of the field and exciter circuit. Other terminal of the voltage sensitive relay is connected to the ground by a capacitor and secondary of one auxiliary transformer.

Here, if any earth fault occurs in the field winding or in the exciter circuit, the relay circuit gets closed via earthed path and hence secondary voltage of the auxiliary transformer will appear across the voltage sensitive relay and the relay will be operated.

The main disadvantage of this system is, there would always be a chance of leakage current through the capacitors to the exciter and field circuit. This may cause unbalancing in magnetic field and hence mechanical stresses in the machine bearings

Another disadvantage of this scheme is that as there is different source of voltage for operation of the relay, thus the protection of rotor is inactive when there is a failure of supply in the AC circuit of the scheme.

DC Injection Method

The drawback of leakage current of AC injection method can be eliminated in DC Injection Method. Here, one terminal of DC voltage sensitive relay is connected with positive terminal of the exciter and another terminal of the relay is connected with the negative terminal of an external DC source. The external DC source is obtained by an auxiliary transformer with bridge rectifier. Here the positive terminal of bridge rectifier is grounded.

It is also seen from the figure below that at the event of any field earth fault or exciter earth fault, the positive potential of the external DC source will appear to the terminal of the relay which was connected to the positive terminal of the exciter. In this way the rectifier output voltage appears across the voltage relay and hence it is operated.

3.3 Induction Motor Protection

- Abnormal Condition
  - Over loading- draws more current- temp rise- winding damage
  - Rotor is locked – due to excessive load- damage winding
  - Loss of supply voltage
  - unbalanced supply voltage – excessive heating
  - under voltage – motor draws more current for same load,
  - over voltage , under frequency,
  - phase sequence reversal of supply voltage – motor runs in other direction than the normal direction (dangerous in case of cranes, elevators)
  - Single phasing – blowing of fuse in any phase (Unbalanced current)

Table 3.1 Induction motor protection for different abnormal conditions

	Abnormal condition	Choice of protection circuit to be employed
1	Mechanical overload	Overload release, thermal overload relay, over current relays, miniature circuit breaker (MCB) with built in trip coil.
2	Stalling or prolonged starting of motor	Thermal relays, Instantaneous overcurrent relay.
3	Under voltage	Under voltage release, under voltage relay.
4	Unbalanced voltage	Negative phase sequence relays.
5	Reverse phase sequence	Phase reversal relay.
6	Phase to phase fault or phase to earth fault	HRC fuse, Instantaneous overcurrent relays. For large motors, differential protection may be employed for economy.
7	Single phasing	Thermal overload relays, single phase preventer.

3.3.1 Protection circuit for IM

A DOL starter (or Direct On Line starter or across the line starter) is a method of starting of a 3 phase induction motor. In DOL Starter an induction motor is connected directly across its 3-phase supply, and the DOL starter applies the full line voltage to the motor terminals. Despite this direct connection, no harm is done to the motor. A DOL motor starter contains protection devices, and in some cases, condition monitoring. A wiring diagram of a DOL starter is shown below:

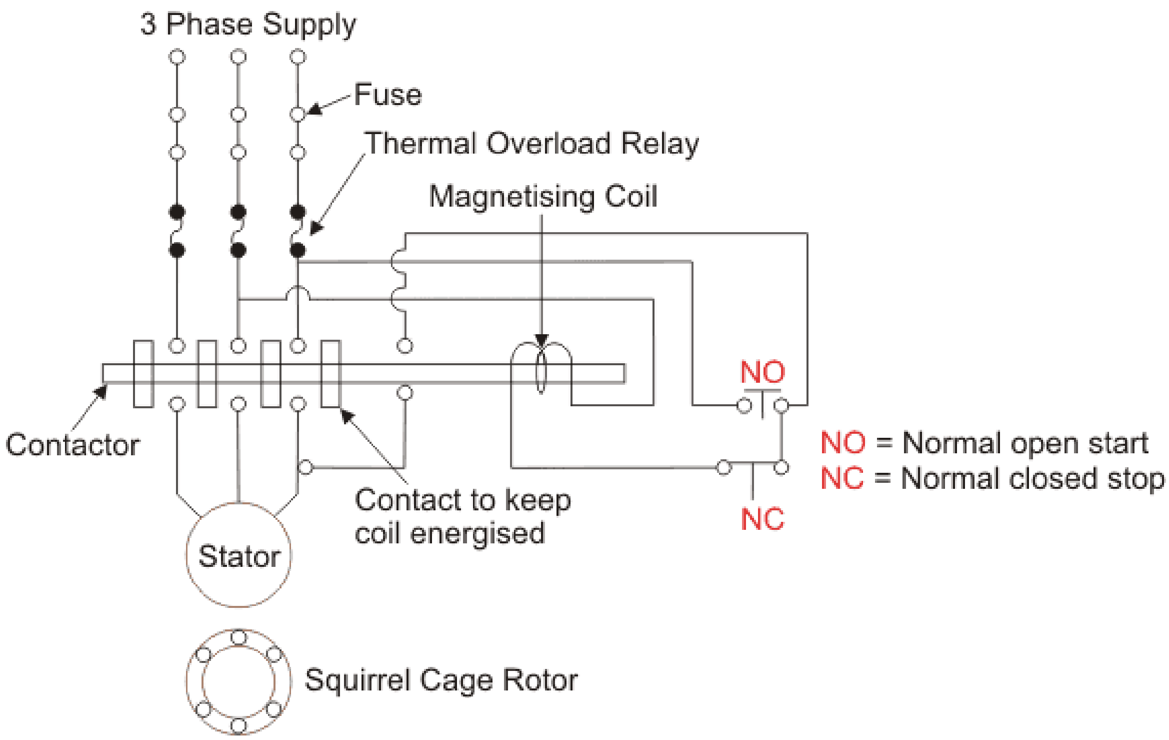

Fig. 3.9 Protection Circuit for Induction motor

Since the DOL starter connects the motor directly to the main supply line, the motor draws a very high inrush current compared to the full load current of the motor (up to 5-8 times higher). The value of this large current decreases as the motor reaches its rated speed.

A direct on line starter can only be used if the high inrush current of the motor does not cause an excessive voltage drop in the supply circuit. If a high voltage drop needs to be avoided, a star delta starter should be used instead. Direct on line starters are commonly used to start small motors, especially 3 phase squirrel cage induction motors.

As we know, the equation for armature current in the motor. $I_a = \frac{(V - E)}{R_a}$ The value of back emf (E) depends upon speed (N), i.e. E is directly proportional to N.

At starting, the value of E is zero. So starting current is very high. In a small rating motor, the rotor has more considerable axial length and small diameter. So it gets accelerated fastly. Hence, speed increases and thus the value of armature current decreases rapidly. Therefore, small rating motors smoothly run when it is connected directly to a 3-phase supply. If we connect a large motor directly across 3-phase line, it would not run smoothly and will be damaged, because it does not get accelerated as fast as a smaller motor since it has short axial length and larger diameter more massive rotor. However, for large rated motors, we can use an oil immersed DOL starter.

3.3.2 Single Phasing Preventer

- Single phasing is nothing but a motor runs when one of the supply is disconnected due to open circuit or improper contact in switch or other electrical equipment failure.
- Single phase preventer is used to protect the induction motor from single phasing fault.
- Single phasing is a very dangerous fault - Which damages the motor stator winding rapidly.
- Normally, the motor runs with the three phase supply - which takes balance current in each phase winding.
- Consider one of the fuse has blown. But the motor still in a rotating position which tries to rotates at the same speed.
- At that same time, the absence phase current will be shifted to the remaining live phases. Therefore, the current in the other phases increases up to 3 times its normal value instantly. This is called a single phasing fault.
- The single phasing leads to an unbalanced current in the motor stator. The component which is present in this unbalanced current called
    - negative sequence component.

Three current transformer is placed in each phase of the power supply. The output of the current transformer is given to the negative sequence filter circuit and which senses the magnitude of unbalance.

The filter circuit will be connected to the control circuit. The control circuit sends the trip command to the circuit breaker if the negative sequence current exceeds the preset value. If the failure of single-phase the unbalance current flow in the motor and the current will be sensed by the negative sequence filter.

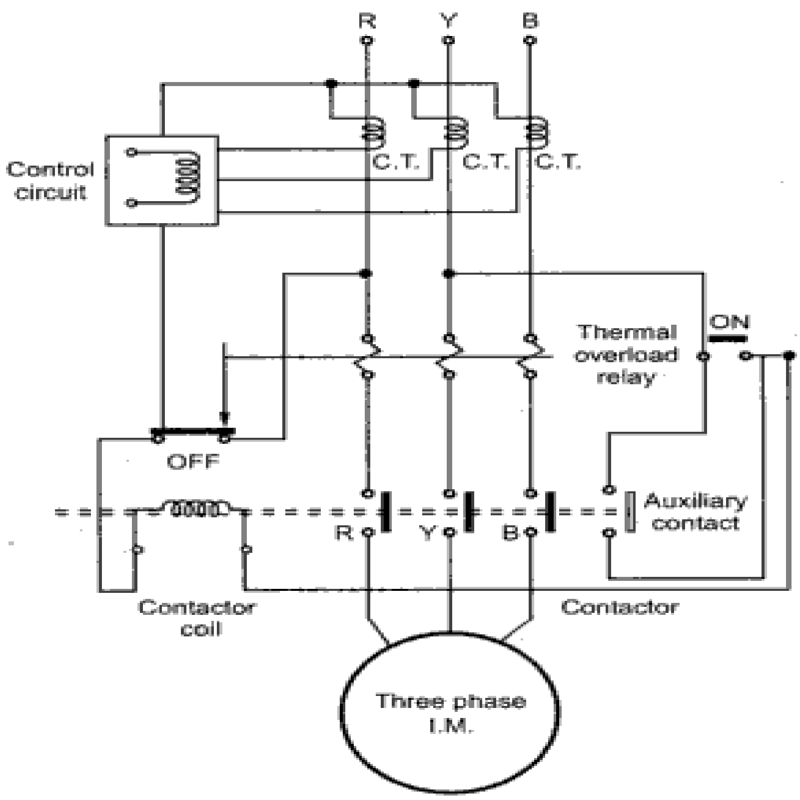

Fig. 3.10 Single phasing preventer

3.3.3 Ground Fault Protection

- Ground fault protection is achieved through Earth leakage circuit breaker(ELCB).
- When the fault current or leakage current flows through the earth return path then it forms earth fault.

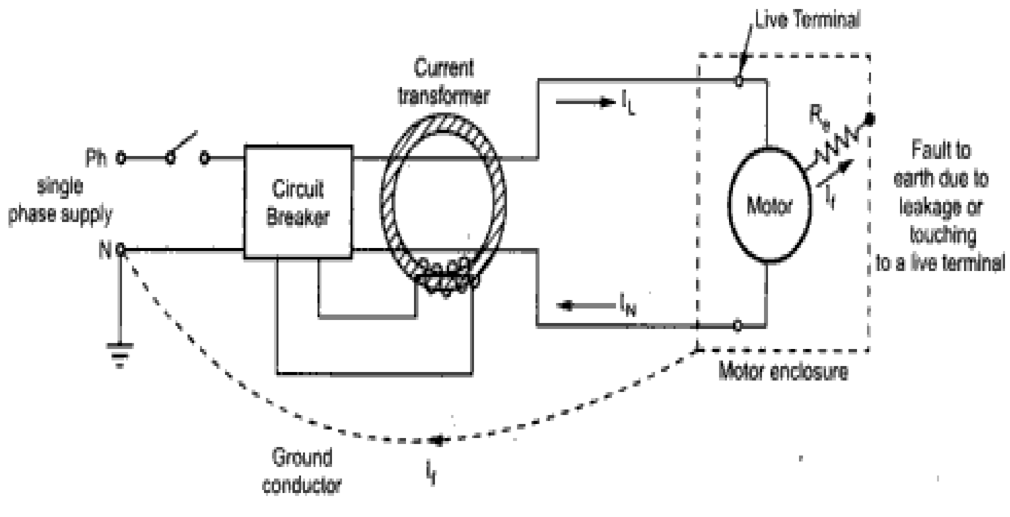

Fig. 3.11 Ground fault protection of IM

- ELCB can operate in 25ms when current exceeds the preset value.

- ELCB consists of a small current transformer connected between a live and neutral wire.
- The secondary winding of CT is connected to relay circuit which can trip the CB.
- Under normal condition
  - Current in line and neutral are the same
  - Net current I_L-I_N through the core of CT is zero.
  - Hence no flux in core, no emf. So breaker does not trip.
- During fault condition
  - Net current through the core will no longer remains zero.
  - Hence flux produced and emf induced in CT. Therefore relay is operated to trip the CB.

3.3.4 Phase Fault Protection

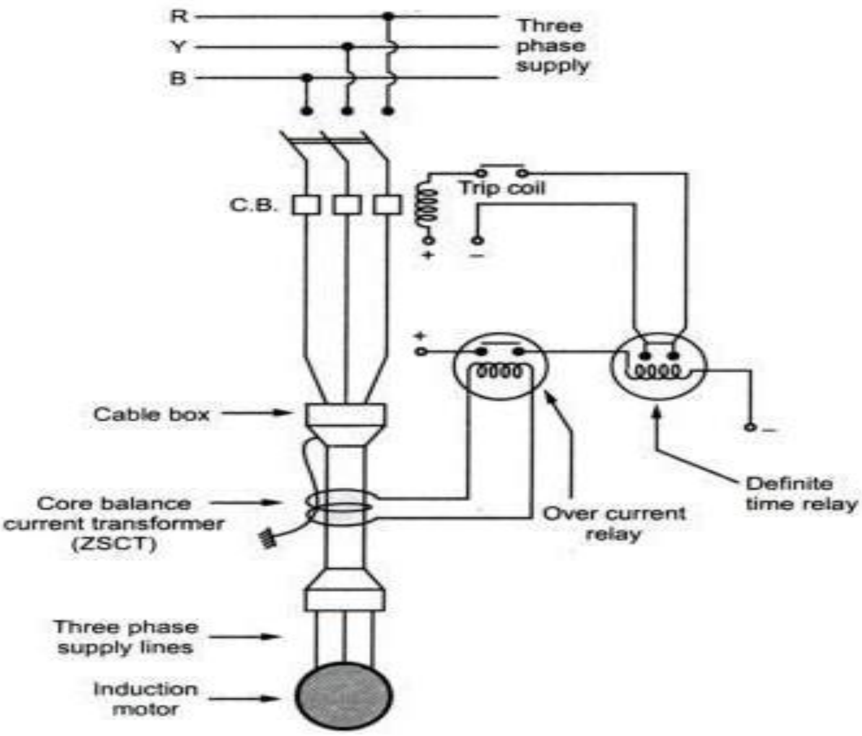

Fig. 3.12 Phase fault protection of IM

- Phase fault protection is nothing but an attracted armature type relay unit is connected in each phase .
- This protection is also called short circuit protection.
- The current transformer sense the motor current as well the short circuit current.
- At the time of a fault (short circuit between the phases), the current increases by 5 to 10 times the full load current of the motor.

- Due to this phase to phase faults can cause burn out of coils and stampings and hence motor should be disconnected as quickly as possible when fault occurs.
- The high speed tripping over current relays are used to provide phase fault protection.
- To avoid relay functioning during starting, the short circuit protection current setting must be just above the maximum starting current of the motor.

3.4 Transformer Protection

3.4.1 Possible Transformer Faults

- Overheating
  - Higher loads – permissible for less time
  - Prolonged overloading- overheating of transformer, failure of cooling system
  - Thermal overload relay, temperature relay, sounding alarms are used.
  - Thermocouples used near winding
- Winding Faults
  - Phase to phase fault
  - Earth fault
  - Interturn fault
  - Overheating or mechanical shocks- deteriorate the winding insulation- in such case SC between phases or between phase and ground or SC between the adjacent turns of same winding exist ------ transformer quickly disconnected – otherwise oil fires.
  - > MVA- Differential protection
  - < MVA- Over current protection
  - High capacity transformer – differential as main protection and over current as back up protection
  - For earth fault protection – restricted earth fault protection, neutral current relays or leakage to frame protection is used.
- Open circuits
  - Open circuit in one of the three phases causes overheating of the transformer.
  - Harmless, therefore manually disconnected.
- Through Faults
  - It is the external fault which occur outside the protected zone.

- Through faults are not detected by differential protection
- Through faults persists for long time can cause thermal and mechanical stress on the transformer.
- Overcurrent relay, zero sequence protection and negative sequence protection are used for through faults
- Overcurrent protection not only protects transformer, it covers busbar and portion of transmission line

• Overfluxing
  - Flux density (B) in the transformer core is proportional to the ratio of the voltage to frequency(V/f)
  - In transformer over fluxing is the dangerous situation in which magnetic flux density increases to extremely high level.
  - The high flux density increases core loss which may lead to overheating of components which in turn may result into internal fault. ($P_h \alpha\, B^{1.6}$, $P_e \alpha\, B^2$)
  - Volts/Hz relay is used

• Other Faults
  - Tap changer fault
  - High voltage surge due to lightning and switching
  - Incipient fault (Slow developing fault) { Buchholz relay is used- oil immersed transformer)

3.4.2 Important points to be considered while considering differential protection for power transformers

1. **In Power transformer, voltage rating of two transformer are different.**
   - HV winding is low current winding,LV winding is high current winding
   - Thus there always exists a difference in current on py and sy sides of power transformer. If CT of same ratio used in both sides, then relay get operated even though there is no fault.
   - To compensate this, CT of different current ratio is used on both sides.
   - If K is the turns ratio of power transformer, then CT on LV side= K * CT on HV side

2. **Phase difference in voltage of HV and LV side**
   - Phase difference in line current of PY and SY sides of power transformer.

- This introduces phase difference of current in CT secondary on both sides of a power transformer.
- Though turns ratio of CT are selected to compensate the turns ratio of power transformer, a differential current exists due to phase difference.
- Such differential current may operate relay without fault.
- To compensate this, secondaries of CT s on star connected side of power transformer are connected in delta while secondaries of CT s on delta connected side of power transformer are connected in star

3.4.3 Percentage Differential Protection for Transformer

Table 3.2 Percentage Differential Protection for Transformer

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

3.5 Different Methods of Transformer Protection

3.5.1 Merz-Price Protection for Star Delta Transformer

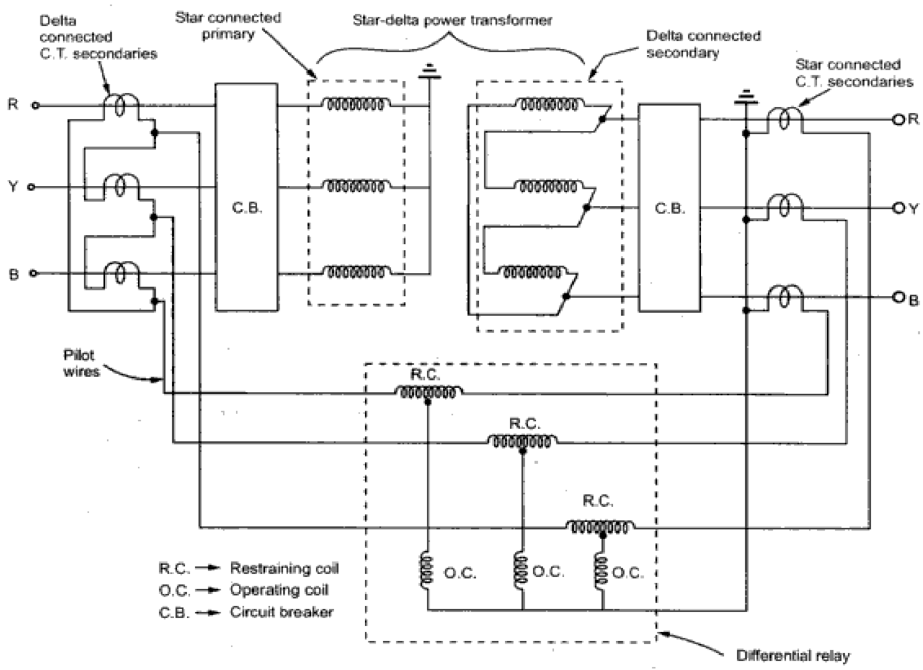

Fig. 3.13 Merz-Price Protection for Star Delta Transformer

- Power transformer –star / delta
- CT secondaries – Delta/star for the phase displacement.
- Star point of power transformer and CT are grounded
- Restraining coil connected across the CT secondary winding
- Operating coil connected between tapping points of restraining coil and star point of CT secondaries.
- Under normal condition
  - With proper selection of turns ratio of CT , the coils are under balanced condition during normal operating conditions. CT carry equal current which are in phase under normal conditions. So no current flows through the relay and relay is inoperative.
- With internal fault in power transformer winding
  - Balance in the CTs get disturbed.
  - The operating coil carry difference of current between two sides of power transformer

- Thus relay operates

- This relay operates for interturn fault too.
  - Turns ratio of PT get affected
  - Due to this currents on both sides of Power Transformer become unbalanced. Thus current flows through the operating coil and relay get operated.

Merz price protection for star star transformer is shown in fig.

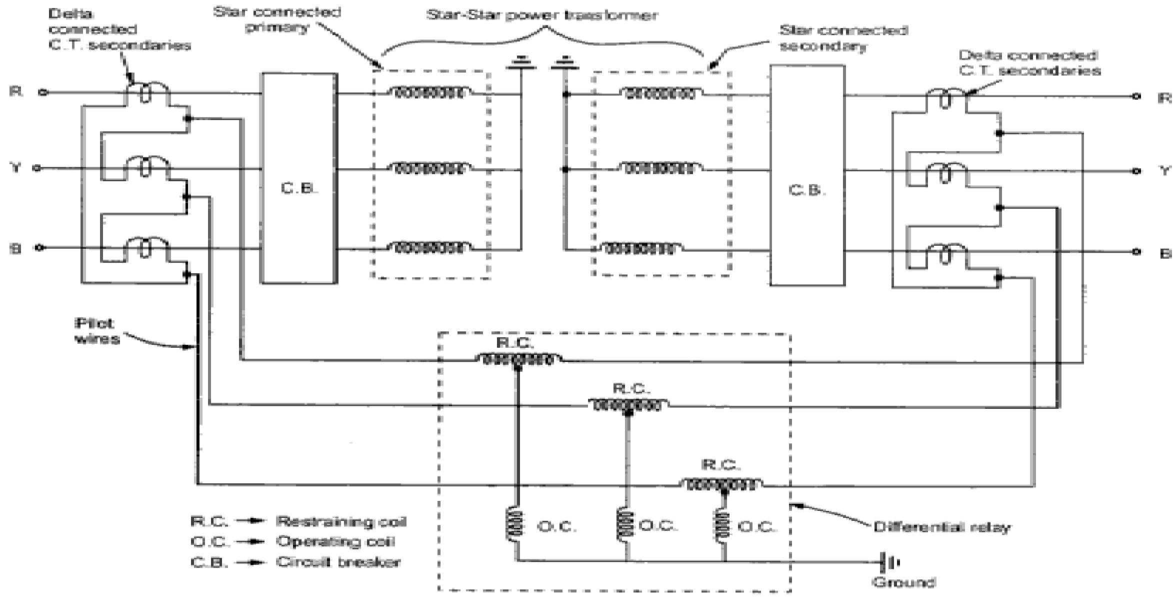

Fig.3.14 Merz-Price Protection for Star Star Transformer

3.5.2Frame Leakage Protection

Frame leakage protection is generally employed in transformer protection. It is nothing but the method of providing an earth fault protection to the transformer.

Here as you can see in the above figure metal-clad switchgear is lightly insulated from earth.

The frame of the switchgear is grounded. This is done through primary of the current transformer which is connected in between.

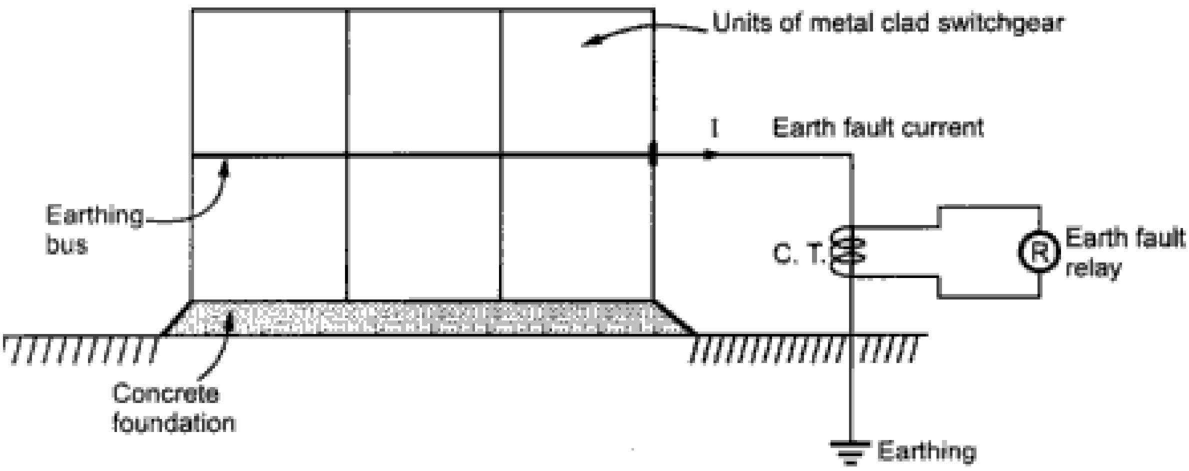

Fig. 3.15 Frame Leakage Protection Scheme For Transformer

The foundation of switchgear is of concrete and all other equipment are lightly insulated from the ground. The resistance of this equipment to the earth is about 12ohm.

Now let us talk about the faulty condition. So when there is an earth fault, Then fault current leaks from the frame to the earth connection which is provided. Thus the primary of the Current transformer senses the current due to which current passes through the sensitive earth fault relay. Due to this, the relay operates.

Such protection is provided only for small transformers. While for large rating transformer the differential protection is enough.

Hence the purpose of frame leakage protection becomes extremely more important because of this it may happen that when any operator goes near the transformer frame and by mistake, he touches the frame then due to the leakage current he may experience electrical shock. Due to that severe electrical shock, there can hugely damage to the particular person's body. Hence to ensure the protection against these the frame leakage protection scheme is implemented.

3.5.3 Basic arrangement of Buchholz Relay

- Buchholz relay is gas operated relay.
- Used for protection of oil immersed transformers against all types of internal faults
  - insulation failure of turns, breakdown of core or excess core heating, the fault is accompanied by production of excess heat.
- Slow developing faults called incipient faults in the transformer tank below oil level operate Buchholz relay which gives alarm.
- If the faults are severe it disconnects the transformer from supply.

- Fault – oil in tank- decomposes- generates gas(Hydrocarbon , CO2 and CO)
- 70% gas – Hydrogen – light- rises upwards towards conservator through the pipe.
- Gas collected in upper portion of Buchholz relay- relay operates-gives an alarm

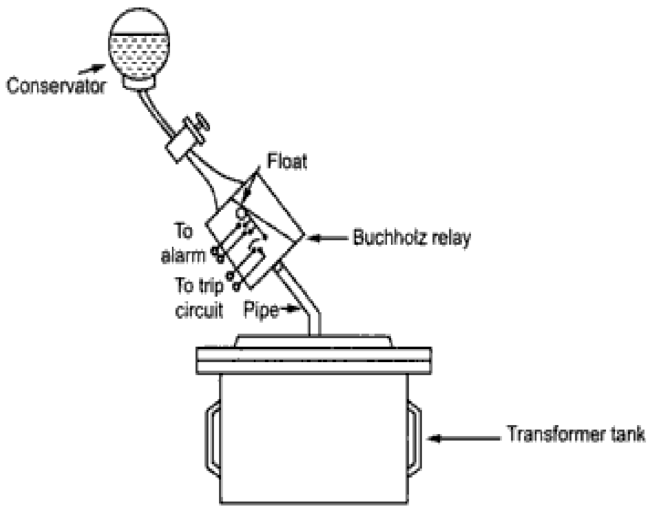

Fig.3.16 Basic arrangement of Buchholz relay

Construction of Buchholz Relay

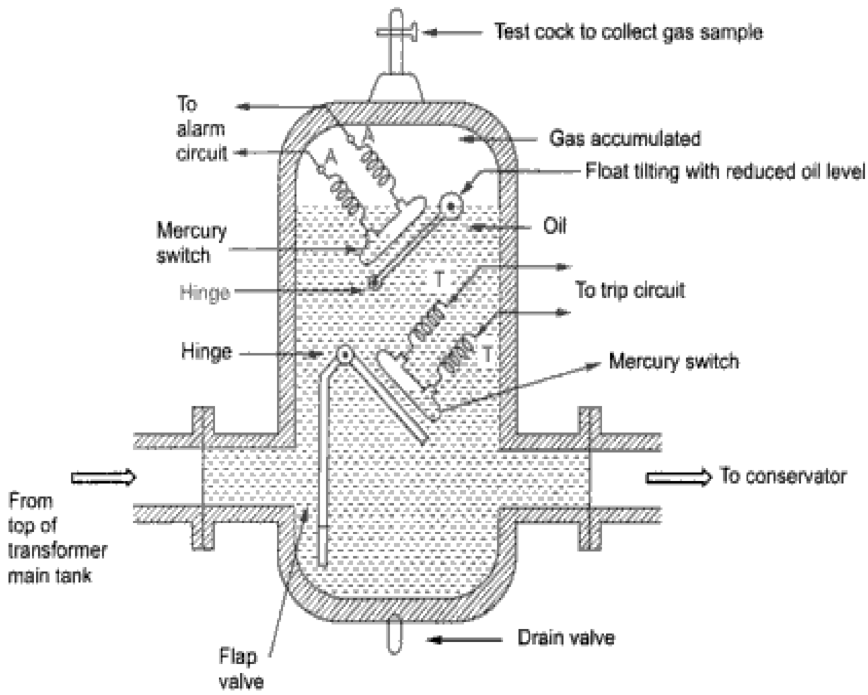

Fig. 3.17 Buchholz relay

- Buchholz relay consists of an oil filled chamber.
- There are two hinged floats, one at the top and other at the bottom in the chamber.
- Each float is accompanied by a mercury switch.

- The mercury switch on the upper float is connected to an alarm circuit and that on the lower float is connected to an external trip breaker.
- **During Minor Faults**
- 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
- 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.
- Sometime due to oil leakage on the main tank air bubbles may be accumulated in the upper part of buchholz container which may also cause fall of oil level in it and alarm circuit is energized.
- Inorder avoid this, gas is collected in the gas release path and tested.
- The presence of; (a) C_2H_2 and H_2 shows arcing in oil between constructional parts; (b) C_2H_2, CH_4 and H_2 shows arcing with some deterioration of phenolic insulation, e.g. fault in tap changer; (c) CH_4, C_2H_4 and H_2 indicates hot spot in core joints; (d) C_2H_4, C_3H_6, H_2 and CO_2 shows a hot spot in the winding.
- **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.
- **Advantages Of Buchholz Relay**
- Buchholz relay indicates the internal faults due to heating and it helps in avoiding the major faults.
- Severity of the fault can be determined without even dismantling the transformer.
- If a major fault occurs, the transformer can be isolated with the help of buchholz relay to prevent accidents.
- **Limitations**

- Can be used only for oil immersed transformers having conservator tanks.
- Relay is slow to operate having minimum operating time of 0.1sec and average time of 0.2sec.
-

3.6 BUS BAR PROTECTION

3.6.1 Frame Leakage Protection

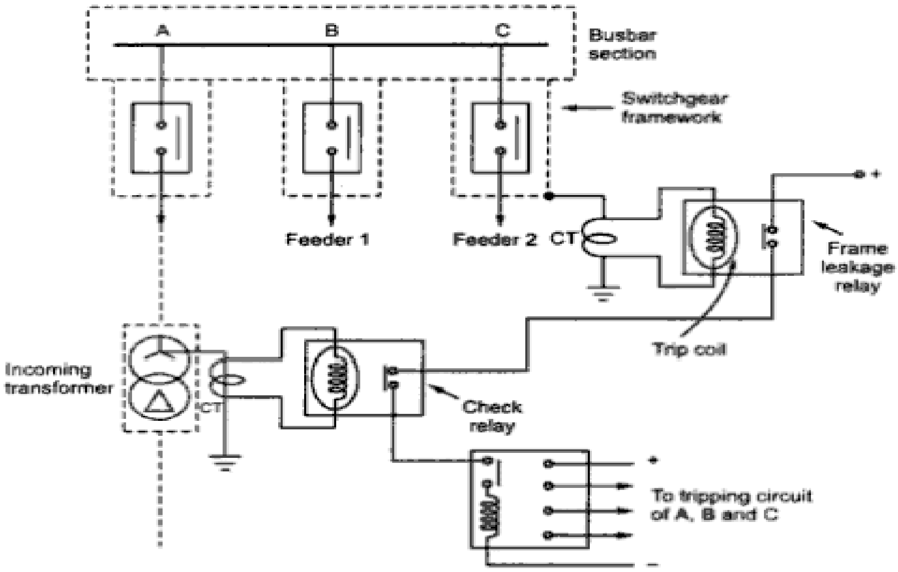

Fig.3.18 Frame leakage protection of bus bar

- Frame Leakage Protection of Busbar is used to protect the busbar, circuit breaker, isolator switches, instrument transformer from busbar earth faults.
- All Busbar used in a power system is neatly bound with high voltage insulation material.
- The switchgear framework is also insulated from lead cable sheaths.
- The bus bar supporting frame will be earthen through a current transformer.
- When the fault in busbar, the fault current flow through supporting frame's earthing arrangement.
- The Current transformer in the earthen frame reads the fault current and if this fault current higher than the pickup current, it energizes the frame leakage relay.
- At that same time, the transformer neutral is connected to ground through the current transformer.
- However, the fault current in the busbar frame reach through the neutral of the transformer, hence the same current will be read by the neutral CT.

- This neutral CT operate the tripping contact.
- Here, The contacts of check relay (neutral leakage relay) and frame leakage relay are in series.
- Thus before tripping circuit gets energized both the relays must operate.
- Once both the relays operate due to earth fault, all the breakers will trip connecting the equipment to the busbar.

Due to check relay, accidental operation of single relay to trip the circuit gets avoided

3.6.2 Circulating Current Protection

Bus bar Differential protection or Circulating Current Protection is working under the principle of differential protection. The current transformers are arranged as shown in the figure. Under normal condition, Incoming current in to the bus bar is equal to the outgoing current from the busbar, therefore the net circulating current is equal to zero. Since the relay become inoperative. Under abnormal condition, the fault in the protected zone, the current become unequal. Therefore, there is circulating will be present in the relay circuit. If the circulating current is higher than the pickup current the relay trips all circuit breaker.

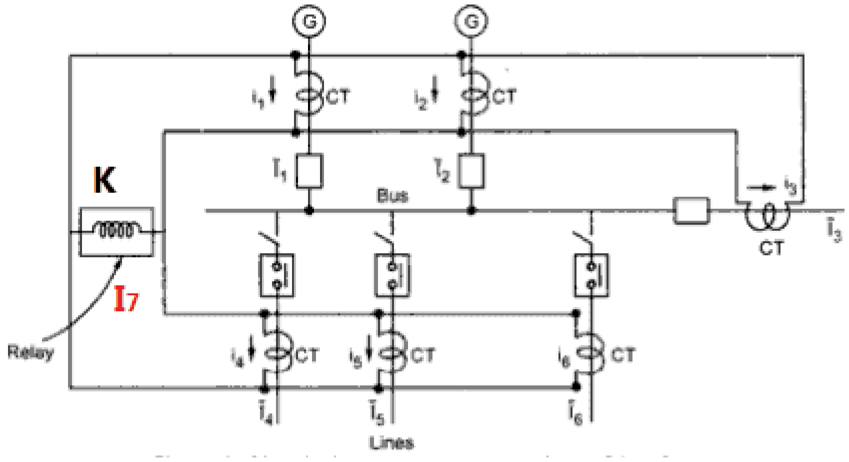

Fig. 3.19 Bus bar differential protection

Consider Six CTs are named as CT 1, 2 ,3, 4, 5 and 6. The number 1 and 2 are the incoming CT and the remaining CTs are outgoing. K is a relay operating coil and the current flow in the CTs are I_1, I_2, I_3, I_4, I_5, I_6 and I_7 is current flow through the relay operating coil K.

Under Normal condition, the current flow in the relay operating coil K is equal to zero I_7=0. Because of vector sum of current at node A is Zero (apply KCL). Since the relay K do not trip the circuit breaker. Consider the short circuit occurs in the bus bar, the incoming current and outgoing current become unequal. Hence the circulating current will be unequal. Therefore, there is a fault current flows in the relay operating coils. If the fault current exceeds the pickup value of the relay, which trips all the circuit breaker associated with the protection.

Notes on Bus bar Differential protection:

- To obtain exact value of circulating current, all current transformers must have exact CT ratio. But in practice there exists a difference in the magnetic conditions of iron cored current transformers and false operation of the relay is possible, at the time of external.
- CT should not be saturated under external heavy fault condition. Due to the Saturated CT, which makes the malfunctioning of the relay i.e unequal current flow in the relay operating coil even the fault is outside of the protected zone. To avoid these CT saturation trips, high impedance differential relays are used. A high resistance is connected in series with relay operating coil to get high impedance relay. This resistance is called stabilizing resistance

3.6.3 High Impedance Differential Protection

- Differential protection of bus bar based on sensing a voltage drop across a high impedance under fault conditions.

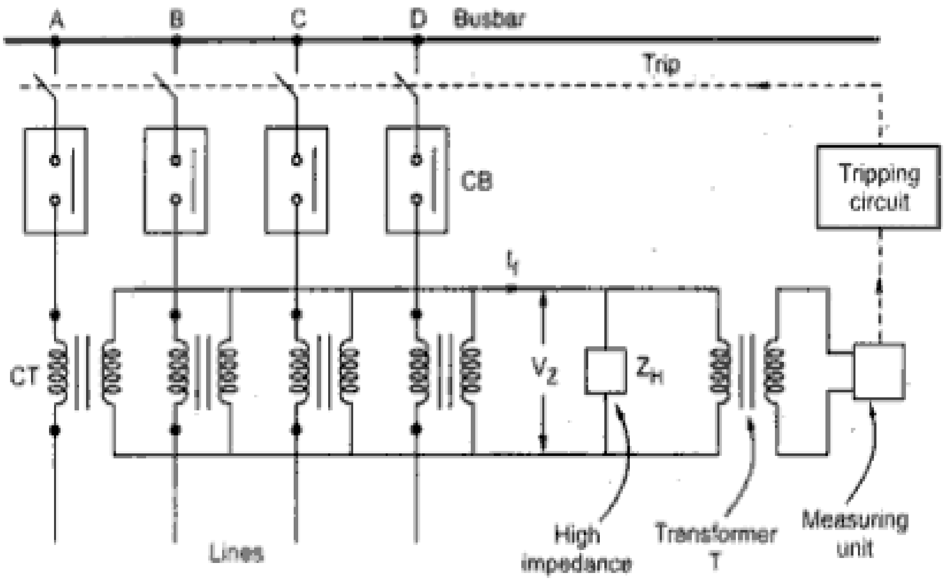

Fig. 3.20 High impedance differential protection for busbar

- Under normal conditions,
  - Vector sum of currents in the lines are zero.
  - Current I_f through the high impedance Z_H is zero.
  - Relay inoperative
- During fault condition

- Unbalanced current exists
- I_f flows through Z_H – cause high voltage drop V_z – Given to transformer- Measuring unit @ secondary measures this voltage drop- trips the relay

3.7 Transmission Line Protection

3.7.1 Transley Scheme

- This scheme is a balanced voltage scheme with the addition of a directional feature.
- An induction disc type relay is used at each end of the protected line section.
- The secondary windings of the relays are interconnected in opposition as a balanced voltage system by pilot wires.
- The upper magnet of the relay carries a summation winding to receive the output of current transformers.

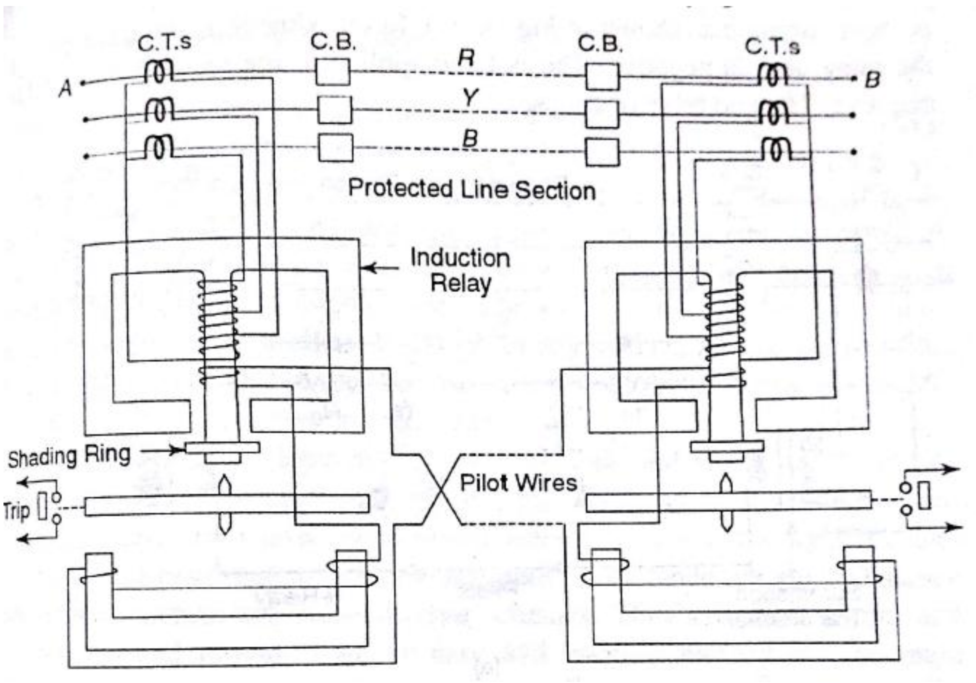

Fig. 3.21 Transley scheme protection of feeder line

- **Under normal conditions and in case of external faults**
  - no current circulates through the pilot wires and hence through the lower magnets of the relays.
  - In these conditions, no operating torque is produced.
  -

- **In case of internal faults**
  - Current flows through the pilot wires and the lower electromagnets of the relay.
  - In this condition, the relay torque is produced from the interaction of the two fluxes.
  - One of the flux is produced directly from the local CT secondary current flowing through the upper magnet of the relay.
  - The second flux is produced by the current flowing through the lower magnet.
  - The current flowing through the lower magnet may be relatively small. Therefore, this scheme is suitable for fairly long pilots having loop resistance up to 1000 ohms.

3.7.2 Carrier Current Protection Scheme

- This is the most widely used scheme for the protection of EHV and UHV power lines.

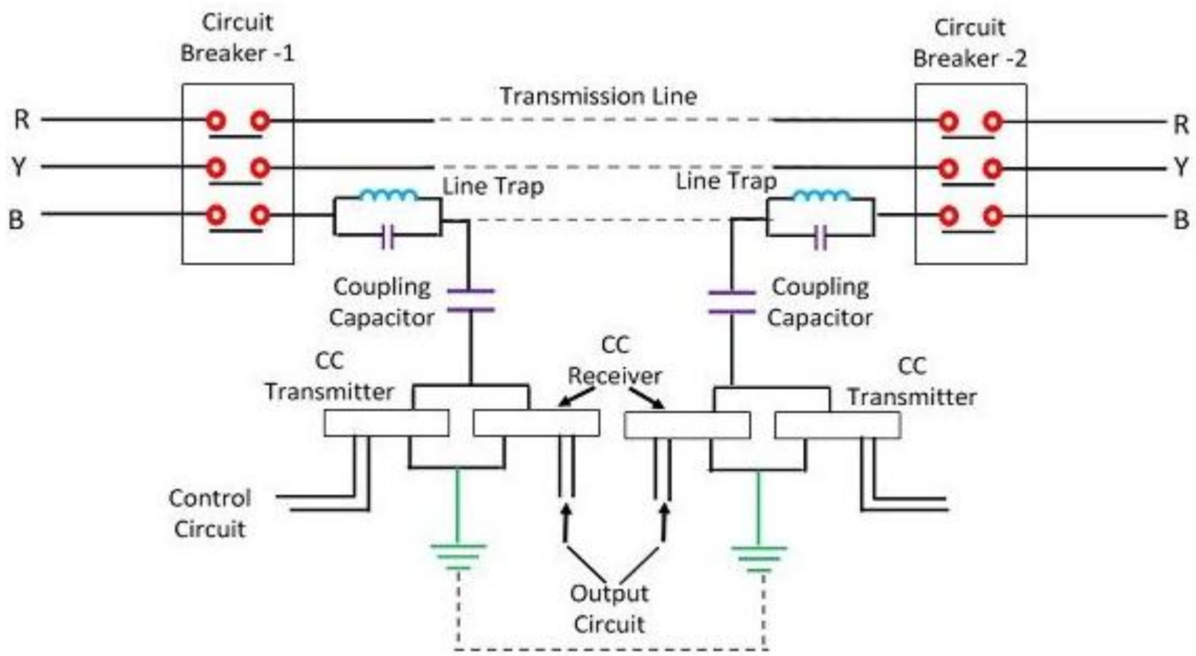

Fig. 3.22 Carrier current protection for transmission line

- In this scheme a carrier channel at high frequency is employed.
- The carrier signal is directly coupled to the same high voltage line that is to be protected.
- The frequency range of the carrier signal is 50 kHz to 700 kHz.
- Below this range, the size and the cost of coupling equipment becomes high whereas above this range, signal attenuation and transmission loss is considerable.

- The power level is about 10-20 W. In this scheme, the conductor of the power line to be protected are used for the transmission of carrier signals.
- The main disadvantage of conventional time-stepped distance protection is that the circuit breakers at both ends of the line do not trip simultaneously when a fault occurs at one of the end zones of the protected line section.
- This may cause instability in the system.
- The carrier current protection or any other unit protection does not suffer from these disadvantages. In unit protection, circuit breakers trip simultaneously at both ends. It is capable of providing high speed protection for the whole length of the protected line section.
- In a carrier current scheme, the carrier signal can be used either to prevent or initiate the tripping of a protective relay.
- When the carrier signal is used to prevent the operation of the relay, the scheme is known as carrier-blocking scheme.
- When the carrier signal is employed to initiate tripping, the scheme is called a carrier intertripping or transfer tripping or permissive tripping scheme.
- The coupling capacitors required for carrier signal can be used also as potential dividers to supply reduced voltage to instruments, relays etc. This eliminates the use of separate potential transformers.
- Two important operating techniques employed for carrier current protection
  - Phase comparison technique
  - Directional comparison technique
- **Phase comparison technique**
  - Phase angle of the current entering one end is compared with the phase angle of the current leaving the other end of the protected line section
  - If the currents at both the ends of the line are in phase, there is no fault on the protected line section. This will be true during normal conditions or in case of external faults.
  - In case of faults on the protected line section, the two currents will be 180° out of phase. In this scheme, the carrier signal is employed as a blocking pilot.
  - NOTE : In the given diagram, the procedure is reversed as the CT connection at both ends are reversed.(During normal condition- 180^{o} out of phase, During Fault condition- both currents are in phase)
- **Directional comparison technique**
  - Direction of power flow at the two ends of the protected line section is compared.

- During normal conditions and in the case of external faults, the power must flow into the protected line section at one end and out of it at the other end.
- In case of an internal fault, the power flows inwards from both ends.

Phase comparison Carrier Current Protection

- In this scheme, the phase angle of the current entering one end of the protected line section is compared with the current leaving the other end.
- The line trap is a parallel resonant circuit tuned to the carrier frequency connected in series with the line conductor at each end of the protected line section.
- This keeps carrier signal confined to the protected line section and does not allow the carrier signal to flow into the neighbouring sections.
- Line trap offers very high impedance to the carrier signal but negligible impedance to the power frequency current.
- There are carrier transmitter and receivers at both the end of the protected line.
- The transmitter and receiver are connected to the power line through a coupling capacitor to withstand high voltage and grounded through an inductance.
- For the transmission of carrier signal either one phase conductor with earth return or two phase conductors can be employed.
- The former is called phase to earth coupling and the latter is called phase to phase coupling.
- The phase to earth coupling is less expensive as the number of coupling capacitors and line traps required is half of that needed for phase to phase coupling.
- However the performance of phase to phase coupling is better compared to phase to earth coupling because of lower attenuation and lower interference levels.

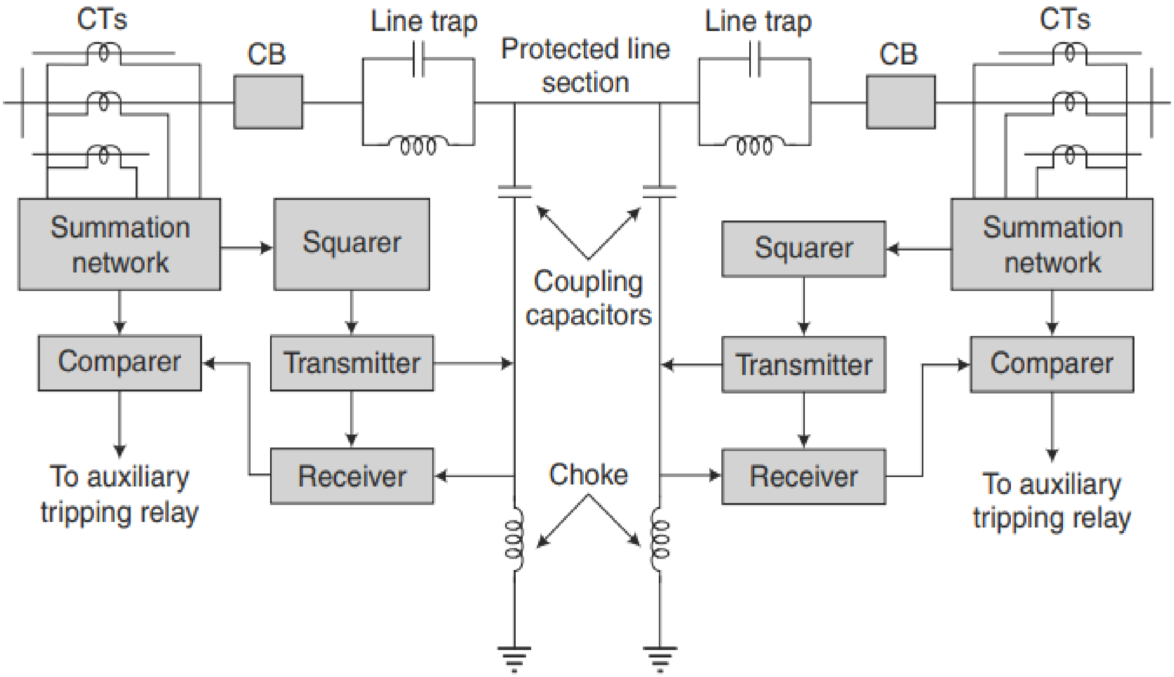

Fig.3.23 Phase comparison Carrier Current Protection

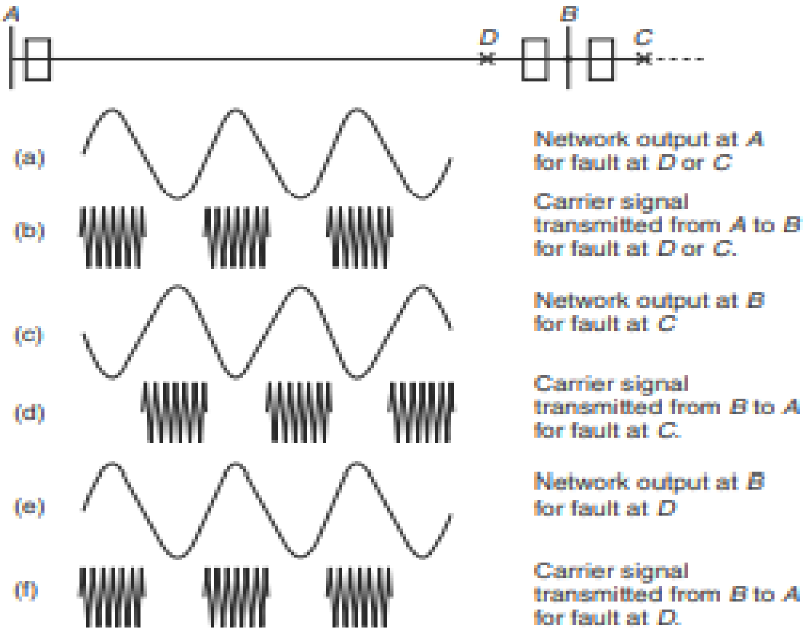

Fig. 3.24 Waveform of carrier and power frequency signal

- The voltage outputs of the summation network at stations A and B are 180° out of phase during normal conditions. This is because the CT connections at the two ends are reversed.
- The carrier signal is transmitted only during positive half cycle of the network output
- Wave (a) shows the output of the summation network at A.

- Wave (b) shows the carrier signal transmitted by the transmitter at A.
- Wave (c) shows the output of the summation network at B for external fault at C.
- Wave (d) shows the carrier signal transmitted by the transmitter at B.
- **For an external fault**,
  - carrier signals are always present in such a way that during one halfcycle, signals are transmitted by the transmitter at A and during the next half-cycle by the transmitter at B.
  - As the carrier signal is a blocking signal and it is always present the relay does not trip.
- **For an internal fault**,
  - the polarity of the network output voltage at B is reversed, as shown by the wave (e).
  - The carrier signal sent by the transmitter at B is shown by wave (f).
  - In case of internal faults, carrier signals are transmitted only during one half-cycle and there is no signal during the other half-cycle.
  - As the carrier signal is not present during the other half-cycle, the relay operates and the circuit breaker trips.
- The comparator receives carrier signal from the receiver. So long as the carrier is present, it does not give an output to the auxiliary tripping relay.
- When the comparator does not receive the carrier signal, it gives an output to the auxiliary tripping relay

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Question Bank

PART – A

Q.No.	Question
1.	What are the difficulties experienced in differential relay in generator protection?
2.	Classify the faults which affects alternator?
3.	Illustrate the limitations of buchholz relay?
4.	List the advantages of bus zone protection.
5.	Classify various bus bar faults.
6.	What are the common methods used for line protection?
7.	List the important faults on power transformers?
8.	List the applications of translay relay.
9.	Write the importance of auxiliary relay in Merz-Price protection?
10.	Define pilot wire protection.

PART – B

Q.No.	Question
1.	An 11KV, 100MVA generator is grounded through a resistance of 6 ohms. The CT has a ratio of 1000/5. The relay is set to operate when there is an out of balance current of 1A. Estimate percentage of the generator winding will be protected by the percentage differential scheme of protection?
2.	Explain the Mertz – Price circulating current protection scheme of alternators with neat diagram.
3.	(a) An 11 kV, 100 MVA generator is provided with a differential scheme of protection. The percentage of generator winding to be protected against phase to ground fault is 85%. The relay is set to operate when there is 20% out of balance current. Determine the value of the resistance to be placed in the neutral to ground connection.

	(b) What is buchholz relay? Which equipment is protected by it? For What type of faults it is employed? Discuss its working principle
4.	Explain the construction and working of buchholz relay. State its advantages and disadvantages.
5.	Elaborate the differential protective scheme of transformer in detail.
6.	Construct a suitable sketch and explain Bus zone protection in a Sub Station.
7.	Explain the construction and working principle of Transley scheme with neat diagram.

UNIT - IV

Power System Protection and Switchgear – SEE1401
UNIT IV- THEORY OF ARC QUENCHING

IV. Theory of Arc Quenching

Arcing phenomena - theory and methods of arc quenching - recovery voltage - restriking voltage - RRRV - Resistance switching - current chopping - capacitive current breaking - Characteristics of fuses - HRC fuse.

4.1 Circuit Breaker

Circuit breaker is a mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time, and automatically breaking currents under specified abnormal circuit conditions such as those of short-circuits (faults). The insulating medium in which circuit interruption is performed is designated by suitable prefix, such as oil circuit breaker, air-break circuit breaker, air blast circuit breaker, sulphur hexafluorid (SF6) circuit breaker, vacuum circuit breaker, etc.

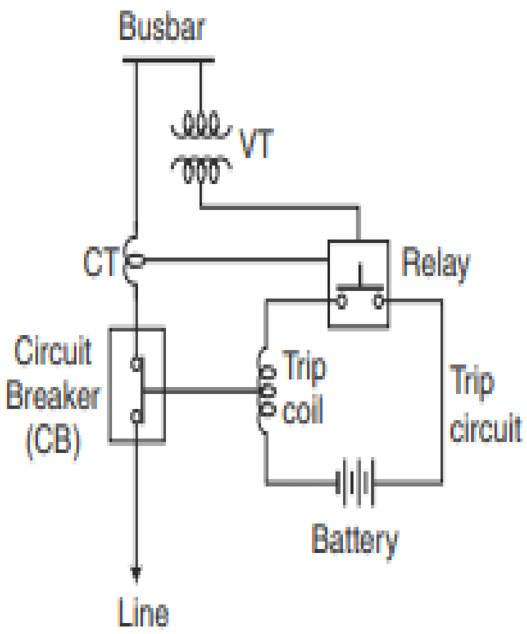


Fig.4.1 Simplified diagram of circuit breaker opening operation

The function of a circuit breaker is to isolate the faulty part of the power system in case of abnormal conditions such as faults. A protective relay detects abnormal conditions and sends a tripping signal to the circuit breaker. After receiving the trip command from the relay, the circuit breaker isolates the faulty part of the power sys- tem. The simplified diagram of circuit breaker control for opening operation is shown in Fig. 4.1. When a fault occurs in the protected circuit (i.e. the line in this case), the relay connected to the CT and VT detects the fault, actuates and closes its contacts to complete the trip circuit. Current flows from the battery in the trip circuit. As the trip coil of the circuit breaker is energized, the circuit breaker operating mechanism is actuated and it operates for the opening operation to disconnect the faulty element.

A circuit breaker has two contacts – a fixed contact and a moving contact. The contacts are placed in a closed cham-ber containing a fluid insulating medium (either liquid or gas) which quenches (extinguishes) the arc formed between the contacts. Under normal conditions the contacts remain in closed position. When the circuit breaker is required to isolate the faulty part, the moving contact moves to interrupt the circuit. On the separation of the contacts, an arc is formed between them and the current continues to flow from one contact to the other through the arc as shown in Fig. 4.2. The circuit is interrupted (isolated) when the arc is finally extinguished.

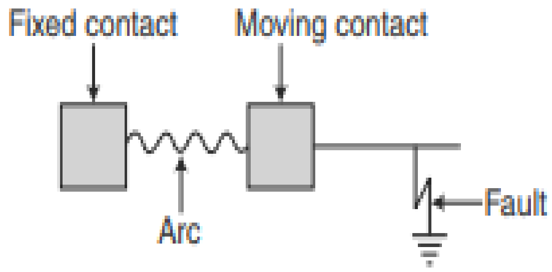


Fig.4.2 Separation of the contacts of Circuit breaker

When the moving contact starts separat- ing, the insulating fluid between the two contacts experiences a vary high electric stress. The electric stress is almost inversely proportional to the distance between twoelectrodes, i.e., between two contacts. Thus, at the instant of contact separation,the insulating medium between the contacts is subjected to extremely high electric stress leading to breakdown. The breakdown of the insulating medium between the contacts results in formation of a conducting channel or an arc between the contacts. As the moving contact moves further away, the arc is also drawn along with it. The arc which is in the plasma form continues to carry the pre-opening current. In spite of physical separation of the two contacts, current continues to flow through the arc and thus, the interruption is not effective. The interruption of the current takes place only when the arc is finally quenched (extinguished) and ceases to exist. Thus, circuit breaking may be called an art of arc quenching.

4.2 FAULT CLEARING TIME OF A CIRCUIT BREAKER

A circuit breaker is required in the power system to give rapid fault clearance, in order to avoid overcurrent damage to equipment and loss of system stability. The fault tripping signal to the circuit breaker is derived from the protective relay via the trip circuit. After fault inception, the relay senses the fault and closes its contacts to complete the trip circuit as shown in Fig. 4.1. The relay takes some time to close its contacts. After closing of the contacts of the trip circuit, the trip coil of the circuit breaker is energized and the operating mechanism of the breaker comes into opera- tion. The contacts of the circuit breaker start separating to clear the fault. On the separation of the contacts, an arc is formed between them and the current continues to flow through the arc. The fault is cleared when the arc is finally extinguished.

Figure 4.3 shows the various components of fault clearing time of a circuit breaker. The fault clearing time is the sum of relaying time and breaker interrupting time.

The various components of the fault clearing time of the circuit breaker are defined as follows:

Relaying time = Time from fault inception to the closure of trip circuit of CB.

Breaker opening time = Time from closure of the trip circuit to the opening

of the contacts of the circuit breaker.

Arcing time = Time from opening of the contacts of CB to final arc extinction.

Breaker interrupting time = Breaker opening time + arcing time

Fault clearing time = Relaying time + breaker interrupting time

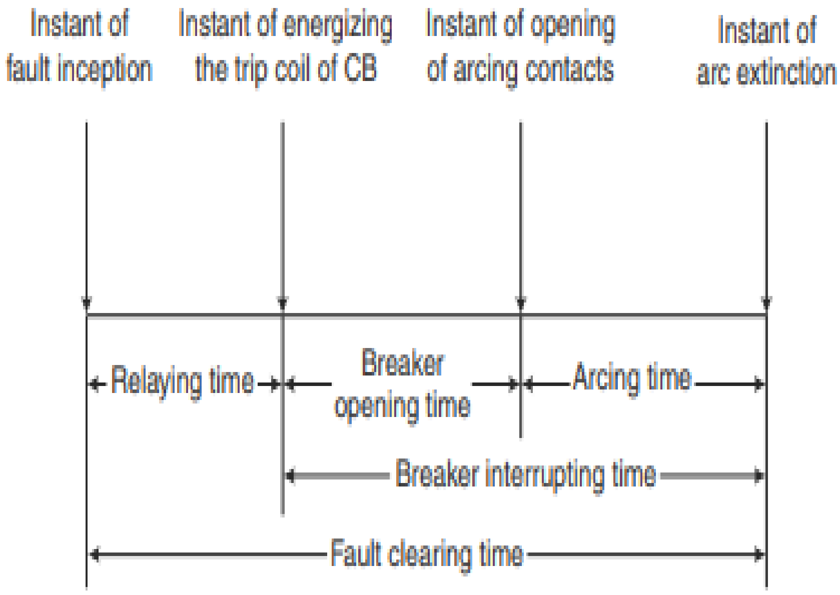


Fig.4.3 Fault clearing time of circuit breaker

The relaying time for electromechanical relays can vary from about one cycle to five cycles. Static relays are faster than electromechanical relays. Numerical relays give very fast operation and their relaying time is within one cycle. The contact opening time of the circuit breaker may be between about one and three cycles. The arcing time is now generally between one and two half-cycles, depending upon the instant in the current half-cycles at which the contacts part. Therefore, fast relays and modern circuit breakers make it possible to achieve fault clearance in as little as about three cycles of 50 Hz current, but the time varies considerably from system to system and in some cases in different parts of one system

4.3 Arc Voltage and Arc Current

The voltage drop across the arc is called arc voltage. As the arc path is purely resistive, the arc voltage is in phase with the arc current. The magnitude of the arc voltage is very low, amounting to only a few percent of the rated voltage. A typical value may be about 3% of the rated voltage.

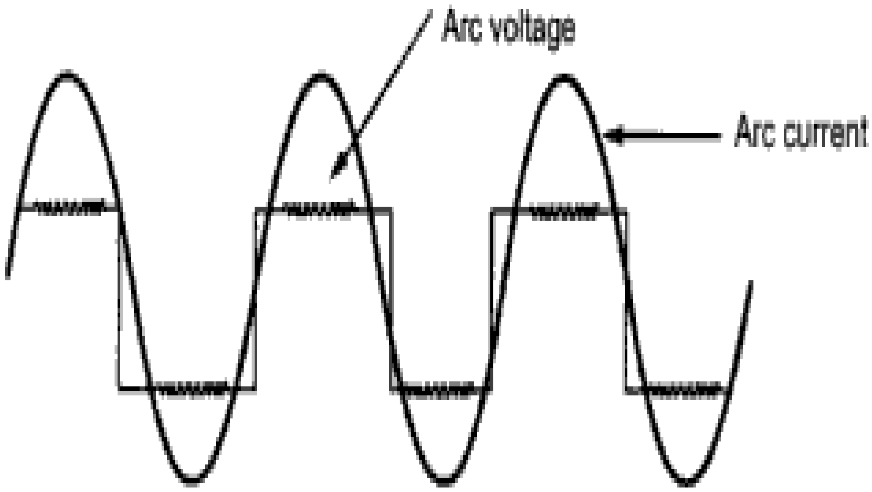


Fig.4.4 Short circuit current and arc voltage.

4.4 ARC INTERRUPTION

There are two methods of arc interruption:

(i) High Resistance Interruption
(ii) Current Zero Interruption

4.4.1 High Resistance Interruption

In this method of arc interruption, its resistance is increased so as to reduce the current to a value insufficient to maintain the arc. The arc resistance can be increased by cool- ing, lengthening, constraining and splitting the arc. When current is interrupted the energy associated with its magnetic field appears in the form of electrostatic energy. A high voltage appears across the contacts of the circuit breaker. If this voltage is very high and more than the withstanding capacity of the gap between the contacts, the arc will strike again. Therefore, this method is not suitable for a large-current interruption. This can be employed for low power ac and dc circuit breakers

4.4.2 Current Zero Interruption

This method is applicable only in case of ac circuit breakers. In case of ac supply, the current wave passes through a zero point, 100 times per second at the supply frequency of 50 Hz. This feature of ac is utilised for arc interruption. The current is not interrupted at any point other than the zero current instant, otherwise a high transient voltage will occur across the contact gap. The current is not allowed to rise again after a zero current occurs. There are two theories to explain the zero current interruption of the arc

(i) Recovery rate theory (Slepain's Theory)
(ii) Energy balance theory (Cassie's Theory)

4.5 Arc Interruption Theories

4.5.1 Recovery rate or Slepian's Theory

The arc is a column of ionised gases. To extinguish the arc, the electrons and ions are to be removed from the gap immediately after the current reaches a natural zero. Ions and electrons can be removed either by recombining them into neutral molecules or by sweeping them away by inserting insulating medium (gas or liquid) into the gap. The arc is interrupted if ions are removed from the gap at a rate faster than the rate of ionisation. In this method, the rate at which the gap recovers its dielectric strength is compared with the rate at which the gap recovers its dielectric strength is compared with the rate at which the restriking voltage (transient voltage) across the gap rises. If the dielectric strength increases more rapidly than the restriking voltage, the arc is extinguished. If the restriking voltage rises more rapidly than the dielectric strength, the ionisation persists and breakdown of the gap occurs, resulting in an arc for another half cycle. Figure 14.5 explains the principle of recovery rate theory

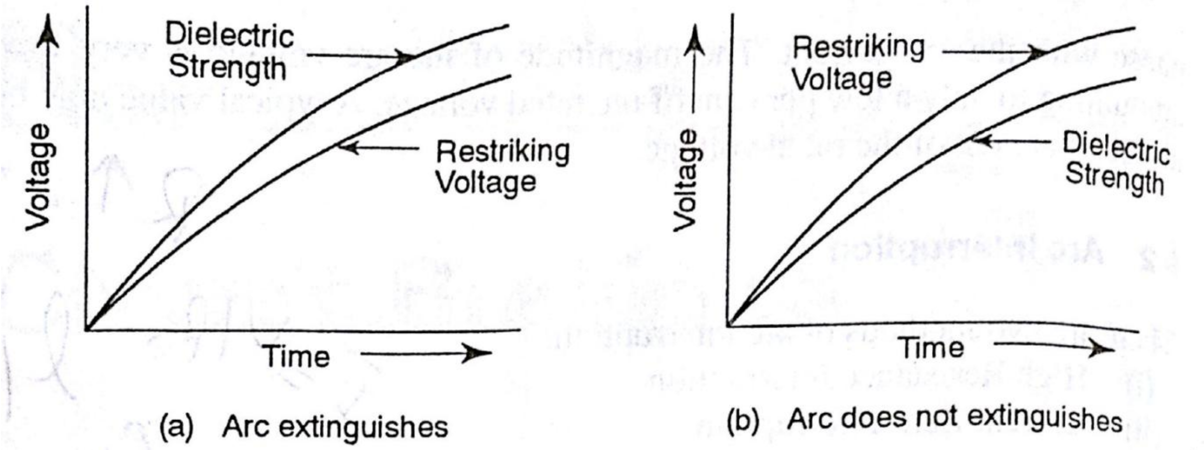


Fig.4.5 Recovery rate theory

4.5.2 Energy balance theory or Cassie's Theory

The space between the contacts contains some ionised gas immediately after current zero and hence, it has a finite post-zero resistance.

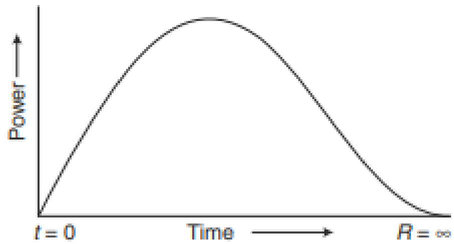


Fig.4.6 Energy balance theory

At the current zero moment,power is zero because restricking volt- age is zero. When the arc is finally extinguished, the power again becomes zero, the gap is fully de-ionised and its resistance is infinitely high. In between these two limits, first the power increases, reaches a maximum valuethen decreases and finally reaches zero value.. Due to the rise of restriking voltage and associated current, energy is generated in the space between the contacts. The energy appears in the form of heat. The circuit breaker is designed to remove this generated heat as early as possible by cooling the gap, giving a blast of air or flow of oil at high veloc- ity and pressure. If the rate of removal of heat is faster than the rate of heat generation the arc is extinguished. If the rate of heat generation is more than the rate of heat dis- sipation, the space breaks down again resulting in an arc for another half cycle

4.6 Restriking Voltage and Recovery Voltage

- The voltage across the contacts of the circuit breaker is arc voltage when the arc persists.

- This voltage becomes the system voltage when the arc is extinguished.

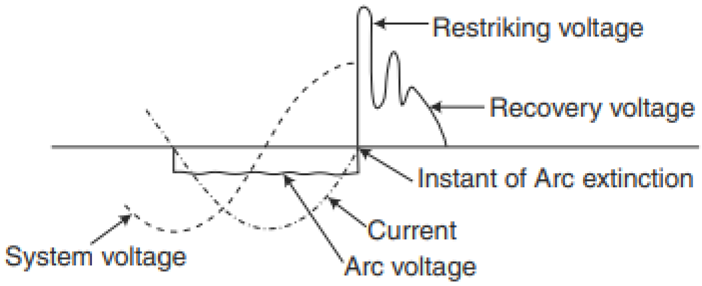


Fig. 4.7 Restriking and recovery voltage

- The arc is extinguished at the instant of current zero.
- After the arc has been extinguished, the voltage across the breaker terminals does not normalise instantaneously but it oscillates and there is a transient condition.
- The transient voltage which appears across the breaker contacts at the instant of arc being extinguished is known as restriking voltage.
- The power frequency rms voltage, which appears across the breaker contacts after the arc is finally extinguished and transient oscillations die out is called recovery voltage

4.7 Restriking Voltage and Rate of Rise of Restriking Voltage (RRRV)

The fault is cleared by the opening of the circuit breaker contacts. The parting of the circuit breaker contacts does not in itself interrupt the current because an arc is established between the parting contacts and the current continues to flow through the arc. Successful interruption depends upon controlling and finally extinguish- ing the arc. Extinction of the arc takes place at the instant when the current passes through zero.

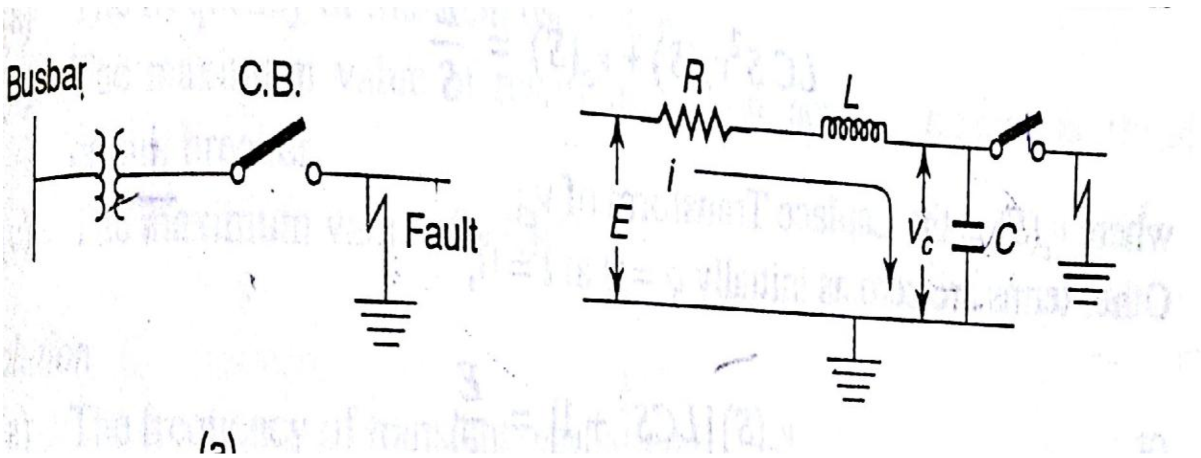


Fig. 8 (a) Fault on feeder near circuit breaker, (b) Equivalent electric circuit for analysis of restriking voltage.

Since the circuit of Fig. 14.8(b) is completely reactive, the voltage at the instant of current zero will be at its peak. The voltage across the circuit breaker contacts, and therefore across the capacitor C, is the arc voltage. In high-voltage circuits it is usually only a small percentage of the system voltage. Hence, the arc voltage may be assumed to be negligible.

$$w_n = \frac{1}{\sqrt{LC}}, \quad \text{therefore, } \frac{1}{LC} = w_n^2$$

or
$$v_c(s) = \frac{w_n^2 V_m}{s(s^2 + w_n^2)} = \frac{w_n V_m}{s}\left(\frac{w_n}{s^2 + w_n^2}\right) \tag{14.9}$$

Taking the inverse Laplace of Eq. (14.9), we get

$$v_c(t) = w_n V_m \int_0^t \sin \omega_n t$$

When the circuit-breaker contacts are opened and the arc is extinguished, the current i is diverted through the capacitance C, resulting in a transient condition. The inductance and the capacitance form a series oscillatory circuit. The voltage across the capacitance which is restriking voltage, rises and oscillates.

From the circuit,

$$L\frac{di}{dt} + \frac{1}{c}\int i\,dt = V_m \tag{14.4}$$

$$i = \frac{dq}{dt} = \frac{d(cv_c)}{dt} \tag{14.5}$$

where, v_c = voltage across the capacitor = Restriking voltage

Therefore,
$$\frac{di}{dt} = \frac{d^2(cv_c)}{dt^2} = c\,\frac{d^2v_c}{dt^2} \tag{14.6}$$

$$\frac{1}{c}\int i\,dt = \frac{q}{c} = v_c \tag{14.7}$$

Substituting these values in Eq. (14.4), we get

$$LC\frac{d^2v_c}{dt^2} + v_c = V_m \tag{14.8}$$

Taking Laplace Transform of both sides of Eq. (14.8), we get

$$LCS^2v_c(s) + v_c(s) = \frac{V_m}{s}$$

where, $v_c(s)$ is the Laplace Transform of v_c.

Other terms are zero as initially $q = 0$ at $t = 0$

or
$$v_c(s)\,[LCS^2 + 1] = \frac{V_m}{s}$$

or
$$v_c(s) = \frac{V_m}{s(LCS^2 + 1)} = \frac{V_m}{LCS\left(s^2 + \frac{1}{LC}\right)}$$

$$w_n = \frac{1}{\sqrt{LC}}, \quad \text{therefore, } \frac{1}{LC} = w_n^2$$

or $$v_c(s) = \frac{w_n^2 V_m}{s(s^2 + w_n^2)} = \frac{w_n V_m}{s}\left(\frac{w_n}{s^2 + w_n^2}\right) \quad (14.9)$$

Taking the inverse Laplace of Eq. (14.9), we get

$$v_c(t) = w_n V_m \int_0^t \sin \omega_n t$$

$$= w_n V_m \left[\frac{-\cos \omega_n t}{w_n}\right]_0^t$$

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

or $$v_c(t) = V_m (1 - \cos \omega_n t)$$

This is the expression for the restriking voltage.

The maximum value of the restriking voltage occurs at $t = \dfrac{\pi}{\omega_n} = \pi\sqrt{LC}$

Hence, the maximum value of restriking voltage = $2V_m$

= 2 × peak value of the system voltage

The amplitude factor of the restriking voltage is defined as the ratio of the peak of the transient voltage to the peak value of the system frequency voltage. If losses are ignored, this factor becomes 2.

The Rate of Rise of Restriking Voltage (RRRV)

$$= \frac{d}{dt}[V_m (1 - \cos \omega_n t)]$$

or $$\text{RRRV} = V_m w_n \sin \omega_n t$$

The maximum value of RRRV occurs when $\omega_n t = \pi/2$ i.e., when $t = \pi/2\omega_n$,

Hence, the maximum value of RRRV = $V_m \omega_n$

4.8 Resistance Switching

To reduce the restriking voltage, RRRV and severity of the transient oscillations, a resistance is connected across the contacts of the circuit breaker.

The resistance is in parallel with the arc.

A part of the arc current flows through this resistance resulting in a decrease in the arc current and increase in the deionisation of the arc path and resistance of the arc.

This process continues and the current through the shunt resistance increases and arc current decreases. Due to the decrease in the arc current, restriking voltage and RRRV are reduced

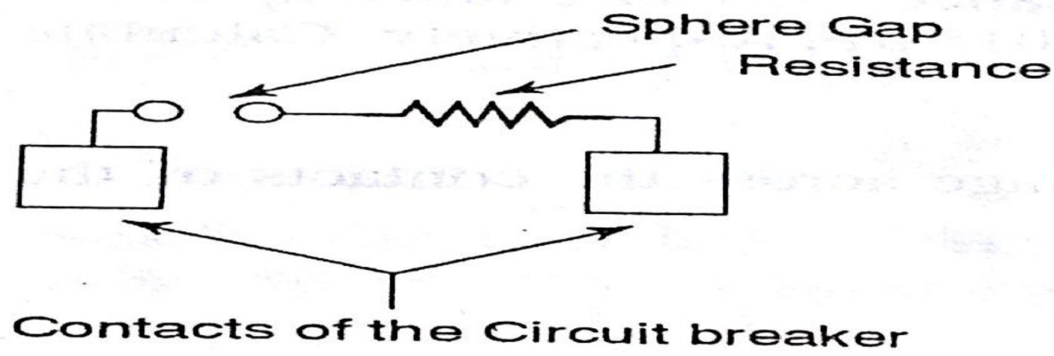


Fig.4.9 Resistance switching

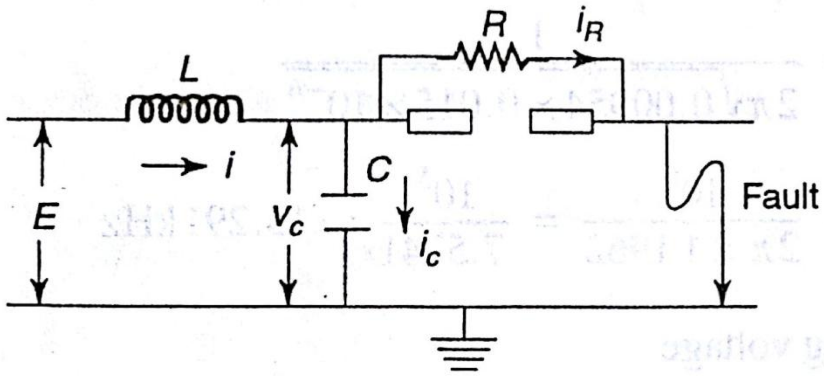


Fig. 4.10 Circuit for analysis of resistance switching

From the given figure ,

Hence, the voltage equation is given by

$$L\frac{di}{dt} + \frac{1}{C}\int i_C\, dt - V_m \quad \text{and} \quad i - i_c + i_R$$

Therefore, the above equation becomes

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

or
$$L\frac{di_c}{dt} + L\frac{di_R}{dt} + v_c = V_m \qquad (14.12)$$

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

Therefore,
$$\frac{di_c}{dt} = \frac{d^2(Cv_c)}{dt^2} = C\frac{d^2v_c}{dt^2} \qquad (14.13)$$

$$\frac{di_R}{dt} = \frac{d(v_c/R)}{dt} = \frac{1}{R}\frac{dv_c}{dt} \qquad (14.14)$$

Substituting these values in Eq. (14.12), we get

$$LC\frac{d^2v_c}{dt^2} + \frac{L}{R}\frac{dv_c}{dt} + v_c = V_m \tag{14.15}$$

Taking Laplace Transform, of both sides of Eq. (14.15), we get

$$LCS^2v_c\,(S) + \frac{L}{R}S\,v_c(S) + v_c(S) = \frac{V_m}{s}$$

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

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

or $$v_c(S) = \frac{V_m}{SLC\left[S^2 + \frac{1}{RC}S + \frac{1}{LC}\right]} \tag{14.16}$$

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

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

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

or $$R^2 \leq \frac{1}{4}\cdot\frac{L}{C} \quad \text{or} \quad R \leq \frac{1}{2}\sqrt{\frac{L}{C}} \tag{14.17}$$

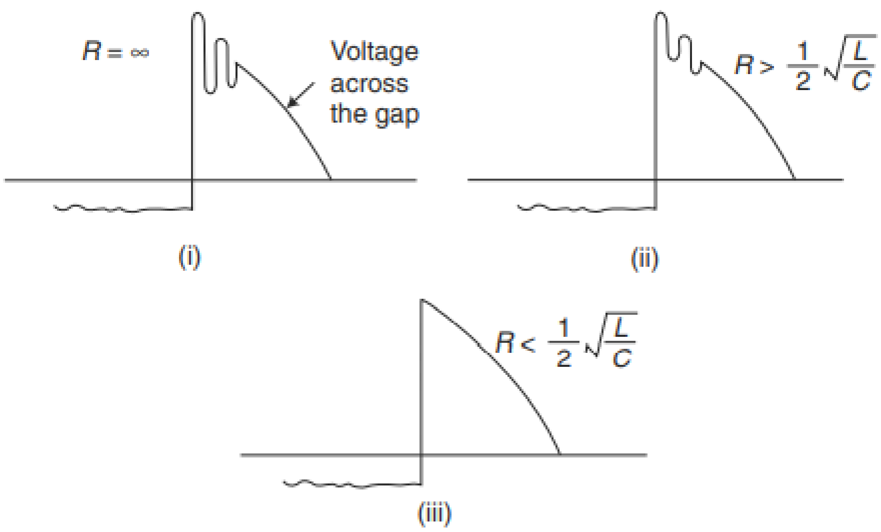


Fig. 4.11 Transient oscillations for different values of R

Therefore, if the value of the resistance connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2}\sqrt{L/C}$ there will be no transient oscillation. If $R > \frac{1}{2}\sqrt{L/C}$, there will be oscillation. $R = \frac{1}{2}\sqrt{L/C}$ is known as critical resistance. Figure 14.11 shows the transient conditions for three different values of R. The frequency of damped oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}} \tag{14.18}$$

4.9 Current Chopping

When low inductive current is being interrupted and the arc quenching force of the circuit breaker is more than necessary to interrupt a low magnitude of current, the cur- rent will be interrupted before its natural zero instant. In such a situation, the energy stored in the magnetic field appears in the form of high voltage across the stray capacitance, which will cause restriking of the arc. The energy stored in the magnetic field is ½ $L\ i^2$, if i is the instantaneous value of the current which is interrupted. This will appear in the form of electrostatic energy equal to ½ Cv^2. As these two energies are equal, they can be related as follows.

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2$$

$$v = i\sqrt{L/C}$$

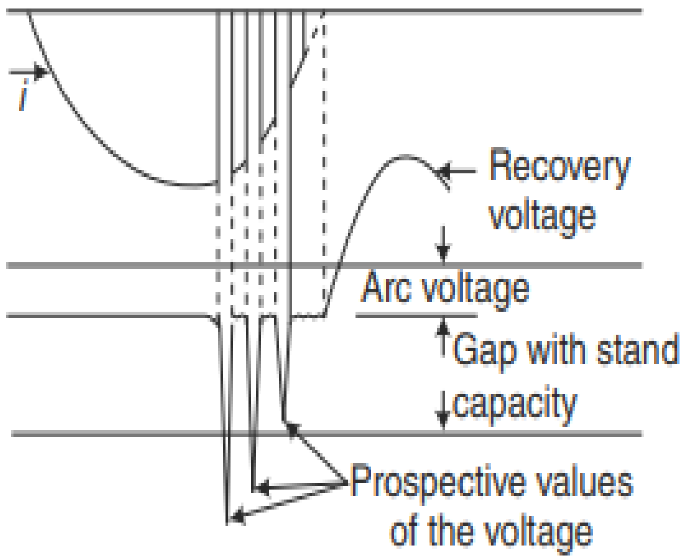


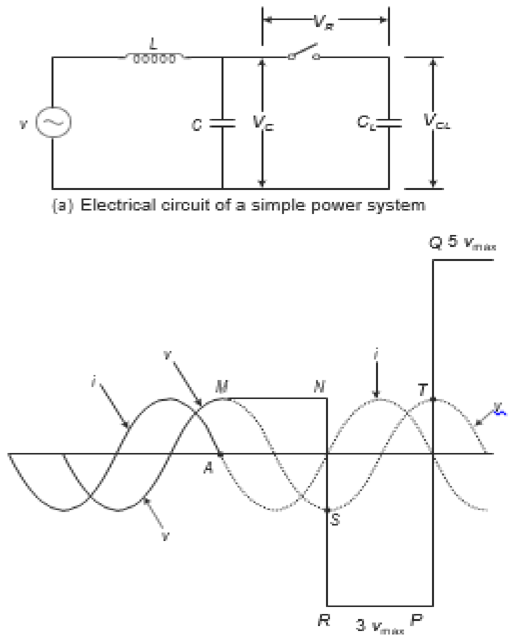
Fig.4.12 Current chopping

If the value of v is more than the withstanding capacity of the gap between the contacts, the arc appears again. Since the quenching force is more, the current is again chopped. This phenomenon continues till the value of v becomes less than the withstanding capacity of the gap. The theoretical value of v is called the prospective value of the voltage.

4.10 Interruption of capacitive current

The interruption of capacitive current produces high voltage transients across the gap of the circuit breaker. This occurs when an unloaded long transmission line or a capacitor bank is switched off. Figure 14.13(a) shows an equivalent electricalcircuit of a simple power system. *C* represents stray capacitance of the circuit breaker. C_L represents line capacitance. The value of C_L is much more than *C*. Figure 14.13(b) showstransientvoltageacrossthegapofthecircuitbreakerwhencapacitivecurrent is interrupted.

At the instance *M*, the capacitive current is zero and the system voltage is maxi- mum. If an interruption occurs, the capacitor C_L remains charged at the maximum valueofthesystemvoltage.Afterinstant*M*,thevoltageacrossthebreakergapisthe difference of V_C and V_{CL}. At instant *N*, i.e. half-cycle from *A*, the voltage across the gap is twice the maximum value of V_C. At this moment, the breaker may restrike. If the arc restrikes, the voltage across the gap becomes practically zero. Thus, the voltageacrossthegapfallsfrom2V_{Cmax}tozero.Aseverehighfrequencyoscillation occurs. The voltage oscillates about point *S* between *R* and *N*, i.e. between –3V_{max} and V_{max}. When restriking current reaches zero, the arc may be interrupted again. At this stage, the capacitor C_L. remains charged at the voltage –3V_{max}. At instant *P*, the system voltage reaches its positive maximum shown by the point *T* in the figure, andatthismomentthevoltageacrossthegapbecomes4V_{max}.Thecapacitivecurrent reacheszeroagainandtheremaybeaninterruption.Iftheinterruptionoccursatthis moment, the transient voltage oscillates between *P* (–3V_{max}) and *Q* (+5V_{max}). In this way, the voltage across the gap goes on increasing. But in practice, it is limited to 4 times the peak value of the system voltage. Thus, it is seen that there is a problem of high transient voltage while interrupting a capacitivecurrent.



(a) Electrical circuit of a simple power system

Transient voltage across the gap of the circuit breaker

Fig.4.13 Interruption of capacitive current

4.11 Fuse related Definitions

(i) Fuse

A fuse is a protective device used for protecting cables and electrical equipment against overloads and/or short-circuits. It breaks the circuit by fusing (melting) the fuse element (or fuse wire) when the current flowing in the circuit exceeds a certain predetermined value. The term fuse in general refers to all parts of the device.

(ii)Fuse Element (or Fuse Wire)

It is that part of the fuse which melts when the current flowing in the circuit exceeds a certain predetermined value and thus breaks the circuit.

(iii) Rated Current

The rated current of a fuse is the current it can carry indefinitely without fusing.

(iv) Minimum Fusing Current

It is the minimum current (rms value) at which the fuse clement will melt.

(v) FusingFactor

It is defined as the ratio of the minimum fusing current to rated current, i.e.

$$\text{Fusing factor} = \frac{\text{Minimum fusing current}}{\text{Rated current}}$$

This factor is always more than unity.

(vi) ProspectiveCurrent

Figure 15.1 shows the first major loop of the fault current. The prospective current (shown dotted) is the current which would have flown in the circuit if the fuse had beenabsent,i.e.ithadbeenreplacedbyalinkofnegligibleresistance.Itismeasured in terms of the rms value of the a.c. (symmetrical) component of the fault current in the first major loop. In Fig. 15.1, I_p is the peak value of the prospectivecurrent.

(vii) Cut-offCurrent

Thecurrentatwhichthefuseelementmeltsiscalledthecut-offcurrent($i_c$inFig.15.1) andismeasuredasaninstantaneousvalue.Itisthuspossibleforaprospectivecurrent (rms value) to be numerically less than the cut-off current. Since the fault current normally having a large first loop generates sufficient heat energy, the fuse element melts well before the peak of the prospective current isreached.

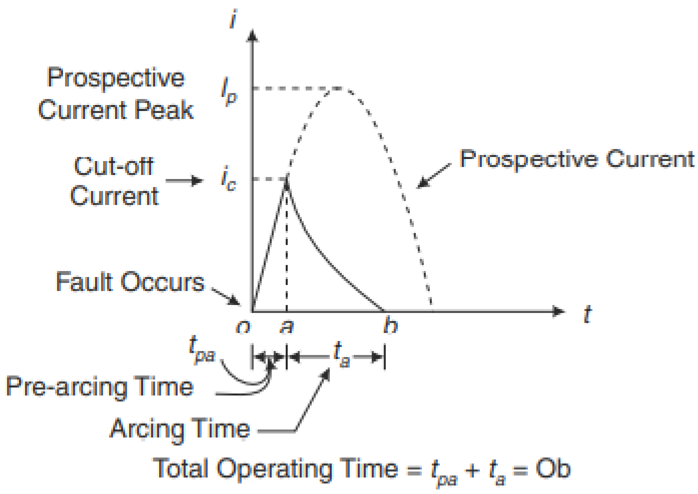


Fig.4.14 Cut- off Characteristics

(viii) Pre-arcingTimeorMeltingTime

This is the time taken from the instant of the commencement of the current which causes cut-off to the instant of cut-off and arc initiation. In Fig *oa* is the pre- arcing time (t_{pa}).

(ix) ArcingTime

This is the time taken from the instant of cut-off (arc initiation) to the instant of arc beingextinguishedorthecurrentfinallybecomingzero.InFig *ab*isthearcing lime (t_a).

(x) Total OperatingTime

It is the sum of the pre-arcing time and the arcing time. In Fig, *ob* is the total operating time, i.e. $t_{pa} + t_a$.

(xi) RupturingCapacity(orBreakingCapacity)

It is the MVA rating of the fuse corresponding to the largest prospective cur- rent which the fuse is capable of breaking (rupturing) at the system voltage. Afuseisneverrequiredtopassanactualcurrentequivalenttoitsrupturingorbreak- ingcapacity.Whenaparticularrupturingcapacityisspecified,itisexpectedthatthe fusewillsuccessfullyoperateinacircuithavingprospectivecurrentequivalenttoits rupturingcapacity;butthefusemeltsmuchearlierduetocut-offaction.Henceafuse never allows to pass a current equivalent to its rupturingcapacity.

4.12 Fuse Characteristics

Figure shows a typical time-current characteristic of a fuse, the current scale being in multiples of the rated current (= 1) and the time scale being logarithm. In practice, this graph is usually given in terms of pre-arcing time and prospective current.

By observation of the characteristic, it is clear that as the prospective current increases, the pre-arcing time decreases. It is also clear that the characteristic becomes asymptotic and there is a minimum current below which the fuse does not operate. This current is called the minimum fusing current. The operating time of the fuse for currents near the minimum fusing current is long

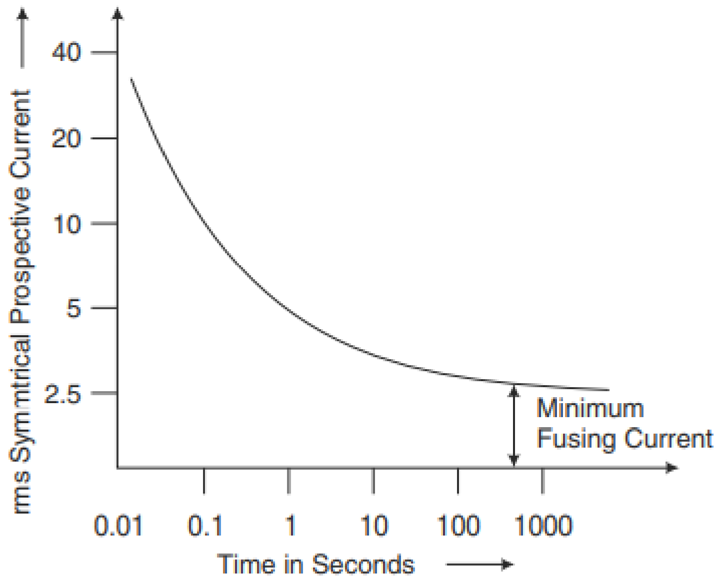


Fig. 4.15 Typical Time- Current characteristics of Fuse

4.13 High Rupturing Capacity (HRC) Cartridge Fuse

The HRC fuses cope with increasing rupturing capacity on the distribution system and overcome the serious disadvantages suffered by the semi-enclosed rewirable fuses.

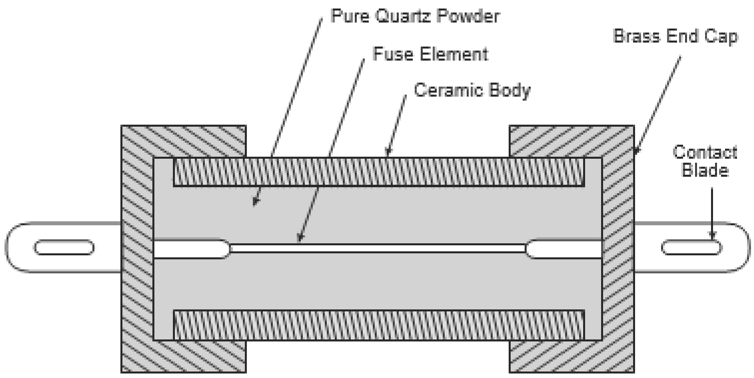


Fig.4.16 HRC Fuse

In an HRC fuse, the fuse element surrounded by an inert arc quenching medium is completely enclosed in an outer body of ceramic material having good mechani- cal strength. The unit in which the fuse element is enclosed is called ‘fuse link’. The fuse link is replaced when it blows off. In its simplest form (Fig.), an HRC fuse consists of a cylindrical body of ceramic material usually steatite, pure silver (or bimetalic) element, pure quartz powder, brass end-caps and copper contact blades. The fuse element is fitted inside the ceramic body and the space within the body sur- rounding the clement is completely filled with pure powdered quartz. The ends of the fuse element arc connected to the metal end-caps which are screwed to the ceramic body by means of special forged screws. End contacts (contact blades) are welded to the metal end-caps. The contact blades arc bolted on the stationary contacts on the panel.

The fuse element is either pure silver or bimetalic in nature. Normally, the fuse element has two or more sections joined together by means of a tin joint. The fuse element in the form of a long cylindrical wire is not used, because after melting, it will form a string of droplets and an arc will be struck between each of the droplets. Later on these droplets will also evaporate and a long arc will be struck. The purpose of the tin joint is to prevent the formation of a long arc. As the melting point of tin is much lower than that of silver, tin will melt first under fault condition and the melting of tin will prevent silver from attaining a high temperature. The shape of the fuse element depends upon the characteristic desired.

When the fuse carries normal rated current, the heat energy generated is not suf- ficient to melt the fuse element. But when a fault occurs, the fuse element melts before the fault current reaches its first peak. As the element melts, it vaporizes and disperses. During the arcing period, the chemical reaction between the metal vapour and quartz powder forms a high resistance substance which helps in quenching the arc. Thus the current is interrupted.

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Question Bank

Part-A

Q.No.	Question
1.	Name the various methods of arc quenching?
2.	Explain the basic concept of d.c circuit breaking.
3.	Define rate of rise of restriking voltage.
4.	List the advantages of HRC fuses?
5.	Define current chopping
6.	Define recovery voltage?
7.	How the arcing in SF_6 circuit breaker is quenched?
8.	Explain the Arc Quenching process.
9.	List the factors on which the arc resistance depends.
10.	Determine the expression for Restriking voltage.

PART – B

Q.No.	Question
1.	Explain briefly about the Arc interruption methods.
2.	For a 132 KV system, the reactance and capacitance up to the location of the circuit breaker is 3 ohms and 0.015μF respectively. Determine the following (a) The frequency of transient oscillation (b) The maximum value of restriking voltage across the contacts of the C B. (c) The maximum value of RRRV.
3.	(a) Explain the principles of arcing phenomena. (b) Describe the concept of capacitive current breaking.
4.	Determine an expression for Restriking voltage and RRRV.
5.	Explain the phenomenon of resistance switching with neat derivation.
6.	Construct a suitable sketch and explain the operation of HRC fuse.
7.	(a) Draw the characteristics of fuses and explain HRC fuse with diagram. (b) Compare AC circuit breaking Vs DC circuit breaking

UNIT - V

Power System Protection and Switchgear – SEE1401
UNIT V- CIRCUIT BREAKERS

V. Circuit Breakers

Classification of circuit breakers - air circuit breakers - oil circuit breakers - vacuum circuit breaker - SF6 circuit Breakers - selection of circuit breakers - rating of circuit breakers - testing of circuit breakers.

5.1 Classification of circuit breakers

Out of the various ways of classification of circuit breakers, the general way and the most important method of classification is on the basis of medium used for insulating and arc quenching. Depending on the arc quenching medium employed, the follow- ing are important types of circuit breakers

(i) Air-break circuit breakers:

(ii) Oil circuit breakers

(iii) Air blast circuit breakers

(iv) Sulphur hexafluoride (SF6) circuit breakers

(v) Vacuum circuit breakers

The development of circuit breakers outlined above has taken place chronologi- cally in order to meet two important requirements of the power system which has progressively grown in size. Firstly, higher and higher fault currents need to be inter- rupted, i.e., breakers need to have larger and larger breaking capacity. Secondly, the fault interruption time needs to be smaller and smaller for maintaining system stability

5.2 Air break circuit breakers

Air-break circuit breakers are quite suitable for high current interruption at low volt- age. In this type of a circuit breaker, air at atmospheric pressure is used as an arc extinguishing medium. Figure 5.1 shows an air-break circuit breaker. It employs two pairs of contacts—main contacts and arcing contacts. The main contacts carry current when the breaker is in closed position. They have low contact resistance. When contacts are opened, the main contacts separate first, the arcing contacts still remain closed. Therefore, the current is shifted from the main contacts to the arcing contacts. The arcing contacts separate later on and the arc is drawn between them.

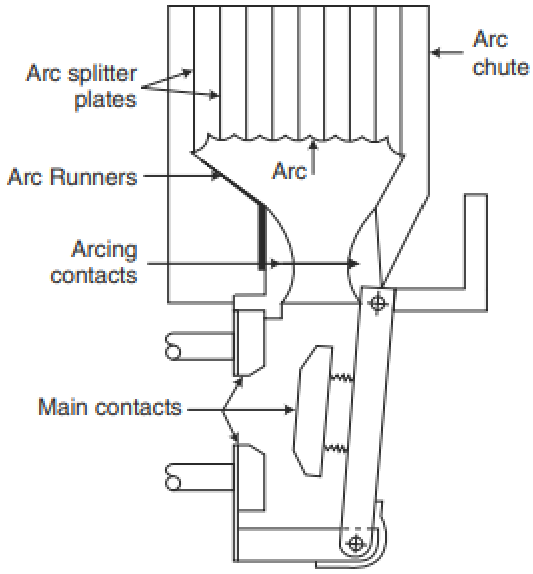

Fig. 5.1Air Break Circuit Breaker

In air-break circuit breakers, the principle of high resistance is employed for arc interruption. The arc resistance is increased by lengthening, splitting and cooling the arc. The arc length is rapidly increased employing arc runners and arc chutes. The arc moves upward by both electromagnetic and thermal effects. It moves along the arc runner and then it is forced into a chute. It is split by arc splitters. A blow-out coil is employed to provide magnetic field to speed up arc movement and to direct the arc into arc splitters. The blow-out coil is not connected in the circuit permanently. It comes in the circuit by the arc automatically during the breaking process. The arc interruption is assisted by current zero in case of ac air break circuit breakers. High resistance is obtained near current zero. AC air-break circuit breakers are available in the voltage range 400 to 12 kV. They are widely used in low and medium voltage system. They are extensively used with electric furnaces, with large motors requiring frequent starting, in a place where chances of fire hazard exist, etc. Air-break circuit breakers are also used in dc circuit up to 12 kV.

5.3 Air Blast circuit breaker

In air blast circuit breakers, compressed air at a pressure of 20-30 kg/cm2 is employed as an arc quenching medium. Air blast circuit breakers are suitable for operating voltage of 132 kV and above. They have also been used in 11 kV–33 kV range for certain applications. At present, SF6 circuit breakers are preferred for 132 kV and above. Vacuum circuit breakers are preferred for 11 kV–33 kV range. Therefore, the air blast circuit breakers are becoming obsolete. The advantages of air blast circuit breakers over oil circuit breakers are:

(i) Cheapness and free availability of the interrupting medium, chemical stability and inertness of air

(ii) High speed operation

(iii) Elimination of fire hazard
(iv) Short and consistent arcing time and therefore, less burning of contacts
(v) Less maintenance
(vi) Suitability for frequent operation
(vii) Facility for high speed reclosure

The disadvantages of an air blast circuit breaker are as follows

(i) An air compressor plant has to be installed and maintained
(ii) Upon arc interruption the air blast circuit breaker produces a high-level noise when air is discharged to the open atmosphere. In residential areas, silencers need to be provided to reduce the noise level to an acceptable level
(iii) Problem of current chopping
(iv) Problem of restriking voltage

Switching resistors and equalising capacitors are generally connected across the interrupters. The switching resistors reduce transient overvoltages and help arc interruption. Capacitors are employed to equalise the voltage across the breaks. The number of breaks depends upon the system voltage. For example, there are 2 for 66 kV, 2 to 4 for 132 kV, 2 to 6 for 220 kV, 4 to 12 for 400 kV, 8 to 12 for 750 kV. The breaking capacities are, 5000 MVA at 66 kV, 10,000 MVA at 132 kV, 20,000 MVA at 220 kV; 35000 MVA at 400 kV, 40,000 MVA at 500 kV; 60,000 MVA at 750 kV. Circuit breakers for higher interrupting capacity have also been designed for 1000 kV and 1100 kV systems.

An air-blast circuit breaker may be either of the following two types.

(i) Cross-blast Circuit Breakers
(ii) Axial-blast Circuit Breakers.

(i) Cross- blast circuit breaker

In a cross-blast type circuit breaker, a high-pressure blast of air is directed perpendicularly to the arc for its interruption. Figure shows a schematic diagram of a cross-blast type circuit breaker. The arc is forced into a suitable chute. Sufficient lengthening of the arc is obtained, resulting in the introduction of appreciable resistance in the arc itself. Therefore, resistance switching is not common in this type of circuit breakers. Cross-blast circuit breakers are suitable for interrupting high current (up to 100 kA) at comparatively lower voltages.

(ii) Axial-blast Circuit Breakers

In an axial-blast type circuit breaker, a high-pressure blast of air is directed longitudinally, i.e. in line with the arc. Figure 5.2(b) and (c) show axial-blast type circuit breakers. Figure 5.2(b) shows a single blast type. Whereas Fig. 5.2(c) shows a double blast type or radial blast type. Axial blast circuit breakers are suitable for EHV and super high voltage application. This is because interrupting chambers can be fully enclosed in porcelain tubes. Resistance switching is employed to reduce the transient overvoltages. The number of breaks depends upon the system voltage, for example, 4 at 220 kV and 8 at 750 kV. Air-blast circuit breakers have also been commissioned for 1100 kV system.

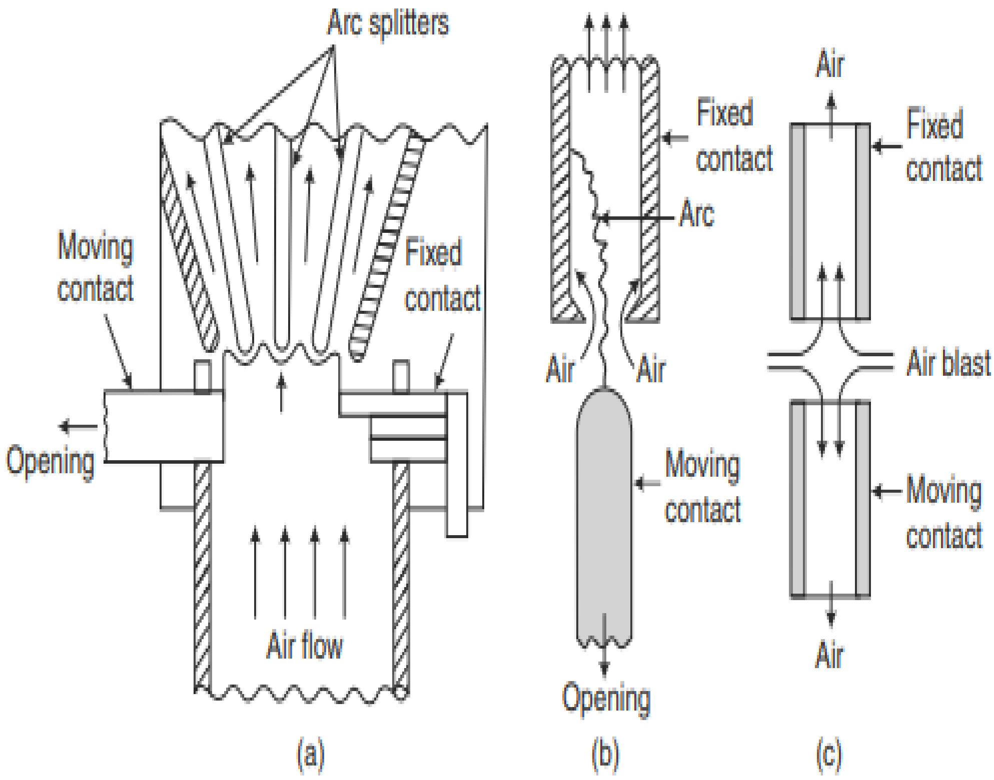

Fig.5.2 a) Air blast circuit breaker, b)single blast type axial-blast circuit breaker, c)Double blast type axial-blast circuit breaker

5.4 Oil circuit breakers

Mineral oil has better insulating properties than air. Due to this very reason it is employed in many electrical equipment including circuit breakers. Oil has also good cooling property. In a circuit breaker when arc is formed, it decomposes oil into gases. Hence, the arc energy is absorbed in decomposing the oil. The main disadvantage of oil is that it is inflammable and may pose a fire hazard. Other disadvantages included the possibility of forming explosive mixture with air and the production of carbon particles in the oil due to heating, which reduces its dielectric strength. Hence, oil circuit breakers are not suitable for heavy current interruption at low voltages due to carbonisation of oil. There are various types of oil circuit breakers developed for use in different situations. Some important types are discussed below.

5.4.1 Plain-break Oil Circuit Breakers

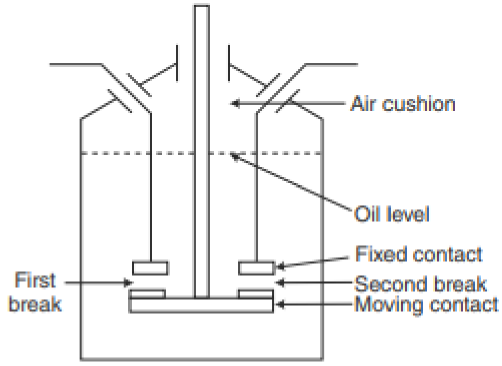

Fig. 5.3 Plain-break Oil Circuit Breakers

In a plain-break oil circuit breaker there is a fixed and a moving contact immersed in oil. The metal tank is strong, weather tight and earthed. Figure 5.3 shows a double break plain oil circuit breaker. When contacts separate there is a severe arc which decomposes the oil into gases. The gas obtained from the oil is mainly hydrogen. The volume of gases produced is about one thousand times that of the oil decomposed. Hence, the oil is pushed away from arc and the gaseous medium surrounds the arc.

The arc quenching factors are as follows. (i) Elongation of the arc. (ii) Formation of gaseous medium in between the fixed and moving contacts. This has a high heat conductivity and high dielectric strength. (iii) Turbulent motion of the oil, resulting from the gases passing through it.

A large gaseous pressure is developed because a large amount of energy is dissipated within the tank. Therefore, the tank of the circuit breaker is made strong to withstand such a large pressure. When gas is formed around the arc, the oil is displaced. To accommodate the displaced oil, an air cushion between the oil surface and the tank is essential. The air cushion also absorbs the mechanical shock produced due to upward oil movement. It is necessary to provide some form of vent fitted in the tank cover for the gas outlet. A sufficient level of oil above the contacts is required to provide substantial oil pressure at the arc.

5.4.2 Self-generated Pressure Oil Circuit-breaker

In this type of circuit-breakers, arc energy is utilised to generate a high pressure in a chamber known as explosion pot or pressure chamber or arc controlling device. The contacts are enclosed within the pot. The pot is made of insulating material and it is placed in the tank. Such breakers have high interrupting capacity. The arcing time is reduced. Since the pressure is developed by the arc itself, it depends upon the magnitude of the current. Therefore, the pressure will be low at low current and high at high values of the current. This creates a problem in designing a suitable explosion pot.

At low current, pressure generated should be sufficient to extinguish the arc. At heavy currents, the pressure should not be too high so as to burst the pot. Various types of explosion pots have been developed to suit various requirements. A few of them have been discussed below.

Plain Explosion Pot

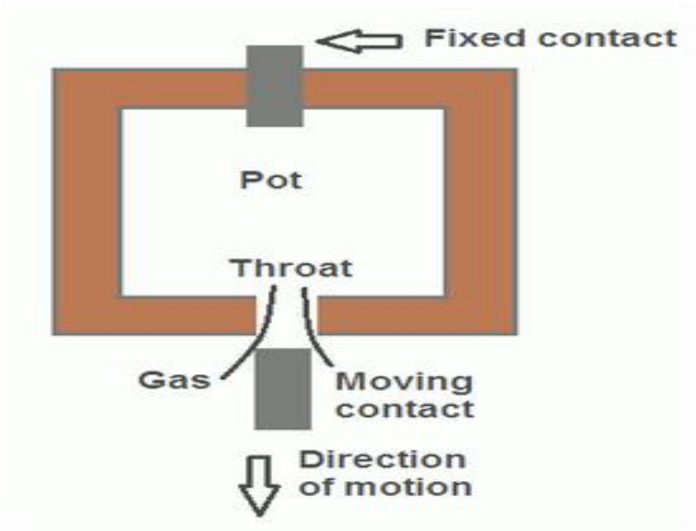

Fig. 5.4 Plain explosion pot

Figure 5.4 shows a plain explosion pot. This is the simplest form of an explosion pot. When the moving contact separates a severs arc is formed. The oil is decomposed and gas is produced. It generates a high pressure within the pot because there is a close fitting throat at the lower end of the pot. The high pressure developed causes turbulent flow of streams of the gas into the arc resulting in arc-extinction. If the arc extinction does not occur within the pot, it occurs immediately after the moving contact leaves the pot, due to the high velocity axial blast of the gas which is released through the throat. Since the arc extinction in the plain explosion pot is performed axially, it is also known as an axial extinction pot. This type of a pot is not suitable for breaking of heavy currents. The pot may burst due to very large pressure. At low currents, the arcing time is more. Hence, this type of an explosion pot is suitable for the interruption of currents of medium range.

Cross-jet Explosion Pot

Figure 5.5 shows a cross-jet explosion pot. It is suitable for high current interruptions. Arc splitters are used to obtain an increased arc length for a given amount of contact travel. When the moving contact is separated from the fixed contact, an arc is formed, as shown in Fig. 5.5(a). The arc is pushed into the arc splitters as shown in Fig. 5.5(b), and finally it is extinguished, as in Fig. 5.5(c). In this type of a pot, the oil blast is across the arc and hence it is known as a cross-jet explosion pot.

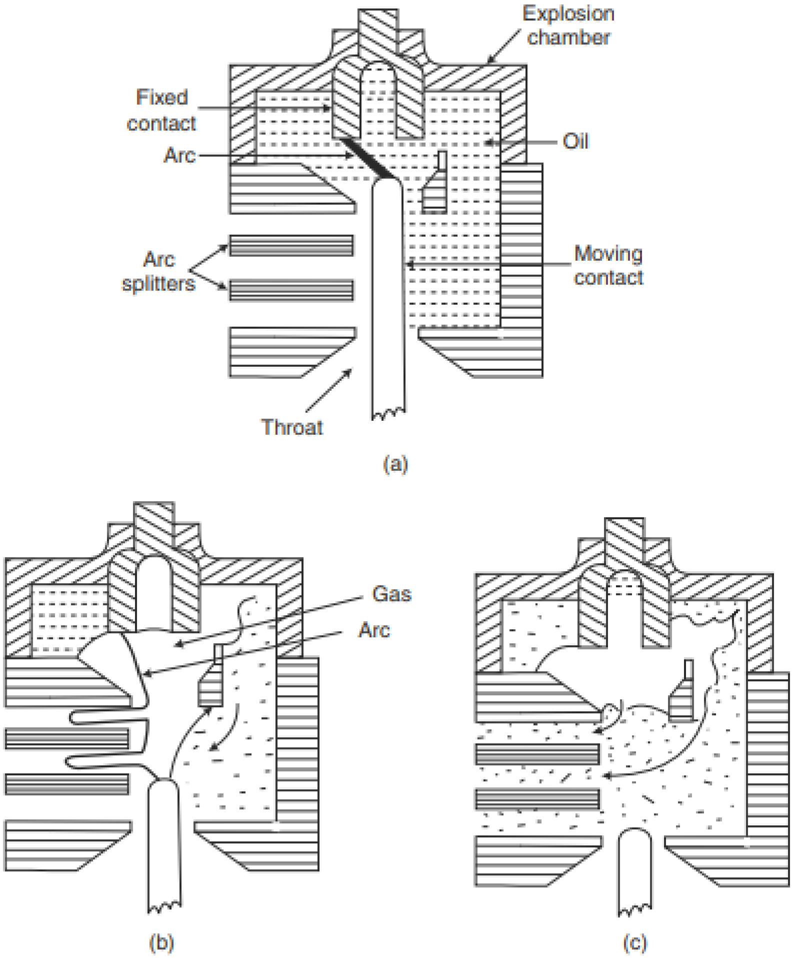

Fig. 5.5 Cross-jet explosion pot

Self-compensated Explosion Pot

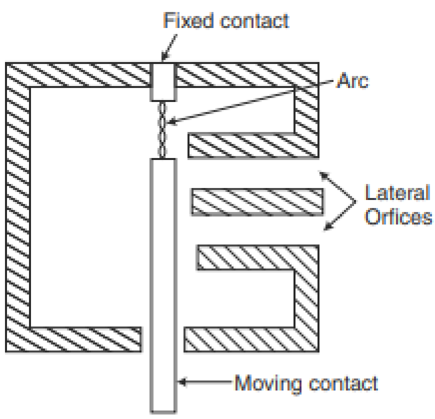

Fig. 5.6 Self-compensated Explosion Pot

This type of a pot is a combination of a cross-jet explosion pot and a plain explosion pot. Figure 5.6 shows a self-compensated explosion pot. Its upper portion is a cross-explosion pot, and the lower portion a plain explosion pot. On heavy currents the rate of gas generation is very high and consequently, the pressure produced is also very high. The arc extinction takes place when the first or second lateral orifice of the arc splitter is uncovered by the moving contact. The pot operates as a cross-jet explosion pot. When the current is low, the pressure is also low in the beginning. So the arc is not extinguished when the tip of the moving contact is in the upper portion of the pot. By the time the moving contact reaches the orifice at the bottom of the pot, sufficient pressure is developed. The arc is extinguished when the tip of the moving contact comes out of the throat. The arc is extinguished by the plain explosion pot action. Thus, it is seen that the pot is suitable for low as well as high current interruptions.

5.4.3 Double Break Oil Circuit Breaker

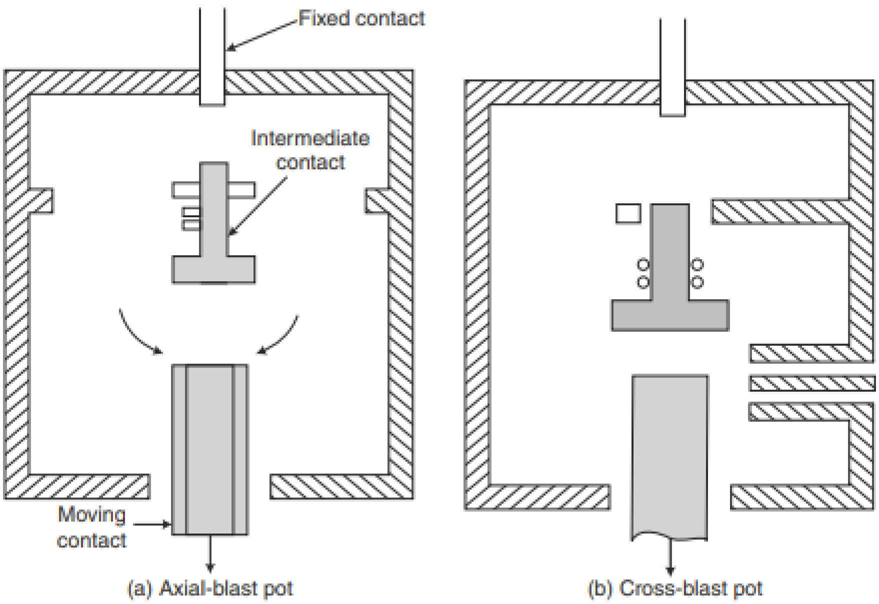

Fig.5.7Double Break Oil Circuit Breaker

To obtain high speed arc interruption, particularly at low currents, various improved designs of the explosion pot have been presented. Double break oil circuit breaker is also one of them. It employs an intermediate contact between the fixed and moving contact. When the moving contact separates, the intermediate contact also follows it. The arc first appears between the fixed contact and the intermediate contact. Soon after, the intermediate contact stops and a second arc appears between the intermediate contact and the moving contact. The second arc is extinguished quickly by employing gas pressure and oil momentum developed by the first arc. Figure 5.7(a) shows an axial blast pot and Fig. 5.7(b) shows a cross blast pot.

5.4.4 Minimum or Low oil circuit breaker

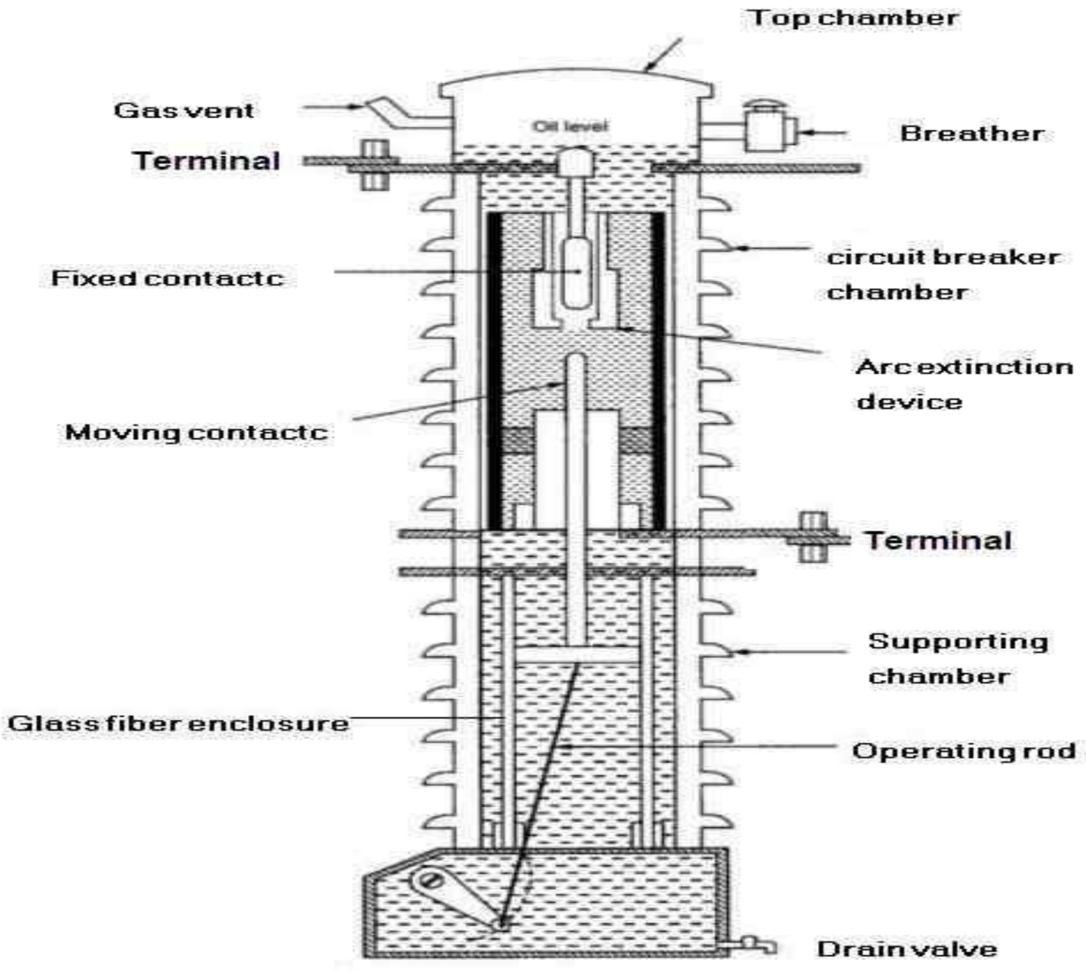

Fig. 5.8 Minimum or low oil circuit breaker

- Oil does two function
  - Arc quenching purpose
  - Insulating live parts from earthed tank
- very small oil - Arc extinction
- Major part of oil - for insulation purpose.
- Due to this called as low oil CB or minimum oil CB.
- Two oil filled chambers
- Upper Chamber
  - Small quantity of oil is used for arc extinguishing purpose called arcing chamber.

- Consists of arc control device, upper fixed contact, lower moving contact and all components are immersed in oil an enclosed in glass fibre.

- Lower Chamber
  - Oil for insulating purpose , does not engage in arc extinguishing process.
- Both upper and lower chambers are surrounded by cylindrical shaped synthetic resin bonded paper with porcelain insulator.
- Operating rod is permanently connected to the moving contact to move it vertically during making and breaking circuit.
- Fault condition
  - Moving and fixed contact get separated – Arc struck – Oil in chamber attains high temperature and vaporise – Hydrogen gas generated.
  - Due to cooling effect of hydrogen, arc cools down and its pressure splits it in to small arcs
- As oil between contact gest vaporised in this process, fresh oil is filled between the contacts. This fresh oil also gets vaporised and generate gases and again fresh oil is filled. This cycle continues until arc is extinguished.
- Oil filling valve
  - An oil filling valve is fitted on top of arc control device.
  - As the oil inside the arc extinction device is vapourised, this valve get opened and fresh oil enters the arc extinction device.
  - When the arc is quenched completely , this valve get closed
- Breather
  - Prevents moisture entry in to the circuit breaker
- Advantages
  - Smaller tank size
  - Less quantity of oil
  - Lower cost
  - Reduced risk of fire
  - Reduced maintenance problem
- Drawback
  - Deterioration of dielectric strength due to high degree of carbonization

5.5 Vacuum circuit breaker

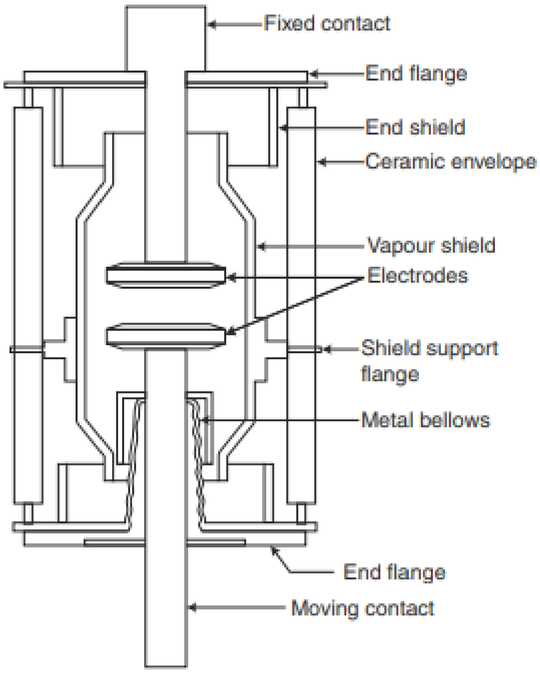

Fig. 5.9 Vacuum circuit breaker

The dielectric strength and arc interrupting ability of high vacuum is superior to those of porcelain, oil, air and SF6 at atmospheric pressure. SF6 at 7 atm. pressure and air at 25 atm. pressure have dielectric strengths higher than that of high vacuum. The pressure of 10^{-5} mm of mercury and below is considered to be high vacuum. Low pressures are generally measured in terms of torr; 1 torr being equal to 1 mm of mercury. It has now become possible to achieve pressures as low as 10^{-8} torr. When contacts separate in a gas, arc is formed due to the ionised molecules of the gas. The mean free path of the gas molecules is small and the ionisation process multiplies the number of electrons to form an electron avalanche. In high vacuum, of the order of 10^{-5} mm of mercury, the mean free path of the residual gas molecules becomes very large. It is of the order of a few metres. Therefore, when contacts are separated by a few mm in high vacuum, an electron travels in the gap without collision. The formation of arc in high vacuum is not possible due to the formation of electron avalanche. In vacuum arc electrons and ions do not come from the medium in which the arc is drawn but they come from the electrodes due to the evaporation of their surface material. The breakdown strength is independent of gas density. It depends only on the gap length and surface condition and the material of the electrode. The breakdown strength of highly polished and thoroughly degassed electrodes is higher. Copper-bismuth, silver-bismuth, silver-lead and copper-lead are good materials for making contacts of the breaker. When contacts are separated in high vacuum, an arc is drawn between them. The arc does not take place on the entire surface of the contacts but only on a few spots. The contact surface is not perfectly smooth. It has certain microprojections. At the time of contact separation, these projections form the last points of separation. The current flows through these points of separation resulting in the formation of a few hot spots. These hot spots emit electrons and act as cathode spots. In addition to thermal emission, electrons emission may be due to field emission and secondary emission.

Figure 5.9 shows the schematic diagram of a vacuum circuit breaker. Its enclosure is made of insulating material such as glass, porcelain or glass fibre reinforced plastic. The vapour condensing shield is made of synthetic resin. This shield is provided to prevent the metal vapour reaching the insulating envelope. As the interrupter has a sealed construction a stainless metallic bellows is used to allow the movement of the lower contact. One of its ends is welded to the moving contact. Its other end is welded to the lower end flange. Its contacts have large disc-shaped faces. These faces contain spiral segments so that the arc current produces axial magnetic field. This geometry helps the arc to move over the contact surface. The movement of arc over the contact surface minimises metal evaporation, and hence erosion of the contact due to arc. Two metal end flanges are provided. They support the fixed contact, outer insulating enclosure, vapour condensing shield and the metallic bellows. The sealing technique is similar to that used in electronic valves.

The vacuum circuit breaker is very simple in construction compared to other types of circuit breaker. The contact separation is about 1 cm which is adequate for current interruption in vacuum. As the breaker is very compact, power required to close and open its contacts is much less compared to other types of breaker. It is capable of interrupting capacitive and small inductive currents, without producing excessive transient over voltages. Vacuum circuit breakers have other advantages like suitability for repeated operations, least maintenance, silent operation, long life, high speed of dielectric recovery, less weight of moving parts, etc. The vapour emission depends on the arc current. In ac, when the current decreases, vapour emission decreases. Near current zero, the rate of vapour emission tends to zero. Immediately after current zero, the remaining vapour condenses and the dielectric strength increases rapidly. At current zero, cathode spots extinguish within 10^{-8} second. The rate of dielectric recovery is many times higher than that obtained in other types of circuit breakers. Its typical value may be as high as 20 kV/micro sec. Vacuum circuit breakers have now become popular for voltage ratings up to 36 kV. Up to 36 kV they employ a single interrupter.

5.6 SF_6 circuit Breakers

Sulphur hexafluoride (SF_6) has good dielectric strength and excellent arc quenching property.Itisaninert,nontoxic,nonflammableandheavygas.Atatmosphericpres- sure, its dielectric strength is about 2.35 times that of air. At 3 atmospheric pressure itsdielectricstrengthismorethanthatoftransformeroil.Itisanelectronegativegas, i.e. it has high affinity for electrons. When a free electron comes in collision with a neutral gas molecule, the electron is absorbed by the neutral gas molecule and a negative ion is formed. As the negative ions so formed are heavy they do not attain sufficient energy to contribute to ionisation of the gas. This property gives a good dielectric property. Besides good dielectric strength, the gas has an excellent prop- erty of recombination after the removal of the source which energizes the arc. This givesanexcellentarcquenchingproperty.Thegashasalsoanexcellentheattransfer property.

Its thermal time constant is about 1000 times shorter than that ofair.

Under normal conditions, SF_6 is chemically inert and it does not attack metals or glass. However, it decomposes to SF_4, SF_2, S_2, F_2, S and F at temperatures of the order of 1000°C. After arc extinction, the products of decomposition recombine in a short time, within about 1 microsecond. In the presence of moisture, the decom- position products can attack contacts, metal parts and rubber sealings in SF_6 circuit breakers. Therefore, the gas in the breaker must be moisture-free. To absorb decom- position products, a mixture soda lime (NaOH + CaO) and activated alumina can be placed in the arcingchamber.

One major disadvantage of SF_6 is its condensation at low temperature. The tem- peratureatwhichSF_6changestoliquiddependsonthepressure.At15atm.pressure, the gas liquefies at a temperature of about 10°C. Hence, SF_6 breakers are equipped withthermostaticallycontrolledheaterswhereversuchlowambienttemperaturesare encountered.

SF_6gasbecauseofitsexcellentinsulatingandarc-quenchingpropertieshasrevo- lutionized the design of high and extra high voltage (EHV) circuit breakers. These properties of SF_6 has made it possible to design circuit breakers with smalleroverall dimensions,shortercontactgaps,whichhelpintheconstructionofoutdoorbreakers with fewer interrupters, and evolution of metalclad (metal enclosed) SF_6 gas insulated switchgear (GIS). SF_6 is particularly suitable for use in metalclad switch- gearwhichisbecomingincreasinglypopularundertheaspectsofhighcompatibility with the environment. SF_6 offers many advantages such as compactness and less maintenance of EHV circuitbreakers.

SF_6 circuit breakers are manufactured in the voltage range 3.3 kV to 765 kV. However, they are preferred for votlages 132 kV and above. The dielectric strength of SF_6 gas increases rapidly after final current zero. SF_6 circuit breakers can with- stand severe RRRV and are capable of breaking capacitive current without restrik- ing.Problemsofcurrentchoppingisminimised.Electricalclearancesareverymuch reduced due to high dielectric strength ofSF_6.

Properties of SF_6Gas

The properties of SF_6 gas can be divided as

(i) Physicalproperties
(ii) Chemicalproperties
(iii) Electricalproperties

1. Physical Properties of SF_6Gas

The physical properties of SF_6 gas are as follows:

(i) Itisacolourless,odourless,non-toxicandnon-inflammablegas.
(ii) Pure gas is not harmful tohealth.
(iii) Itisingasstateatnormaltemperatureandpressure.
(iv) It is heavy gas having density 5 times that of air at 20°C and atmospheric pressure.
(v) The gas starts liquifying at certain low temperatures. The

temperature of liquification depends on pressure. At 15 atm. pressure, the gas liquifies at a temperature of about10°C.

(vi) It has an excellent heat transfer property. The heat transfer capability of SF_6 is2to2.5timesthatofairatsamepressure.

(vii) Theheatcontentpropertyismuchhigherthanair.ThispropertyofSF$_6$assists cooling of arc space after currentzero.

2. *Chemical Properties of SF_6Gas*

(i) It is chemically stable at atmospheric pressure and at temperatures up to 500°C.

(ii) It is a chemically inertgas.

The property of chemical inertness of this gas is advantageous in switchgear. Because of this property, it has exceptionally low reactivity and does not at- tackmetals,glass,plastics,etc.Thelifeofcontactsandothermetallicpartsis longerinSF$_6$gas.Thecomponentsdonotgetoxidisedordeteriorated.Hence the maintenance requirements arereduced.

(iii) Moisture is very harmful to the properties of this gas. In the presence of moisture, hydrogen fluoride is formed during arcing which can attack the metallic and insulating parts of the circuitbreaker.

(iv) Itisnon-corrosiveonallmetalsatambienttemperatures.

(v) It is an electronegative gas. The ability of an atom to attract and hold electrons is designated as its ‘electronegativity’. Because of electronegativity, the arc-time constant (the time between current zero and the instant at which the conductance of contact spaces reaches zero value) of SF_6 gas is very low (£ 1 m s) and the rate of rise of dielectric strength is high. Hence SF_6 circuit breakersaresuitableforswitchingconditioninvolvinghighRRRV.

(vi) The products of decomposition of SF_6 recombine in a short time after arc extinction. During arc extinction process, SF_6 decomposes to some extent into SF_4, SF_2, S_2, F_2, S and F at temperatures of the order of 1000°C. The products of decomposition recombine to form the original gas in a short time upon cooling. The remainder of the decomposition products is absorbed by a mixtureofsodalime(NaOH+CaO)andactivatedalumina.

3. *Electrical Properties of SF_6Gas*

(i) Dielectric properties

Its dielectric strength at atmospheric pressure is 2.35 times that of air and 30% less thanthatofdielectricoilusedinoilcircuitbreakers.Theexcellentdielectricstreng th ofSF$_6$gasisbecauseofelectronegativity(electronattachment)propertyofSF$_6$m ol- ecules. In the attachment process, free electrons collide with the neutral gas mol- ecules to form negative ions by the followingprocesses.

Direct attachment process: $SF_6 + e \rightarrow SF_6^-$

Dissociative attachment process: $SF_6 + e \rightarrow SF_5^- + F$

The negative ions formed are heavier and immobile as compared to the free elec- trons and therefore under a given electric field the ions do not accumulate sufficient energytoleadtocumulativeionizationinthegas.Thisprocessisaneffectivewayof removingelectrons.Otherwise,thiswouldhavecontributedtothecumulativeionisa- tion, to the current growth and to the sparkover of the gas. Therefore, this property gives rise to very high dielectric strength for SF_6gas.

Thedielectricstrengthofthegasincreaseswithpressure.Atthreetimestheatmo- spheric pressure, its dielectric strength is more than that of dielectric oil used in oil circuit breakers. The dielectric strengths of SF_6, air and dielectric oil as a function of pressure for a particular electrode configuration and a gap of 1 cm is shown in Fig. 5.10

SF_6gasmaintainshighdielectricstrengthevenaftermixingwithair.Amixtureof 30%SF_6and70%airbyvolumehasadielectricstrengthtwicethatofairatthesame pressure. Below 30% of SF_6 by volume, the dielectric strength fallssharply.

Becauseofelectronegativityofthegas,itsarc-timeconstantisverylow(£1ms). The arc-time constant is defined as the time required for the medium to regain its dielectric strength after final currentzero.

(ii)Corona inceptionvoltage

Corona inception voltage for SF_6 in a non-uniform electric field is also considerably higher than that for air.

(iii) Dielectricconstant

Because of being non-polar (i.e., dipole moment is zero), the dielectric constant of SF_6 is independent of the frequency of the applied voltage. Further, the dielectric constant changes by only 7% over a pressure range of 0 to 22 atmospheres.

(iv) Arc-interruptingcapacity

Besides possessing a high dielectric strength, the molecules of SF_6 whendissociated duetosparkovers,recombinerapidlyafterremovalofthesourcewhichenergizesthe spark(arc)andthegasrecoversitsdielectricstrength.ThismakesSF$_6$veryeffective inquenchingthearc.SF_6isapproximately100timesaseffectiveasairinquenching arc. Figure 5.11 compares the arc quenching ability of SF_6 andair.

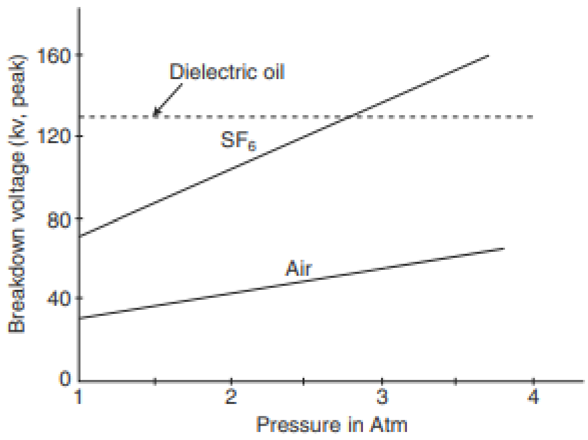

Fig. 5.10 Breakdown voltages of SF6 , air and dielectric oil as a function of pressure

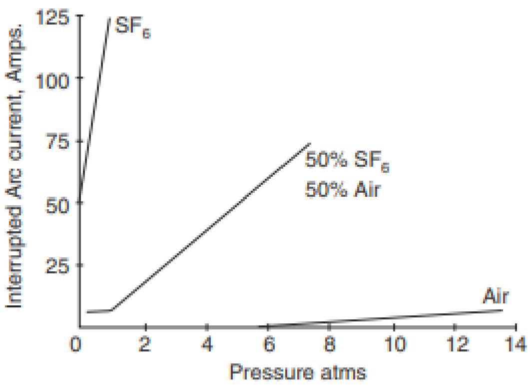

Fig. 5.11 Current interrupting capacity of SF_6, air and a mixture of both gases

The arc quenching property of SF_6 can be due to several factors, especially, its largeelectronattachmentrate.Ifthefreeelectronsinanelectricfieldcanbeabsorbed before they attain sufficient energy to create additional electrons by collision, the breakdown mechanism can be delayed or evenstopped.

The arc temperature in SF_6 is lower than that in air for the same arc current and radius. The high heat transfer capability and low arc temperature also provide an excellent arc quenching (extinguishing) capacity toSF_6.

ArcExtinctioninSF$_6$CircuitBreakers

The final extinction of the arc requires a rapid increase of the dielectric strength between the contacts of the circuit breaker, which can be achieved either by the deionisationofthearcpathorbythereplacementoftheionisedgasbycoolfreshgas. The various deionisation processes are high pressure, cooling by conduction, forced convection andturbulence.

The basic requirement in arc extinction is not only the dielectric strength, but also, high rate of recovery of dielectric strength. In SF_6 gas, the dielectric strengthis quickly regained because electrons get attached with the molecules to become ions.

This is due to electronegativity property of SF_6gas.

In SF_6 circuit breakers, SF_6 gas is blown axially along the arc during the arcing period.Thegasremovestheheatfromthearcbyaxialconvectionandradialdissipa- tion.Asaresultofthis,thediameterofthearcisreducedduringthedecreasingnode ofthecurrentwave.Thearcdiameterbecomesverysmallatcurrentzero.Inorderto extinguish the arc, the turbulent flow of the gas isintroduced.

From the properties of SF_6, it is clear that it is a remarkable medium for arc extinction. The arc extinguishing properties of SF_6 are improved by moderate rates of forced gas flow through the arc space.

TheSF_6gasatatmosphericpressurecaninterruptcurrentsoftheorderof100times the value of those that can be interrupted in air with a plain breakerinterrupter.

In SF_6 circuit breakers, the gas is made to flow from a high pressure zone to a lowpressurezonethroughaconvergent-divergentnozzle.Themassflowdependson nozzle-throat diameter, the pressure ratio and the time of flow. The location of the nozzle is such that the gas flows axially over the arc length. In the divergent portion ofthenozzle,thegasflowattainsalmostsupersonicspeedandtherebythegastakes away the heat from the periphery of the arc, causing reduction in the diameter of the arc. The arc diameter finally becomes almost zero at current zero and the arc is extinguished.AfterfillingthecontactspacewithfreshSF_6gas,thedielectricstrength of the contact space is rapidly recovered due to electronegativity of the gas and tur- bulent flow of the fresh gas in the contactspace.

Types of SF_6 CircuitBreakers

The following are two principal types of SF_6 circuit breakers:

(i) ***Double Pressure Type SF_6 Circuit Breaker***This type of circuit breaker employs a double pressure system in which the gas from a high-pressure compart- ment is released into the low-pressure compartment through a nozzle during the arc extinction process. This type of SF_6 circuit breaker has becomeobsolete.

(ii) ***Puffer-type (Single-pressure Type) SF_6 Circuit Breaker***In this type of circuit breaker the SF_6 gas is compressed by the moving cylinder system and is released through a nozzle during arc extinction. This is the most popular design of SF_6 circuit breaker over wide range of voltages from 3.3 kV to 765kV.

Double pressure type SF_6 circuit breaker

This is the early design of SF_6 circuit breakers which employed a double pressure system. In this system, SF_6 gas at high pressure of 14 to 18 atmospheric pressure stored in a separate tank is released into the arcing zone to cool the arc and build up thedielectricstrengthofthecontactgapafterarcextinction.Itsoperatingprincipleis similar to that of air-blast circuit breakers. Because of their complicated design and construction due to the requirement of various auxiliaries such as gas compressors, high pressure storage tank, filters and gas monitoring and controlling devices, this type of circuit breakers have becomeobsolete.

Puffer-type SF_6 circuit breaker

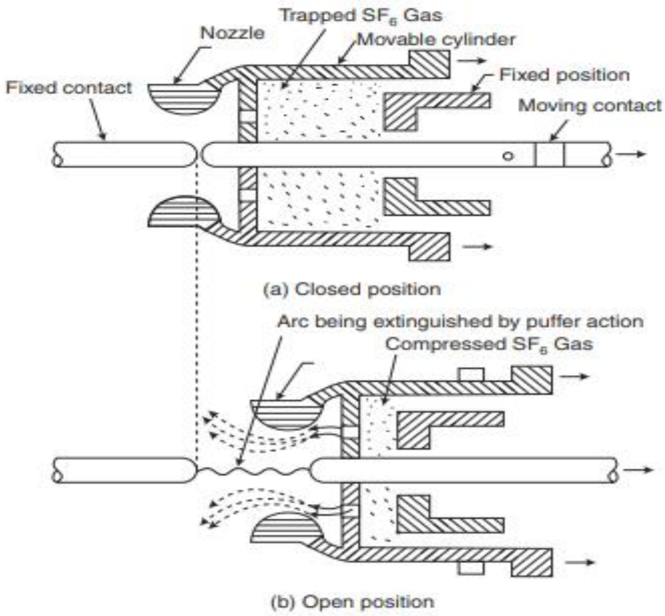

Fig. 5.12 Puffer-type SF_6 Circuit breaker

This type of circuit breakers are also sometimes called single-pressure or impulse type SF_6 circuit breakers. In this type of breakers, gas is compressed by a moving cylindersystemandisreleasedthroughanozzletoquenchthearc.Thistypeisavail- able in the voltage range 3.3 kV to 765kV.

Figure5.12(a)showsapuffer-typebreakerinclosedposition.Themovingcylin- derandthemovingcontactarecoupledtogether.Whenthecontactsseparateandthe moving cylinder moves, the trapped gas is compressed. The trapped gas is released throughanozzleandflowsaxiallytoquenchthearcasshowninFig.5.12(b).There are two types of tank designs. Live tank design and dead tank design. In live tank design, interrupters are supported on porcelain insulators. In the dead tank design, interrupters are placed in SF_6 filled-tank which is at earth potential. Live tankdesign is preferred for outdoor substations.

A number of interrupters (connected in series) on insulating supports are employed for EHV systems up to 765 kV. Two interrupters are used in a 420 kV system. Breaking time of 2 to 3 cycles can be achieved. In the circuit breaker the steady pressure of the gas is kept at 5 kg/cm^2. The gas pressure in the interrupter compartment increases rapidly to a level much above its steady value to quench the arc.

Advantages of SF_6 CircuitBreakers

(i) LowgasvelocitiesandpressuresemployedintheSF_6circuitbreakersprevent currentchoppingandcapacitivecurrentsareinterruptedwithoutrestriking.

(ii) These circuit breakers are compact, and have smaller overall dimensions and shorter contact gaps. They have less number of interrupters and require less mantenance.

(iii) Since the gas is non-inflammable, and chemically stable and the products of decompositionarenotexplosive,thereisnodangeroffireorexplosion.

(iv) Since the same gas is recirculated in the circuit, the requirement of SF_6 gas issmall.

(v) The operation of the circuit breaker is noiseless because there is no exhaust toatmosphereasincaseofairblastcircuitbreakers

(vi) Because of excellent arc quenching properties of SF_6, the arcing time is very short and hence the contact erosion is less. The contacts can be run at higher temperatures withoutdeterioration.

(vii) BecauseofinertnessoftheSF$_6$gas,thecontactcorrosionisverysmall.Hence contacts do not sufferoxidation.

(viii) The sealed construction of the circuit breaker avoids the contamination by moisture, dust, sand etc. Hence the performance of the circuit breaker is not affected by the atmosphericconditions.

(ix) Tracking or insulation breakdown is eliminated, because there are no carbon deposits following an arcing inside thesystem.

(x) Because of the excellent insulating properties of the SF_6, contact gap is drasticallyreduced.

(xi) As these circuit breakers are totally enclosed and sealed from atmosphere, they are particularly suitable for use in such environments where explosion hazardsexist.

Disadvantages of SF_6 CircuitBreakers

(xii) Problems of perfect sealing. There may be leakage of SF_6 gas because of imperfectjoints.

(xiii) SF_6 gas is suffocating to some extent. In case of leakage in the breaker tank, SF_6 gas may lead to suffocation of the operating personnel.

(xiv) ArcedSF_6gasispoisonousandshouldnotbeinhaledorletout.

(xv) Influx of moisture in the breaker is very harmful to SF_6 circuit breaker. There are several cases of failures because ofit.

(xvi) There is necessity of mechanism of higher energy level for puffer-types SF_6 circuitbreakers.Lowerspeedsduetofriction,misalignmentcancausefailure of thebreaker.

(xvii) Internalpartsshouldbecleanedthoroughlyduringperiodicmaintenanceunder clean and dryenvironment.

Specialfacilitiesarerequiredfortransportingthegas,transferringthegasand maintaining the quality of the gas. The performance and reliability of the SF_6 circuitbreakerisaffectedduetodeteriorationofqualityofthegas.

5.7 Selection of circuit breakers

Table 5.1 shows the summary of various types of circuit breakers, their voltage ranges and arc quenching medium they employ. Table 5.2 shows the choice of circuit breakers for various voltage ranges.

Table 5.1 Types of circuit breakers

Type	*Arc Quenching Medium*	*Voltage Range and Breaking Capacity*
Miniature circuit breakers	Air at atmospheric pressure	400-600V; for small current rating
Air-break circuit breaker	Air at atmospheric pressure	400 V-11 kV; 5-750 MVA
Minimum oil breakers	Transformer oil circuit	3.3 kV-220 kV; 150-25000 MVA
Vacuum circuit breakers	Vacuum	3.3 kV-33 kV; 250-2000 MVA
SF_6 circuit breakers	SF_6 at 5 kg/cm^2 pressure	3.3-765 kV; 1000-50,000 MVA
Air blast circuit breakers	Compressed air at high pressure (20-30 kg/cm^2)	66 kV-1100 kV; 2500-60,000 MVA

Table.5.2 Selection of circuit breakers

Table 14.2 Selection of circuit breakers		
Rated Voltage	*Choice of circuit Breakers*	*Remark*
Below 1 kV	Air-break CB	
3.3 kV-33 kV	Vacuum CB, SF_6 CB, minimum oil CB	Vacuum preferred
132 kV-220 kV	SF_6 CB, air blast CB, minimum oil CB	SF_6 preferred
400 kV-760 kV	SF_6 CB, air blast CB	SF_6 is preferred

Earlier oil circuit breakers were preferred in the voltage range of 3.3 kV-66 kV. Between 132 kV and 220 kV, either oil circuit breakers or air blast circuit breakers were recommended. For voltages 400 kV and above, air blast circuit breakers were preferred. The present trend is to recommend vacuum or SF_6 circuit breakers in the voltage range 3.3 kV-33 kV. For 132 kV and above, SF_6 circuit breakers are preferred. Up to 1 kV, air break circuit breakers are used. Air blast circuit breakers are becoming obsolete and oil circuit breakers are being superseded by SF_6 and vacuum circuit breakers.

5.8 Rating of circuit breakers

A circuit breaker has to perform the following major duties under short-circuit conditions.

(i) To open the contacts to clear the fault
(ii) To close the contacts onto a fault
(iii) To carry fault current for a short time while another circuit breaker is clearing the fault.

Additional to rated voltage , current and frequency, circuit breakers has some important ratings.

They are:

1)Rated short circuit breaking current.

2)Rated short circuit making current.

3)Rated operating sequence of circuit breaker.

4)Rated voltage, current & frequency.

Short Circuit Breaking Current of Circuit Breaker

It is of two types

1)Symmetrical breaking capacity

It is the rms value of the ac component of the fault current that the circuit breaker is capable of breaking under specified conditions of recovery voltage.

2)Asymmetrical breaking capacity

It is the value of the total current comprising of both ac and dc components of the fault current that the circuit breaker can break under specified conditions of recovery voltage.

BC = root(3) * rated voltage in kv*rated current in kA

- Rated current symmetrical – Breaking capacity symmetrical
- Rated current asymmetrical – Breaking capacity asymmetrical

2)Rated short circuit making current

The rated making current is defined as the peak value of total current in the first cycle at which a circuit breaker can be closed onto a short ckt

Making capacity =root(2)*1.8*symmetrical breaking capacity

3)Rated voltage, current & frequency.

The rated current is the rms value of the current that a CB can carry continuously without any temperature rise in excess of its specified limit.

The Circuit Breaker must be rated for power frequency withstands voltage for a specific time only. Generally the time is 60 seconds. Making power frequency withstand capacity, more than 60 second is not economical and not practically desired as all the abnormal situations of electrical power system are definitely cleared within much smaller period than 60 seconds.

4)Rated operating sequence of circuit breaker.

The operating duty of a circuit breaker prescribes its operation which can be performed at time intervals.

The sequence of rated operating duty of a circuit breaker has been specified as:**O-t-CO-t’-CO**

5.9 Testing of circuit breakers

There are two types of tests of circuit breakers namely routine tests and type tests. Routine tests are performed on every piece of circuit breaker in the premises of the manufacturer. The purpose of the routine tests is to confirm the proper functioning of a circuit breaker. Type tests are performed in a high voltage laboratory, such tests are performed on sample pieces of circuit breakers of each type to confirm their charac- teristics and rated capacities according to their design. These tests are not performed on every piece of circuit breaker. All routine and type tests are performed according to Indian Standard (IS) codes or International Electromechanical Commission (IEC) codes or British Standard (BS) codes.

A few important type tests, such as breaking capacity, making capacity, short-time current rating tests will be discussed here. These tests come in the category of short circuit testing of circuit breakers. For circuit breakers of smaller capacity, these tests are carried out by direct testing techniques. Circuit breakers of large capacities are tested by the synthetic testing method. In addition to short circuit tests, mechanical tests, thermal tests, dielectric tests (power frequency tests, impulse tests), capacitivecharging-current breaking test, small inductive breaking current test, etc. are also performed. For details see the relevant IS codes.

5.9.1 Short-circuit Testing Stations

There are two types of short-circuit testing stations.

(i) Field type testing station

(ii) Laboratory type testing station

In a field type testing station, the power required for testing is derived from a large power system. The circuit breaker to be tested is connected to the power system. Large amount of power is easily available for testing. Hence, this method of testing is economical for testing of circuit breakers, particularly high voltage circuit breakers. But it lacks flexibility. Its drawbacks are:

(i) For research and development work, tests cannot be repeated again and again without disturbing the power system

(ii) The power available for testing varies, depending upon the loading conditions of the system.

(iii) It is very difficult to control the transient recovery voltage, RRRV, etc.

In a laboratory type testing station, the power required for testing is taken form specially designed generators which are installed in the laboratory for such testing. Its advantages are:

(i) For research and development work, tests can be carried out again and again to confirm the designed characteristics and capacity.

(ii) Current, voltage, restriking voltage, RRRV, etc. can be controlled conve- niently.

(iii) Tests for circuit breakers of large capacity can be carried out using synthetic testing.

The drawbacks of laboratory type testing stations are:

(i) High cost of installation.

(ii) Availability of limited power for testing of circuit breakers

Short-circuit Generator

In a laboratory, short-circuit generators are used to provide power for testing. The design of such generators is different from a conventional generator. These are spe- cially designed to have very low reactance to give the maximum short-circuit output. To withstand high electromagnetic forces their windings are specially braced and made rugged. They are provided with a flywheel to supply kinetic energy during short circuits. This also helps in speed regulation of the set. The generator is driven by a three-phase induction motor.

The short-circuit current has a demagnetising effect on the field of generator. This results in reducing the field current. Consequently, the generator's emf is reduced. Impulse excitation or super excitation is employed to counteract the damagnetisation effect of armature reaction. At the time of short-circuit, the field current is increased to about 8 to 10 times its normal value.

Short-circuit Transformer

Such a transformer has a low reactance and it is designed to withstand repeated short-circuits. To get different voltage for tests, its windings are arranged in sec- tions. By series and parallel combinations of these sections, the desired test voltage is obtained. To get lower voltage than the generated voltage, a three-phase transformer is generally used. For voltage higher than the generated voltages, normally banks of single phase transformers are employed. As the transformers remain in the circuit for a short time, they do not poses any cooling problem.

Master Circuit Breaker

It is used as a backup circuit breaker. If the circuit breaker under test fails to operate, the master circuit breakers opens. The master circuit breaker is set to operate at a predetermined time after the initiation of the short-circuit. After every test, it isolates the circuit breaker under test form the supply source. Its capacity is more than the capacity of the circuit breaker under test.

Making Switch

This switch is used to apply short-circuit current at the desired moment during the test. The making switch is closed after closing the master circuit breaker and the test circuit breaker. It must be bounce-free to avoid its burning or contact welding. To achieve this, a high pressure is used in the chamber. Its speed is also kept high.

Capacitors

Capacitor are used to control RRRV. They are used in synthetic testing which will be discussed while describing such testing. Capacitors are also used for voltage measurement purpose.

Reactors and Resistors

Resistors and reactors are used to control short-circuit test current. They also control power factor. The resistor controls the rate of decay of the dc component of the current. They control the transient recovery voltage.

5.9.2 Testing Procedure

During the short-circuit test, several switching operations are performed in a sequence in a very short time. For example, the sequence of switching operations for breaking capacity test is as follows.

(i) After running the driving motor of the short-circuit generator to a certain speed it is switched off.

(ii) Impulse excitation is switched on.

(iii) Master circuit breaker is closed.

(iv) Oscillograph is switched on.

(v) Making switch is closed.

(vi) Circuit breaker under test is opened.

(vii) Master circuit breaker is opened.

(viii) Exciter circuit of the short-circuit generator is switched off.

It is not possible to perform this sequence of operations manually. There is an automatic control for the purpose. The time of operation for the above sequence is of the order of 0.2 second.

5.9.3 Direct Testing

In direct testing, the circuit breaker is tested under the conditions which actually exist on power systems. It is subjected to restriking voltage which is expected in practical situations. Figure 14.30 shows an arrangement for direct testing. The reactor *X* is to control short-circuit current. *C*, *R*1 and *R*2 are to adjust transient restriking voltage. Short-circuit tests to be performed are as follows.

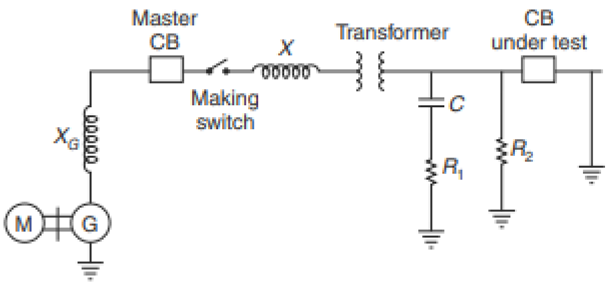

Fig. 5.13 Direct testing of circuit breaker

Test for Breaking Capacity First of all, the master circuit breaker and the circuit breaker under test are closed. Then the short-circuit current is passed by closing the making switch. The shortcircuit current is interrupted by opening the breaker under test at the desired moment. The following measurements are taken.

(i) Symmetrical breaking current

(ii) Asymmetrical breaking current

(iii) Recovery voltage

(iv) Frequency of oscillation and RRRV.

The circuit breaker must be capable of breaking all currents up to its rated capacity. As it is not possible to test at all values of current, tests are performed at 10%, 30%, 60% and 100% of its rated breaking current.

Test for Making Capacity

The master circuit breaker and the making switch are closed first, then the short-cir- cuit is initiated by closing the circuit breaker under test. The rated making current, i.e. the peak value of the first major loop of the short-circuit current wave is measured.

Duty Cycle Test

The following duty cycle tests are performed.

(i) B – 3 – B – 3 – B tests are performed at 10%, 30%, and 60% of the rated symmetrical breaking capacityB – 3 – MB – 3 – MB tests are performed (a) at not less than 100% of the rated symmetrical breaking capacity and (b) at not less than 100% of the rated making capacity.

This test can also be performed as two separate tests.

(a) M – 3 – M make test

(b) B – 3 – B – 3 – B break test

(ii) B – 3 – B – 3 – B tests are performed at not less than 100% of the rated asymmetrical breaking capacity.

Here B denotes the breaking operation and M denotes the making operation, while MB denotes the making operation followed by the breaking operation without any intentional time delay.

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Question Bank

PART – A

Q.No.	Question
1.	Define the term making capacity of circuit breakers.
2.	Classify the types of circuit breaker
3.	Justify Why SF6 gas is preferred in circuit breakers?
4.	Enumerate the Importance of the contact material for vacuum circuit breaker.
5.	List any two dielectric properties of SF_6
6.	Name few testing methods used for testing of circuit breakers
7.	What are the types of air blast circuit breakers?
8.	List the routine tests conducted on circuit breakers.
9.	List the demerits of Vacuum circuit breaker?
10.	Enumerate the Importance of SF6 circuit breakers?

PART – B

Q.No.	Question
1.	Explain the constructional details of Vacuum CB and explain its principle of operation and working.
2.	Explain briefly about the Minimum oil circuit breaker with a neat sketch.
3.	Explain the construction, operating principles and merits of SF6 Circuit breaker.
4.	Identify rupturing capacity, making capacity and short time rating and rated current of the circuit breaker.
5.	(a) Explain the construction, operation and application of Air-blast circuit – breaker. (b) List out the various routine tests on circuit breakers.
6.	With neat diagram explain the principle and working of a double break oil circuit breaker. What are the merits and demerits?
7.	Explain the various tests conducted on circuit breaker.