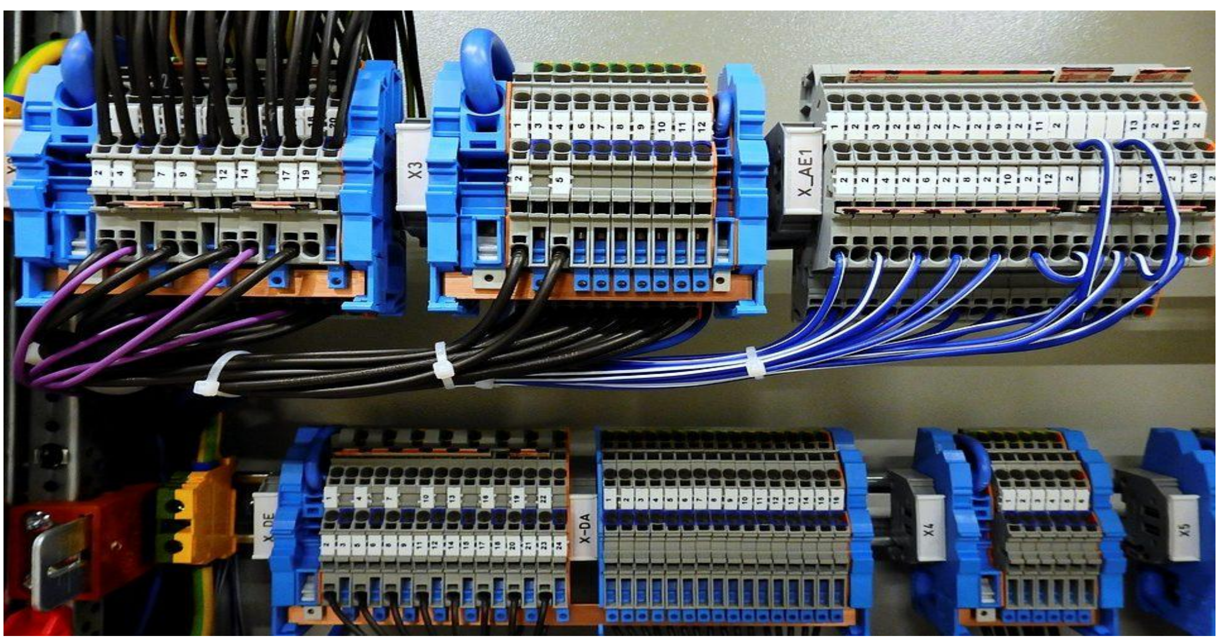
A Reference Manual on Switchgear and Protection

For Bachelor in Electrical and Electronics Engineering

Pokhara University



Er. Sandeep Neupane

Table of Contents

Unit 1: Introduction to Protection System 1

1.1 Introduction 1

1.2 Protection System Components & Its Terminologies 1

1.3 Essential Qualities of Protective Relaying 2

1.4 Need of Protection Scheme in Power System 3

1.5 Backup Protection, Co-ordination and Protection Zone 4

1.6 Nature and Causes of Fault 4

1.6.1 Selection of Bases 6

1.6.2 Analysis of Symmetrical Fault 7

1.6.3 Fault MVA and Fault Current 8

1.7 Relay 8

1.7.1 Classification of relays 8

1.7.2 Terminologies used in Protective Relays 11

1.8 Numerical Solution 14

Unit 2: Relays 21

2.1 Introduction, Basic Trip Circuit and Auxiliary switch 21

2.2 Tripping Scheme in Circuit Breaker 22

2.2.1 Relay with make type contact: 22

2.2.2 Relay with break type contact: 23

2.3 Electromagnet Attraction relays 23

2.3.1 Attracted Armature Relays 24

2.4 Induction Type Relay 26

2.4.1 Torque production 26

2.4.2 Induction Disc Relay 28

2.4.3 Wattmetric Induction disc type relay 28

2.4.4 Induction cup relay 29

2.5 Design Consideration of Electromagnetic Relays 30

Unit 3: Relay Application and Characteristics 33

3.1 Non-Directional Induction type over-current Relay 33

3.1.1 Time Current Characteristics 33

3.1.2 Operation 33

3.1.3 Determination of Relay Operating Time 34

3.2 Directional Relay (Induction Type) 35
3.3 Differential Relay 35
3.3.1 Current Differential Relays 36
3.3.2 Biased or Percentage-Differential Relay 37
3.3.3 Voltage Balance Differential Relay 40
3.4 Universal Relay Torque Equation 41
3.5 Distance Protection 41
3.5.1 Impedance type Distance Relay 42
3.5.2 Reactance Type Distance Relay 43
3.5.3 Mho Type Distance Relay 44
3.6 Numerical Solution 45
Unit 4: Circuit Breaking and Theory of Arc Quenching 50
4.1 Introduction 50
4.1.1 Arc phenomenon 50
4.1.2 Arc extinction 50
4.1.3 Methods of arc extinction 51
4.1.4 Theories of Arc Interruption 51
4.2 Stages of circuit breaker operation 52
4.3 Restriking voltage and Recovery voltage 53
4.3.1 Mathematical expression for active recovery voltage in a 3-phase circuit 53
4.3.2 Mathematical expression for Restriking Voltage Transient 54
4.3.3 Restriking Voltage Transient 55
4.4 HVDC Circuit Breaker 57
4.5 Current Chopping 58
4.7 Numerical Solution 59
Unit 5: Circuit Breaker 63
5.1 Duties of Circuit Breaker 63
5.2 Classification of Circuit Breaker 63
5.4 Moulded Case Circuit Breaker 65
5.5 Air Blast Circuit Breaker 66
5.6 Air Break Circuit Breaker 67
5.8 Vacuum Circuit Breaker 70
5.9 Oil Circuit Breaker 71
5.10 Minimum Oil Circuit Breaker 72

5.11Auto Reclosure 73
5.12 Circuit Breaker Rating 74
5.13 Testing of circuit Breaker 75
5.14 Numerical Solution 76
Unit 6: Transformer Protection 78
6.1 Possible Transformer Fault 78
6.2 Buchholz Relay 79
6.3 Percentage Differential Protection for Transformers 80
6.3.1 Merz-Price Protection for Star-Delta Transformer 81
6.3.2 Merz-Price Protection for Star-Star Transformer 82
6.4 Problem Encountered in Differential Protection 83
6.5 Numerical Solution 84
Unit 7: Generator Protection 86
7.1 Generator Fault 86
7.1.1 Stator Winding Faults 86
7.1.2. Field Winding or Rotor Circuit Faults 87
7.1.3 Abnormal Operating Conditions 88
7.2 Method of Earth Fault Detection 88
7.3 Restricted and Unrestricted Earth Fault Protection 90
7.4 Merz-Price Protection of Alternator Stator Windings 91
7.5 Stator Inter Turn Protection 93
7.6 Rotor Earth Fault Protection 94
7.7 Loss of Excitation Protection 95
7.8 Negative Sequence Relay 96
7.9 Numerical Solution 98
Unit 8: Protection of Bus Bar 105
8.1 Backup Protection for Bus-Bars 105
8.2 Frame Leakage Protection 106
8.3 Differential Over Current Protection 106
Unit 9: Feeder and Transmission Line Protection 109
9.1 Time Graded Protection 109
9.1.1 Protection of Radial Feeders 109
9.1.2 Protection of Parallel Feeders 110
9.1.3 Protection of Ring Main System 111

9.2 Differential Pilot Wire Protection 112
9.3 Distance Protection of Transmission Line 113
9.3.1 Adjustment of Distance Relay 114
9.4 Numerical Solution 115
Unit 10: Digital Protection Device and Protection Scheme 116
10.1 Essential Component of Static Relay 116
10.2 Comparison of Static and Electromagnetic Relays 116
10.3 Static Over Current Relays 117
10.4 Directional Static Over Current Relay 117
10.5 Static Differential Relay 118
10.8 Carrier Current Protection of Transmission Lines 123
10.8.1 Methods of Carrier Current Protection 124
10.8.2 Advantage of Carrier Current Protection 125
References 126

Unit 1: Introduction to Protection System

1.1 Introduction

All electrical machines, apparatus and other forms of electrical equipment must satisfy two main requirements i.e they must be able to operate continuously under normal service conditions and must be able to withstand short time over-currents and over-voltages such as may arise during emergent conditions. For operation of electrical machines and apparatus with full reliability in normal operating conditions, the following two requirements must be met.

Rated current ≥ Actual load current

Rated voltage ≥ Working voltage of the piece of equipment

Nominal or rated current is that maximum current with which a given piece of electrical apparatus or machine will be able to operate continuously throughout its service life.

The rated voltage of a piece of electrical apparatus or a machine is the value of the line voltage given on its name plate, this value being equal to the nominal line voltage of the circuit it must operate in.

All electrical installations and circuits are subjected to the danger of a fault leading to short circuiting and flow of current in the equipment greatly exceeding the rated value is termed as abnormal conditions.

Short circuit currents are harmful for two reasons- the first is that even a short time flow of heavy current will overheat the equipment, the second is that the flow of short circuit currents through the current carrying parts produces forces of electrodynamic interaction which may destroy or damage the equipment.

1.2 Protection System Components & Its Terminologies

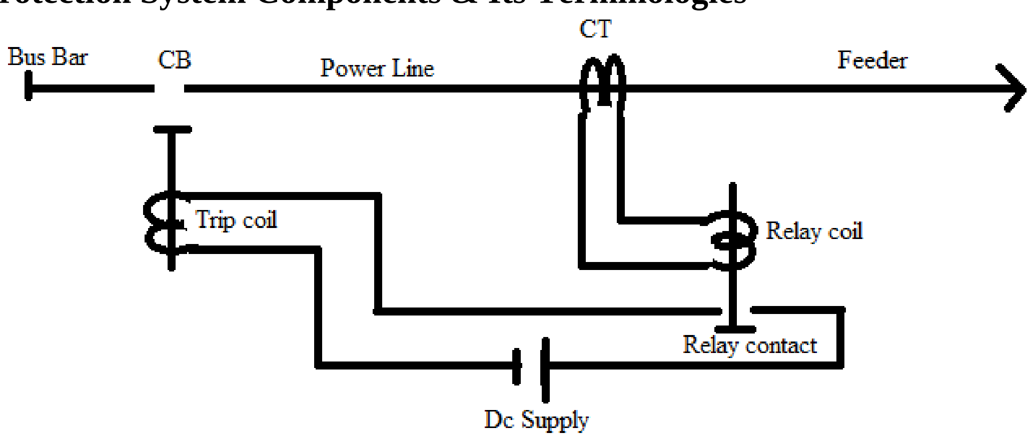


Figure 1: Schematic of protection scheme

Switch-Gear: Any device or combination of devices, capable of making or breaking circuit on all conditions including fault is termed as switch-gear.

Circuit Breaker: The circuit breaker is a switch device capable of breaking and reclosing a circuit under all conditions including when the system is faulted and the currents are at their greatest values.

Fuses: Fuse is a protective device used for protecting circuit against damage from an excessive current due to fault or overload. The circuit is interrupted by melting of fuse wire.

Isolator: It is a manual device for breaking or making a circuit at no-load condition. However, it should be able to carry fault current for short time during which the fault shall be cleared by an interrupting device elsewhere in the system.

Protective Relay: A relay is an electrical device designed to perform switching action to energize the trip coil of a circuit breaker or to operate an alarm signal, during fault in the system.

Instrument Transformer: These are the transformers of special design used for the purpose of processing the signals for the relay to operate in the event of an abnormal conditions or fault in system.

Trip Coil: Trip coil of CB operates the release mechanism of the breaker and opens it after energizing through the supply obtained via relay contacts & dc source.

Trip Circuit: The circuit which supplies current to energize the trip coil of the breaker through relay contacts is called trip circuit.

Relay Contacts: Relay may have one or more contacts which are closed or opened during the switching actions in the event of fault condition.

1.3 Essential Qualities of Protective Relaying

The basic requirements of a protective system are as follows:

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

b) Reliability: A protective system must operate reliably when a fault occurs in its zone of protection. The failure of a protective system may be due to the failure of any one or more elements of the protective system. Its important elements are the protective relay, circuit breaker, 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 the relaying equipment also contribute to reliability. The contact pressure, the contact material of the relay, and the prevention of contact contamination are also very important from the reliability point of view. A typical value of reliability of a protective scheme is 95%.

c) 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.

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

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

1.4 Need of Protection Scheme in Power System

As the system is large, so the condition of severity and abnormalities and the system has to have a control and protection scheme to sustain the safety, reliability and availability of the system. Fault can damage or disrupt power system in several ways.

a) Fault typically allow abnormally large current to flow, resulting in overheating of power system components.
b) The fault is usually a short circuit and exist as an electrical arc. The extremely high temperature of an arc will vaporize any substance causing destruction and fire.
c) Fault can lower or raise the system voltage outside the acceptable range.
d) Fault can cause the 3-phase system to become unbalanced.
e) Fault block the flow of power.

Thus, to prevent the damage and disruptions due to faults and to sustain a healthy, reliable and safe system, a power system has to incorporate a protection scheme.

1.5 Backup Protection, Co-ordination and Protection Zone

Protection Zone: A part of the system protected by certain protective scheme is called protection zone. The entire power system is covered by several protective zones and no-part of the system is left unprotected. When the fault occurs in a given zone, then only the CB within that zone will be opened and thus only the faulty element will be isolated without disturbing the rest of the system.

Co-ordination: Relay protection co-ordination means that the downstream devices should activate before upstream devices. This minimize the portion of the system affected by the fault or their disturbance.

Backup Protection: Backup protection is the name given to a protection which backs up the main protection whenever the latter fails in operation. Backup protection is important to the proper functioning of good system of electrical protection since cent percent reliability not only of protective scheme but also of associated CTs and PTs & CB cannot be guaranteed.

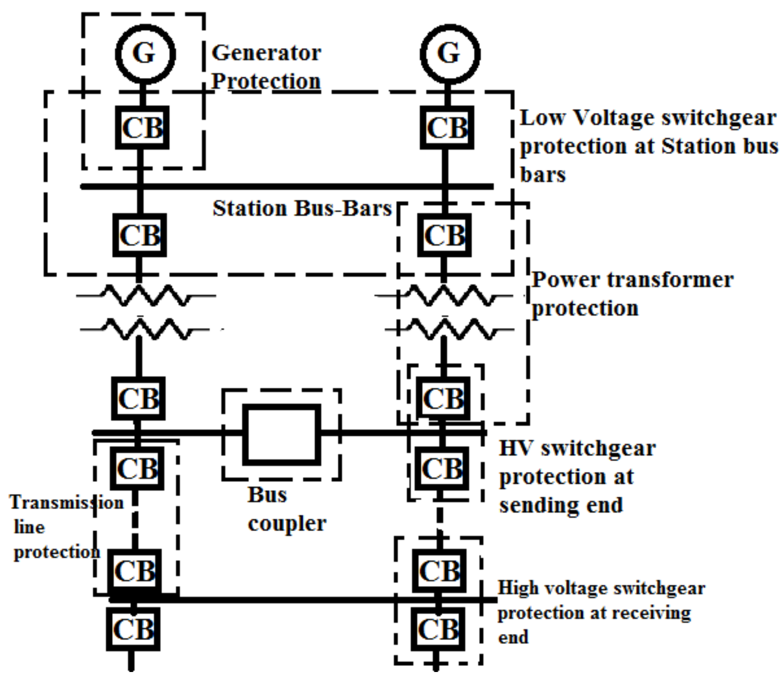


Figure 2: Protection System

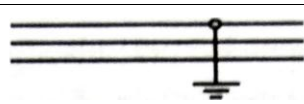
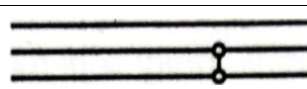
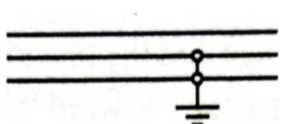
1.6 Nature and Causes of Fault

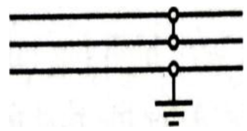
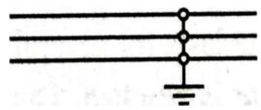
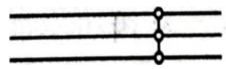
Faults are caused either by insulation failures or by conducting path failures. The failure of insulation results in short circuits which are very harmful as they may damage some equipment of the power system. Most of the faults on transmission and distribution lines are caused by over-voltages due to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

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

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

Certain faults occur due to the poor quality of system components or because of a faulty system design. Hence, the occurrence of such faults can be reduced by improving the system design, by using components and materials of good quality and by better operation and maintenance. However, the faults cannot be eliminated completely. The most common and dangerous fault, that occurs in a power system, is the short circuit or shunt fault. They occur as a result of breakdowns in the insulation of current carrying phase conductors relative to earth or in the insulation between phases. In 3-phase ac power circuits, the short circuit faults can be classed as follows:

S.N	Type of Short-Circuit Fault	Representation	Percentage Occurrence	Description
1	Single phase to ground (L-G)		70	Due to breakdown of insulation between one of the phases and earth
2	Phase to phase (L-L)		15	Due to breakdown of insulation between either of the two phases
3	Two phases to ground (L-L-G)		10	Due to breakdown of insulation between two phases and earth

4	Phase to phase and third phase to ground		2 or 3	A combination of faults given at no.1 &2 i.e break down of insulation between two phases and simultaneous breakdown of insulation between the third phase and earth
5	All the three phases to ground (L-L-L-G)		2 or 3	Due to breakdown of insulation between all the phases as well as to earth
6	All the three phases shorted(L-L-L)		2 or 3	Due to breakdown of insulation between all the three phases

The first four types of faults are of an unsymmetrical nature and give rise to unsymmetrical currents i.e different currents in the three phases. The latter two types of faults are of symmetrical nature and give rise to symmetrical current i.e., equal fault currents in the three phases with 120° displacement. The balanced three phase fault is very rare in occurrence, accounting for only about 5% of the total, but is the severest of all types of faults and thus imposes the most severe duty on circuit breakers and is used in the determination of the circuit breaker rating. The symmetrical three phase faults, generally occur due to carelessness of operating personal.

A fault involving all three phases is known as symmetrical (balanced) fault while one involving only one or two phases is known as unsymmetrical fault. Majority of the fault is unsymmetrical fault.

The short circuit current in an ac system are determined mainly by the reactance of the alternators, transformers and lines up to the point of the fault in the case of phase to phase faults. When the fault is between phase and earth, the resistance of the earth plays an important role in limiting the currents.

1.6.1 Selection of Bases

For a common representation, base KVA and base voltage are to be chosen. Then the base current and base impedance can be expressed as follows:

Base current (I_B) = $\frac{Base\ KVA\ (KVA_B)}{Base\ KV\ (KV_B)}$ amperes

Base impedance (Z_B) = $\frac{Base\ Voltage\ in\ volts\ (V_B)}{Base\ current\ in\ amperes\ \ (I_B)}$ ohms

$$= \frac{V_B \times V_B}{I_B \times V_B} = \frac{V_B{}^2}{V_B I_B} = \frac{\left(\frac{V_B}{1000}\right)\times\left(\frac{V_B}{1000}\right)\times 1000}{\frac{V_B I_B}{1000}} = \frac{(KV_B{}^2)\times 1000}{KVA_B} = \frac{(KV_B{}^2)}{MVA_B} \text{ ohms}$$

For a single phase, phase to neutral voltage, KVA per phase are taken as bases while in three phase system, three phase line to line voltage and three phase KVA are used as bases. The base values in a system are so selected that per unit voltages and currents in the system are approximately unity. Sometimes the base KVA is chosen equal to the sum of the ratings of the various equipment in the system or equal to the KVA rating of the largest unit connected in the system.

In a three phase, system rather than obtaining the per unit values per phase quantities, the per unit values can be obtained directly by using three phase quantities (total KVA, line to line voltage and current). Let KVA_B be the base KVA (total output of three phases) and KV_B be the base line to line voltage in KV. Assuming star connection

Base current (I_B) = $\frac{KVA_B}{\sqrt{3}KV_B}$ amperes

Base impedance (Z_B) = $\frac{KV_B \times 1000}{\sqrt{3} \times I_B} = \frac{KV_B}{\sqrt{3}} \times \frac{\sqrt{3}KV_B}{KVA_B} \times 1000 = \frac{(KV_B{}^2) \times 1000}{KVA_B} = \frac{(KV_B{}^2)}{MVA_B}$ ohms

Per unit impedance, $Z_{pu} = \frac{Actual\ impedance}{Base\ impedance} = \frac{Actual\ impedance \times KVA_B}{(KV_B)^2 \times 1000}$

Per unit impedance to new base,

$$Z_{pu\ new} = Z_{pu\ old} \times \frac{KVA_{new}}{KVA_{old}} \times \frac{(KV_{old})^2}{(KV_{new})^2}$$

1.6.2 Analysis of Symmetrical Fault

Symmetrical (L-L-L) fault occurs infrequently, as for example, when a line, which has been made safe for maintenance and/ or repairs by clamping all the three phases to earth, is accidentally made alive or when, due to slow fault clearance, an earth fault spreads across to the other two phases or when a mechanical excavator cuts quickly through a whole cable. It is an important type of fault in that it results in an easy calculation.

The analysis of symmetrical (L-L-L) faults includes the determination of the voltage at any point (or bus) in the power system network, the current in any branch and value of reactance necessary to limit the fault current to any desired value. Such calculations provide the necessary data for selection of circuit breakers and design of protective scheme. The circuit breaker MVA breaking capacity is based on 3phase fault MVA. Since the circuit breakers are manufactured in preferred standard sizes, e.g., 250, 500, 750 MVA, high precision is not required in calculations of 3-phase fault level at a point in a power system. Moreover, the system impedances are also never known accurately. To make complete and accurate calculations is virtually impossible, and certainly too tedious for operational work. It is customary to perform the short-circuit analysis under the following simplifying assumptions:

- Load currents are considered negligible as compared to fault currents.
- Shunt elements in the transformer model that account for magnetizing current and core loss are neglected. The transformer is represented by a reactance in series, as transformer resistance is quite low in comparison with its reactance.
- Shunt capacitances of the transmission lines are neglected.
- System resistance is neglected and only inductive reactance of the system is considered. This assumption cannot be applied in case overhead lines or underground cables of considerable length are included in the network. A transmission line is represented by series reactance (and resistance).

- The emfs of all the generators are assumed to be equal to $1\measuredangle 0°$ per unit. This means that the system voltage is at its nominal value and the system is operating on no load at the time of occurrence of fault.

For simple systems, calculations can be made by network reduction technique. However, for modern complex systems, ac network analyzers or digital computers are used for fault calculation.

1.6.3 Fault MVA and Fault Current

Per unit fault (or short circuit current), $I_{sc\,pu} = \frac{pu\ voltage\ at\ fault\ point}{pu\ X_{equivalent}}$

Per unit fault level (MVA) = $\sqrt{3} \times per\ unit\ fault\ current\ \times per\ unit\ source\ voltage$

$or, Fault\ MVA = \frac{Base\ MVA}{pu\ X_{equivalent}}$ MVA (lagging)

Fault current (I_{sc}) = $\frac{Fault\ MVA \times 10^3}{\sqrt{3} \times Base\ KV}\ amperes$

1.7 Relay

A relay is a key component in the power system protection and is a device that based on the information received from the power system operating under abnormal condition performs switching action to energize the trip coil of circuit breaker which then opens the power circuit and the system is protected from the severity of faulted condition.

1.7.1 Classification of relays

Protective relays can be classified in various ways depending on the technology used for their construction, their speed of operation, their generation of development, function, etc., and will be discussed in more details in the following chapters.

a) Classification of Protective Relays Based on Technology

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

- Electromechanical relays
- Static relays
- Numerical relays

Electromechanical Relays

Electromechanical relays are further classified into two categories, i.e., electromagnetic relays, and thermal relays. Electromagnetic relays work on the principle of either electromagnetic attraction or electromagnetic induction. Thermal relays utilize the electrothermal effect of the actuating current for their operation.

First of all, electromagnetic relays working on the principle of electromagnetic attraction were developed. These relays were called attracted armature-type electromagnetic relays. This type of relay operates through an armature which is attracted to an electromagnet or through a plunger drawn into a solenoid. Plunger type electromagnetic relays are used for instantaneous units for detecting over current or overvoltage conditions.

Attracted armature-type electromagnetic relays are the simplest type which respond to ac as well as dc. Initially, attracted armature-type relays were called electromagnetic relays. Later on, induction type electromagnetic relays were developed. These relays use electromagnetic induction principle for their operation, and hence work with ac quantities only. Electromagnetic relays contain an electromagnet (or a permanent magnet) and a moving part. When the actuating quantity exceeds a certain predetermined value, an operating torque is developed which is applied on the moving part. This causes the moving part to travel and to finally close a contact to energize the trip coil of the circuit breaker.

Since both attracted armature and induction type electromagnetic relays operate by mechanical forces generated on moving parts due to electromagnetic forces created by the input quantities, these relays were called electromechanical relays. The term 'electromechanical relays' has been used to designate all the electromagnetic relays which use either electromagnetic attraction or electromagnetic induction principle for their operation and thermal relays which operate as a result of electrothermic forces created by the input quantities. Sometimes both the terms, i.e., electromagnetic relays and electromechanical relays are used in parallel.

Static Relays

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

Numerical Relays

Numerical relays are the latest development in this area, These relays acquire the sequential samples of the ac quantities in numeric (digital) data form through the data acquisition system, and process the data numerically using an algorithm to calculate the fault discriminants and make trip decisions, Numerical relays have been developed because of tremendous advancement in VLSI and computer hardware technology. They are based on numerical (digital) devices, e.g., microprocessors, microcontrollers, Digital Signal Processors (DSPs), etc. At present microprocessor/ microcontroller-based numerical relays are widely used. These relays use different relaying algorithms to process the acquired information. Microprocessor/microcontroller-based relays are called numerical relays specifically if they calculate the algorithm numerically. The term ‘digital relay' was originally used to designate a previous-generation relay with analog measurement circuits and digital coincidence time measurement (angle measurement) using microprocessors. Now a days the term ‘numerical relay' is widely used in place of ‘digital relay'. Sometimes, both terms are used in parallel. Similarly, the term 'numerical protection' is widely used in place of 'digital protection' Sometimes both these terms are also used in parallel,

The present downward trend in the cost of very Large Scale Integrated (VLSI) circuits has encouraged wide application of numerical relays for the protection of modern complex power networks. Economical, powerful and sophisticated numerical devices (e.g., microprocessors, microcontrollers, DSPs, etc) are available today because of tremendous advancement in computer hardware technology. Various efficient and fast relaying algorithms which form a part of the software and are used to process the acquired information are also available today, Hence, there is a growing trend to develop and use numerical relays for the protection of various components of the modern complex power system. Numerical relaying has become a viable alternative to the traditional relaying systems employing electromechanical and static relays. Intelligent numerical relays using artificial Intelligence techniques such as Artificial Neural Networks (ANNs) and Fuzzy Logic Systems are presently under active research and development stage.

The main features of numerical relays are their economy, compactness, flexibility reliability, self-monitoring and self-checking capability, multiple functions, low burden on instruments transformers and improved performance over conventional relays of electromechanical and static types,

b) Classification of Protective Relays Based on Speed of Operation

Protective relays can be generally classified by their speed of operation as follows:

- Instantaneous relays
- Time-delay relays
- High-speed relays
- Ultra-high-speed relays

Instantaneous Relays

In these relays, no intentional time delay is introduced to slow down their response. These relays operate as soon as a secure decision is made.

Time-delay Relays

In these relays, an intentional time delay is introduced between the relay decision time and the initiation of the trip action.

High-speed Relays

These relays operate in less than a specified time. The specified time in present practice is 60 milliseconds (3 cycles on a 50 Hz system).

Ultra High-speed Relays

Though this term is not included in the relay standard but these relays are commonly considered to operate within 5 milliseconds.

c) Classification of Protective Relays Based on their Generation of Development

Relays can be classified into the following categories, depending on generation of their development.

- First-generation relays: Electromechanical relays
- Second-generation relays: Static relays
- Third-generation relays: Numerical relays.

d) Classification of Protective Relays Based on their Function

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

- Overcurrent relays
- Undervoltage relays
- Impedance relays
- Underfrequency relays
- Directional relays

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

1.7.2 Terminologies used in Protective Relays

Protective Relay: It is an electrical device designed to initiate isolation of a part of an electrical installation, or to operate an alarm signal, in the event of an abnormal condition or a fault.

Energizing Quantity: It is an electrical quantity i.e., current or voltage either alone or in combination with other electrical quantities, required for the operation of the relay.

Relay Time: It is the time between the instant of fault occurrence and the instant of closure of relay contacts.

Breaker Time: It is the time between the instant at circuit breaker operates and opens the contacts, to the instant of extinguishing the arc completely.

Fault Clearing Time: The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is fault clearing time. It is sum of the relay time and circuit breaker time.

Pickup: A relay is said to be picked up when it moves from the 'OFF' position to 'ON' position. Thus, when relay operates it is said that relay has picked up.

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

Dropout or Reset: A relay is said to be dropout or reset when it comes back to original position i.e. when relay contacts open from its closed position. The value of an actuating quantity current or voltage below which the relay resets is called reset value of that relay.

Time Delay: The time taken by relay to operate after it has sensed the fault is called time delay of relay. Some relays are instantaneous while in some relays intentionally a time delay is provided.

Sealing Relays or Holding Relays: The relay contacts are designed for light weight and hence, they are therefore very delicate. When the protective relay closes its contacts, it is relieved from other duties such as time lag, tripping etc. These duties are performed by auxiliary relays which are also called sealing relays or holding relays.

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

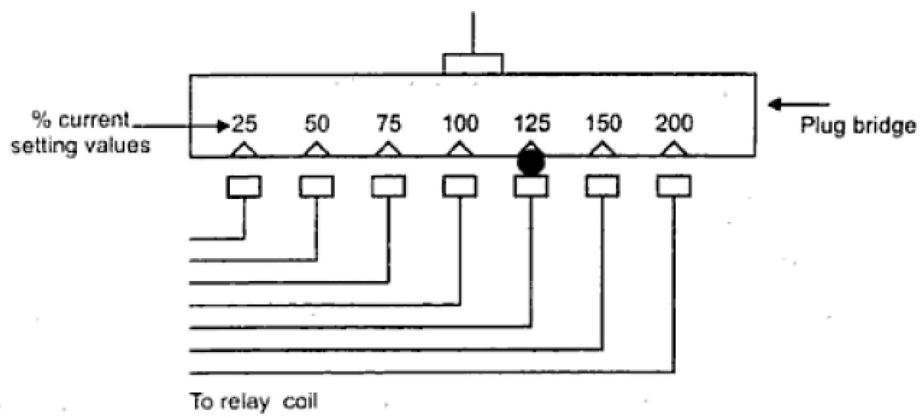


Figure 3:Tapping for current setting

Thus, the value of pickup current can be obtained as,
Pickup current = % current setting x rated secondary current of C.T.
So, if C.T. is 500 / 10 A i.e. rated secondary current is 10A and the current setting is 150then pickup current is 1.5 x 10 = 15 A i.e. 150% of 10. So, when relay coil current is greater than or equal to pick-up values, relay operates.

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

$$\text{PSM} = \frac{Fault\ current\ in\ relay\ coil}{pickup\ value} = \frac{I_R}{current\ setting * rated\ sec.current\ of\ CT}$$

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

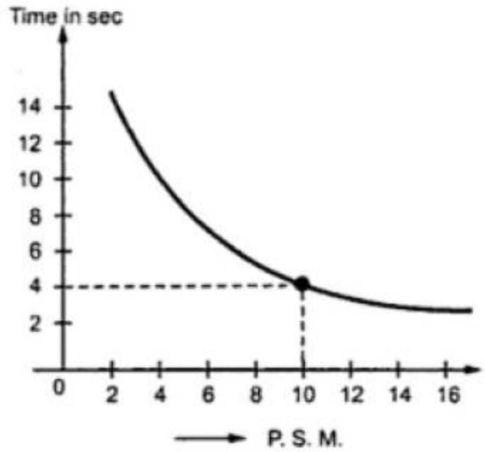


Figure 4:Time / P.S.M. curve

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

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

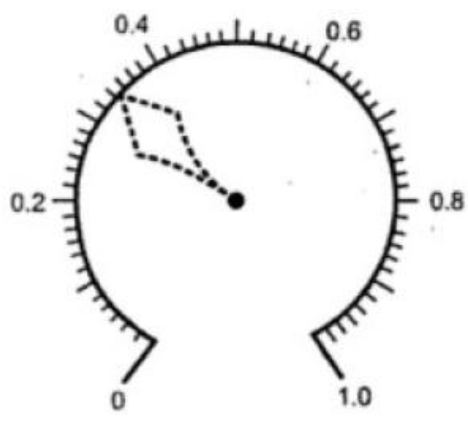


Figure 5:Time-setting multiplier

The value of time-setting multiplier along with the time obtained from time/P.S.M. curve decides the actual time of operation of the relay. For example, if time-setting multiplier is selected as 0.2 while time corresponding to P.S.M. of 10 is 4 seconds then, Actual time of operation = time in seconds x time-setting multiplier = 4 x 0.2 = 0.8 seconds

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

Unit Protection: A protective system in which the protection zone is clearly defined by the C.T. boundaries is called unit protection. Such systems work for internal faults only.

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

1.8 Numerical Solution

1) Base voltage = 1,100 volts. Base kVA = 10^6. What is base impedance ?

Solution : Base kVA $= 10^6$

$$\text{Base kV} = \frac{1{,}100}{1{,}000} = 1.1\ \text{kV}$$

$$\text{Base current, } I_B = \frac{kVA_B}{kV_B} = \frac{10^6}{1.1}$$

$$\text{Base impedance, } Z_B = \frac{kV_B \times 1{,}000}{I_B} = \frac{1.1 \times 1{,}000 \times 1.1}{10^6}$$

$$= 0.00121\ \Omega\ \textbf{Ans.}$$

Base impedance can also be determined directly by substituting the values of base kVA and base kV in Eq. and we get

$$Z_B = \frac{(kV_B)^2 \times 1{,}000}{kVA_B} = \frac{(1.1)^2 \times 1{,}000}{10^6}$$

$$= 0.00121\ \Omega\ \textbf{Ans.}$$

2) **If the resistance in ohms is 5 Ω, find the per unit value. Given base kVA = 10 and base kV = 11.**

Solution : Resistance, R = 5 Ω

$$\text{Base resistance, } R_B = \frac{(kV_B)^2 \times 1{,}000}{kVA_B} = \frac{(11)^2 \times 1{,}000}{10}$$

$$= 12{,}100\ \Omega$$

$$\text{Per unit resistance, } R_{pu} = \frac{R}{R_B} = \frac{5}{12{,}100} = 0.000413 \text{ pu} \quad \textbf{Ans.}$$

3) **A single-phase transformer is rated as 2.5 kVA, 11/0.4 kV. If the leakage reactance is 0.96 Ω when referred to low-voltage side, then determine its leakage reactance in per unit.**

Solution : Base voltage, $kV_B = 0.4$ kV

Base kVA, $kVA_B = 2.5$ kVA

Low-voltage side base impedance,

$$Z_{BLV} = \frac{(kV_B)^2 \times 1{,}000}{kVA_B} = \frac{(0.4)^2 \times 1{,}000}{2.5} = 64\ \Omega$$

Leakage reactance in per unit,

$$Z_{pu} = \frac{\text{Actual reactance}}{\text{Base impedance}} = \frac{0.96}{64} = 0.015 \text{ pu} \quad \text{Ans.}$$

4) **A 30 MVA, 11 kV generator has a reactance of 0.2 pu referred to its ratings as bases. Determine the per unit reactance when referred to base kVA of 50,000 kVA and base kV of 33 kV.**

Solution : Old base kVA = 30,000 kVA

Old base kV = 11 kV

Old per unit impedance,

$$Z_{pu\ old} = 0.2 \text{ pu}$$

New base kVA = 50,000 kVA

New base kV = 33 kV

New per unit impedance,

$$Z_{pu\ new} = Z_{pu\ old} \times \frac{\text{New base kVA}}{\text{Old base kVA}} \times \left(\frac{\text{Old base kV}}{\text{New base kV}}\right)^2$$

$$= 0.2 \times \frac{50{,}000}{30{,}000} \times \left(\frac{11}{33}\right)^2 = 0.037 \text{ pu} \quad \textbf{Ans.}$$

5) A 3-phase, 10,000 kVA, 11 kV alternator has a subtransient reactance of 8%. A 3-phase short circuit occurs at its terminals. Determine the fault current and fault MVA.

Solution : Alternator percentage reactance is based on its own voltage and kVA ratings. Let us choose 10,000 kVA as base kVA and 11 kV as base kV

$$\text{Base current, } I_B = \frac{\text{Base kVA}}{\sqrt{3} \times \text{base kV}} = \frac{10{,}000}{\sqrt{3} \times 11} = 525 \text{ A}$$

$$\text{Per unit fault current, } I_{sc\,pu} = \frac{\text{PU voltage}}{\text{PU reactance}} = \frac{1}{0.08}$$

$$= 12.5 \angle -90^\circ \text{ A}$$

$$\text{Fault current, } I_{sc} = I_{sc\,pu} \times I_B = 12.5 \times 525 = 6{,}562 \text{ A } \textbf{Ans.}$$

$$\text{Fault power} = \sqrt{3} \times I_{sc} \times \text{source voltage} \times 10^{-6} \text{ MVA}$$

$$= \sqrt{3} \times 6{,}562 \times 11{,}000 \times 10^{-6}$$

$$= 125 \text{ MVA } \textbf{Ans.}$$

Alternative Method :

$$\text{Fault MVA} = \frac{\text{Base MVA}}{X_{pu}} = \frac{10{,}000 \times 10^{-3}}{8/100}$$

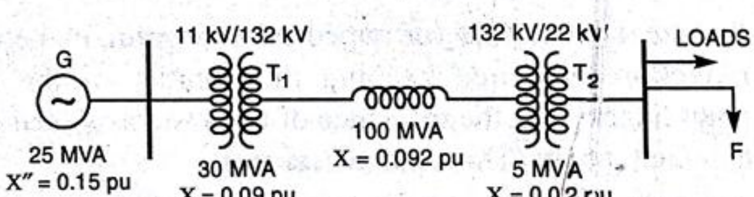
$$= 125 \text{ MVA } \textbf{Ans.}$$

$$\text{Fault current, } I_{sc} = \frac{\text{Fault MVA} \times 10^3}{\sqrt{3} \times \text{base kV}}$$

$$= \frac{125 \times 1{,}000}{\sqrt{3} \times 11} = 6{,}562 \angle -90^\circ \text{ A } \textbf{Ans.}$$

6) A symmetrical 3-phase short circuit occurs on the 22 kV bus-bars of the circuit shown as one line diagram in Fig. Calculate the fault current and the fault apparent power.

Solution : Let base kVA for the complete system be 100 MVA.



Base kV on generator side = 11 kV

Base kV on feeder side = 132 kV

Base kV for load = 22 kV

$$\text{Per unit reactance of generator} = 0.15 \times \frac{100}{25} = 0.6 \text{ pu}$$

$$\text{Per unit reactance of transformer, } T_1 = 0.09 \times \frac{100}{30} = 0.3 \text{ pu}$$

$$\text{Per unit reactance of transformer, } T_2 = 0.02 \times \frac{100}{5} = 0.4 \text{ pu}$$

Per unit reactance of transmission line = 0.092 pu

$$\text{Total per unit reactance up to fault} = j(0.6 + 0.3 + 0.4 + 0.092) = j1.392 \text{ pu}$$

Per unit reactance diagram is shown in Fig. 4.11.

Assuming prefault voltage of the generator to be $1 \angle 0°$ pu

Per unit fault current,

$$I_{sc\ pu} = \frac{\text{Per unit prefault voltage}}{\text{Per unit reactance (total)}}$$

$$= \frac{1 \angle 0°}{1.392 \angle 90°}$$

$$= 0.7184 \angle -90° \text{ pu}$$

$$\text{Base current, } I_B = \frac{\text{Base MVA} \times 1{,}000}{\sqrt{3} \times \text{base kV}}$$

$$= \frac{100 \times 1{,}000}{\sqrt{3} \times 22} = 2{,}624 \text{ A}$$

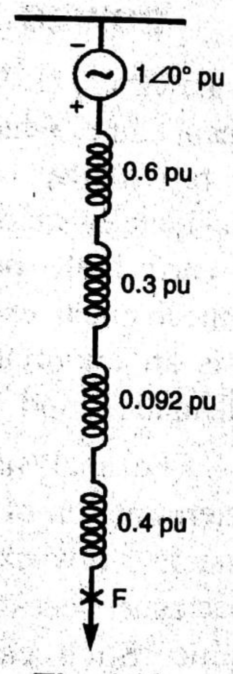


Fig. 4.11

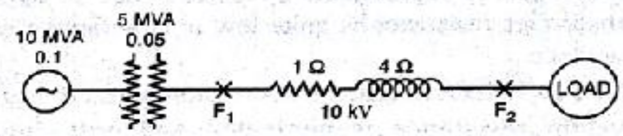
$$\text{Fault current, } I_{sc} = I_{sc\ pu} \times I_B$$
$$= 0.7184 \times 2{,}624$$
$$= 1{,}885 \text{ A} \quad \textbf{Ans.}$$

Fault apparent power

$$= I_{sc\ pu} \times \text{per unit prefault voltage}$$
$$= 0.7184 \times 1$$
$$= 0.7184 \text{ pu} = 0.7184 \times 100 = 71.84 \text{ MVA} \quad \textbf{Ans.}$$

7) **A 3-phase transmission line operating at 10 kV and having a resistance of 1 Ω and reactance 4 Ω is connected to the generating station bus-bars through 5 MVA step-up transformer having a reactance of 5%. The bus-bars are supplied by 10 MVA alternator having 10% reactance. Calculate the short-circuit kVA fed to symmetrical fault between phases if it occurs : (i) at the load end of transmission line, (ii) at the high voltage terminals of the transformer.**

Solution : Single line diagram for the network is given in Fig.



Let the base MVA for the complete system be 10 MVA

$$\text{Per unit reactance of alternator} = \frac{10}{100} = 0.1 \text{ pu}$$

$$\text{Per unit reactance of transformer} = \frac{5}{100} \times \frac{10}{5} = 0.1 \text{ pu}$$

$$\text{Actual impedance of line} = (1 + j4)\ \Omega$$

$$= 4.1231 \angle 75.96°\ \Omega$$

$$\text{PU impedance of line} = \text{Actual impedance} \times \frac{\text{Base MVA}}{(kV_B)^2}$$

$$= 4.1231 \angle 75.96° \times \frac{10}{10^2}$$

$$= 0.41231 \angle 75.96° \text{ pu}$$

$$= (0.1 + j0.4) \text{ pu}$$

The pu reactance diagram is shown in Fig. 4.13.

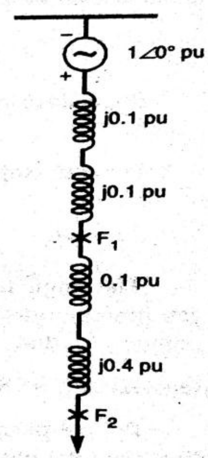


Fig. 4.13

(i) For a fault at the load end of the transmission line

Total per unit impedance

$$= j0.1 + j0.1 + 0.1 + j0.4$$

$$= (0.1 + j0.6) \text{ pu}$$

$$= 0.6083 \angle 80.54° \text{ pu}$$

Short-circuit kVA

$$= \frac{\text{Base MVA} \times 1{,}000}{\text{Total per unit impedance}}$$

$$= \frac{10 \times 1{,}000}{0.6083}$$

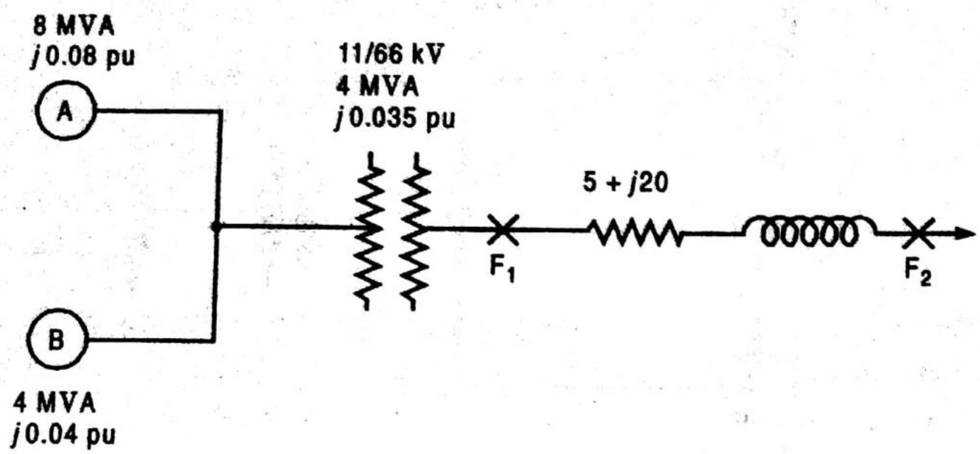
$$= 16{,}440 \text{ kVA} \quad \textbf{Ans.}$$

(ii) For a fault at high voltage terminals of transformer

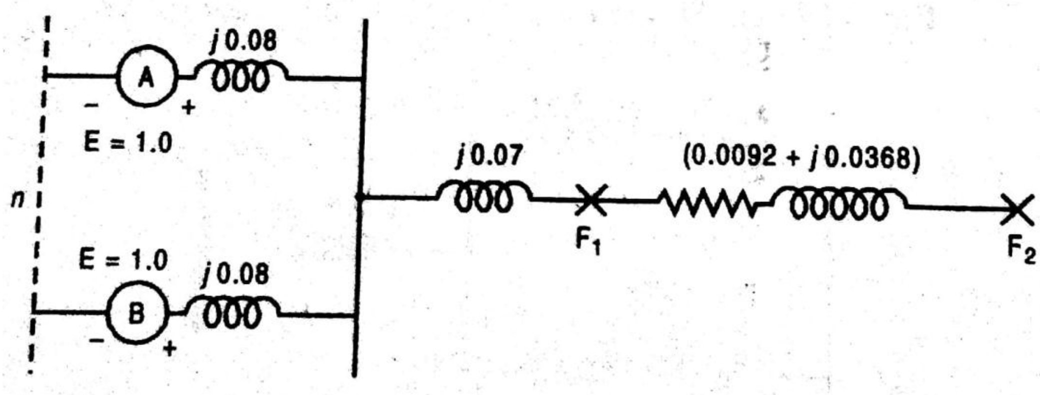
$$\text{Total per unit impedance} = j0.1 + j0.1 = j0.2 \text{ pu}$$

$$\text{Short circuit kVA} = \frac{10 \times 1{,}000}{0.2} = 50{,}000 \text{ kVA} \quad \textbf{Ans.}$$

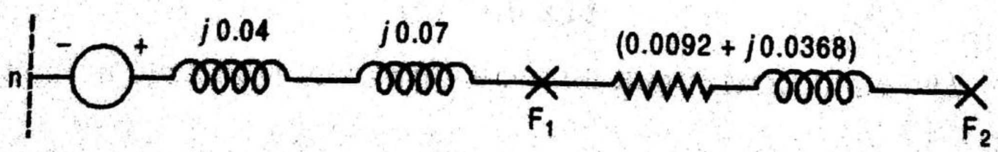
Example 4.7. Two 3-phase 11 kV generators of capacities 8 MVA and 4 MVA and subtransient reactances of 8% and 4% respectively operate in parallel. The generating station is connected to a transmission line of 200 km length, through a step-up transformer of capacity 4 MVA, and having percentage reactance of 3.5%. The resistance and reactance of the transmission line per km of its length are 0.025 Ω and 0.1 Ω respectively and it operates at 66 kV. Calculate the short-circuit MVA for a phase-to-phase faults at the receiving end of the transmission line and at the sending end.



(a) Single Line Diagram of System



(b) Reactance Diagram



(c) Reduced Reactance Diagram

Solution : Single line diagram of the network is shown in Fig. 4.18 (*a*). Let base kVA for complete system be 8,000 kVA, base kV for generator side be 11 kV and transmission line side 66 kV.

Per unit reactance of generator A,

$$= \frac{8}{100} = 0.08$$

Per unit reactance of generator B,

$$= \frac{4}{100} \times \frac{8,000}{4,000} = 0.08$$

Per unit reactance of transformer

$$= \frac{3.5}{100} \times \frac{8,000}{4,000} = 0.07$$

Impedance of transmission line

$$= 200\,(0.025 + j\,0.1) = (5 + j\,20)\,\Omega$$

Per unit impedance of transmission line

$$= \frac{(5 + j20) \times 8,000}{(66)^2 \times 1,000} = (0.0092 + j\,0.0368) \text{ pu}$$

The single line impedance diagram corresponding to Fig. 4.18 (*a*) can now be drawn as in Fig. 4.18 (*b*), which when further simplified reduces to that shown in Fig. 4.18 (*c*) because equivalent of two reactances (j 0.08 each) in parallel comes out to be $\frac{j\,0.08}{2} = j\,0.04$ pu.

For a 3-phase fault at the sending end (F_1) side of the transmission line, the total impedance up to the fault point $= j\,0.04 + j\,0.07 = j\,0.11$.

$$\text{Short-circuit MVA} = \frac{\text{Base MVA}}{\text{Per unit reactance}} = \frac{8,000 \times 10^{-3}}{0.11}$$

$$= 72.73 \quad \textbf{Ans.}$$

For a 3-phase fault at the receiving end (F_2) side of the transmission line, the total impedance up to the fault point

$$= j\,0.04 + j\,0.07 + (0.0092 + j\,0.0368)$$

$$= (0.0092 + j\,0.1468) \text{ pu} = 0.1471 \angle 86.4^\circ$$

$$\text{Short-circuit MVA} = \frac{\text{Base MVA}}{\text{Per unit impedance}} = \frac{8,000 \times 10^{-3}}{0.1471}$$

$$= 54.4 \quad \textbf{Ans.}$$

Unit 2: Relays

2.1 Introduction, Basic Trip Circuit and Auxiliary switch

The protective relay may be defined as an electrical device interposed between the main circuit and the circuit breaker in such a manner that any abnormality in the circuit acts on the relay, which in turn, if the abnormality is of a dangerous character, causes the breaker to open and so to isolate the faulty element. The relay ensures the safety of the circuit equipment from any damage which might be otherwise caused by the fault. The proper operation of the power system requires an efficient, reliable and fast acting protection scheme, which basically consists of protective relays and switching devices. A protective relay, acting as a brain behind the whole system, senses the fault, locates it, and sends a command to appropriate circuit breaker to isolate only the faulty section, thus keeping the rest of the healthy system functional. It detects abnormal conditions on a power system by constantly monitoring the electrical quantities of the system, which are different under normal and abnormal (fault) conditions. The basic electrical quantities which are likely to change during abnormal conditions are current, voltage, phase angle (direction) and frequency, Protective relays utilize one or more of these quantities to detect abnormal conditions on a power system.

The basic relay circuit is illustrated in Figure. There are two ways in which the circuit breaker trip coil is energized, In one method, the station battery is used to supply the current in the trip coil after the relay contacts are closed by the operation of the relay In the second method, as soon as the relay operates, the CT secondary current flows through the trip coil and energizes it. This method does not require a station battery and it is used for the protection of feeders.

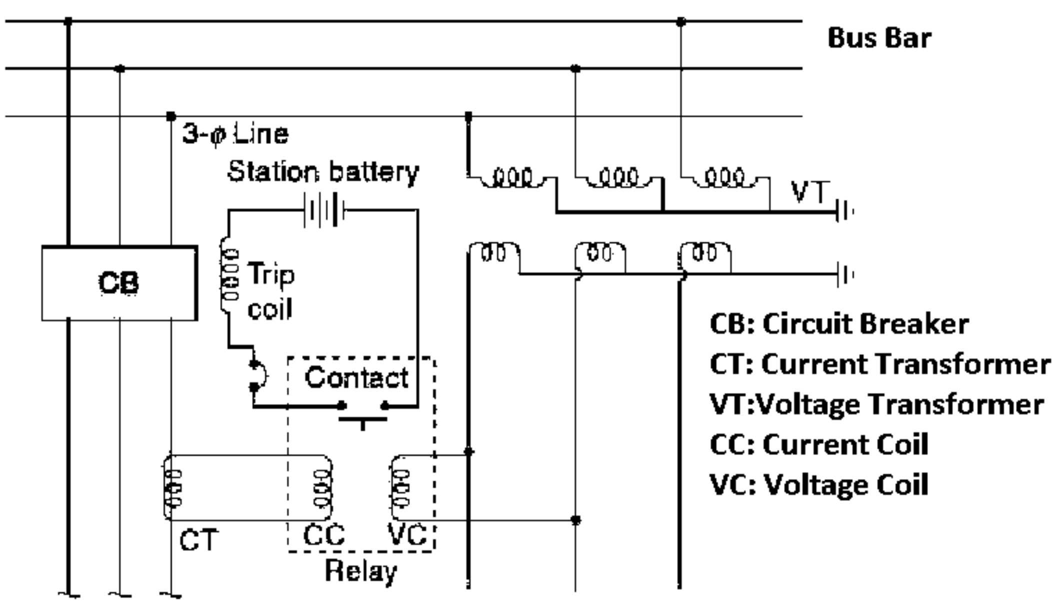


Figure 6: Relay connection

An auxiliary switch is connected in series with the trip-coil circuit. It is mechanically interlocked with the operating mechanism of the circuit breaker so that the auxiliary switch opens when the circuit breaker opens. The opening of the auxiliary switch prevents unnecessary drainage of the battery. When the trip-coil of the circuit breaker is energized, it actuates a mechanism of the circuit breaker, which causes the operating force to come into action to open the circuit breaker.

2.2 Tripping Scheme in Circuit Breaker

Basically, two types of tripping schemes which are given below

- Relay with make type contact.
- Relay with break type contact.

2.2.1 Relay with make type contact:

In this scheme, the relays are connected in the stare, and contacts of each relay are connected in parallel and this parallel unit of contacts is connected in series with breaker trip coil to battery supply. Now we describe, how does trip the breaker when a fault occurs on any of the phases, the relay will close the contact by which the tripping circuit is completed hence the trip coil of the breaker is energized which opens the circuit breaker along with its auxiliary switch. When the supply of current to fault path is stopped, the relay contact comes to normal position, then the trip coil is de-energized. The schematic drawing of the above scheme is shown in the figure.

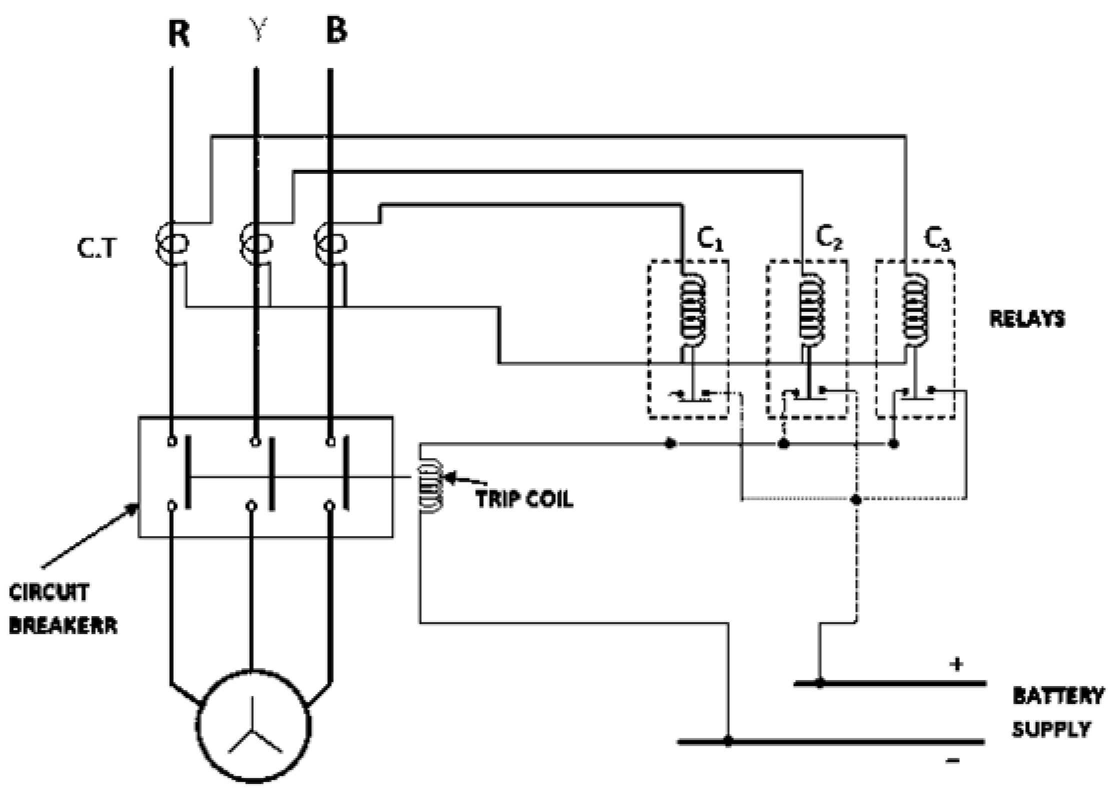


Figure 7: Schematic arrangement of system having relay with make type contact

2.2.2 Relay with break type contact:

In this type of scheme, the tripping circuit drives energy from the main supply source through C.T's secondary coil. The relay elements and the trip coil of each phase of the circuit breaker are connected in series and are connected as to form a star connection. Now we describe how the circuit breaker breaks at fault condition. At normal condition, the relay contacts are closed and hence no current flow through the breaker trip coil. When a fault occurs, the relay contacts are opened and circuit breaker trip coil is energized to open the circuit breaker. The schematic drawing of the above scheme is shown in the figure.

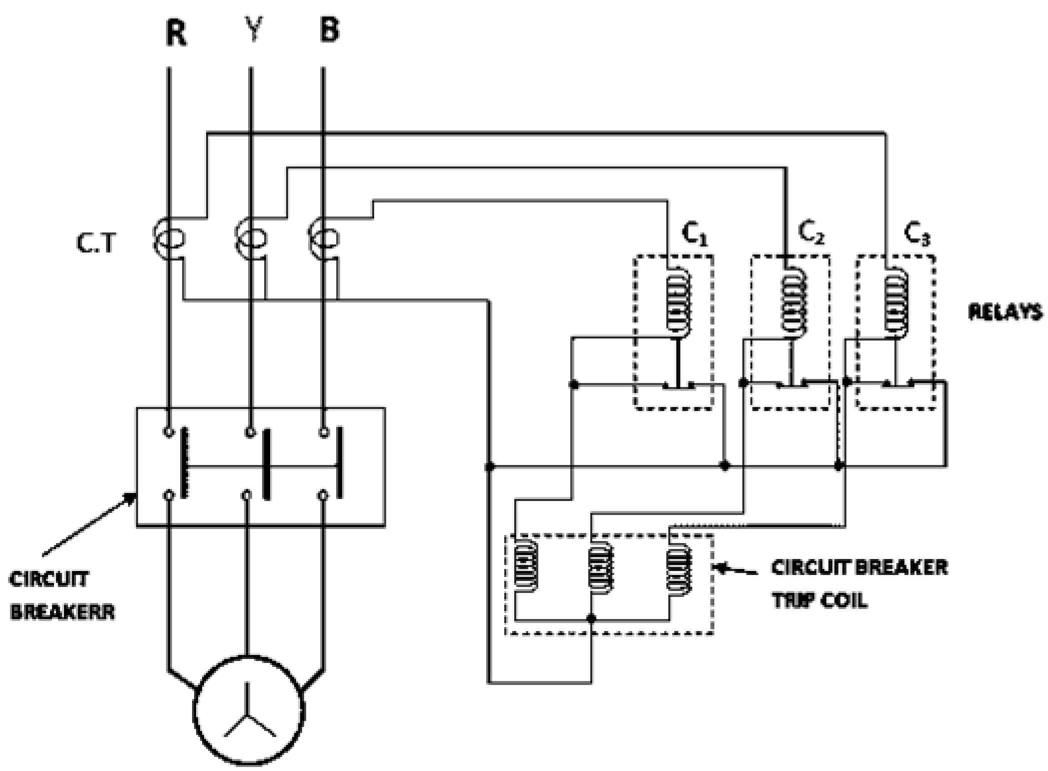


Figure 8:Schematic arrangement of system having relay with break type contacts and equipped with CTs

2.3 Electromagnet Attraction relays

Electromagnet attraction type relays are the simplest type of relays which respond to both ac and dc quantities. The basic principle of operation are the development of electromagnetic force on a movable member by the magnetic flux produced by the operating current. The movable member in turn, will move to close tripping contacts.

Figure shows the constructional features of the various types of attracted armature relay. In the plunger and hinged type armature type the restraining force is obtained by the spring action, whereas in the balanced beam type, the restraining coil is used to keep the relay in normal position. Whenever the operating coil is energized and the overpowers the restraining spring or coil, the movable member of the relay moves and closes the trip contacts and thus energizes the trip coil of the circuit breaker which opens the power circuit.

The spring or the restraining coil brings back the relay in normal position when the operating coil gets de-energized or the current flow is less than the set value for the relay operation. The threshold value of the current that start the movement for relay operation is called pickup current.

The operating torque is proportional to the square of current flowing through the coil. With dc, the torque developed is constant and if it exceeds the restraining torque or force caused by the controlling spring, the relay operates reliably. In case of ac quantity electromagnetic force developed is

$F_e = kI^2 = k[I_{max} \sin wt]^2 = \frac{1}{2}k[I_{max}{}^2 - I_{max}{}^2 \cos 2wt]$

It shows that the electromagnetic force consists of two components, one constant independent of time ($\frac{1}{2}kI_{max}{}^2$) and another dependent upon time and pulsating at double the supply frequency ($\frac{1}{2}kI_{max}{}^2\cos 2wt$).

2.3.1 Attracted Armature Relays

Attracted armature relays are the simplest type which respond to ac as well as dc. These relays operate through an armature which is attracted to an electromagnet or through a plunger which is drawn into a solenoid. All these relays use the same electromagnetic attraction principle for their operation, The electromagnetic force exerted on the moving element, the armature or plunger, is proportional to the square of the flux in the air gap or the square of the current, In dc relays this force is constant. In case of ac relays, the total electromagnetic force pulsates at double the frequency. The motion of the moving element is controlled by an opposing force generally due to gravity or a spring.

The following are the different types of construction of attracted armature relays.

- Hinged armature type
- Plunger type
- Balanced beam type
- Moving-coil type
- Polarized moving-iron type
- Reed type

a) Hinged Armature-Type Relays

Figure below shows a hinged armature-type construction. The coil is energized by an operating quantity proportional to the system current or voltage. The operating quantity produces a magnetic flux which in turn produces an electromagnetic force. The electromagnetic force is proportional to the square of the flux in the air gap or the square of the current. The attractive force increases as the armature approaches the pole of the electromagnet. This type of a relay is used for the protection of small machines, equipment etc. It is also used for auxiliary relays, such as indicating flags, slave relays, alarm relays, etc.

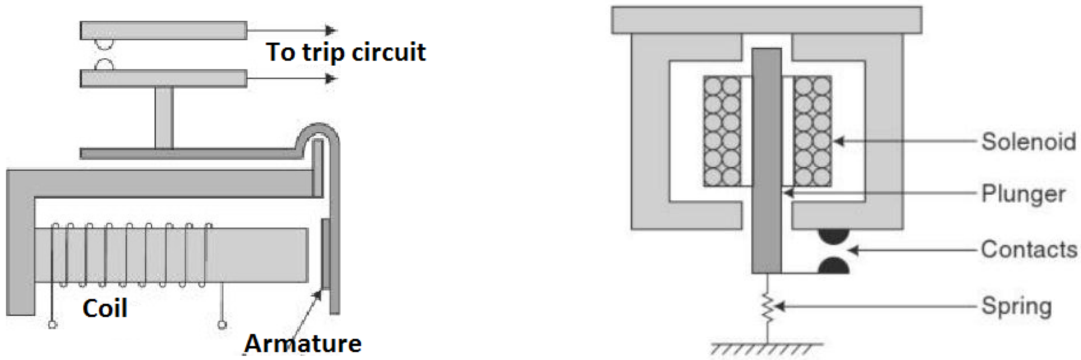


Figure 9: a) Hinged armature type relay b) Plunger type relay

b) Plunger type relays

Figure above shows a plunger-type relay. In this type of a relay, there is a solenoid and an iron plunger which moves in and out of the solenoid to make and break the contact. The movement of the plunger is controlled by a spring. This type of Spring construction has however become obsolete as it draws more current.

c) Balanced Beam relays

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

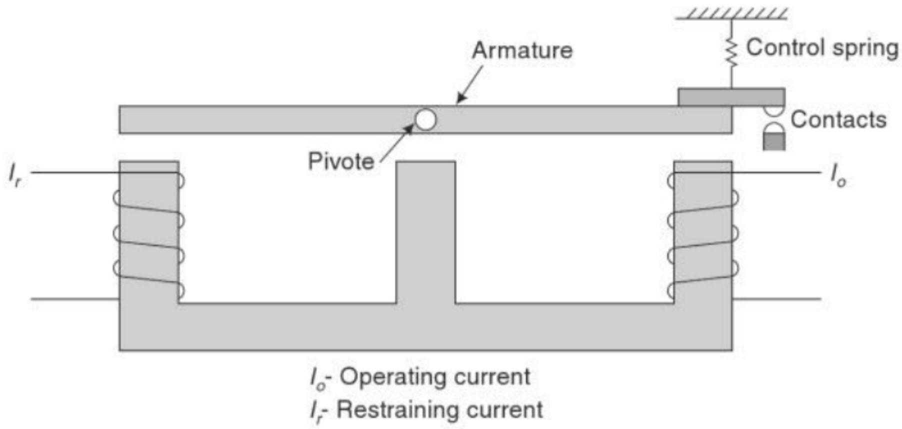


Figure 10: Balanced Beam relays

2.4 Induction Type Relay

Induction relays use electromagnetic induction principle for their operation. Their principle of operation is same as that of a single-phase induction motor. Hence, they can be used for ac currents only. Two types of construction of these Relays are fairly standard: one with an induction disc and the other with an induction cup. In both types of relays, the moving element (disc or cup) is equivalent to the rotor of the induction motor. There is one contrast from the induction motor, i.e., the iron associated with the rotor in the relay is stationary. The moving element acts as a carrier of rotor currents, whereas the magnetic circuit is completed through stationary magnetic elements. Two sources of alternating magnetic flux in which the moving element may turn are required for the operation of induction-type relays. In order to produce an operating torque, the two fluxes must have a phase difference between them.

2.4.1 Torque production

Fluxes ϕ_1 and ϕ_2 are produced in a disc type construction by shading technique. In watt-metric type construction, ϕ_1 is produced by the upper magnet and ϕ_2 by the lower magnet. A voltage is induced in a coil wound on the lower magnet by transformer action. The current flowing in this coil produces flux ϕ_2. In case of the cup type construction, ϕ_1 and ϕ_2 are produced by pairs of coils, as shown in Fig. 2.13. The theory given below is true for both disc type and cup type induction relays. Figure 2.14 shows how force is produced in a rotor which is cut by ϕ_1 and ϕ_2. These fluxes are alternating quantities and can be expressed as follows.

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

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

Voltages induced in the rotor are:

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

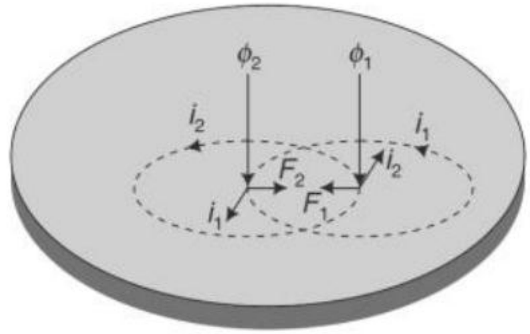


Fig. 2.14 *Torque produced in an induction relay*

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

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

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

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

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

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

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

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

$$F = KMN \sin \theta$$

2.4.2 Induction Disc Relay

Figure below shows a simple theoretical figure of shaded pole induction type relay. The rotating disc is made of aluminum. In the shaded pole type construction, a C-shaped electromagnet is used, One half of each pole of the electromagnet is surrounded by a copper band known as the shading ring, The shaded portion of the pole produces a flux which is displaced in space and time with respect to the flux produced by the unshaded portion of the pole. Thus, two alternating fluxes displaced in space and time cut the disc and produce eddy currents in it. Torques are produced by the interaction of each flux with the eddy current produced by the other flux. The resultant torque causes the disc to rotate.

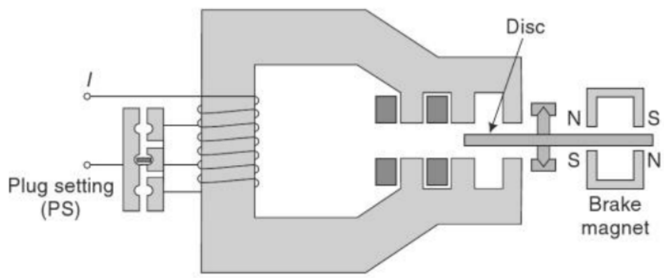


Figure 11: Shaded pole induction disc type relay

2.4.3 Wattmetric Induction disc type relay

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

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

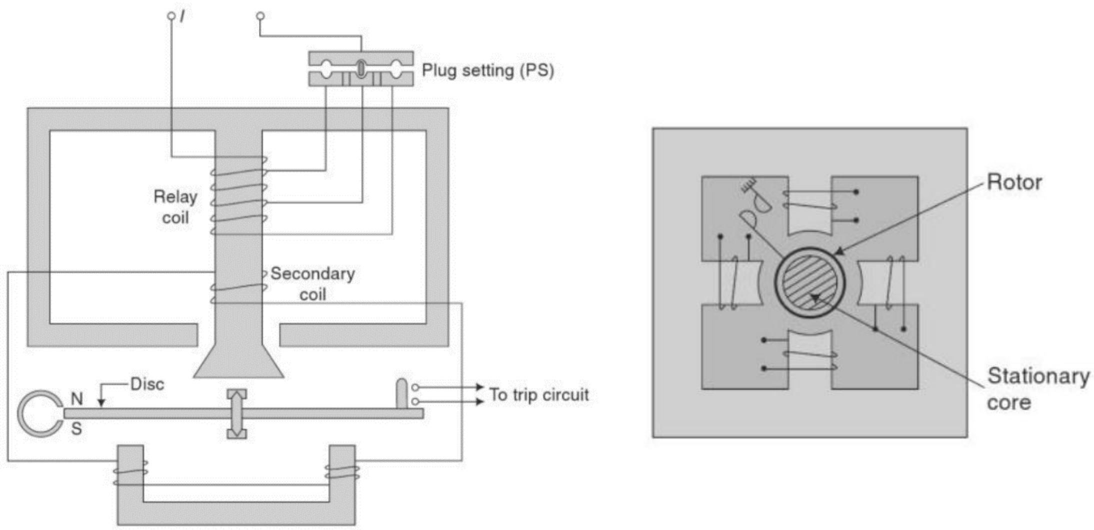


Figure 12: a) Wattmetric type induction disc relay b) Induction cup relay

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

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

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

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

2.4.4 Induction cup relay

Figure above shows an induction cup relay. A stationary iron core is placed inside the rotating cup to decrease the air gap without increasing inertia. The spindle of the cup carries an arm which closes contacts. A spring is employed to provide a resetting torque. When two actuating quantities are applied, one may produce an operating torque while the other may produce restraining torque. Brake magnets are not used with induction cup type relays. Induction cup relay operates on the same principle as that of an induction motor. It employs a 4 or 8-pole structure.

The rotor is a hollow cylinder (inverted cup). Two pairs of coils, as shown in the figure, produce a rotating field which induces current in the rotor. A torque is produced due to the interaction between the rotating flux and the induced current, which causes rotation. The inertia of the cup is much less than that of a disc. The magnetic system is more efficient and hence the magnetic leakage in the magnetic circuit is minimum. This type of a magnetic system also reduces the resistance of the induced current path in the rotor. Due to the low weight of the rotor and efficient magnetic system its torque per VA is about three times that of an induction disc type construction, Thus, its VA burden is greatly reduced. It possesses high sensitivity, high speed and produces a steady non-vibrating torque. Its parasitic torques due to current or voltage alone are small. Its operating time is to the order of 0.01 second. Thus, with its high torque/inertia ratio, it is quite suitable for higher speeds of operation.

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

2.5 Design Consideration of Electromagnetic Relays

The Relay Design and Construction is normally divided into the following stages:

- Selection of the operating characteristics.
- Selection of proper construction.
- Design of the contact movement from the point of view of utmost reliability**.**

The relay operating characteristic must match with the abnormal operating characteristic of the system. In other words, it should clearly show the conditions for tripping under various abnormal operating conditions. The most important considerations in the Relay Design and Construction are reliability, simplicity of construction and circuitry.

The Relay Design and Construction is divided into the following:

- Contacts;
- Bearings;

- Electromechanical design; and
- Terminations and housing.

1. Contacts: Contact performance is probably the most important item affecting reliability of the relay. Corrosion or dust deposition can cause nonoperation of relay, consequently the material and shape of the contacts are of considerable importance.
A good contact system design provides restricted contact resistance as well as reduced contact wear. The contact materials used are gold, gold alloys, platinum, and silver. The selection of the contact material depends on a number of factors like the voltage per contact break, the current to break as well as the type of atmospheric pollution under which these contacts are operated. However, there is no one ideal contact material which can be used universally under all conditions. There is also no method by which the suitability of contact material for use under any condition can be derived.

The following factors are to be considered for selecting a suitable contact material.

1. The nature of the current to be interrupted, i.e., direct or alternating.
2. Voltage at break and make operations.
3. The value of the currents to be interrupted.
4. Frequency of operation.
5. The actual speed of contact at make or break (this covers the arc duration and contact bounce).
6. The contact shapes.
7. The contact closing force.

On the basis of practical experiences, the following are some of the rules recommended in the design of contact system of a relay:

- The contacts should be bounce proof to avoid arcing at the contacts thereby reducing the maintenance which ultimately results in increasing its life.
- Contact pressure is another very important factor to be kept in An increase in contact pressure leads to decrease in voltage drop or contact resistance.
- To promote accuracy and avoid sticking after long periods of inaction, the relay should be designed to maximum torque/friction ratio.
- The value of current that can be interrupted by a pair of contact in a.c. circuit is 2 to 8 times than that in a d.c. circuit**.**

In general, domed shaped contacts or the cylindrical contacts at right angles give the best performance.

2. Bearing: The various arrangements in use are:

- **Single ball bearings:** Used for high sensitivity and low friction, a single ball bearing between two cup-shaped sapphire jewels is in use.
- **Multi-ball bearings:** Miniature types of less than 1.6 mm diameter are These provide low friction and greater resistance to shock and combine side-thrust and end-thrust in a single bearing.

- **Pivot and jewel bearings:** This is the most common type for precision relays, e.g. induction relays. Modern relays have spring-mounted jewels so that shocks are taken on a shoulder and not on the jewel.
- **Knife edge bearings:** These are used for hinged armature relays which normally operate many contacts.

3. Electromechanical Design: It consists of the design of the magnetic circuit and the mechanical fixtures of core, yoke and the armature.The reluctance of the magnetic path is kept to a minimum by enlarging the pole face which makes the magnetic circuit more efficient.
D.C. electromagnets are usually less expensive and more efficient than a.c. electromagnets. But small a.c. electromagnets made from soft iron, low carbon steel core having a slot for mounting a shaded ring are quite Common. The relay coil current is usually limited to 5A and the coil voltage to 220V, but still the insulation for the relay coil is designed to withstand at least 4 KV. The relay coil is designed to carry about 15 times the normal current for one second. From the mechanical strength consideration it is desirable that the conductor diameter must not be less than 0.05 cm even if the above considerations are satisfied.

4. Terminations and Housing: The assembly of armature with magnet and the base is done with the help of a spring. The spring is insulated from the armature by moulded blocks. These moulded blocks provide dimensional stability and better appearance economically. Materials used for springs are stainless steel, nickel silver, phosphorous bronze and berillium copper, whereas for moulded blocks nylon is used. The fixed contacts are usually rivetted or spot-welded on to the terminal link.

Unit 3: Relay Application and Characteristics

3.1 Non-Directional Induction type over-current Relay

A protective relay which operates when the load current exceeds a preset value, is called an overcurrent relay. The value of the preset current above which the relay operates is known as its pick-up value. Overcurrent relays offer the cheapest and simplest form of protection. These relays are used for the protection of distribution lines, large motors, power equipment, industrial systems, etc. Overcurrent relays are also used on some sub-transmission lines which cannot justify more expensive protection such as distance or pilot relays. A scheme which incorporates overcurrent relays for the protection of an element of a power system, is known as an overcurrent protection scheme or overcurrent protection. An overcurrent protection scheme may include one or more overcurrent relays,

At present, electromechanical relays are widely used for overcurrent protection. The induction disc type is commonly used. With the development of numerical relays based on microprocessors or microcontrollers, there is a growing trend to use numerical overcurrent relays for overcurrent protection.

3.1.1 Time Current Characteristics

Instantaneous relay: In these relays complete operation takes place after a very short (negligible) time duration from the incidence of the current or other quantity resulting in operation. The time of operation of such relays is lesser than 0.2 sec.

Definite time lag relays: In these relays the time of operation is sensibly independent of the magnitude of the current or of other quantity causing operation.

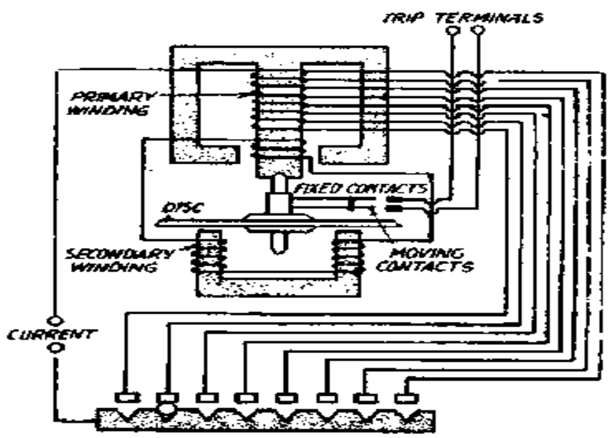
Inverse time lag relays: In these relays the time of operation is approximately inversely proportional to the magnitude of the current or other quantity causing operation.

Inverse definite minimum time (IDMT) lag relays: Such a relay is one in which operating time is approximately inversely proportional to fault current near pickup value and becomes substantially constant slightly above the pickup value of the relay. This is achieved by using a core of electromagnet which gets saturated for currents slightly greater than the pickup current.

3.1.2 Operation

Consider the constructional detail figure of a wattmetric type IDMT relay. The operating coil is also called primary winding of the relay, is tapped to correspond to different current settings, usually covering the range of 50-200% in seven equal steps of the rated current of secondary winding of CT connected to relay. The tapping's are brought out to a plug bridge or current setting bridge for easy selection. For any current above that chosen, the rotor will rotate and moving arm attached to the rotor spindle will close the pair of trip contacts at the end of its travel. A current less than the setting movement is prevented by a restraining spring coil also attached to the spindle of the disc. Thus the current setting device enables discrimination to be maintained at low overloads where two relays in series have current transformer of same ratio. The relay is also fitted with an adjustment known as the time setting multiplier, a device which controls the position to which the rotor in the relay resets after operation and thereby determining the travel the rotor has to make before it closes its tripping contact. This adjuster has a scale marked on its knob for the time setting from 0.05 to 1.0. A standard IDMT relay will have definite minimum time of 2.2

second, for operation at maximum time setting of 1.0. Thus if at unity time multiplier setting we obtain the definite minimum time of 2.2 sec. at 0.5 setting on the time multiplier, we shall get the definite minimum time of 1.1 sec and at 0.05 we shall obtain 0.11 sec as DMT. Using the different time multiplier for each, discrimination can be obtained between them regardless of current magnitude.



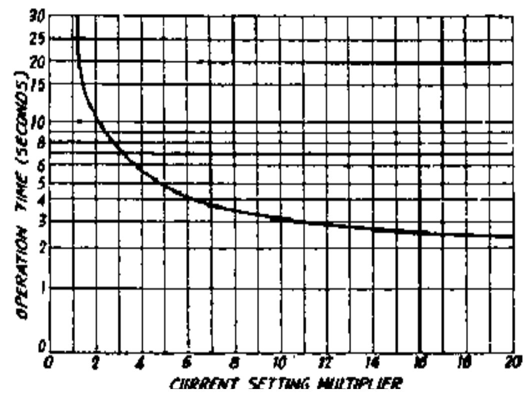


Figure 13: a) Wattmetric Induction type IDMT Relay b) PSM Vs Time Characteristics

3.1.3 Determination of Relay Operating Time

For determination of actual operating time of a relay the data required is i) Time-PSM curve ii) Current Setting iii) Time setting iv) Fault Current v) CT ratio

The actual operating time of relay is determined by following steps

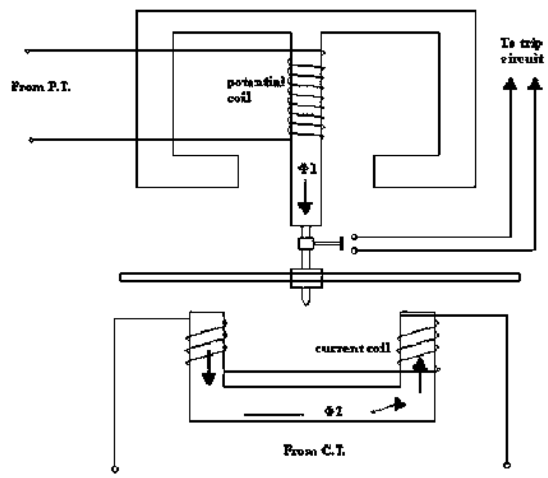
1. Determination of relay current from fault current I_f and CT ratio x:y from the expression.
   Relay current $I_R = I_f * \frac{y}{x}$
2. Determination of relay current setting multiplier (PSM) which is given as,
   PSM = $\frac{Fault\ current\ in\ relay\ coil}{pickup\ value} = \frac{I_R}{current\ setting * rated\ sec.current\ of\ CT}$
   $= \frac{I_R}{\frac{I_P}{100} * y}$
   Where I_p is the percent current setting of relay
3. Determination of the operating time of relay corresponding to calculated PSM from T-PSM curve
4. Determination of the operating time of relay by multiplying the time obtained in step 3 by the Time setting multiplier in use.

3.2 Directional Relay (Induction Type)

The directional power relay operates when the power through the relay will be reversing. i.e generator supply to the network fails and the power from other sources in the system try to feed the power to this unit in the reverse direction.

The principle of operation of this type of relay is similar to that of an overcurrent induction relay. The difference lies in the fact that in case of overcurrent relay the torque is developed due to the interaction of magnetic fields obtained from the current in circuit through CT, while in the case of directional power relay the driving torque is derived from the interaction of the fields produced from both voltage and current sources of the circuits it protects. Since the relay has both voltage and current coils, the relay is essentially a wattmeter and the direction of the torque developed in the relay depends upon the direction of the current in relation to the voltage with which it is associated i.e the relay recognizes the phase difference between voltage and current.

Figure shows the constructional details of induction type directional power relay. It is essentially consist of an aluminum disc which is force to rotate in between the poles of two electromagnets. The upper electromagnet has a winding called voltage or potential coil, on the middle limb connected to the circuit voltage source through PT.



The lower electromagnet has a separate winding called the current coil, connected to the secondary of CT in the line to be protected. The current coil is protected with numbers of tapping's connected to the plug bridge, so as to give the desired current setting. The restraint torque is provided by a spiral spring.

The torque developed on the disc suspended between the two magnets is proportional to VI. When the power flows in the normal direction, the torque developed on the disc assisted by the spring tends to turn away the moving contact from the fixed trip contact. Thus, the relay remains un operative. A reversal current in the circuit reverses the torque produced on the disc and when this is large enough to overcome the control spring torque, the disc rotates in the reverse direction and moving contact closes the trip circuit. This causes the operation of the circuit breaker to disconnect the faulty section.

3.3 Differential Relay

Differential protective relaying is the most positive in selectivity and in action. It operates on the principle of comparison between the phase angle and magnitudes of two or more-similar electrical quantities. Comparing two electrical quantities in a circuit by means of differential relays is simple in application and positive in action.

For example, in comparison of the current entering a line and the current leaving it, if more current enters the protected line than leaves it, the extra current must flow in the fault. The difference between the two electrical quantities can operate a relay to isolate the circuit.

A differential relay is defined as the relay that operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined amount.

This means that for a differential relay, it should have:

(i) Two or more similar electrical quantities and

(ii) These quantities should have phase displacement (normally approximately 180°) for the operation of the relay.

Almost any type of relay, when connected in a certain way, can be made to operate as a differential relay. In other words, it is not so much the relay construction as the way the relay is connected in a circuit that makes it a differential relay. Most of the differential relays are of the "current differential" type in which phasor difference between the current entering the winding and current leaving the winding is used for sensing and relay operation.

Differential protection is generally unit protection. The protected zone is exactly determined by the location of CTs and PTs. The phasor difference is achieved by suitable connections of secondaries of CTs or PTs.

Differential protection principle is employed for the protection of generators, generator-transformer units, transformers, feeders (transmission lines), large motors and bus-bars.

3.3.1 Current Differential Relays

An arrangement of an overcurrent relay connected to operate as differential relay is shown in Figure. The dotted line represents the system element that is to be protected by the differential relay. This system element might be a length of circuit, a portion of the bus or a winding of a generator or that of a transformer. A pair of CTs are fitted on either end of the section to be protected. The secondaries of CTs are connected in series with the help of pilot wires in such a way that they carry the induced currents in the same direction. The operating coil of an overcurrent relay is connected across the CT secondary circuit, as shown in Figure.

Normally when there is no fault or there is an external fault Figure (a)the currents in the two CT's secondaries are equal and the relay operating coil, therefore, does not carry any current.

But should a short circuit develop anywhere between internal fault the two CTs, the conditions will exist as shown in Figure (b). If the current flows to the fault from both sides as shown, the sum of the CT secondary currents will flow through the differential relay. It is not necessary that fault current flows to the fault from both sides to cause secondary current to flow to the differential relay.

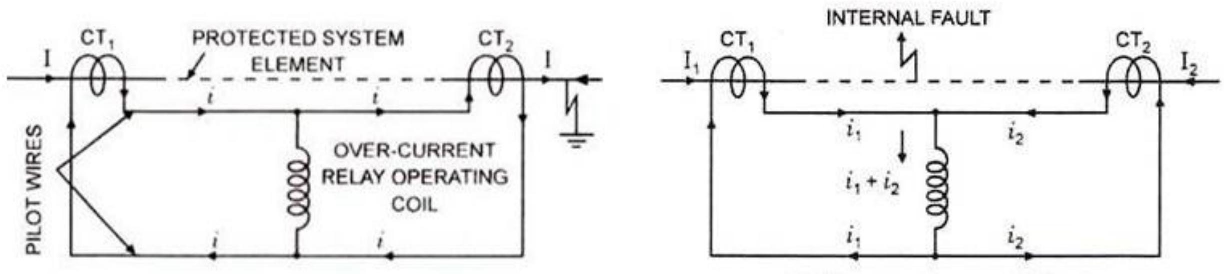
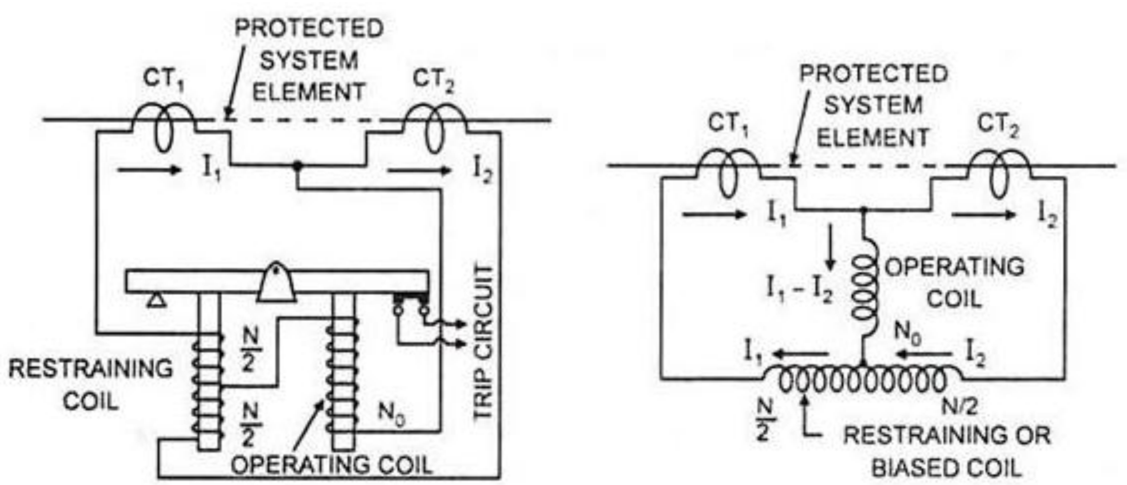


Figure 14: a) For an External Fault b) For an internal fault

A flow on one side only, or even some current flowing out of one side while a larger current entering the other side will cause a differential current to flow through the relay operating coil. In the other words, the differential relay current will be proportional to the phasor difference between the currents entering and leaving the protected element; and, if the differential current exceeds the relay's pick-up value, the relay will operate.

3.3.2 Biased or Percentage-Differential Relay

The most extensively used form of differential relay is the percentage-differential or beam biased relay. This is essentially the same as the overcurrent type of current- balance relay, but it is connected in a differential circuit, as illustrated in Figure (a). Schematic arrangement is shown in Figure(a) while equivalent circuit is shown in Figure (b).



(a) Schematic Arrangement *(b) Equivalent Circuit Diagram*

Figure 15: Biased or percentage differential relay

This system consists of an additional restraining coil connected in the pilot wires, as shown in the figure and current induced in both CTs flows through it. The operating coil is connected to the mid-point of the restraining coil. The reason for using this modification in circulating current differential relay is to overcome the trouble arising out of differences in CT ratios for high values of external short-circuit currents.

The torque due to restraining coil prevents the closing of trip circuit contacts, while the torque due to operating coil tends to close the trip circuit contacts. Under normal operating conditions and through load conditions, the torque developed by restraining coil is greater than the operating coil torque. Thus, the relay remains inoperative. When an internal fault occurs, the operating torque exceeds the restraining torque. Consequently, the trip circuit contacts are closed to open the circuit breaker. The restraining torque may be adjusted by varying the number of turns of the restraining coil.

The differential current required to operate this relay is a variable quantity, owing to the effect of the restraining coil. The differential current in the operating coil is proportional to $(I_1 - I_2)$ and the equivalent current in the restraining coil is proportional to $[(I_1 + I_2)/2]$ as the operating coil is connected to the mid-point of the restraining coil.

The torque developed by the operating coil is proportional to the ampere-turns i.e., $T_0 \propto (I_1 - I_2) N_0$ where N_0 is the number of turns on the operating coil. The torque due to restraining coil $T \propto [(I_1 + I_2)/2]N$.

Where, N is the number of turns on the restraining coil. For external faults both I_1 and I_2 increase and thereby the restraining torque increases which prevents the mal-operation.

It is clear from the operating characteristic of the relay, that except for the effect of the control spring at low currents, the ratio of the differential operating current to the average restraining current is a fixed percentage. This is why it is known as percentage-differential relay. The relay is also called the biased-differential relay because the restraining coil is also called a biased coil as it provides additional flux.

The percentage or biased differential relay has a rising pick-up characteristic. So, with the increase of magnitude of through current, the relay is restrained against mal-operation.

Figure below shows the comparison of a simple overcurrent relay with a percentage-differential relay under such conditions. An overcurrent relay having the same minimum pick-up as a percentage-differential relay would operate undesirably when the differential current merely exceeded the value X, while there would be no tendency for the percentage-differential relay to operate.

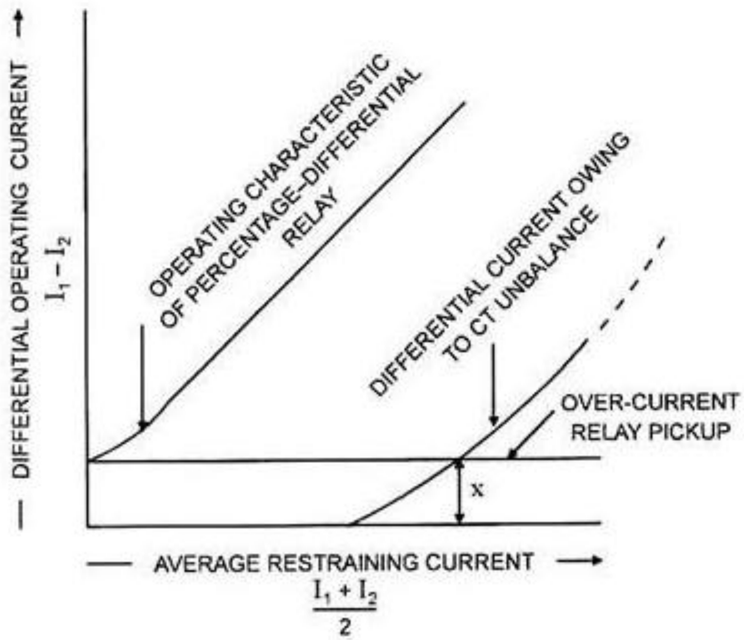


Figure 16: Comparison between simple overcurrent relay and percentage differential relay

Induction Type Biased Differential Relay:

In the simplest electromagnetic form the relay is shown in Figure. Such a relay consists of a pivoted disc free to rotate in the air gaps of two electromagnets, a portion of each pole of which is fitted with a copper shading ring. This ring can be moved further into, or out of the pole.

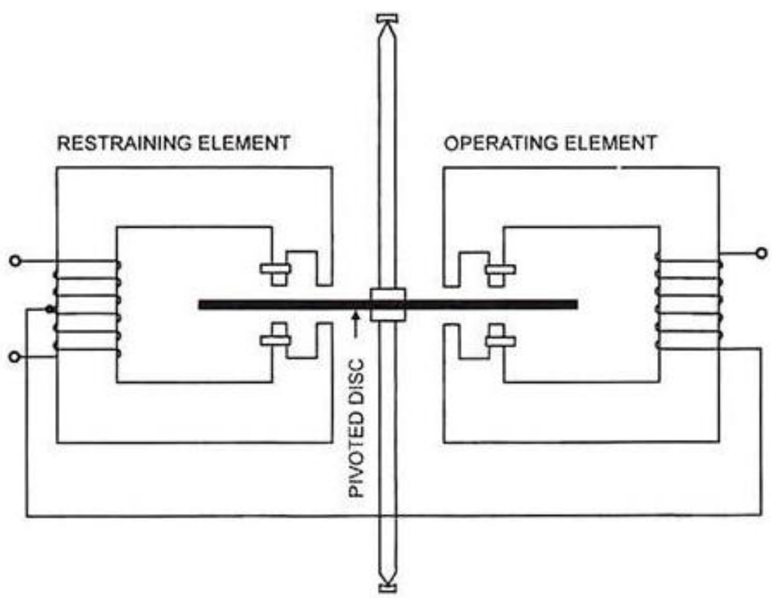


Figure 17: Induction type biased differential relay

The disc experiences two torques—one due to the operating element and the other due to restraining element. If the shading rings were in the same position on each element, the resulting torque experienced by the disc would be zero. But if the shading rings of restraining element were moved further into the iron core, the torque exerted by the restraint element will exceed than that of the operating element.

3.3.3 Voltage Balance Differential Relay

The differential relays are known as current balance relays. Such relays are convenient where both ends of the protected element are close together e.g., with generator or transformer protection but do not suit for the protection of feeders. If such relays are used for feeder protection of several km length, the secondary emfs of the CTs would be required to circulate about 1 or 5 A at full load or several times the current during external fault conditions, round a pilot loop of fairly high impedance. Such a burden is impracticable for any economic design of CT. Another class of relays is the voltage balance differential relays, which are preferred for the feeder protection.

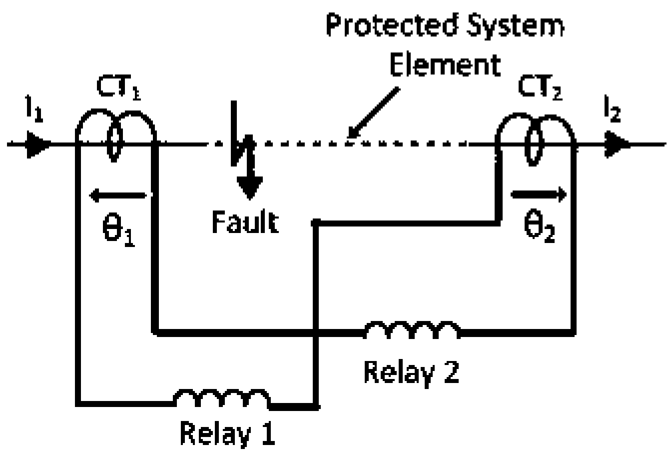


Figure 18: Voltage balanced differential relay

In this arrangement, two similar current transformers are connected at either end of the system element under protection (such as a feeder) by means of pilot wires. The relays are connected in series with the pilot wires, one at each end. The relative polarity of the CTs is such that there is no current through the relay under normal operating conditions and through fault conditions. The CTs used in such protection should be such that they should induce voltages in the secondary linearly with respect to the current. Since the magnitude of fault current is very large, in order that the voltage should be a linear function of such large currents the CTs should be air-cored.

When a fault occurs in the protected zone, the currents in the two primaries will differ from one another and so voltages induced in the secondaries of the CTs will differ and circulating current will flow through the operating coils of the relays. Thus, the trip circuit will be closed and the circuit breaker will open.

To provide for capacity currents, the relays employed may be overcurrent type which should operate only when the difference of the currents on both sides exceeds certain value.

In this system no restraining coil or balancing resistance or overload coil is required.

Though this method is more reliable than current balance or circulating current system but has great disadvantage that CTs do not carry current so acts as open circuited and inserts high impedance in the circuit. This method may be employed for protection of feeders, alternators and transformers. For use on transformers, the turn-ratio of power transformers must be kept in view.

3.4 Universal Relay Torque Equation

Protection relay mostly consist of some arrangement of electromagnets. These electromagnets have either current winding or voltage winding and in some-cases, both the winding. Current through the winding produces magnetic fluxes and the torque is produced by interaction between the fluxes of the same winding or between the fluxes of both the winding.

Torque developed by current winding = K_1I^2

Torque developed by voltage winding = K_2V^2

If both the current and voltage winding are used, the torque developed by the interaction between the fluxes = $K_3VI \cos(\theta - T)$

Where, θ is the angle between V and I and T is the relay maximum torque angle.

If the relay consists of all the three elements, the torque will be developed due to all the three causes and therefore its torque in general will be given as,

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

Where, K_1,K_2,K_3 are tap settings or constants of I and V & K_4 is the mechanical restraint due to spring or gravity.

By assigning plus or minus signs to certain of the constants and letting others to zero and sometimes by adding other similar terms the operating characteristics of all types of protective relay can be obtained.

In case of overcurrent relay $K_2 = K_3 = 0$

$T = K_1I^2 - K_4$

Similarly, for directional relay $K_1 = K_2 = 0$

$T = K_3VI \cos(\theta - T) - K_4$

3.5 Distance Protection

Distance protection is the name given to the protection whose action depends upon the distance of the feeding point to the fault. The time of operation of such protection is a function of ratio of voltage and current i.e., impedance. This impedance between the relay and fault depends upon the electrical distance between them. Principle types of distance relays are impedance relays, reactance relays & admittance or mho relays.

3.5.1 Impedance type Distance Relay

An impedance relay is a voltage restrained overcurrent relay. The relay measures impedance upto the point of fault and gives tripping command if this impedance is less than the relay setting Z. Relay setting Z is known as replica impedance and is proportional to the set impedance i.e. impedance up to the reach of relay. The relay monitors continuously the line current I through CT and the bus voltage through PT and operates when the V/I ratio falls below the set value.

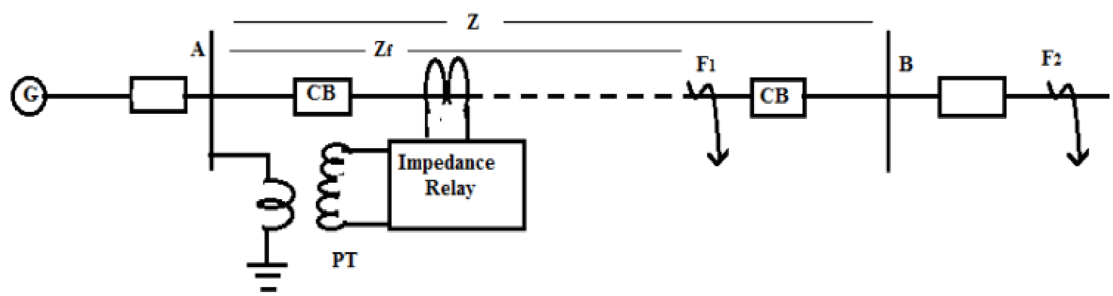
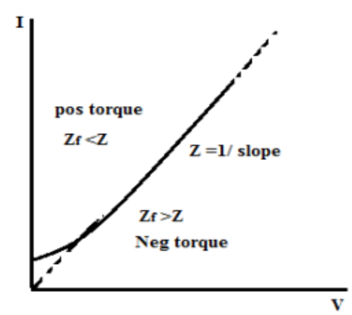


Figure 19: Impedance type distance relay

The principle of operation is illustrated in figure. The voltage element of relay is excited through a PT from the line under protection and current element of relay is excited from a current transformer (CT) in series with the line. The portion AB is the protected zone. Under normal operating condition the impedance of protected line is Z. The impedance, ratio of the bus voltage and fault current (V/I), between the point where the relay is located and point of fault will be less than Z in case of F_1 so the relay operates. But in case of F_2, the V/I will be more than Z, so relay contacts don't operate.

The impedance relay is a double actuating quantity relay and essentially consists of two elements current operated and voltage operated. The current element produces a positive or pick-up torque while the voltage elements develops a negative or reset torque. Taking spring control effect as $-K_3$, the torque equation of relay is;



$T = K_1I^2 - K_2V^2 - K_3$ …………(i)

Where V and I are rms value of voltage and current respectively. At balance point, When the relay is on the verge of operating the net torque is zero and

$$K_2V^2 = K_1i^2 - K_3$$

$$\text{Or } \frac{V}{I} = Z = \sqrt{\frac{K_1}{k_2} - \frac{K_3}{k_2 I^2}}$$

Neglecting the effect of spring

$Z = \sqrt{\frac{K_1}{k_2}}$ = const…………(ii)

3.5.2 Reactance Type Distance Relay

Reactance type relay is a very high-speed relay. It consists of two units- an overcurrent element developing positive torque and a current voltage directional element which either aids or opposes the overcurrent element depending on the phase angle between current and voltage. This means a reactance relay is an overcurrent relay with directional restraint. The directional element is arranged to develop maximum negative torque when its current lags behind its voltage by 90°.

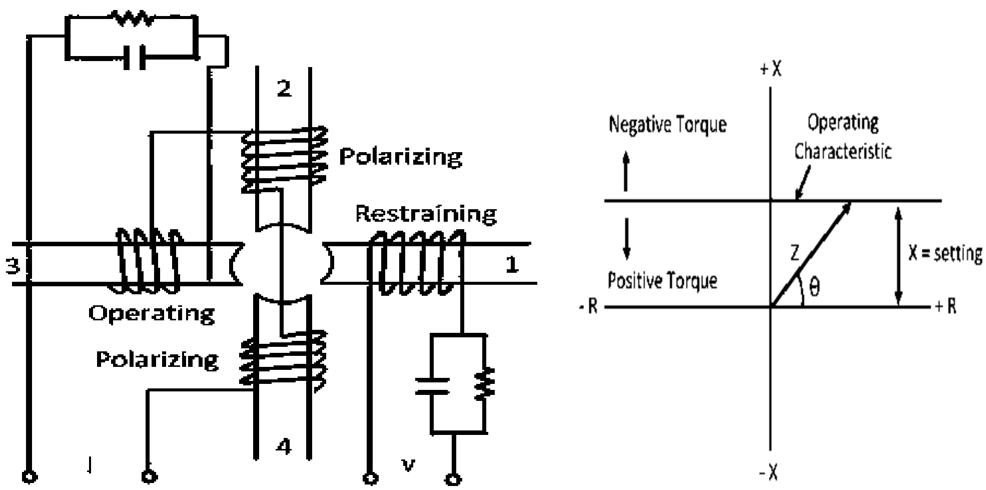


Figure 20:a) Reactance type distance relay b) Operating Characteristics

It has four pole structure carrying operating, polarizing and restraining coils as shown in figure. The operating torque is developed by the interaction of fluxes due to current carrying coils i.e. interaction of fluxes of poles 2, 3, 4 and the restraining torque is produced by the interaction of fluxes due to the poles 1, 2, 4. Thus the operating torque will be proportional to I^2 while the restraining torque will be proportional to VI Cos(θ -90°). The desired torque angle is obtained with the help of resistance, capacitance circuits as shown.

If the spring control effect is indicated by K_3 , the torque equation becomes

$T = K_1I^2 - K_2VICos(\theta - 90°) - K_3$

Where θ is defined as positive when I lags behind V

Or, $T = K_1I^2 - K_2VISin\theta - K_3$

At balance point, the net torque is zero and hence

$K_1I^2 - K_2VISin\theta - K_3 = 0$

$K_1I^2 = K_2VISin\theta + K_3$

$K_1 = K_2\frac{V}{I}\sin\theta + \frac{K_3}{I^2}$

$ZSin\theta = X = \frac{K_1}{k_2}$

3.5.3 Mho Type Distance Relay

Mho relay is also high-speed relay and is also known as admittance relay. It is also sometimes called an angle impedance relay. In this relay operating torque is obtained by the volt-ampere element and restraining torque is developed due to voltage element. It means mho relay is a voltage restrained directional relay.

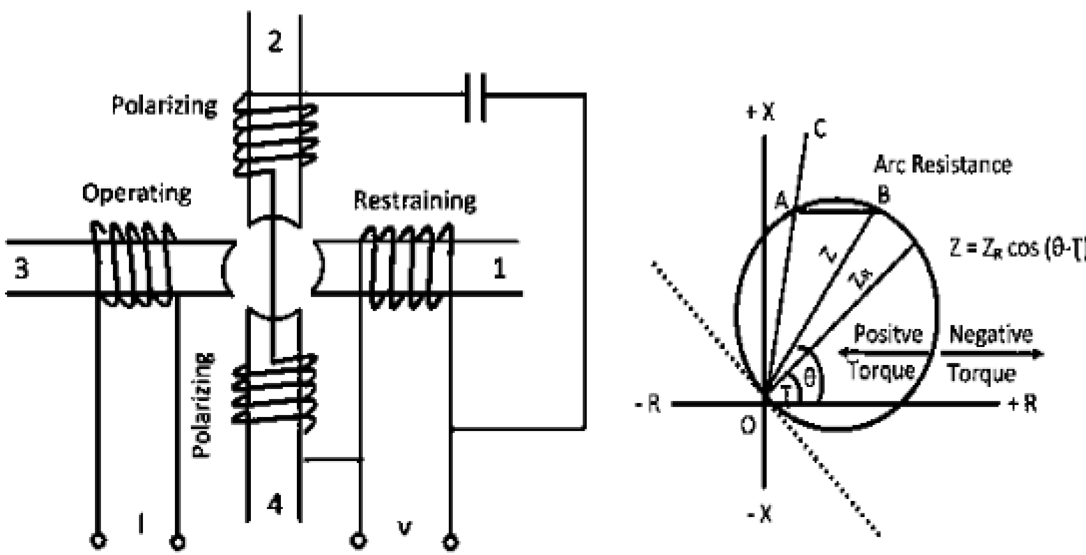


Figure 21:a) Mho type distance relay b) operating characteristics

The operating torque is developed by the interaction of fluxes due to the poles 2, 3, 4 and the restraining torque due to poles 1, 2 and 4.

If the spring control effect is indicated by K_3 , the torque equation becomes

$T = K_1VICos(\theta - T) - K_2V^2 - K_3$

Where θ and T are defined as positive when I lags behind V. At balance point, the net torque is zero and hence

$K_1VICos(\theta - T) - K_2V^2 - K_3 = 0$

$\frac{K_1}{K_2}Cos(\theta - T) - \frac{K_3}{K_2VI} - \frac{V}{I} = Z$

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

$YCos(\theta - T) = \frac{K_2}{K_1}$ =const.

Where Y is the admittance in mho.

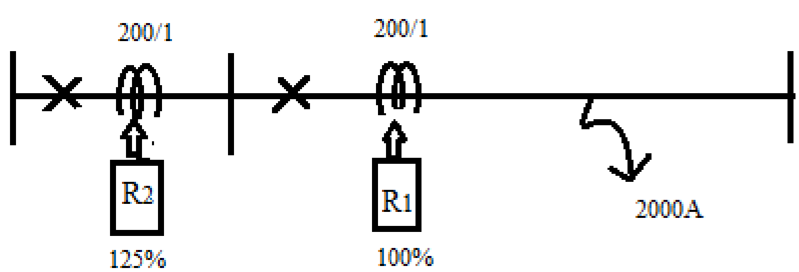
3.6 Numerical Solution

1) Determine the time of operation of an IDMT relay of rating 5A and having setting of 125% and TSM = 0.5 . The relay is connected through CT of 400/5A. The fault current is 4000A. The operating time for PSM of 8 is 3.2 seconds.

   Here;
   Fault current I_f =4000A
   CT ratio = 400/5
   Relay current I_R = 4000*$\frac{5}{400}$ = 50 A
   Pick up value of relay = current setting*Rated sec. current of CT
   = $\frac{125}{100}$ * 5 = 6.25A
   Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{50}{6.25} = 8$

   Time corresponding to the PSM of 8 from the given data is 3.2 sec.
   So the actual operating time = 3.2 * TSM
   = 3.2*0.5 = 1.6 sec

2) Reference to figure below, given that



Fault current = 2000A; Relay 1 set on 100%; CT ratio= 200/1

Relay 2 set on 125% for discrimination the time gradient margin between the relays is o.5 seconds.

Determine the time of operation of the two relays assuming that the both relays have the characteristics as shown in the table and relay 1 has the TSM = 0.2. Also determine the TSM of relay 2.

Plug setting multiplier	2	3.6	5	8	10	15	20
Time in sec. for a time multiplier of 1	10	6	3.9	3.15	2.8	2.2	2.1

Here;

For relay 1

Relay current I_R = 2000*1/200 = 10A

Pick up current I_P = 100/100*1 = 1A

Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{10}{1}$ = 10

Time corresponding to the PSM of 10 from the given data is 2.8 sec.

So the actual operating time = 2.8 * TSM

= 2.8*0.2 = 0.56 sec

For relay 2

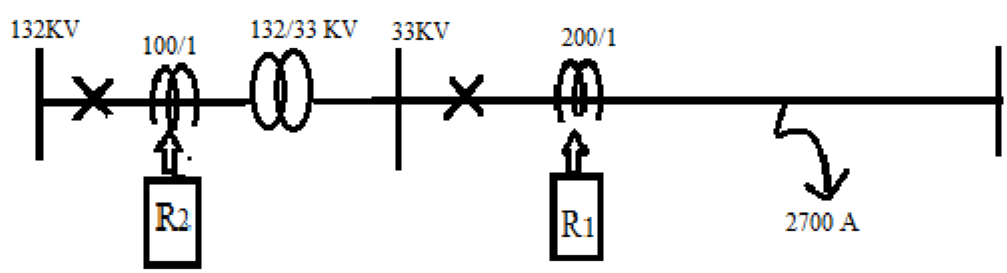
Relay current I_R = 2000*1/200 = 10A
Pick up current I_P = 125/100*1 = 1.25A
Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{10}{1.25}$ = 8

Time corresponding to the PSM of 10 from the given data is 3.15 sec.

But actual operating time for operation of relay 2 = Time of operation of relay 1 + Time grading margin = 0.56 + 0.5 = 1.06 sec

TSM = 1.06/3.15 = 0.3365

3) It is given that fault current level at 33kv side is 2700; CT ratio at 33 KV side is 200:1 and 132 side is 100:1. If both the relays R1 and R2 are set for 100% plug setting, determine the operating time for both relays when time grading margin of 0.6 sec is given and TSM for relay 1 is 0.15.



Here;
For relay 1

Relay current I_R = 2700*1/200 = 13.5A
Pick up current I_P = 100/100*1 = 1A
Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{13.5}{1}$ = 13.5

Time corresponding to the PSM of 13.5 from the given data is 2.6 sec.
So, the actual operating time = 2.6 * TSM
= 2.6*0.15 = 0.39 sec

For relay 2
Fault current on 132kv side = 2700*33/132 = 675A
Relay current I_R = 675*1/100 = 6.75A
Pick up current I_P = 100/100*1 = 1A
Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{6.75}{1}$ = 6.75
Time corresponding to the PSM of 6.75 from the given data is 3.6 sec.
But actual operating time for operation of relay 2 = Time of operation of relay 1 + Time grading margin = 0.39 + 0.6 = 0.99 sec
TSM = 0.99/3.6 = 0.275

4) A 20 MVA transformer which is used to operate at 30% overload feeds an 11kv busbar through a CB. The transformer CB is equipped with a 1000/5 CT and the feeder CB with 400/5 CT and both CT feed IDMT relay having the following characteristics.

PSM	2	3	5	10	15	20
Time (sec.)	10	6	4.1	3	2.5	2.2

The relay on the feeder CB has 125% plug setting and a 0.3 TSM. If a fault current of 5000A flows from the transformer to the feeder, determine

I) Operating time of feeder relay
II) Suggest the suitable plug setting and the time multiplier setting of the transformer relay to ensure adequate discrimination of 0.5s between the transformer relay and feeder relay.
Here;

For Feeder relay
Relay current I_R = 5000*5/400 = 62.5A
Pick up current I_P = 125/100*5 = 6.25A
Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{62.5}{6.25}$ = 10

Time corresponding to the PSM of 10 from the given data is 3 sec.
So, the actual operating time = 3 * TSM
= 2.8*0.3 = 0.9 sec

For Transformer relay

Transformer Overload current = $1.3*\frac{20*10^6}{\sqrt{3}*11000}$ = 1365A

Relay current I_R = 1365*5/1000 = 6.825A

Pick up current I_P = PS * 5, where PS means plug setting

Since the transformer relay must not operate the overload current

PS>$\frac{6.825}{5}$> 1,365 or 136.5%

So the nearest higher than 136.5% is 150% (since steps of 25%)

Transformer Pickup current = 150/100*5 = 7.5A

Transformer relay current corresponding to fault current of 5000A =5000*5/1000 = 25A

Plug setting Multiplier of relay, PSM = $\frac{I_R}{Pick\ up\ value\ of\ relay} = \frac{25}{7.5}$ = 3.33

Time corresponding to the PSM of 3.33 from the curve is 5.6 sec.

But actual operating time for operation of relay 2 = Time of operation of relay 1 + Time grading margin = 0.9 + 0.5 = 1.4 sec

TSM = 1.4/5.6 = 0.25.

Example 9.8. A line section has an impedance of 3.6 + j6 ohms. Show it on R-X diagram as impedance phasor. If the relay is adjusted to operate for zero impedance short circuit at the end of the line section, show on the same R-X diagram operating characteristics of (*i*) an impedance relay (*ii*) a reactance relay and (*iii*) admittance or mho relay, used for the purpose. Assume that the centre of the mho relay operating characteristic lies on the line impedance phasor. If an arcing short-circuit occurs having an impedance of 2 + *j*0 Ω anywhere along the line, determine for each type of distance relay the maximum portion of the line that can be protected.

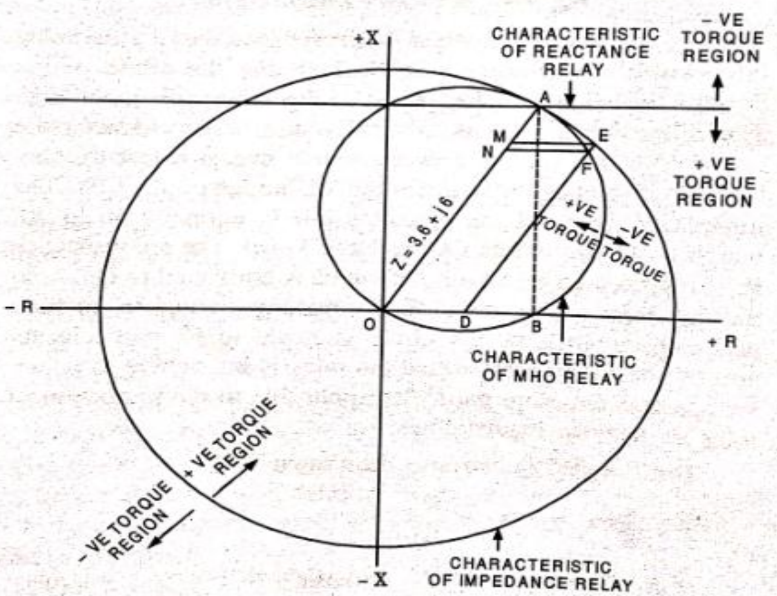


Fig. 9.49

Solution : The characteristics of the relays are shown in Fig. 9.49. OA is the impedance phasor of $(3.6 + j6)$ ohms; OB = 3.6 units and BA = 6 units. The circle with O as centre and OA as radius represents the characteristic of impedance relay. A straight line drawn parallel to the R-axis at a distance of 6 units corresponding to the reactance of the line represents the characteristic of the reactance relay. The circle drawn on OA as diameter represents the characteristic of the admittance or mho relay for the protection of the given line.

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

Then $\frac{OM}{OA} \times 100$ gives the percentage of line protected by the impedance relay and $\frac{ON}{OA} \times 100$ gives the percentage of line protected by the mho relay.

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

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

Unit 4: Circuit Breaking and Theory of Arc Quenching

4.1 Introduction

Circuit breakers are mechanical devices designed to close or open contact members, thus closing or opening of an electrical circuit under normal or abnormal conditions.

Features:

- It carries the full load current continuously without overheating or damage.
- It opens and closes the circuit on no load and load.
- It makes and breaks the normal operating current.
- It makes and breaks the short circuit currents of magnitude up to which it is designed for.

The circuit breakers are rated in terms of maximum voltage, number of poles, frequency, maximum continuous current carrying capacity, maximum interrupting capacity and maximum momentary and 4-S current carrying capacity.

Operating principle: A circuit breaker is a switching and current interrupting device. It consists essentially of fixed and moving contacts which are touching each other and carry the current under normal conditions i.e., when circuit breaker is closed. When the circuit breaker is closed, the current carrying contacts called electrodes, engage each other under pressure of a spring. Whenever a fault occurs on any part of the power system, the trip coils of the breaker get energized and the moving contacts are pulled apart by some mechanism, thus closing the circuit.

4.1.1 Arc phenomenon

The arc consists of a column of ionized gas having molecules which have lost one or more electrons. The electrons being negatively charged are attracted towards the positive contact i.e anode with a high velocity and on the way they detach more electrons by impact. The positive ions are attracted towards the negative contact i.e., cathode, but as they comprise almost the entire weight of the atom, they move towards it relatively slowly. Thus, current flow is caused due to movement of electrodes.

- By high voltage gradient at the cathode resulting into field emission.
- By increase of temperature resulting into thermionic emission.

4.1.2 Arc extinction

When current carrying contacts of a circuit breaker are parted, an arc is formed which persists during the brief period after separation of contacts. The circuit breaker should be capable of extinguishing the arc without causing any damage to the equipment or danger to personnel. The arc plays a vital role in the behavior of the circuit breakers. The interruption of dc arcs is relatively more difficult than ac arcs.

Factors responsible for arc between the contacts

- Potential difference between the contacts

- Ionized particles between the contacts

4.1.3 Methods of arc extinction

1) **High resistance method:** In this case the arc is controlled in such a way that its effective resistance increases with the time so that the current is reduced to such a value that the heat produced by it is not sufficient to maintain the arc and thus the current is interrupted or the arc is extinguished.
   a) **Cooling of arc:** Cooling removes the heat from the arc. Cooling is brought about by bringing the arc in contact with cool air.
   b) **Increasing the length of arc:** The length of the arc can be increased by increasing the gap length between the contacts but it is not practicable to draw the arc out.
   c) **Reducing the cross section of arc:** The cross section of an arc can be reduced by having a small area of contacts or by letting the arc pass through a narrow opening.
   d) **Splitting of arc:** The resistance of the arc can be increased by splitting the arc into a number of small arcs in series.
2) **Low resistance or current zero interruption:** This method is applicable only in ac circuit interruption because there is natural zero of current 100 times in a second for 50 Hz, three phase system. This property of ac circuit is exploited for interruption purposes and the current is not allowed to rise again after a zero occurs. In this method the arc resistance is kept low until the current is zero where the arc extinguishes naturally and is prevented from restriking after it has gone out at a current zero. The problem is, therefore, to remove the ions and electrons either by causing them to recombine into neutral molecules or by sweeping hem away, as soon as the current becomes zero, so that rising contact voltage or restriking voltage cannot breakdown the space between the contacts. This can be achieved by the following methods:

- Lengthening of the gap
- Increasing the pressure in the vicinity of the arc
- Cooling
- Blast effect

4.1.4 Theories of Arc Interruption

a) Energy Balance or Cassie Theory

When the contact of circuit breaker is about to open, restriking voltage is zero, hence generated heat would be zero and when the contacts are fully open there is infinite resistance this again make no production of heat. We can conclude from this that the maximum generated heat is lying between these two cases and can be approximated, now this theory is based on the fact that the rate of generation of heat between the contacts of circuit breaker is lower than the rate at which heat between the contact is dissipated. Thus, if it is possible to remove the generated heat by cooling, lengthening and splitting the arc at a high rate the generation, arc can be extinguished.

b) Recovery rate or Slepian's Theory

The arc is due to the ionization of the gap between the contact of the circuit breaker. Thus the resistance at the initial stage is very small i.e. when the contact are closed and as the contact separates the resistance starts increasing. If we remove ions at the initial stage either by recombining them into neutral molecules or inserting insulation at a rate faster than the rate of ionization, the arc can be interrupted. The ionization at zero current depends on the voltages known as restriking voltage.

Arc voltage: As the contacts of the circuit breaker apart, an arc is formed. The voltage that appears across the contact of the circuit breaker is called the arc voltage.

By Ayrton's equation

$e_a = A + \frac{B}{i_a}$

$A = \alpha + \gamma l$ α = 30 V γ = 10 V/cm

$B = \beta + \delta l$ β = 10 VA δ = 30 VA/cm

Arc voltage is high when the arc current is low and vice versa.

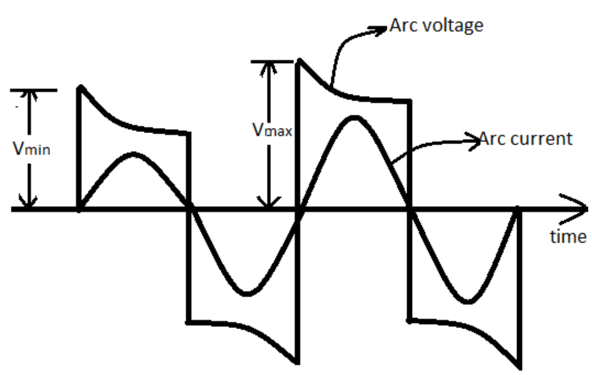
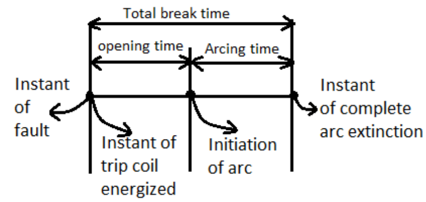


Figure 22: Arc Voltage Waveform

4.2 Stages of circuit breaker operation

The circuit is not interrupted instantly as soon as the trip coil is energized. Because, there always exists a certain depth of engagement or wipe between the fixed and the moving contact, it takes some time to separate the moving contact from the fixed contact. As soon as the contacts separated a heavy arc is formed between them and the circuit is still not interrupted because arc current will be flowing in the circuit. It is only after the complete extinction of the arc in the breaker the circuit is said to be interrupted by the breaker.

The first stage is the time interval between the instant of energization of the trip coil to the instant of contact separation and is called the 'opening time' of the breaker. The second stage of the operation time is the time interval between the instant of contact separation to the instant of arc extinction and is called the arcing time of the breaker.



4.3 Restriking voltage and Recovery voltage

At current zero, a high frequency transient voltage appears across the breaker contacts and is caused by the rapid distribution of energy between the magnetic and electric fields associated with the plant and transmission lines of the power system. This transient voltage is known as restriking voltage. Thus, restriking voltage may be defined as the resultant transient voltage which appears across the breaker contacts at the instant of arc extinction.

However, the transient component vanishes rapidly (after a short time less than 0.1 mS) due to damping effect of system resistance and the normal frequency system voltage is established. This voltage across the breaker contacts is called the recovery voltage. Thus, recovery voltage may be defined as the power frequency rms voltage which appears across the breaker contacts after the transient oscillations die out and final extinction of arc has resulted in all the poles.

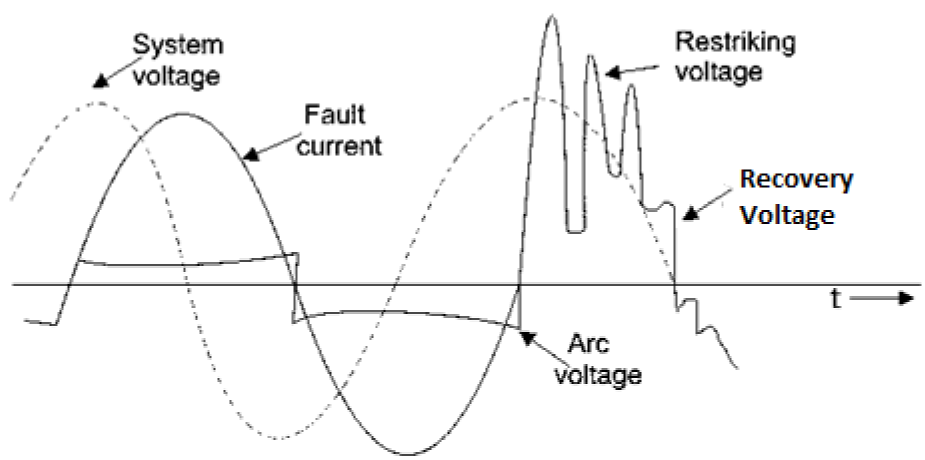


Figure 23: Arc interruption theory

4.3.1 Mathematical expression for active recovery voltage in a 3-phase circuit

Let phase to neutral (rms) value of the system voltage be V volts. Hence, maximum value of phase to neutral voltage V_{max} is given as

$$V_{max} = \sqrt{2}\text{V}$$

The active recovery voltage between phase and neutral is given as $V_{max} \sin\varphi$

In general, active recovery voltage can be given as

$V_r = K_1 K_2 K_3 V_{max} \sin\varphi$

Where V_r is the phase to phase value of active recovery voltage

K_1 is the demagnetizing factor due to which the recovery voltage will be less than the system voltage

$K_1 = \frac{Recovery\ Voltage}{System\ Voltage}$

K_2 is a condition or phase factor i.e., it depends on the condition whether the symmetrical fault is grounded or not i.e., its value is 1 if the fault involves ground and 1.5 for ungrounded fault

K_3 is a third constant whose value is unity if the active recovery voltage between phase and neutral is to be obtained and its value is $\sqrt{3}$ if the active recovery voltage between two lines is desired.

4.3.2 Mathematical expression for Restriking Voltage Transient

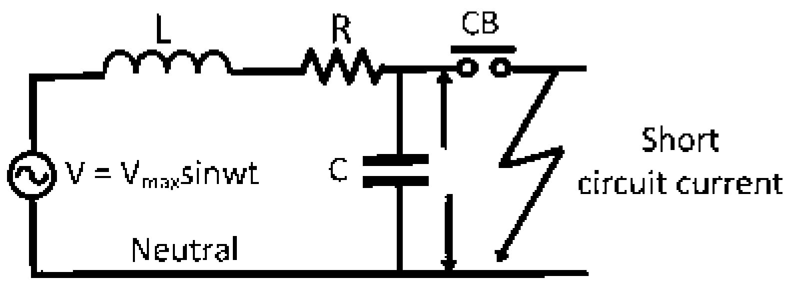


Figure 24: Faults and its equivalent circuit

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

i=$i_L + i_C$

or i=$\frac{1}{L}\int v\,dt + C\frac{dv}{dt}$

$\therefore \frac{di}{dt} = \frac{v}{L} + C\frac{d^2v}{dt^2}$ ………………. (1)

Assuming zero time at zero currents when t=0, and further

v=$V_{max}\cos\omega t$

i=$\frac{V_{max}}{\omega L}\sin\omega t$ before opening of circuit breaker

$\frac{di}{dt} = \frac{V_{max}}{\omega L} \times \omega\cos\omega t$

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

Substituting in equation 1 we have

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

The solution of this standard equation is

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

the above expression is the expression for restriking voltage where V_{max} is the peak value of recovery voltage (phase-neutral), t is the time in seconds, L is the inductance in hennery, C is the capacitance in farads and v is the restriking voltage in volts.

The maximum value of restriking voltage is $2V_{max}$ and occurs at t =$\frac{\pi}{\omega}$ or t=$\pi\sqrt{LC}$

4.3.3 Restriking Voltage Transient

Electrically a power system is an oscillatory network so that it is logical to expect that the interruption of fault current will give rise to a transient, whose frequency depends on the constants of the circuit. It has been pointed out earlier that this transient voltage is referred to as Restriking Voltage Transient, which occurs immediately following arc extinction. The arc voltage across the contacts at this instant is normally quite low, whereas the power frequency voltage in the circuit is at or near its peak value.

Classification of Restriking Transients

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

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

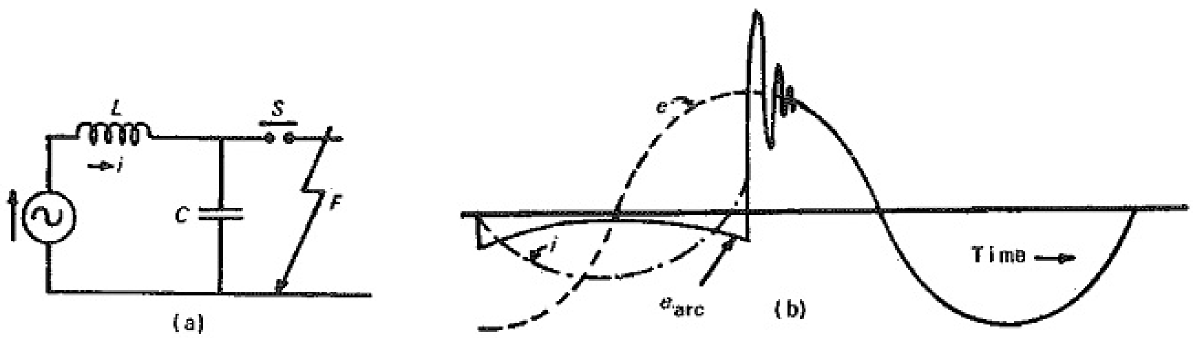


Figure 25: Single Frequency Oscillatory Transients a) Basic circuit b)Waveform

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

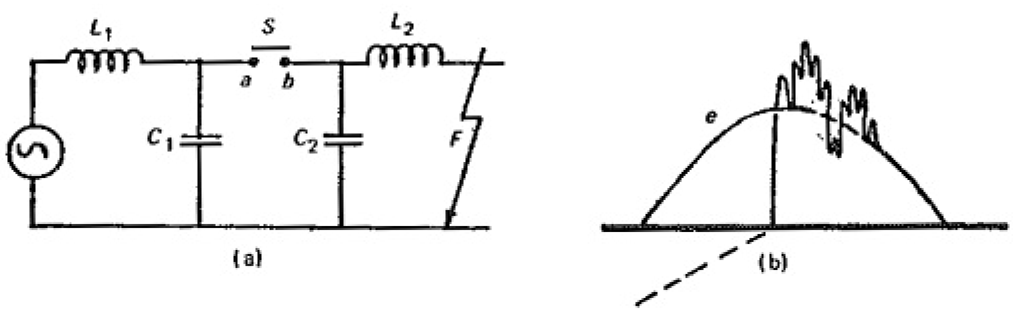


Figure 26:Double Frequency Transients a) Basic Circuit b) Waveform

Characteristic of Restriking Voltage

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

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

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

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

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

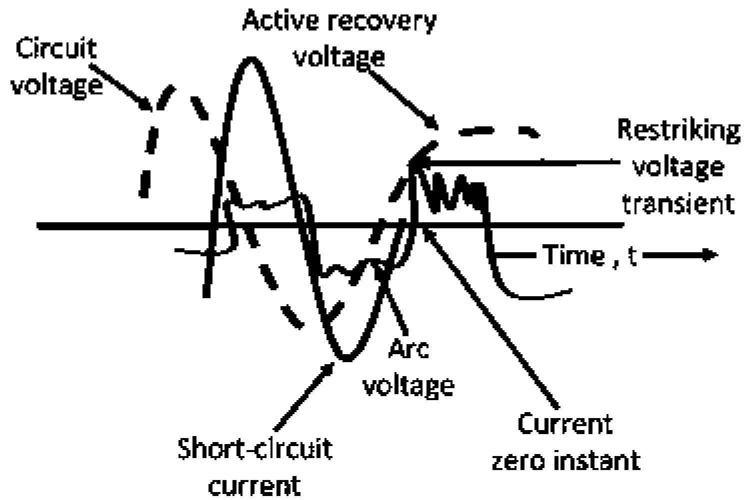


Figure 27:Arc extinction

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

Expression for RRRV

The expression for the restriking voltage can be expressed as

v=$V_{max}\left[1-\cos\frac{t}{\sqrt{LC}}\right]$

and RRRV = $\frac{dv}{dt}=\frac{V_{max}}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}$

RRRV will be maximum when $\sin\frac{t}{\sqrt{LC}}=1\ or\ t=\frac{\pi}{2}\sqrt{LC}$

Hence maximum value of RRRV, $RRRV_{max}=\frac{V_{max}}{\sqrt{LC}}$

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

$\frac{dv}{dt}=0\ or\sin\frac{t}{\sqrt{LC}}=0$ or t = $\pi\sqrt{LC}$

4.4 HVDC Circuit Breaker

The circuit breaker applied in high voltage dc systems is known as HVDC circuit breaker. Light duty CBs is rare because fault current can be controlled easily by firing angle of converters. Current zero interruption in AC breaker is easier, so the energy is also zero. Since, the dc waveform does not have current zeros, the problem is complex. The HVDC circuit breaker design needs creation of artificial current zero, prevention of re-strikes and dissipation of stored energy.

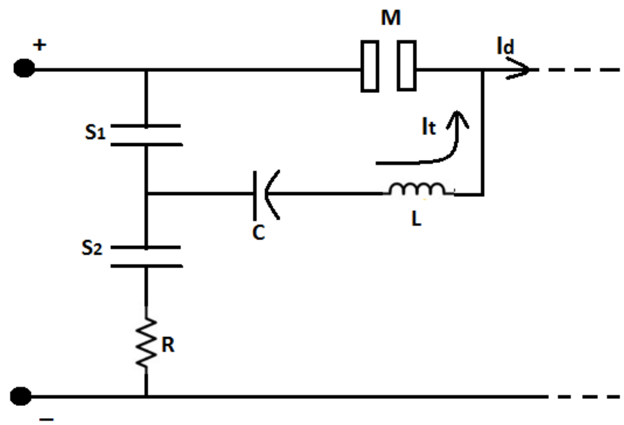


Fig: Schematic circuit

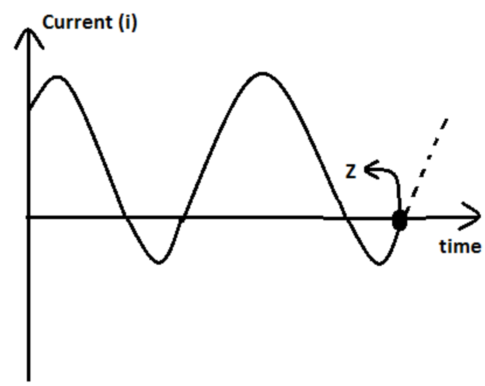


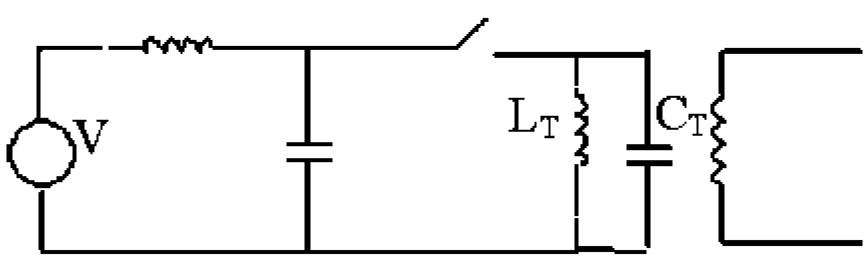
Fig: Waveform

- For arc quenching, artificial current zero principle is used.
- Parallel L-C circuit is introduced to oscillate the current.
- Arc is extinguished at any current zeros.
- M is conventional circuit breaker, S_1 and S_2 are two auxiliary contacts.
- During normal conditions, S_1 is open, main contact M and charging contact S_2 remain closed.
- So, the capacitor C is charged by line voltage through high resistance R.
- For interrupting circuit current I_d, S_2 opens and S_1 is closed, so that the capacitor C discharges through inductance L.
- M and S_1 face oscillatory current as shown in figure. Thus, circuit is broken at artificial current zero 'Z'.

4.5 Current Chopping

Usually, CB is designed to interrupt very high magnitude of fault current. In case of low current CB assumes current zero even it is not and the contacts of CB separates. When this CB is used to disconnect the transformer at no load,

- The current is very small
- Current is highly inductive



If CB's contacts get separated but and I is not zero. There is some electromagnetic energy stored in transformer core which is equal to $\frac{1}{2}{I_L}^2L$

Where, I_L = Instantaneous current when CB's contacts get separated.

If this energy gets some path, it tries to get released.

Energy in inductor $= \frac{1}{2} I_L^2 L_L$ &

Electrostatic energy in capacitor $= \frac{1}{2} C_T V^2$

Total Energy $= \frac{1}{2} I_L^2 L + \frac{1}{2} C_T V^2$

After the CB interruption,

both the energy gets converted into electrostatic energy.

So, Energy $= \frac{1}{2} C_T V_{new}^2$

Therefore,

$$\frac{1}{2} C_T V_{new}^2 = \frac{1}{2} I_L^2 L + \frac{1}{2} C_T V^2$$

$$V_{new} = \sqrt{\frac{L_T}{C_T} I_L^2 + V^2}$$

Case-1: If I_L is interrupted at $I_L(t)=0$

There will be no over-voltage. $V_{new} = V$

Case-2: If I_L is interrupted at peak value i.e. $I_L(t)$ at peak

Here, V=0

$$V_{new} = \sqrt{I_L^2 \frac{L_T}{C_T}} = I_{LMax} \sqrt{\frac{L_T}{C_T}}$$

$$\sqrt{\frac{L_T}{C_T}} = Surge\ impedance\ of\ transformeer$$

Surge impedance of transformer is greater than that of transmission line as:

L_T is high and C_T is low.

4.7 Numerical Solution

1) A 50 Hz, 11 KV generator is connected to a power system. The system inductance and capacitance per phase are 10 mH and 0.02 μF respectively. Calculate (a) the maximum

voltage across the contacts of the circuit breaker at an instant when it passes through zero (b) frequency of transient oscillation (c) average rate of rise of voltage up to the first peak of oscillation. Neglect resistance.

- **Solution**

a) Active recovery voltage (phase to neutral) = $\sqrt{2} \times \frac{11}{\sqrt{3}}$ = 8.98 KV

Maximum restriking voltage (phase to neutral) = 2× active recovery voltage

= 2× 8.98 = 17.96 KV

b) Frequency of transient oscillation (f) = $\frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{10\times10^{-3}\times0.02\times10^{-6}}}$

= 11.254 KHz

c) The average rate of rise of restriking voltage up to the first peak is given as $\frac{Maximum\ restriking\ voltage}{Time\ up\ to\ first\ peak}$ and first peak restriking voltage occurs at t = $\pi\sqrt{LC}$

∴ Average rate of rise of restriking voltage = $\frac{2V_{max}}{\pi\sqrt{LC}} = \frac{17.96}{\pi\sqrt{10\times10^{-3}\times0.02\times10^{-6}}}$

= 0.404 KV/μS

2) In a short circuit test on a 3-pole, 110 KV circuit breaker pf of the fault was 0.4, the recovery voltage was 0.95 times full line value. The breaking current was symmetrical. The frequency of oscillation of restriking voltage was 15,000 c/s. Estimate the average rate of rise of restriking voltage. The neutral is grounded and the fault involves earth.

- **Solution**

The peak value of line to neutral voltage (V_{max}) = $\frac{110\sqrt{2}}{\sqrt{3}}$ = 89.8 KV

Power factor, cos φ = 0.4

Similarly, sin φ = sin (cos^{-1} φ) = 0.9165

Recovery voltage is 0.95 times peak value

The active recovery voltage is given as $V_r = K_1K_2K_3\ V_{max} \sin\varphi$ volts

Where, K_1 is multiplying factor due to system voltage and is equal to 0.95

K_2 is a condition or phase factor and is unity in this case since the fault involves ground and 1.5 as the fault does not involve ground

K_3 is unity for recovery voltage between phase and neutral.

So recovery voltage (from line to neutral)

V_r = 0.95 × 1 × 1× 89.8 × 0.9165 = 78.2 KV

Time to reach the peak restriking voltage, t = $\pi\sqrt{LC} = \frac{2\pi\sqrt{LC}}{2} = \frac{1}{2f_n}$

= $\frac{1}{2\times15,000}$ = 33.33 μs

Average RRRV = $\frac{2\times recovery\ voltage}{t} = \frac{2\times78.2}{33.33}$ = 4.692 KV/ μs

3) A 50 Hz 3-phase alternator with grounded neutral has an inductance of 1.6 mH per phase and is connected to the bus bars through a circuit breaker. The capacitance to earth of the circuit between the alternator and the circuit breaker is 0.0032 μF per phase. Due to a short on the bus bars the breaker opens when the rms value of the current is 8,000 A. Determine the frequency of oscillations, active recovery voltage, time for maximum RRRV and maximum RRRV.

➢ **Solution**

Frequency of oscillation, $f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.0032\times10^{-6}}}$ = 70.34 KHz

Short circuit current = 8,000 A

Reactance = $2\pi fL = 2\pi \times 50 \times 1.6\times 10^{-3}$ = 0.5026 Ω

Recovery voltage = short circuit current × reactance = 8000 ×0.5026 = 4021 V rms

Active recovery voltage, $V_{max} = \sqrt{2} \times 4021$ = 5687 V (line- neutral)

Time to attain maximum RRRV, $t = \frac{\pi\sqrt{LC}}{2} = \frac{\pi\sqrt{1.6\times10^{-3}\times0.0032\times10^{-6}}}{2}$ = 3.55 μs

Maximum RRRV, $RRRV_{max} = \frac{V_{max}}{\sqrt{LC}} = \frac{5687}{\sqrt{1.6\times10^{-3}\times0.0032\times10^{-6}}}$ = 2.513 KV/ μs

4) In a 220 KV system, the reactance and capacitance up to the location of a circuit breaker are 8 Ω and 0.025 μF respectively. A resistance of 600 Ω is connected across the contacts of the circuit breaker. Determine (a) natural frequency of oscillation (b) damped frequency of oscillation (c) critical value of resistance which will give no transient oscillation (d) the value of resistance which will give damped frequency of oscillation, one fourth of the natural frequency of oscillation.

➢ **Solution**

System capacitance up to CB, C = 0.025×10^{-6} F

System inductance up to CB, $L = \frac{X_l}{2\pi f} = \frac{8}{2\pi\times50}$ = 0.0255 H

Resistance connected across breaker contacts, R = 600 Ω

Natural frequency of oscillation, $f_n = = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0225\times0.025\times10^{-6}}}$ = 6.3 KHz

Damped frequency of oscillation $f_n^{I} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$

$$= \frac{1}{2\pi}\sqrt{\frac{1}{0.0225\times0.025\times10^{-6}} - \frac{1}{4(0.025\times10^{-6})^2\times600^2}} = 3.41 \text{ KHz}$$

Critical value of resistance to eliminate transient oscillation, $R = 0.5\sqrt{\frac{L}{C}}$

$$= 0.5\sqrt{\frac{0.0225}{0.025\times10^{-6}}} = 504.6\ \Omega$$

Let the resistance of R Ω be connected across the breaker contacts so that damped frequency of oscillation becomes, one fourth of the natural frequency of oscillations i.e $\frac{6.3}{4}$ = 1.575 KHz

$$1575 = \frac{1}{2\pi}\sqrt{\frac{1}{0.0225\times 0.025\times 10^{-6}} - \frac{1}{4(0.025\times 10^{-6})^2\times R^2}} \quad \therefore R = 521.5\ \Omega$$

Example 7.7. In a system of 132 kV, the circuit phase to ground capacitance is 0.02 μF and the circuit inductance is 5 H. The circuit breaker interrupts a magnetising current of 5 A (peak). Find :

(*i*) The voltage across the circuit breaker contacts after the current interruption.

(*ii*) The value of resistance to be used across the contacts to suppress restriking voltage.

Solution : (*i*) Voltage across the circuit breaker contacts after the interruption of 5 A current

$$v = i\sqrt{\frac{L}{C}} = 5\sqrt{\frac{5}{0.02\times 10^{-6}}} = 79{,}000 \text{ V or } 79 \text{ kV } \textbf{Ans.}$$

...Refer to Eq. (7.16)

(*ii*) Value of resistance to be used across the breaker contacts to suppress restriking voltage

$$R = 0.5\sqrt{\frac{L}{C}} = 0.5\sqrt{\frac{5}{0.02\times 10^{-6}}} = 7.9 \text{ k}\Omega \textbf{ Ans.}$$

Unit 5: Circuit Breaker

Circuit breakers are mechanical devices designed to close or open contact members, thus closing or opening of an electrical circuit under normal or abnormal conditions.

5.1 Duties of Circuit Breaker

- It must be capable of closing, breaking and carrying full load rated current of the circuit without any excessive temperature rise (not more than 35℃).
- It must be capable of breaking the heavy currents which flow when a short circuit occurred in the circuit in which it is connected.
- It must be capable of closing on to the circuit when it carries fault currents and re-opens immediately to clear the fault from the system.
- It must be capable of carrying current of short circuit magnitude until the fault is cleared by another breaker nearest to the point of fault.
- Lastly, but not the least it must be capable of withstanding the effects of arcing at its contacts and the severe electromagnetic forces and thermal conditions which arise due to the flow of heavy currents in the circuit under the fault conditions.
- Interruption of small inductive currents.
- Switching of capacitors banks.
- Interruption of terminal faults.
- Asynchronous switching.

5.2 Classification of Circuit Breaker

There are several methods of classification of circuit breakers. The most general way of the rating of a circuit breaker is by the arc extinction medium. The arc extinction can easily be done by using the different medium like air, insulator, gas, vacuum, dielectric, etc.

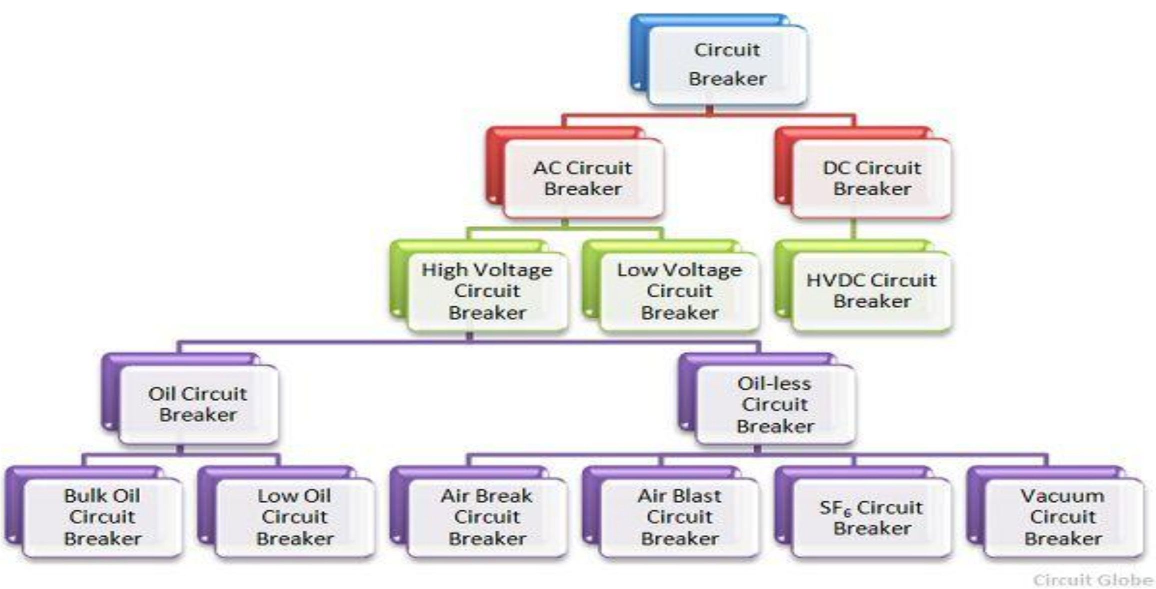


Figure 28: Classification of Circuit Breaker

By the arc extinction medium, the circuit breaker is categorized into four types. They are the air break circuit breaker, air blast circuit breaker, Sulphur-hexafluoride circuit breaker and vacuum circuit breaker. The classification of the circuit breaker is shown in the figure above.

5.3 Miniature Circuit Breaker:

Nowadays we use more commonly MCB in low voltage electrical network instead of fuse. There are two arrangement of operation of MCB. One due to thermal effect of over current and other due to electromagnetic effect of over current. The thermal operation of MCB is achieved with a bimetallic strip whenever continues over current flows through MCB, the bimetallic strip is heated and deflects by bending. This deflection of bimetallic strip releases mechanical latch. As this mechanical latch is attached with operating mechanism, it causes to open the MCB contacts. But during short circuit calculation, sudden rising of current causes electromechanical displacement of plunger associated with tripping coil or solenoid of MCB. The plunger strikes the trip lever causing immediate release of latch mechanism consequently open the circuit breaker contacts.

Advantages of MCB compared to fuse

- It automatically switches off the electrical circuit during abnormal condition of the network means in over load condition as well as faulty condition. MCB is much more sensitive to over current than fuse.
- Handling MCB is more electrically safe than fuse.
- As the switch operating knob comes at its off position during tripping the faulty zone of the electrical circuit can be easily be identified.
- Quick restoration is possible by just switching on operation.

Disadvantage

- MCB unit system is costlier than fuse unit system.

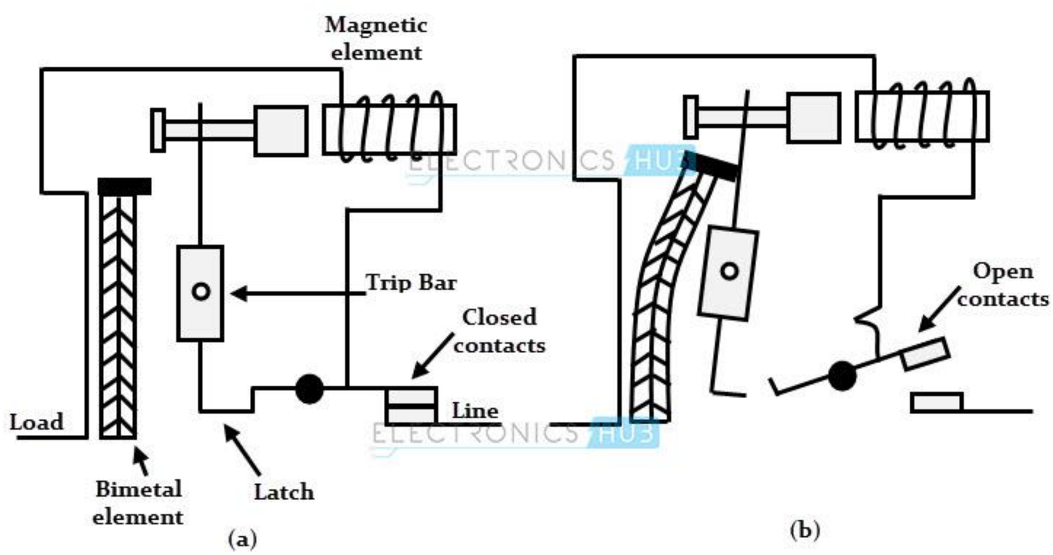


Figure 29: Working of MCB

Types of MCB based on tripping characteristics

a) **Type B:** This type of MCB trips between 3-5 times full load current. Type B devices are mainly used in residential applications or light commercial applications where connected loads are primarily lighting fixtures, domestic appliances with mainly resistive elements. The surge current levels in such cases are relatively low.
b) **Type C:** This type of MCB trips between 5-10 times full load current. This is used in commercial or industrial type of applications where there could be chances of higher values of short circuit currents in the circuit. The connected loads are mainly inductive in nature (e.g induction motors) of fluorescent lighting.
c) **Type D:** This type of MCB trips between 10-20 times full load current. These MCBS are used in specialty industrial/commercial uses where current inrush can be very high e.g include transformers or x-ray machines, large winding motors, etc.

All the above three types of MCBs provide tripping protection within one tenth of a second.

5.4 Moulded Case Circuit Breaker

Moulded case circuit breakers are designed to provide circuit protection for low voltage distribution systems. They will protect connected devices against both overloads and short circuits.

MCCBs are composed of five main components:

a) **Frame:** The frame also known as the molded case, provides an insulated housing to mount to mount all the circuit breaker components.
b) **Operating mechanism:** The operating mechanism handles the opening and closing of the contacts. The speed that the contacts open or close is independent of how fast the handle is moved. The position of handle indicates the status of the contacts whether they are closed, open or tripped. The handle will be in a midway position when the contacts are tripped.
c) **Arc extinguisher:** An arc is created whenever a circuit breaker interrupts a current flow. The arc extinguishers job is to confine and divide that arc, thereby extinguishing it.
d) **Contacts:** This unit provides the connection on normal condition and opens the circuit during abnormal condition.
e) **Trip unit:** The function of the trip unit is to trip the operating mechanism in the event of a short circuit or a prolonged overload of current. Protection is provided by combining a temperature sensitive device with a current sensitive electromagnetic device, both of which act mechanically on the trip mechanism.

Figure 30: MCCB

To provide short circuit protection, electromechanical trip circuit breakers have adjustable magnetic elements. To provide overload protection, electromechanical trip circuit breakers contain thermal trip elements. Breakers that use a combined of magnetic elements and thermal elements are often called thermo magnetic breakers.

5.5 Air Blast Circuit Breaker

Air blast circuit breaker used compressed air or gas as the arc interrupting medium. In the air blast, circuit breaker compressed air is stored in a tank and released through a nozzle to produce a high-velocity jet; this is used to extinguish the arc. Air blast circuit breakers are used for indoor services in the medium high voltage field and medium rupturing capacity. Generally, up to voltages of 15 KV and rupturing capacities of 2500 MVA. The air blast circuit breaker is now employed in high voltage circuits in the outdoors switch yard for 220 KV lines.

Though gasses such as carbon dioxide, nitrogen, freon or hydrogen are used as the arc interrupting medium, compressed air is the accepted circuit breaking medium for gas blast circuit breakers. The circuit breaking capacities of nitrogen are similar to compressed air and hence no advantage of using it. Carbon dioxide has the drawback of its being difficult to control owing to freezing at valves and other restricted passages. Freon has high dielectric strength and good arc extinguishing properties, but it is expensive, and it is disintegrated by the arc into acid-forming elements.

Principle of Arc Extinction in Air Blast Circuit Breaker

The air blast needs an additional compressed air system which supplies air to the air receiver. When opening air is required, compressed air is admitted to the arc extinction chamber. It pushes away the moving contacts. In doing so, the contacts are pulled apart, and the air blast moves away the ionized gas along with it and assists arc extinction. Air blast extinguishes the arc within one or more cycles, and the arc chamber is filled with high-pressure air, which prevents restrikes. The air blast circuit breakers fall under the category of external extinguishing energy type. The energy supplied for arc quenching is achieved from the high-pressure air, and it is free from the current to be interrupted.

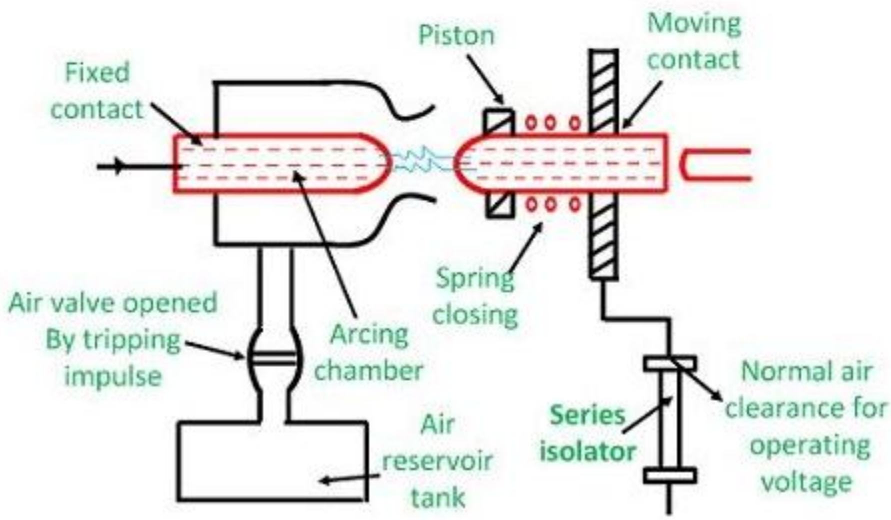


Figure 31: Axial Air Blast Circuit Breaker

Drawback of Air Blast Circuit Breaker

In the air blast circuit breaker, it is necessary that the compressed air at the correct pressure must be available all the times, involving in the largest installation of a plant with two or more compressors. The maintenance of this plant and the problem of air leakages at the pipe fittings are some factors which operate against air blast circuit breaker and it costly for low voltage as compared to oil or air break circuit breaker.

5.6 Air Break Circuit Breaker

Air Circuit Breaker (ACBs) are used for medium and low voltages. In air circuit breakers, the interrupting contacts are situated in air instead of any other medium. The arc produced is chopped into number of small arcs by the arc chute as it rises due to heat and magnetic force. In such CB high resistance principle is employed for effective arc extinction. The arc is lengthened by means of the arc runners and arc chutes thus increasing the resistance. Arc resistance can be increased in the following ways:

- **Cooling:** When the temperature is decreased by cooling the voltage required to maintain the ionization of the air increase which in turn increases the resistance.
- **Lengthening:** As the length of the arc increases the resistance also increases.
- **Splitting:** An appreciable voltage is absorbed at the two contact surfaces so that on splitting of an arc into a number of small arcs in series the voltage available for the actual column is reduced.

Air circuit breakers consist of two set contacts viz. main contact and arcing contact. The arc chute is used for arc extinction process. When the fault occurs in the system, the main contacts are separated initially, the current then shifts towards the arcing contacts. The arcing contacts also separate now drawing an arc between them. This arc is then moved up by arc chutes along the arc runner. The arc moves upwards and is split by the arc splitter plates. The arc is then extinguished by the high resistance method.

A drawback of arc chute principle is the inefficiency at low currents where the electromagnetic fields are weak. With, the increase in operating voltage and rupturing capacity, such a breaker become bulky, the arc chutes become more complex and the initial cost increases.

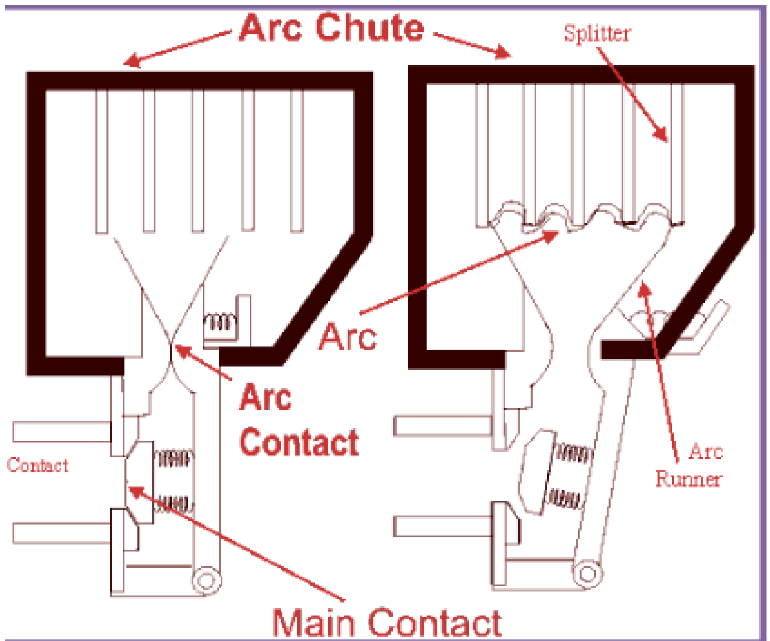


Figure 32: Air Break Circuit Breaker

Drawback of Air Break Circuit Breaker

A drawback of arc chute principle is its inefficiency at low currents where the electromagnetic fields are weak. The chute itself is not necessarily less efficient in its lengthening and deionizing action than at high currents, but the arc movement into the chute tends to become slower, and high-speed interruption is not necessarily obtained

Application: ACBs are usually applied for control of power station auxiliaries and industrial plants switchgears. They are also used for control of motor loads and furnaces where repeated switching is to be performed.

5.7 SF_6 Circuit Breaker

Sulphur-hexaflouride (SF_6) is an inert insulating gas, which is becoming increasingly popular in modern switchgear designs both as an insulating as well as an arc-quenching medium. It has following advantages.

- Very good insulating strength.
- High affinity for electrodes which ultimately give rise to high dielectric strength to SF_6.
- Heat transferability much higher than air.

- Chemically stable without any chance of carbon decomposition.

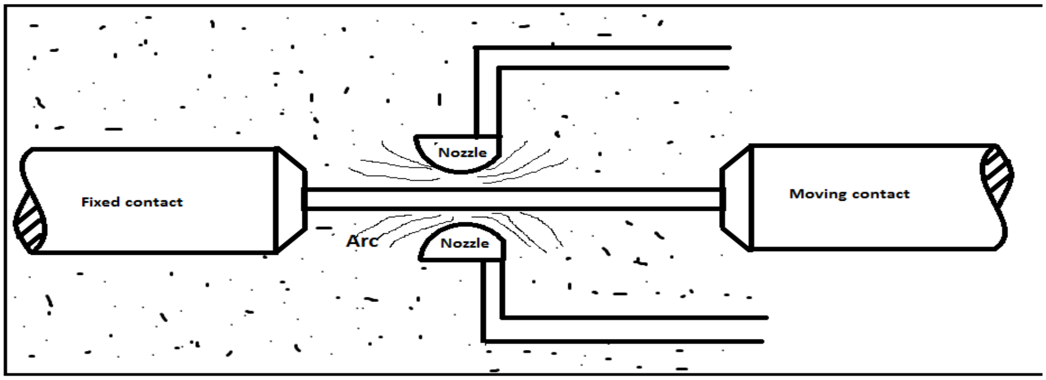


Figure 33: SF_6 Circuit Breaker

For medium and low voltage installations, the SF_6 circuit breaker remains the same construction wise as that for oil and air circuit breakers mentioned above except for the arc interrupting chamber which is of a special design filled with SF_6. In SF_6 circuit breaker, the current continues to flow after contact separation through the arc whose plasma consists of ionized SF_6 gas. For, as long as it is burning, the arc is subjected to a constant flow of gas which extracts heat from it. The arc is extinguished at a current zero, when the heat is extracted by the falling current. The continuing flow of gas finally de-ionizes the contact gap and establishes the dielectric strength required to prevent a re-strike. As SF_6 has high affinity for electrons whenever a free electrons collides with the neutral gas molecule negative ions are formed. The electron is absorbed by the neutral gas molecule.

$SF_6 + e^- \rightarrow SF_6{}^-$

$SF_6 + e^- \rightarrow SF_5{}^- + F$

The negative ions formed as shown above will be heavier as compared to free electrons and under a given electric field the ions will not attain sufficient energy to initiate cumulative ionization in the gas. In this way the gas de-ionizes and establishes the dielectric strength required to prevent a re-strike.

Advantages:

- Dielectric strength of SF_6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.
- Gives noiseless operation due to its closed gas circuit.
- There is no risk of fire as SF_6 is non inflammable.
- There are no carbon deposits.

Disadvantages:

- SF_6 breakers are costly due to high cost of SF_6.

- SF_6 gas has to be reconditioned after every operation of the breaker additional equipment is required for this purpose.

Application: SF_6 breakers have been used for voltage 115 KV to 230 KV, power rating 10 MVA to 20 MVA and interrupting time less than 3 cycles.

5.8 Vacuum Circuit Breaker

Vacuum circuit breakers are also similar in construction like the other types of breakers, expect that the breaking medium is vacuum and the medium sealed to ensure vacuum. The use of vacuum for arc extinction has the following advantages:

- Vacuum has high dielectric strength.
- When contacts get open during operation in AC systems, the current is interrupted at first current zero instant which causes the dielectric strength between the contacts to build up at a very high rate than that can be achieved with other CBs.
- Ideally vacuum is such a dielectric in which arc should not persist.

When the VCBs operates, the fixed contact and moving contact shown in figure separate. Metal vapor is then released from the contacts which fills the vacuum between the contacts and thus maintains the arc. Metal vapor formed is actually known as plasma which is the combination of electrons and positive ions. After the first current zero instant is reached the plasma vanishes and the medium regains its dielectric strength. The arc will now get extinguished as only vacuum is left between the contacts. Because it is virtually impossible for electricity to flow in a vacuum, the early designs displayed the ability of current chopping i.e switching off the current at a point on the cycle other than current zero. This sudden instantaneous collapse of the current generated extremely high voltage spikes and surges into the system causing failure of equipment.

Advantages:

- Vacuum circuit breaker is self contained does not need filling of gas or oil. They do not need auxiliary air system, oil handling system, etc. No need of periodic refilling.
- No emission of gas, pollution free
- Non explosive
- Silent operation
- Suitable for capacitor switching, cable switching, industrial switching.
- Constant contact resistance
- Constant dielectric

Disadvantages:

- For interruption of low magnetizing currents in certain range, additional surge suppressors are required in parallel with each phase of a VCB.
- It requires high technology for production.
- It is more expensive.

Application:

- They can be used along with static over current relays.
- It is used for very high speed making switches in industrial applications.
- When voltages are high and current to be interrupted is low, these breakers have definite superiority over the oil or air circuit breakers.
- For low fault interrupting capacities the cost is low in comparison to other interrupting devices.

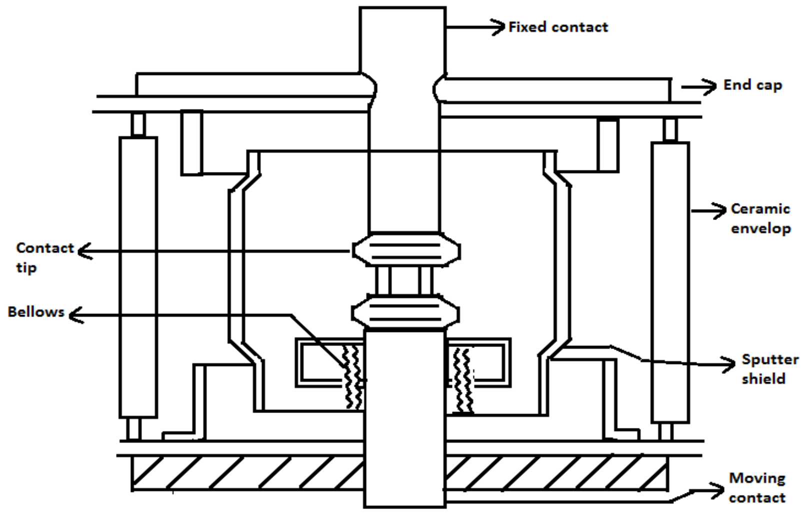


Figure 34: Vacuum Circuit Breaker

5.9 Oil Circuit Breaker

Oil circuit breakers (OCBs) are the oldest type of circuit breakers. Oil circuit breakers are usually employed for high voltage application up to 11 KV with a current rating up to 2400 A. In OCBs the main contacts are immersed in oil and the oil acts as the ionizing medium between the contacts. The oil is mineral type, with high dielectric strength to withstand the voltage across the contacts under normal conditions.

OCBs may be of various types, but regardless of that the basic of arc extinction process remains same in all CBs. When main contacts are separated during the operation of the CBs an arc will be produced. The arc will thus generate heat decomposing the oil around the main contacts and liberate gases (mostly hydrogen). The production of the hydrogen gas in this manner appreciable increases the dielectric strength of the gap between the contacts which aids in the arc extinction process. Oil has the following advantages:

- Ability of cool oil to flow into the space after current zero and arc goes out.
- Cooling surface presented by oil.
- Action of oil as an insulator lending to more compact design of switchgear.
- Absorption of energy by decomposition of oil.

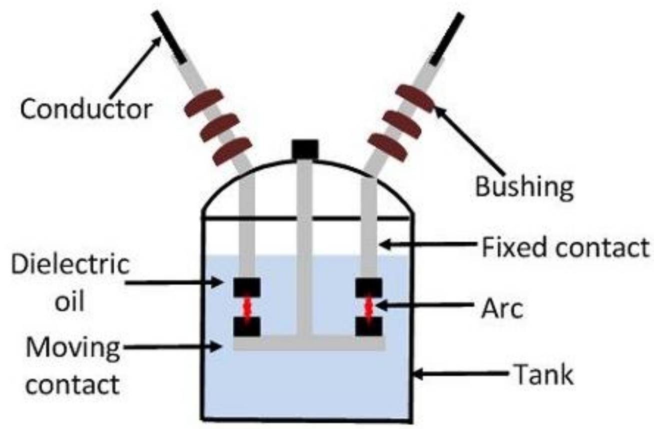


Figure 35: Oil Circuit Breaker

Disadvantages of Oil as an Arc Quenching

- The oil used in oil circuit breaker is inflammable and hence, cause a fire hazard.
- There is a risk of formation of explosive mixture with air.
- Due to decomposition of oil in the arc, the carbon particles are generated which polluted the oil and hence the dielectric strength of the oil decreases.

5.10 Minimum Oil Circuit Breaker

In this type of circuit breaker minimum oil is used as an arc quenching medium and it is mounted on a porcelain insulator to insulate it from the earth. The arc chamber of such type of circuit breaker is enclosed in a bakelised paper. The lower portion of this breaker is supported by the porcelain and the upper porcelain enclosed the contacts. This circuit breaker is of the single breaker type in which a moving contact tube moves in a vertical line to make or break contact with the upper fixed contacts mounted within the arc control devices. A lower ring of fixed contacts is in permanent contact with the moving arm to provide the other terminal of the phase unit. Within the moving contact, the tube is a fixed piston. When the moving contact moves downwards, it forces the insulating oil to enter into the arc control devices. Thus, the arc gets extinguished.

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

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

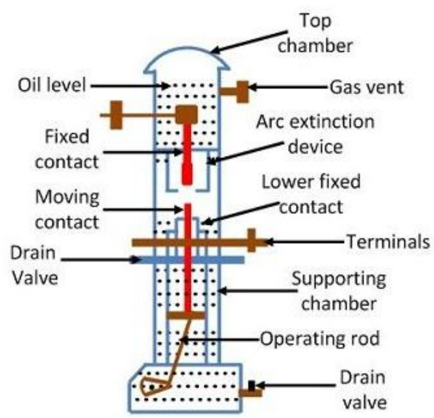


Figure 36: Minimum Oil Circuit Breaker

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

Application: It is used for voltage application up to 11 KV with a current rating up to 2400 A. major application are in power system transmission and distribution networks between 11 KV to 66 KV rated voltage and fault level of 150 MVA to 1000 MVA.

5.11Auto Reclosure

In electric power distribution, a recloser or auto recloser, is a circuit breaker equipped with a mechanism that can automatically close the breaker after it has been opened due to a fault. Reclosers are used on overhead distribution systems to detect and interrupt momentary faults. Since many short circuit on overhead lines clear themselves, a recloser improves service continuity by automatically restoring power to the line after a momentary fault. About 90% faults are due to lightning, birds, tree branches, etc. So, the fault energy is to be interrupted for a short period, after arc the arc extinction line can be re-energized. For this auto reclosure schemes may be used.

- It consists of breaker or oil immersed switch actuated by relays which operate for predetermined current values and open when these limit exceeds.
- The breaker recloses after a short interval and re opens again if excess current persist.
- It can be set 3 or 4 operations before itself locked and open only with manual operation after fault clearance.
- Auto-reclosures are employed in unattended substations, rural distribution schemes.
- Most of the faults are ground faults, so single phase auto reclosing improves the stability thereby maintaining the rest two healthy phases uninterrupted.
- Auto reclosing may be single or three phase type.
- Rupturing capacity of reclosure is chosen properly as per other CBs.
- Rapid auto reclosing type takes about 20 cycles (0.4 seconds).

- Delayed auto reclosing type takes 5 to 30 seconds.
- Synchronism is not needed for high speed reclosure.
- But for delayed reclosures, synchronism is necessary before reclosing.

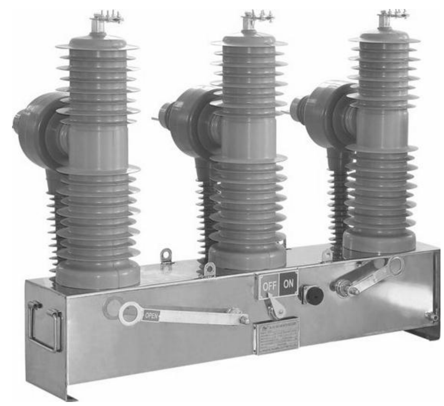


Figure 37: Auto Recloser

5.12 Circuit Breaker Rating

The rating of a circuit breaker is given according to the duties that are performed by it. Apart from the normal working of CBs, the circuit breakers are required to perform following 3 major duties under short circuit conditions.

- A circuit breaker must be capable of breaking the circuit and isolating the faulty section in case of a fault. This is described as breaking capacity of a CB.
- Since in practice a CB is put on 2-3 times in order to ensure the permanency of the fault i.e it must be capable of making circuit in the greatest asymmetrical peak in current wave. This refers to making capacity of a CB.
- When a CB works in conjunction with the other CBs and in case of a fault on any section the breakers in the sound sections should not trip i.e a circuit must be capable of carrying fault currents safely for a short time while another circuit breaker (in series) is clearing the fault. This refers to short time capacity of a circuit breaker.

Rated voltage: The rated maximum voltage of a CB is the highest rms voltage above nominal system voltage, for which the CB is designed and is the upper limit for operation. The rated voltage is expressed in KV rms and refers phase to phase voltage for three phase circuit.

Rated current: The rated normal current of a CB is the rms value of the current which the CB shall be able to carry at rated frequency and at the rated voltage continuously, under specified conditions. The important condition is the temperature rise of the various components of the CB under normal loads.

Rated frequency: The rated frequency of a CB is the frequency at which it is designed to operate. Standard frequency is 50 Hz. Applications at other frequencies need special considerations.

Operating duty: The operating duty of a CB consists of the prescribed number of unit operations at stated intervals. The operating sequence denotes the sequence of opening and closing operations which the CB can perform under specified conditions.

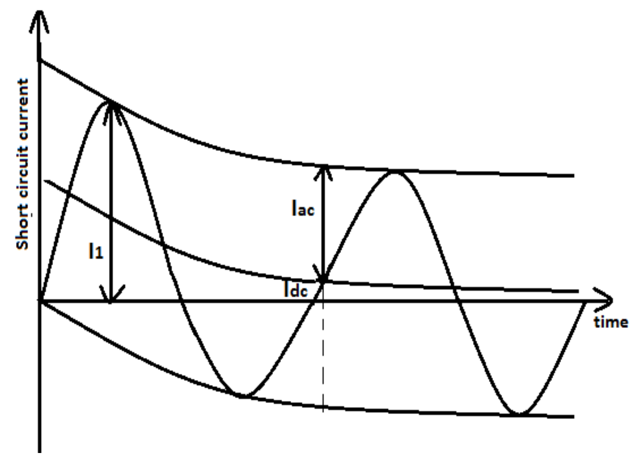
a) **Breaking capacity:** This term expresses the highest rms value of short circuit current that the CB is capable of breaking under specified conditions of transient recovery voltage and power frequency. It is expressed in KA rms at contact .

Let, at the instant of separation of contacts

AC components of short circuit current, $I_{ac} = x$

DC component of short circuit current, $I_{dc} = y$

Now, symmetrical breaking current = RMS value of ac component of short circuit at the instant of separation of contacts = $\frac{x}{\sqrt{2}}$



Asymmetrical breaking current = RMS value of the combined sums of ac and dc components

$$= \sqrt{\left(\frac{x}{\sqrt{2}}\right)^2 + y^2}$$

The breaking capacity of a circuit breaker in MVA is given as

= $\sqrt{3}$ × rated voltage in KV × rated breaking current in KA

b) **Making capacity:** The making capacity of the circuit breaker depends upon its ability to withstand the effects of electromagnetic forces which are proportional to the square of the peak value of the making current. For determination of making current of a CB, we must multiply symmetrical breaking current by $\sqrt{2}$ to convert the rms value to peak value and then by 1.8 to take into the account of 'doubling effect' of maximum asymmetry.

Making capacity = 2.55 × symmetrical breaking capacity

c) **Short time current rating:** The short time current of a CB is the rms value of current that a circuit breaker can carry in a fully closed position without damage, for the specified time interval under prescribed conditions. It is normally expressed in terms of KA for a period of 1 second or 4 seconds, known as one second rating and four second rating respectively. These ratings are based on thermal limitations.

5.13 Testing of circuit Breaker

The CBs being the vital component of power system protection, they have to operate very efficiently and correctly as per their designated rating. Thus, it is very important to test the circuit breaker frequently so that it does not malfunction, which may be too costly for the system operation.

a) **Routine test:** The purpose of routine tests is to check the correctness of the assembly and the materials used in the CB.
   1) **Operational tests:** These tests are to check the operational assembly and parts of the breaker and to check that they have proper movement for operation.
   2) **Measurement of resistance:** The resistance of the pathway of the current in the CB is measured from which the correctness of the materials used for contacts cab be judged.
   3) **Dielectric strength tests:** These tests are conducted for testing the insulation provided in the breaker and include following tests.
      - **Power frequency test:** Test voltage with frequency 15 to 100 Hz is applied between poles and earth and across terminals with the circuit breaker open. The voltage increased and maintained at test value for 1 minute. The breaker should be able to withstand without any problem.
      - **Impulse test:** Impulse voltage of specified shape and magnitude is applied to the CB and the breaker insulation should be able to withstand without any damage to the contact and insulation.

b) **Types test:** These tests are performed for the purpose of providing the correctness of the design rating values of the breakers and include the following:

1) **Mechanical test:** This test is carried to check the mechanical strength of the joints and parts of the breaker. The circuit breaker is opened and closed 500 times without any current flowing in the breaker. After the test there should be no distortion or wear of any parts of the breaker.
2) **Thermal test:** This test is carried to check the capability of the breaker to carry its rated current for long time without exceeding the temperature limit. The rated current of the breaker at rated frequency is passed through the breaker with the breaker closed and the temperature is measured by means of a thermometer or a thermo couple with temperature indicator. The temperature should not exceed than 35℃ at any time.
3) **Short-circuit tests:** These tests are conducted to verify the short circuit ratings of the breaker and include the following:
   - Making capacity test
   - Breaking capacity test
   - Short-time rating test

5.14 Numerical Solution

1) An 11 KV, 500 MVA circuit breaker suddenly closes on to a fault. Determine a) the symmetrical breaking current b) the asymmetrical breaking current assuming 50 % dc component c) the peak making current d) the short time current rating

- **Solution**

  Rupturing capacity = 500 MVA
  Operating voltage = 11 KV

Symmetrical breaking current = $\frac{\text{Rupturing capacity in MVA}}{\sqrt{3}\times\text{Operating voltage in KV}}$ KA = $\frac{500}{\sqrt{3}\times 11}$ = 26.24 KA (rms)

Ac component of short circuit current, x = $\sqrt{2}\times$ Symmetrical breaking current

= $\sqrt{2}\times 26.24$ = KA

DC component of short circuit current, y =50% of x = 18.55 KA

Asymmetrical breaking current = $\sqrt{(\frac{X}{\sqrt{2}})^2 + y^2}$ = $\sqrt{26.24^2 + 18.55^2}$ = 32.13 KA (rms)

Peak making current = 2.55 × Symmetrical breaking current

= 2.55 × 26.24 = 66.9 KA

Short time current rating = 32.13 KA

Unit 6: Transformer Protection

There are different kinds of transformers such as two winding or three winding electrical power transformers, auto transformer, regulating transformers, earthing transformers, rectifier transformers etc. Different transformers demand different schemes of transformer protection depending upon their importance, winding connections, earthing methods and mode of operation etc.

It is common practice to provide Buchholz relay protection to all 0.5 MVA and above transformers. While for all small size distribution transformers, only high voltage fuses are used as main protective device. For all larger rated and important distribution transformers, over current protection along with restricted earth fault protection is applied. Differential protection should be provided in the transformers rated above 5 MVA. Depending upon the normal service condition, nature of transformer faults, degree of sustained over load, scheme of tap changing, and many other factors, the suitable transformer protection schemes are chosen.

6.1 Possible Transformer Fault

Although an electrical power transformer is a static device, but internal stresses arising from abnormal system conditions, must be taken into consideration. A transformer generally suffers from following types of transformer fault-

1. Over current due to overloads and external short circuits,
2. Terminal faults,
3. Winding faults,
4. Incipient faults.

All the above mentioned, transformer faults cause mechanical and thermal stresses inside the transformer winding and its connecting terminals. Thermal stresses lead to overheating which ultimately affect the insulation system of transformer. Deterioration of insulation leads to winding faults. Sometime failure of transformer cooling system, leads to overheating of transformer. So, the transformer protection schemes are very much required.

The general winding faults in transformer are either earth faults or inter-turns faults. Phase to phase winding faults in a transformer is rare. The phase faults in an electrical transformer may be occurred due to bushing flash over and faults in tap changer equipment. Whatever may be the faults, the transformer must be isolated instantly during fault otherwise major breakdown may occur in the electrical power system.

Incipient faults are internal faults which constitute no immediate hazard. But it these faults are over looked and not taken care of, these may lead to major faults. The faults in this group are mainly inter-lamination short circuit due to insulation failure between core lamination, lowering the oil level due to oil leakage, blockage of oil flow paths. All these faults lead to overheating. So, transformer protection scheme is required for incipient transformer faults also. The earth fault, very nearer to neutral point of transformer star winding may also be considered as an incipient fault.

6.2 Buchholz Relay

Whenever the fault occurs inside the transformer, the oil of the tank gets overheated and gases are generated. The generation of the gases may be slow or violent depending upon whether the fault is minor or heavy short circuit. Most short circuit are developed either by impulse breakdown between adjacent turns at the end turns of the winding or as a very poor initial contact which will immediately heat to arcing temperature. The heat generated by the high local current causes the transformer oil to decompose and produce gas which can be used to detect the winding faults.

The construction of the Buchholz relay is shown in the figure. It consists of two hinged floats in a metallic chamber located in the pipe connection between the conservator and the transformer tank. One of the floats is near the top of chamber and actuates the mercury switch connected to the external alarm circuit. The other float is opposite to the orifice of the pipe to the transformer and actuates the mercury switch connected to the tripping circuit.

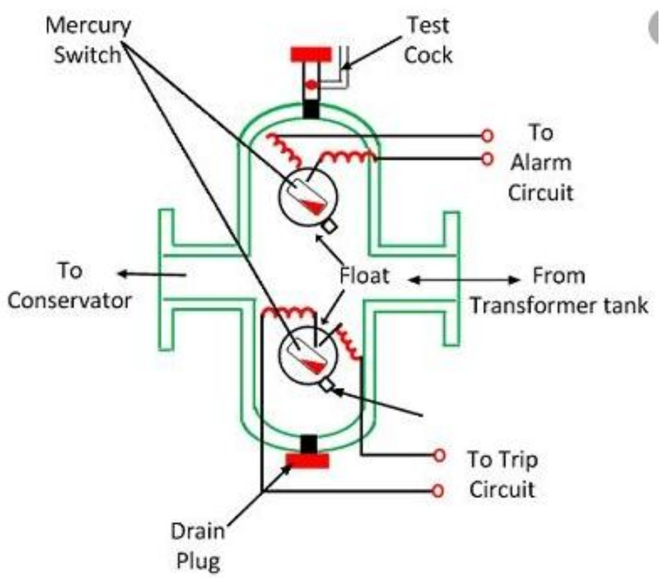


Figure 38: Buchholz Relay

Whenever a minor fault occurs, heat is produced due to current leakage, some of the oil in the transformer tank evaporates and some vapors collect in the top of the chamber while passing to the conservator tank. When the predetermined amount of the vapors accumulates in the top of the chamber the oil level falls, the mercury type switch attached to the float is tilted and so closes the alarm circuit and rings the bell. So, the operator knows that there is some incipient fault in the transformer. The transformer is disconnected at the earliest possible and the gas sampled is tested. Buchholz relay gives an alarm so that the transformer can be disconnected before the incipient fault grows into a severe one.

When the severe fault occurs large volume of gas is evolved so that the lower float containing mercury switch mounted on the hinged type float is tilted and the trip coil is energized. Thereafter the transformer is removed from the service.

6.3 Percentage Differential Protection for Transformers

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

The principle of such a protection scheme is the comparison of the currents entering and leaving the ends of a transformer. The vector difference of currents passes through the operating coil while the average current passes through the restraining coil. In normal conditions, the two currents at the two ends of the transformer are equal and balance is maintained. So no currents flow through the operating coil of the relay and relay is inoperative. But when there is phase to phase fault or phase to ground fault, this balance gets disturbed. The difference current flows through the operating coil due to which relay operates, tripping the circuit breaker. Compared to the differential protection used in generators, there are certain important points which must be taken care of while using such protection for the power transformers. These points are,

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

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

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

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

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

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

3. The neutrals of C.T. star and power transformer stars are grounded.

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

For the sake of understanding, the connection of C.T. secondaries in delta for star side of power transformer and the connection of C.T. secondaries in star for delta side of power transformer is shown in the Fig.1(a) and (b).

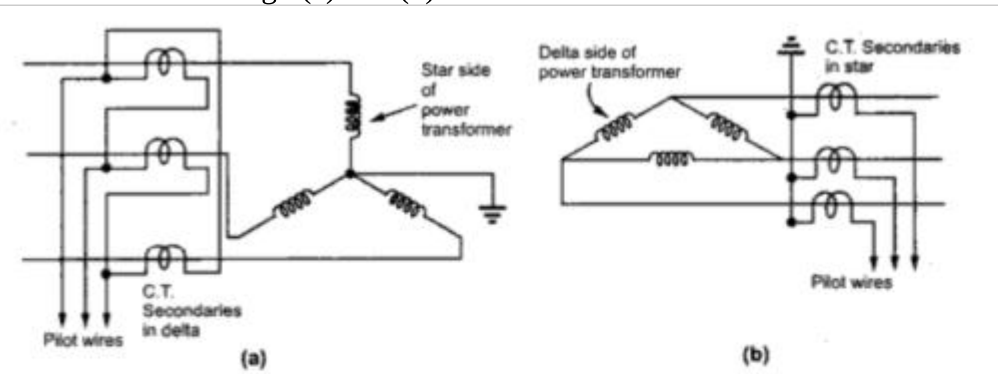


Figure 39: Connection of C.Ts on Star/Delta Transformer

6.3.1 Merz-Price Protection for Star-Delta Transformer

Let us study the Merz-Price protection for the star-delta power transformer. The primary of the power transformer is star connected while the secondary is delta connected. Hence to compensate for the phase difference, the C.T. secondaries on primary side must be connected in delta while the C.T. secondaries on delta side must be connected in star. The star point of the power transformer primary as well as the star connected C.T. secondaries must be grounded. The circuit diagram of the scheme is shown in the Figure

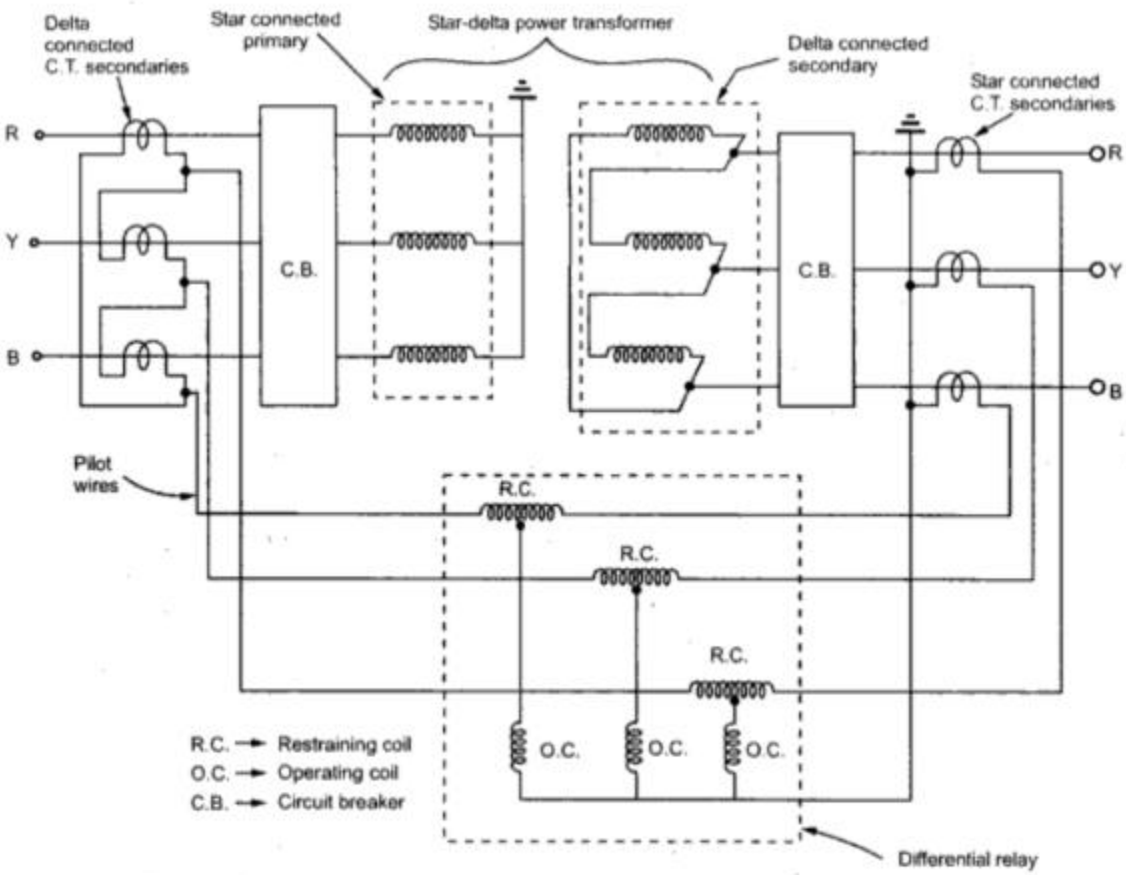


Figure 40: Merz Price protection for Star/Delta Transformer

The restraining coils are connected across the C.T. secondary windings while the operating coils are connected between the tapping points on the restraining coils and the star point of C.T. secondaries. With the proper selection of turns ratio of C.T.s the coils are under balanced condition during normal operating conditions. The C.T. secondaries carry equal currents which are in phase under normal conditions. So, no current flows through the relay and the relay is inoperative. With an internal fault in power transformer windings, the balance in the C.T.s get disturbed. The operating coils of differential relay carry currents proportional to the difference of current between the two sides of a power transformer. This causes the relay operation which trips the main circuit breakers on both the sides of the power transformer.

6.3.2 Merz-Price Protection for Star-Star Transformer

The Figure shows the Merz-Price protection system for the star-star power transformer. Both primary and secondary of the power transformer are connected in star and hence C.T. secondaries. The operating coils are connected between the tapping on the restraining coil and the ground. The operation of the scheme remains same for any type of power transformer as discussed for star-star power transformer.

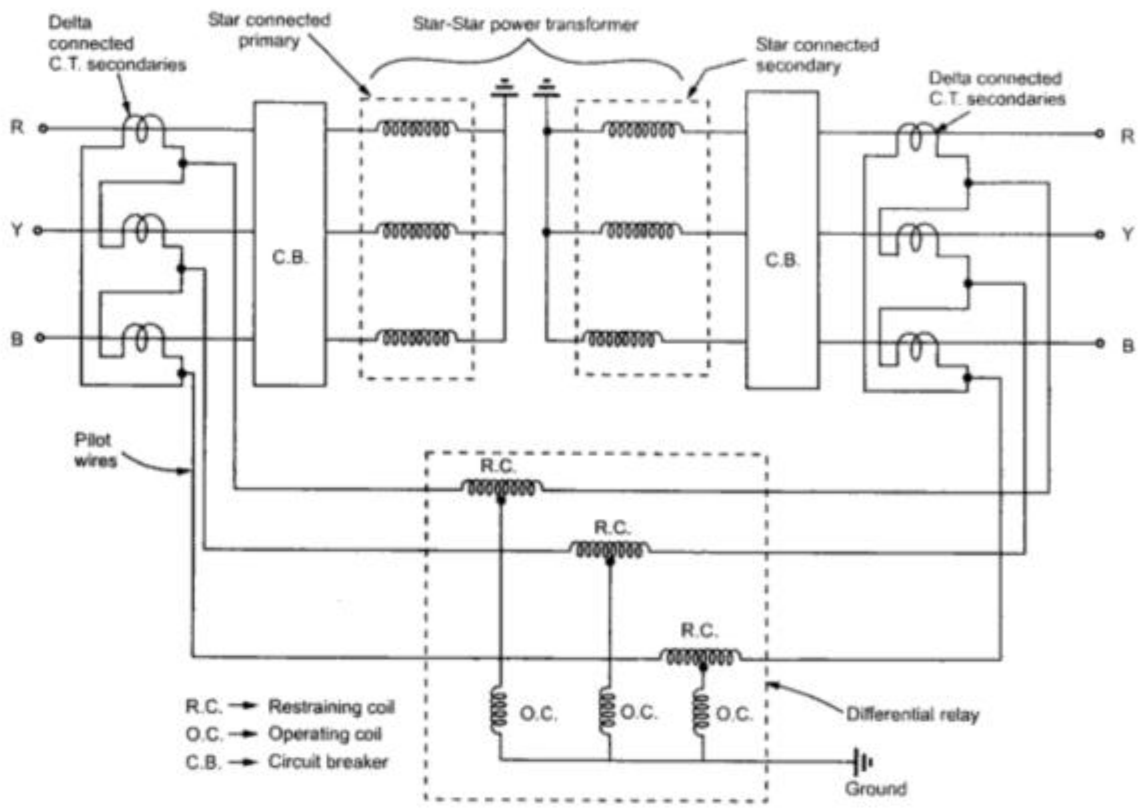


Figure 41:Merz-Price Protection for Star/Star power Transformer

6.4 Problem Encountered in Differential Protection

a) CT Characteristics: Unless saturation is avoided, the difference in CT characteristics due to different ratios being required in circuits of different voltages may cause appreciable difference in the respective secondary currents whenever through-faults occur. This trouble is aggravated in the case of transformers due to unequal ratio CTs being employed on either side of the protected transformer. A source of ratio error which results in circulating currents under through-fault condition is the unequal burden imposed on the CTs due to unequal lead lengths.

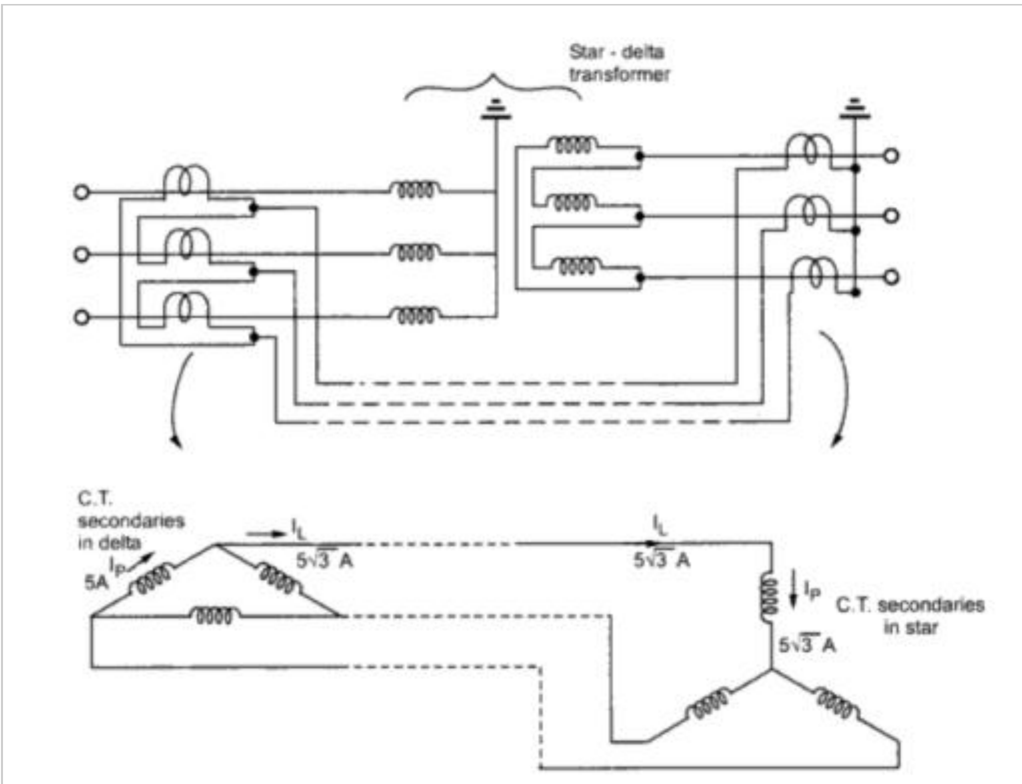
b) Ratio Change as a Result of Tapping: Tap changing equipment is a common feature of a power transformer which effectively alters the turns ratio. Compensating for this effect by varying the tapping on differential-protection CTs is impracticable. Biased or percentage differential relays ensure stability with the amount of unbalance occurring at the extremities of the tap-change range. Biased relays are better suited to the overall protection of variable-ratio transformers.

c) Magnetizing Inrush Current: When the transformer is energized, the transient inrush of magnetizing current flowing into the transformer may be as great as ten times full-load current and it decays relatively slowly. This is bound to operate the Differential Protection of Transformers

falsely. The magnitude of the magnetizing inrush current is a function of the permanent flux trapped in the transformer core and the instant on the voltage cycle when it is switched on.
There are a number of ways of ensuring immunity from operation by magnetizing surges. Firstly, the relay may be given a setting higher than the maximum inrush current; secondly, the time setting may be made long enough for the magnetizing current to fall to a value below the primary operating current before the relay operates. These simple remedies are incompatible with high speed and low primary operating current. In the third method the harmonic content of the current flowing in the operating circuit is filtered out and passed through a restraining coil.

6.5 Numerical Solution

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



Solution

The arrangement is shown in the Figure

On the primary side, which is 400 V side of transformer the current is 1000 A.
Hence C.T.s primary will carry current of 1000 A.
The C.T. ratio is 1000/5 on the primary side hence the current in C.T.
Secondaries which is phase current of delta connected C.T.s is,

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

This is shown in the Fig.4

$I_L = \sqrt{3}\ Ip = 5\sqrt{3}$ A

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

The same current flows through the star connected C.T. secondaries. Hence, each secondaries of C.T. on the secondary side of transformer carries a current of $5\sqrt{3}$ A.

For the power transformer the apparent power on both sides must be same.

Primary apparent power = Secondary apparent power

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

$\sqrt{3} \times 400 \times 1000 = \sqrt{3} \times 33000 \times I_{L2}$

$I_{L2} = (400 \times 1000)/33000 = 12.12$ A

Thus, each primary of C.T.s connected in star carries a current of 12.12 A. while each secondary of C.T.s connected in star carries a current of $5\sqrt{3}$ A.

Hence the C.T. ratio on 33 kV side is,

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

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

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

Here;

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

So, voltage per phase = Line voltage = 6600V

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

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

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

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

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

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

Here;

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

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

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

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

So, phase voltage = Line voltage= 11KV

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

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

Unit 7: Generator Protection

A generator is subjected to electrical stresses imposed on the insulation of the machine, mechanical forces acting on the various parts of the machine, and temperature rise. These are the main factors which make protection necessary for the generator or alternator. Even when properly used, a machine in its perfect running condition does not only maintain its specified rated performance for many years, but it does also repeatedly withstand certain excess of overload.

Preventive measures must be taken against overloads and abnormal conditions of the machine so that it can serve safely. Even ensuring an efficient design, construction, operation, and preventive means of protection – the risk of a fault cannot be completely eliminated from any machine. The devices used in generator protection, ensure that when a fault arises, it is eliminated as quickly as possible.

An electrical generator can be subjected to either an internal fault or external fault or both. The generators are normally connected to an electrical power system, hence any fault occurred in the power system should also be cleared from the generator as soon as possible otherwise it may create permanent damage in the generator.

The number and variety of faults occur in a generator are huge. That is why generator or alternator is protected with several protective schemes. Generator protection is of both discriminative and non-discriminative type. Great care is to be taken in coordinating the systems used and the settings adopted to ensure that a sensitive, selective and discriminative generator protection scheme is achieved.

The various forms of protection applied to the generator can be categorized into two manners,

1. Protective relays to detect faults occurring outside the generator.
2. Protective relays to detect faults occurring inside the generator.

7.1 Generator Fault

Generator faults can be considered under the following heads: 1. Stator Winding Faults 2. Field Winding or Rotor Circuit Faults 3. Abnormal Operating Conditions.

7.1.1 Stator Winding Faults

Such faults occur mainly due to the insulation failure of the stator coils. The main types of stator winding faults are

- Phase-to-earth faults
- Phase-to-phase faults and
- Inter-turn faults involving turns of the same phase winding.

The stator winding faults are the most dangerous and are likely to cause considerable damage to the expensive machinery. So, automatic protection is absolutely necessary to clear such faults in the shortest possible time in order to minimise the extent of damage.

Phase-to-phase faults and phase inter-turn faults are less common, these usually develop into an earth fault. Inter-turn faults are more difficult to be detected.

The effect of earth fault in the stator is two-fold:
(i) Arcing to core, which welds laminations together, causing eddy current hot spots on subsequent use. Repairs to this condition involve expenditure of considerable money and time.

(ii) Severe heating in the conductors damaging them and the insulation with possible fire breaks.

7.1.2. Field Winding or Rotor Circuit Faults

Faults in the rotor circuit may be either earth faults (conductor-to-earth faults) or inter-turn faults, which are caused by severe mechanical and thermal stresses. The field system is normally not grounded (i.e., remains isolated from the earth) and, therefore, a single fault between field winding and rotor body due to insulation breakdown does not give rise to any fault current. However, a second earth fault will short circuit some part of the rotor winding and may thereby develop an unsymmetrical field system, giving unbalanced force on the rotor. This can cause severe vibration of the rotor with possible damage to the bearings. Thus, a single earth fault can be tolerated for a while but it should not be allowed to continue. Rotor earth fault protection is provided in case of large generators.

Owing to a fault, there may be an unbalance in the three-phase stator currents. According to the theory of symmetrical components, unbalance three-phase currents have a negative sequence component, which rotates at synchronous speed in a direction opposite to the direction of rotation of rotor. So, double frequency currents are induced in the rotor. This causes overheating of rotor and possible damage to the rotor. Unbalanced currents may also cause severe vibration, but the overheating problem is more acute. Rotor temperature indicators are used with large generators for detecting rotor overheating due to unbalanced loading of generator.

Rotor open-circuit faults, though rare, can cause arcing and thus result on serious conditions.

Reduced excitation may occur due to open circuit or short circuit in the field or exciter circuits or a fault in automatic voltage regulator. When a generator loses its field excitation it speeds up slightly and continues to run as an induction generator deriving excitation from the system and supplying power at a leading power factor. A fall in voltage will also occur due to loss to excitation which may result in loss of synchronism and system stability. There is also the possibility of overheating of the rotor due to induced currents in the rotor and damper windings. This can be avoided by using a tripping scheme which is so arranged that opening of field circuit breaker causes the tripping of generator unit breaker.

7.1.3 Abnormal Operating Conditions

The abnormal operating conditions that are likely to occur in a generator are:
i) Failure of prime mover (turbine) resulting in operation of the generator as a synchronous motor

(ii) Failure of field

(iii) Unbalanced loading and subsequent heating of generator

(iv) Overloading

(v) Over-voltage at generator terminals

(vi) Over-speed

(vii) Ventilation failure and

(viii) Current leakage in the body of the generator.

7.2 Method of Earth Fault Detection

1. Residual CT connection Method: In this method each phase will have CT, the secondaries of which are connected in residual manner and a relay is connected. Under normal condition without any earth fault, the current in the lines sum up to zero. So, also the current in the secondaries of the CTs, so that there will be no residual current flowing in the relay. When the earth fault occurs between a line and earth , the current in the faulty line will be much higher compare to other normal healthy lines, so that the balance in the secondaries of the CTs is upset and the out of balance(residual) current will flow in the circuit which will operate to disconnect the associated circuit breaker.

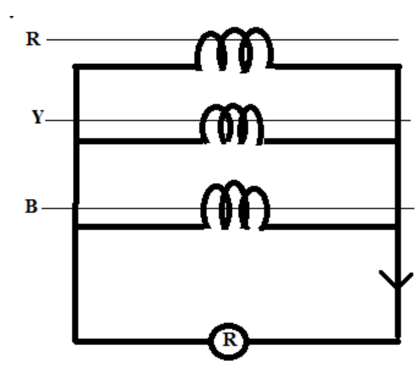


Figure 42: Residual CT Connection

2. Core Balance Method: In this, three primary conductors or lines are enclosed by a ring core, such that the fluxes produced by the line current are made to interact in the core. A relay is connected through CT which encloses the ring as shown. Under the normal condition, the three-line currents balance together so also the flux produced by them, so that there will not be any residual or net flux in the core and the relay 'R' will not operate. When an earth fault occurs in any of the lines the current flowing in it will be in the form of fault which will be much higher compare to healthy one.

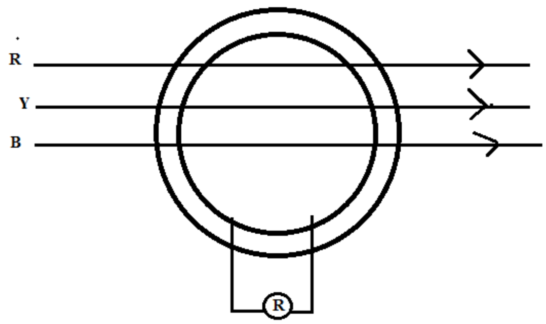


Figure 43: Core Balance Method

Because of this unbalance line currents there will be the net flux in the core which will induce current in the CT thereby the relay will operate to isolate the fault.

3. Earth Lead Methods: In this method, single current transformer is inserted in the neutral earth connection of a generator or transformer. Relay 'R' is connected to the secondary of the CT. In normal condition without any earth fault there will not be any flow of current in the neutral earth connection line, so that the relay will not operate. Whenever the earth fault occurs, a high fault current will flow in the ground through neutral earth connection and the grounded line. This will energize the relay to operate and subsequently operation of the breaker to isolate the fault.

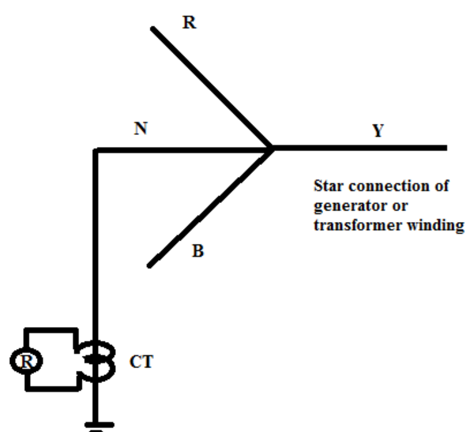


Figure 44: Earth Lead Method

7.3 Restricted and Unrestricted Earth Fault Protection

Restricted Earth Fault Protection: This type of protection are usually used for earth fault protection of supply source like generators and transformers. A CT inserted in the neutral connection to the earth [earth lead method of unrestricted type] is connected in parallel with three lines CTs connected in residual CTs form as shown. Figure shows the flow of the circulating current in the power circuits and the relay circuits under the conditions of fault within the zone [i.e., within the residual CT connection and external to the protected zone respectively]. It is clear from the figure that the scheme will now discriminate between faults external to the protected zone & those within the zone, operating only for the latter case.

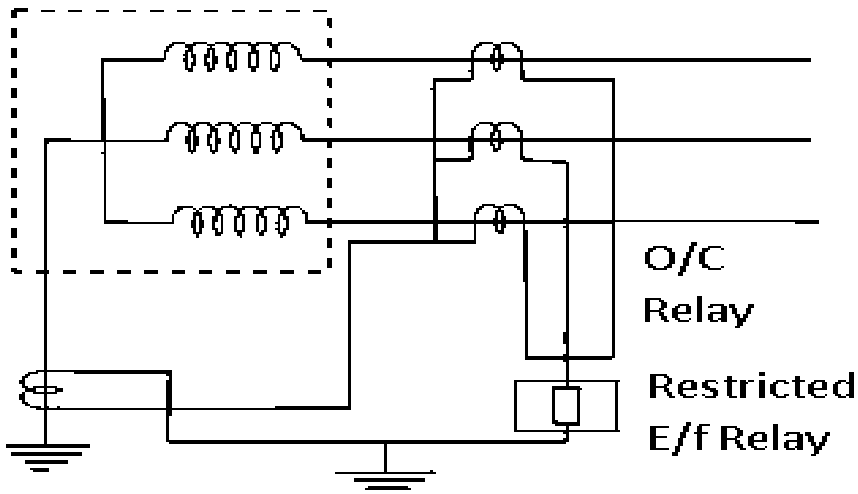


Figure 45: Restricted Earth Fault Protection

Unrestricted Earth Fault Protection: The unrestricted type earth fault protection if applied to an open-ended radial feeder, this will function to isolate the feeder when an earth fault occurs on the feeder. But if the scheme is applied to an incoming feeder it will function to isolate feeder, even through the fault may be on an outgoing feeder. This is also true if applied to generator or transformer circuits. In all cases, the earth fault may occur at point well beyond the circuit to which the protection is applied, but because the scheme cannot discriminate the CB controlling the source of supply may be opened unnecessarily. If the earth fault protection methods as described earlier are applied to protect feeders, it should be applied to individual outgoing feeders which gives supply to group of feeder circuit. And if it is applied to the generator or Transformer. Circuit, it should be modified to a type known as restricted earth fault protection.

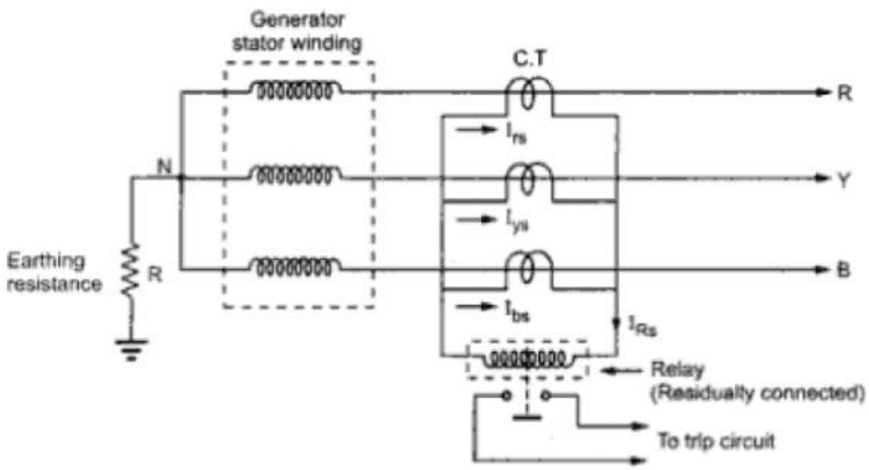


Figure 46: Unrestricted Earth Fault Protection

7.4 Merz-Price Protection of Alternator Stator Windings

This is most commonly used protection scheme for the alternator stator windings. The scheme is also called biased differential protection and percentage differential protection. In this method, the currents at the two ends of the protected section are sensed using current transformers. The wires connecting relay coils to the current transformer secondaries are called pilot wires.

Under normal conditions, when there is no fault in the windings, the currents in the pilot wires fed from C.T. secondaries are equal. The differential current i_1 - i_2 through the operating coils of the relay is zero. Hence the relay is inoperative and system is said to be balanced.

When fault occurs inside the protected section of the stator windings, the differential current i_1 - i_2 flows through the operating coils of the relay. Due to this current, the relay operates. This trips the generators circuit breaker to isolate the faulty section. The is also disconnected and is discharged through a suitable impedance. The Figure 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. The C.T.s are connected in star and are provided on both, the outgoing side and machine winding connections to earth side. 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 tapping from restraining coils and the C.T. neutral earthing connection.

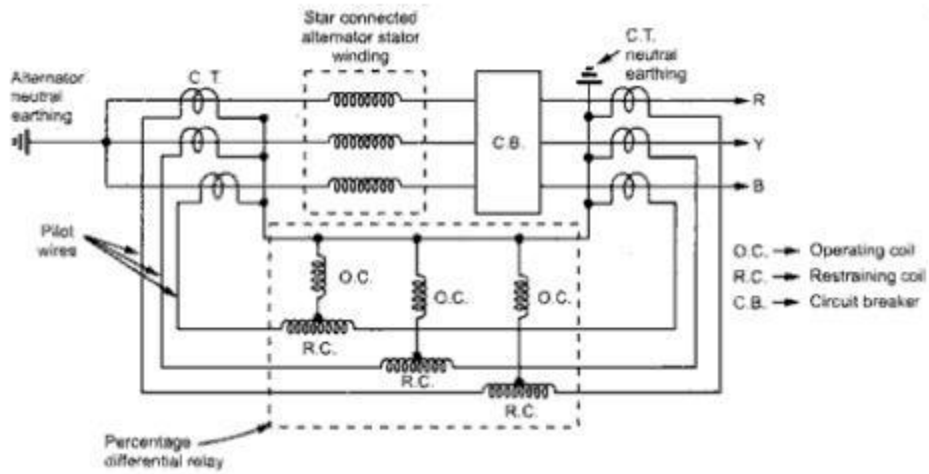


Figure 47: Merz-Price protection for star connected alternator

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

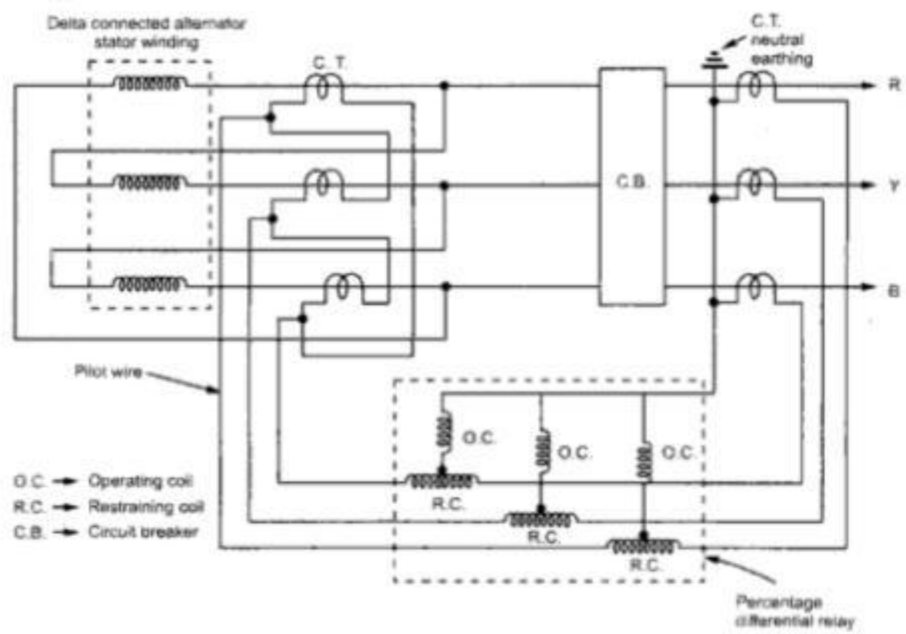


Figure 48:Merz-Price protection for delta connected alternator

The C.T.s on the delta connected machine winding side are connected in delta while the C.T.s at outgoing ends are connected in star. The restraining coils are placed in each phase, energized by the secondary connections of C.T.s while the operating coils are energized from the restraining coil tapping and the C.T. neutral earthing.

If there is a fault due to a short circuit in the protected zone of the windings, it produces a difference between the currents in the primary windings of C.T.s on both sides of the generator winding of the same phase. This results in a difference between the secondary currents pf the two currents transformers. Thus, under fault conditions, a differential current flow through the operating coils which is responsible to trip the relay and open the circuit breaker. The differential relay operation depends on the relation between the current in the operating coil and that in the restraining coil.

7.5 Stator Inter Turn Protection

Inter turn stator winding fault can easily be detected by stator differential protection or stator earth fault protection. Hence, it is not very essential to provide special protection scheme for inter turn faults occurred in stator winding. This type of faults is generated if the insulation between conductors (with different potential) in the same slot is punctured. This type of fault rapidly changes to earth fault. The high voltage generator contains a large number of conductors per slot in the stator winding hence, in these cases the additional inter turn fault protection of the stator winding may be essential. Moreover, in modern practice, inter turn protection is becoming essential for all large generating units. Several methods can be adopted for providing inter turn protection to the stator winding of generator. Cross differential method is most common among them. In this scheme the winding for each phase is divided into two parallel paths.

Each of the paths is fitted with identical current transformer. The secondary of these current transformers are connected in cross. The current transformer secondary's are cross connected because currents at the primary of both CTs are entering unlike the case of differential protection of transformer where current entering from one side and leaving to other side of the transformer. The differential relay along with series stabilizing resistor are connected across the CT secondary loop as shown in the figure. If any inter turn fault occurs in any path of the stator winding, there will be an unbalanced in the CT secondary circuits thereby actuates 87 differential relays. Cross differential protection scheme should be applied in each of the phases individually as shown.

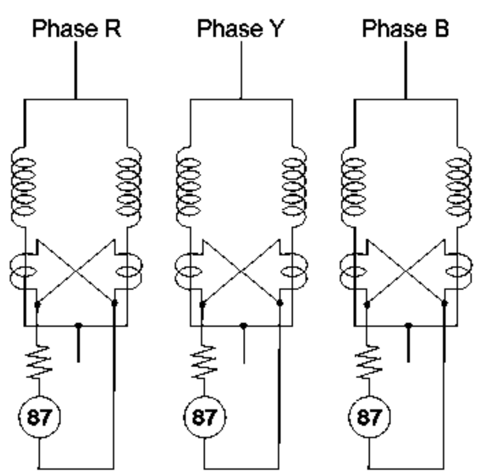


Figure 49: Generator inter turn fault protection based on cross differential protection

7.6 Rotor Earth Fault Protection

The rotor of the generator is normally unearthed i.e. remain isolated from the earth and therefore the single fault due to insulation breakdown will not rise the fault current. A single fault will not affect the rotor, but if the fault occurs, continues then it will damage the field winding of the generator. For a large generator, the rotor earth fault protection system is used for the protection of the field winding.

When the one earth fault occurs in the rotor then it is not necessary that the system is completely trip, only the relay indicates that the fault has occurred. So that the generator should be taken out of service at leisure. The methods of rotor earth fault protection are explained below.

a) Rotor Earth Fault Protection by Using High Resistance

In this method, a high resistance is connected across the field winding of the rotor. The midpoint of the resistor is grounded through a sensitive relay. When the fault occurs, the relay detects the fault and send the tripping command to the breaker.

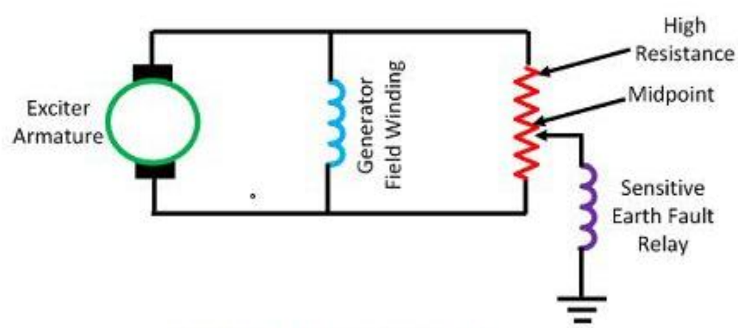


Figure 50: Rotor Earth Fault Protection by Using High Resistance

The major disadvantage of such type of system it that it can detect the fault for most of the rotor circuit except the rotor center point. This difficulty can be overcome by shifting the tap on the resistor from Centre to somewhere else. Thus, the relay can detect the midpoint fault of the rotor.

b) AC and DC Injection Methods for Rotor Earth Fault Protection

In this method, alternating current is injected into the field winding circuit and ground along with a sensitive overvoltage relay and a current limiting capacitor. A single earth fault in the rotor will complete the circuit comprises the alternating current source, sensitive relay and earth fault. Thus, the earth fault is sensed by the relay.

The major disadvantage of such type of system is the leakage current that flows through the capacitor. This current unbalanced the magnetic field and increase the stress on the magnetic bearing. Another disadvantage of alternating current is that the relay cannot pick up the current that normally flow through the capacitance to the ground. Thus, the care must be taken to avoid resonance between the capacitance and the relay inductance.

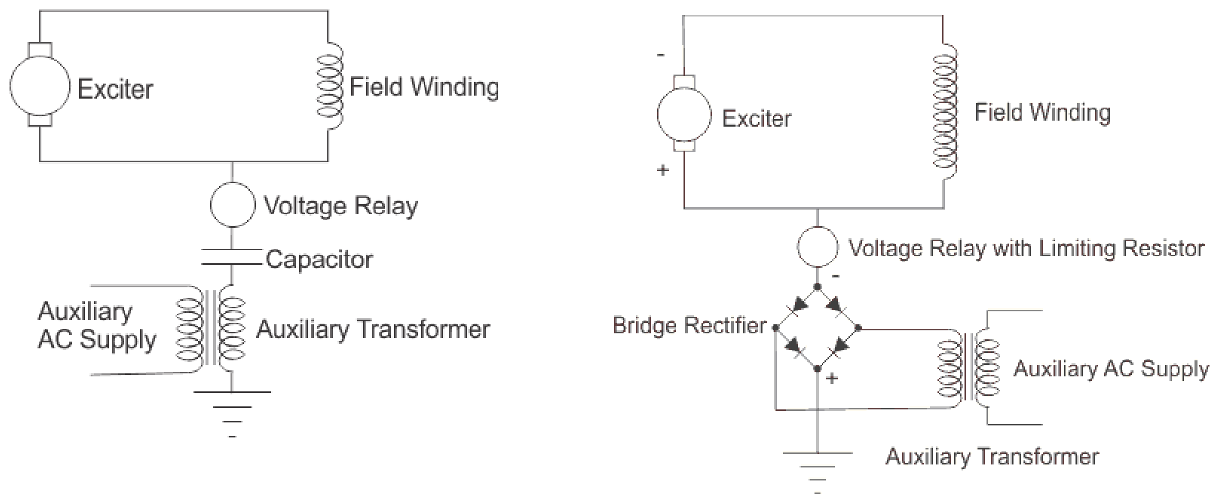


Figure 51: AC and DC Injection Methods for Rotor Earth Fault Protection

The problem of the AC injection system can be overcome by using the DC injection method. This method is simple and has no problem of leakage currents. The one terminal of the sensitive relay is connected to the exciter, and the other terminal is connected to the negative terminal of the DC source. The positive terminal of the DC source is grounded. When the earth fault occurs, the fault current will complete the circuit path, and the fault is sensed by the relay.

7.7 Loss of Excitation Protection

Loss of field or excitation can be caused in the generator due to excitation failure. In larger sized generator, energy for excitation is often taken from a separate auxiliary source or from a separately driven DC generator. The failure of auxiliary supply or failure of driving motor can also cause the loss of excitation in a generator. Failure of excitation that is failure of field system in the generator makes the generator run at a speed above the synchronous speed. In that situation the generator or alternator becomes an induction generator which draws magnetizing current from the system. Although this situation does not create any problem in the system immediately but over loading of the stator and overheating of the rotor due to continuous operation of the machine in this mode may create problems in the system in long-run. Therefore, special care should be taken for rectifying the field or excitation system of the generator immediately after failure of that system. The generator should be isolated from rest of the system till the field system is properly restored.

we use an undercurrent relay connected in shunt with main field winding circuit. This relay will operate if the excitation current comes below its predetermined value. If the relay is to operate for complete loss of field along, it must have a setting lies well below the minimum excitation current value which can be 8% of the rated full load current. Again, when loss of field occurs due to failure of exciter but not due to problem in the field circuit (field circuit remains intact) there will be an induced current at slip frequency in the field circuit. This situation makes the relay to pick up and drop off as per slip frequency of the induced current in the field. This problem can be overcome in the following manner.

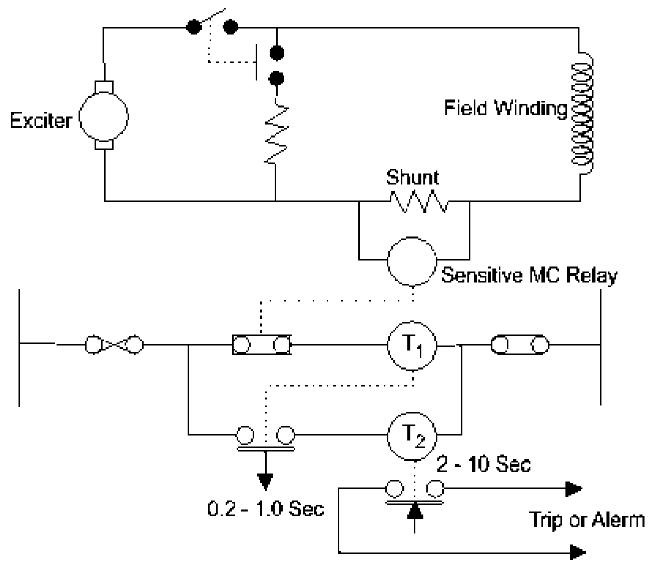


Figure 52: Loss of Excitation Protection

In this case a setting of 5% of normal of full load current is recommended. There is a normally closed contact attached with the undercurrent relay. This normally closed contact remains open as the relay coil is energized by shunted excitation current during normal operation of the excitation system. As soon as there is any failure of excitation system, the relay coil becomes de-energized and the normally closed contact closes the supply across the coil of timing relay T_1.
As the relay coil is energized, the normally open contact of this relay T_1 is closed. This contact closes the supply across another timing relay T_2 with an adjustable pickup time delay of 2 to 10 seconds. Relay T_1 is time delayed on drop off to stabilize scheme again slip frequency effect. Relay T_2 closes its contacts after the prescribed time delay to either shut down the set or initiate an alarm. It is time delayed on pickup to prevent spurious operation of the scheme during an external fault.

7.8 Negative Sequence Relay

Negative Sequence Relay is used to protect the alternator/generator from unbalance loading and negative sequence component. The negative sequence current flows in the generator winding due to phase to phase short circuit. The negative sequence currents cause the overheating of generator/alternator/motor/transformer's winding. Negative sequence relays are generally used to give protection to generators and motors against unbalanced currents.

Negative Sequence Relay Operation

Before understanding about the Negative sequence relay, you must know what is negative sequence. Negative sequence is nothing but A balanced three-phase system with the opposite phase sequence as the original sequence which means the set of the three phasors are equal in magnitude, spaced 120° apart from each other and having the phase sequence opposite to that of the original phasors.

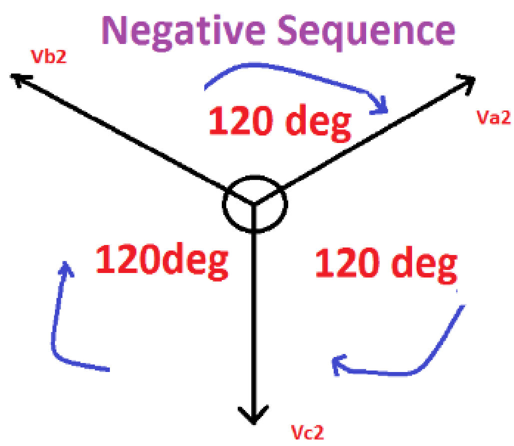


Figure 53: Symmetrical Component Negative Sequence

Under balanced condition, the generator delivers equal currents in all three-phase either star connected or delta connected loads. Here the vector sum of negative sequence current is zero, hence net unbalance current is zero. Here, the unbalance may occur due to circuit breaker operation, circuit breaker failures or system faults. Hence the negative sequence current starts flowing in the stator winding, which creates additional flux in the air gap which rotates in opposite direction to that of rotor synchronous speed. This flux induces currents in the rotor body, wedges, retaining rings at twice the line frequency. Due to this mismatch, the rotor body temperature starts increasing. But if the magnitude of these negative sequence current is high, then this opposite direction potentially affects the normal operating direction of the turbine. It leads to serious damage to the turbine-generator set.

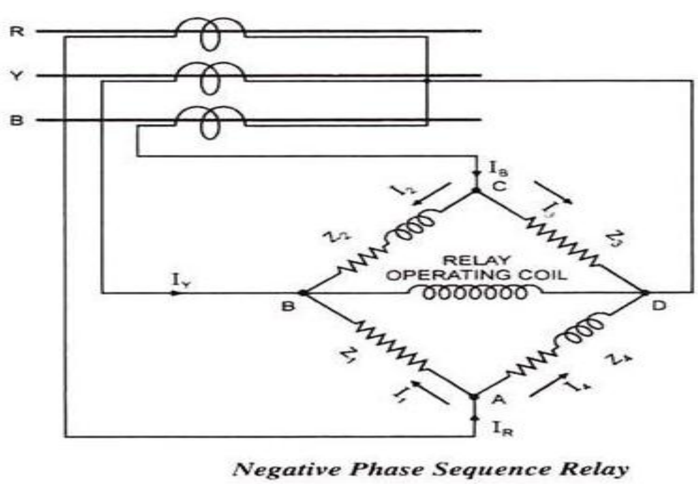


Figure 54: Negative Sequence Relay

Generally, negative sequence relays are having two stage of tripping. The first stage tripping is given to the grid circuit breaker as the grid is infinite loads, the second stage of tripping will be given to the generator circuit breaker.

7.9 Numerical Solution

Example 11.1. Calculate the required value of neutral resistance for a 3-phase 11 kV alternator, so as to protect 70% of the winding against earth fault by a relay with pick-up current of 5 A. The neutral CT has a ratio of 250/5.

[*G.B. Technical Univ. Switchgear and Protection 2011-12*]

Solution : The minimum current which will operate the relay during fault conditions

= Relay pick-up current × CT ratio

$$= 5 \times \frac{250}{5} = 250 \text{ A} \qquad \ldots(i)$$

Let the earthing resistance required to protect the 70% of the winding *i.e.*,

$$x = (100 - 70) \text{ } i.e., 30\%$$

The emf induced in 30% of the winding

$$= \frac{11{,}000}{\sqrt{3}} \times \frac{30}{100} = 1{,}100\sqrt{3} \text{ V}$$

Earth fault current which 30% of the winding will cause

$$= \frac{1{,}100\sqrt{3}}{R} \qquad \ldots(ii)$$

Equating expressions (*i*) and (*ii*), we have

$$\frac{1{,}100\sqrt{3}}{R} = 250$$

$$\text{or } R = \frac{1{,}100\sqrt{3}}{250} = 7.621\ \Omega \ \textbf{Ans.}$$

Example 11.2. An alternator rated at 10 kV protected by the balanced circulating current system has its neutral grounded through a resistance of 10 ohms. The protective relay is set to operate when there is an out-of-balance current of 1.8 amp in the pilot wires, which are connected to the secondary windings of 1,000/5 ratio current transformers.

Determine

(*i*) the percentage winding which remains unprotected.

(*ii*) the minimum value of earthing resistance required to protect 80% of the winding.

[U.P. Technical Univ. Switchgear and Protection 2006-07]

Solution : The minimum current which will operate the relay during fault condition

$$= 1.8 \times \frac{1{,}000}{5} = 360 \text{ A} \qquad \ldots(i)$$

(*i*) Let x% of the winding be unprotected.

The emf induced in this part of winding

$$= \frac{10{,}000}{\sqrt{3}} \times \frac{x}{100} = \frac{100}{\sqrt{3}} x \text{ volts}$$

Earth fault current which x% winding will cause

$$= \frac{\text{EMF induced in the unprotected portion of winding}}{\text{Earth resistance}}$$

$$= \frac{\frac{100}{\sqrt{3}} x}{10} = \frac{10}{\sqrt{3}} x \qquad \ldots(ii)$$

Equating expressions (*i*) and (*ii*), we have

$$\frac{10}{\sqrt{3}} x = 360$$

$$\text{or } x = \frac{360\sqrt{3}}{10} = 62.35\%$$

i.e., Percentage of winding which remains unprotected = 62.35% **Ans.**

(*ii*) Let the earthing resistance required to protect the 80% of the winding (*i.e.*, unprotected portion is 20%) be R ohms

EMF induced in 20% of the winding

$$= \frac{10{,}000}{\sqrt{3}} \times \frac{20}{100} = \frac{2{,}000}{\sqrt{3}} \text{ V}$$

Earth fault current which 20% of the winding will cause

$$= \frac{2{,}000/\sqrt{3}}{R} \qquad ...(iii)$$

Equating expressions (*i*) and (*iii*), we have

$$\frac{2{,}000}{\sqrt{3}R} = 360$$

$$R = \frac{2{,}000}{360\sqrt{3}} = 3.2\ \Omega \quad \textbf{Ans.}$$

Example 11.3. A 5,000 kVA, 6,600 V, star-connected alternator has a synchronous reactance of 2 ohms per phase and 0.5 ohm resistance. It is protected by a Merz-Price balanced current system which operates when out-of-balance current exceeds 30% of load current. Determine what proportion of alternator winding is unprotected if the star point is earthed through a resistance of 6.5 ohms.

Solution : Let x % of the winding be unprotected

The equivalent impedance of x % of the winding

$$= (0.5 + j2) \times \frac{x}{100} \ \Omega$$

Earthing resistance $= 6.5\ \Omega$

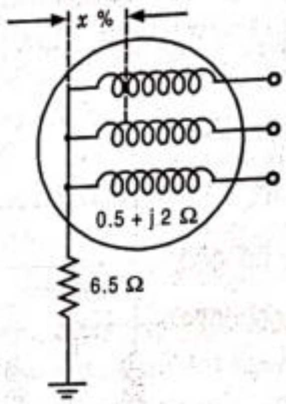


Fig. 11.12

Impedance offered by x % of the winding (unprotected winding) to earthed fault current

$$= 6.5 + (0.5 + j2) \times \frac{x}{100}$$

$$= (6.5 + 0.005x + j0.02x) \text{ ohms}$$

Full-load current of alternator

$$= \frac{5{,}000 \times 1{,}000}{\sqrt{3} \times 6{,}600} = 437.4 \text{ A}$$

Out-of-balance current which can cause relay operation

$$= 30 \text{ per cent of } 437.4 \text{ A}$$

$$i.e., \ \frac{30}{100} \times 437.4 = 131.2 \text{ A} \quad ...(i)$$

The voltage induced in x % of winding

$$= \frac{6,600}{\sqrt{3}} \times \frac{x}{100} = \frac{66}{\sqrt{3}} x \text{ volts}$$

The earth fault current caused by the voltage induced in the unprotected winding

$$= \frac{\frac{66x}{\sqrt{3}}}{\text{Earth fault impedance}} = \frac{66x}{\sqrt{3} \times (6.5 + 0.005x + j0.02x)}$$

The earth fault current will be mainly governed by the earth fault resistance, so neglecting the generator reactance for the unprotected portion of winding,

$$\text{Fault current} = \frac{66x}{\sqrt{3} \times (6.5 + 0.005x)} \qquad ...(ii)$$

Equating expressions (*i*) and (*ii*), we have

$$\frac{66x}{\sqrt{3} \times (6.5 + 0.005x)} = 131.2$$

$$\text{or } x = 22.77 \text{ \%} \quad \textbf{Ans.}$$

Example 11.4. Find the portion of winding protected against earth fault on a 11 kV, 50 MVA star-connected alternator having a reactance of 1.5 ohm per phase and negligible resistance. The generator neutral is grounded with 10 ohm. Merz-Price protection

scheme is used which operates when the out-of-balance current exceeds 5% of the full-load current.

[U.P. Technical Univ. Switchgear and Protection 2007-08]

Solution : Let x% of the winding be unprotected.

The equivalent impedance of x% of the winding

$$= (0 + j1.5) \times \frac{x}{100}\ \Omega$$

Earthing resistance = 10 Ω

Impedance offered by x% of the winding (unprotected winding) to earth fault current

$$= 10 + \frac{j1.5x}{100} = 10 + j0.015x$$

Full-load current of alternator = $\dfrac{50 \times 10^6}{\sqrt{3} \times 11{,}000}$ = 2,624 A

Out-of-balance current which can cause operation of relay

$$= 5\% \text{ of } 2{,}624 \text{ A } i.e., \frac{5}{100} \times 2{,}624 = 131.2 \text{ A}$$

The voltage induced in x% of winding

$$= \frac{11{,}000}{\sqrt{3}} \times \frac{x}{100} = \frac{110}{\sqrt{3}} x \text{ volts}$$

The earth fault current caused by the voltage induced in the unprotected winding

$$= \frac{110x / \sqrt{3}}{\text{Earth fault impedance}} = \frac{110x}{\sqrt{3}(10 + j0.015x)}$$

The earth fault current will be mainly governed by the earth fault resistance, so neglecting the generator reactance for the unprotected portion of the winding,

$$\text{Fault current} = \frac{110x}{\sqrt{3} \times 10} = 131.2$$

$$\text{or } x = \frac{131.2 \times \sqrt{3}}{11x} = 20.66\%$$

Portion of winding protected

$$= \left(1 - \frac{x}{100}\right) \times 100 = \left(1 - \frac{20.66}{100}\right) \times 100$$

$$= 79.34\% \quad \textbf{Ans.}$$

Example 11.6. A 6.6 kV, 10 MVA star-connected alternator has a reactance of 2 ohms per phase and negligible resistance. Merz-Price protection is used for protection of winding. The neutral grounding resistance is 5 ohms. If only 10% of the winding is to remain unprotected, determine the setting of the relay.

[*GATE 1996*]

Solution : Voltage per phase, $V_p = \dfrac{6.6 \times 1{,}000}{\sqrt{3}} = 3{,}810.5$ V

Voltage induced in the unprotected portion (10%) of the winding

$$= 3,\,810.5 \times \frac{10}{100} = 381.05 \text{ V}$$

Impedance offered by 10 % of winding (unprotected winding) to earthed fault current

$$= 5 + j2 \times \frac{10}{100} = (5 + j\,0.2)\ \Omega$$

The earth fault current caused by voltage induced in the unprotected winding

$$= \frac{381.05}{5 + j0.2} = \frac{381.05}{5.004} = 76.15 \text{ A}$$

$$\text{Full-load current} = \frac{\text{MVA rating} \times 10^6}{\sqrt{3}\ \text{kV rating} \times 1{,}000}$$

$$= \frac{10 \times 10^6}{\sqrt{3} \times 6.6 \times 1{,}000} = 874.77 \text{ A}$$

$$\text{Relay setting} = \frac{\text{Earth fault current}}{\text{Full-load current}} \times 100 = \frac{76.15}{874.77} \times 100$$

$$= 8.7\ \% \quad \textbf{Ans.}$$

Unit 8: Protection of Bus Bar

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

According to the statistical information, the majority of the faults are single phase in nature and are, in part, temporary in character. The causes of the bus zone faults are:

- Failure of support insulator, due to material deterioration, resulting in earth fault.
- Flash over across support insulator, caused by prolonged and excessive Over-voltages.
- Faulty operations performed by the attending personnel.
- Heavily polluted insulator causing flash over.
- Foreign objects accidently falling across bus bars.
- Failure of circuit breaker to interrupt fault current or failure to clear under through fault conditions.

8.1 Backup Protection for Bus-Bars

This is the simple way of protecting the bus-bar from the fault. The fault occurs on the bus-bar because of the supplying system. So, the backup protection is provided to the supply system. The figure below shows the simple arrangement for the protection of bus-bar. The bus A is protected by the distance protection of the bus B. If the fault occurs on A, then the B will operate. The operating times of the relay will be 0.4 seconds.

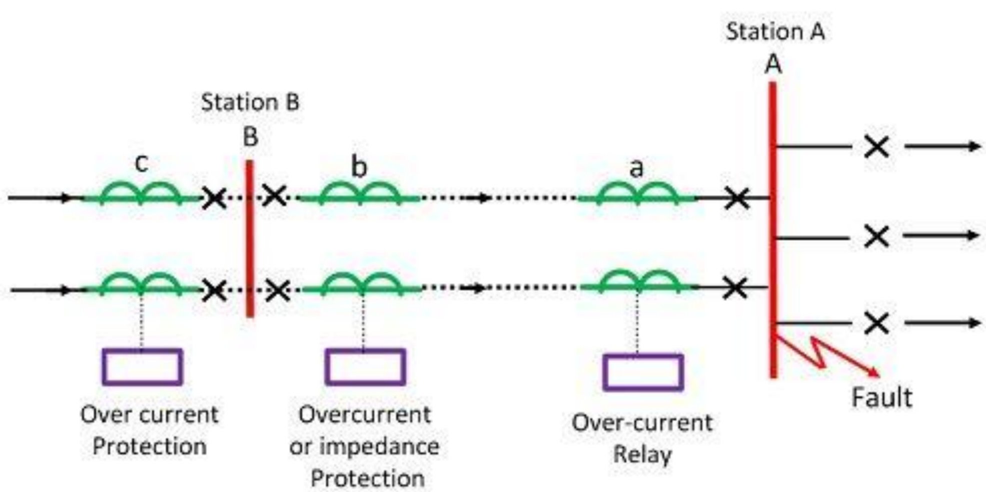


Figure 55: Back Up Protection for Bus Bars

The bus-bar protection system has few disadvantages likes the protection system is slow. Such system is mainly used for the protection of the transmission lines. But as the protection system is very economical, thereby it is also used for the bus-bar protection.

This protective scheme is not used for small switchgear system. The backup protection system has many disadvantages likes delayed in action, disconnections of more circuits for two or more transmission line requires etc.

8.2 Frame Leakage Protection

This method insulates the bus-supporting structure and its switchgear from the ground, interconnecting all the framework, circuit breakers tanks, etc. and provided a single ground tank connection through a CT that feeds an overcurrent relay. The overcurrent relay controls a multi-contact auxiliary relay that trips the breakers of all circuits connected to the bus.

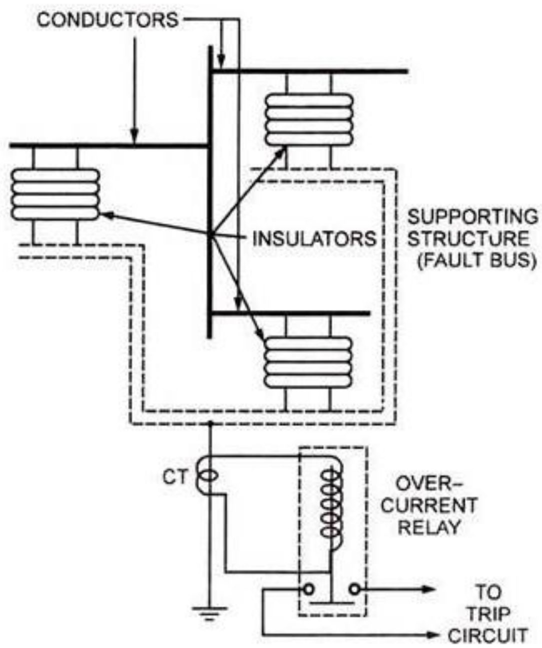


Figure 56: Frame Leakage Protection Scheme

In such type of protection, the only metal supporting structure or fault-bus is grounded through a CT, secondary of which is connected to an overcurrent relay. Under normal operating condition, the relay remains inoperative, but fault involving a connection between a conductor and the ground supporting structure will result in current flow to ground through the fault bus, causing the relay to operate. The operation of the relay will trip all the breakers connecting equipment to the bus.

8.3 Differential Over Current Protection

a) Current Differential Protection

The current differential protection scheme works on the principle of the circulating current which states that the current enters into the bus-bar is equal to the current leaving the bus-bar. The sum of the incoming and outgoing junction is equal to zero. If the sum of current is not equal to zero, then the fault occurs in the system. The differential protection scheme is used both for the protection of the phase-to-phase fault and for the ground fault.

Schematic diagram of bus differential protection relay is shown in the figure below. The current transformers are placed on both the incoming and the outgoing end of the bus-bar. The secondary terminals of the current transformer are parallel connected to each other.

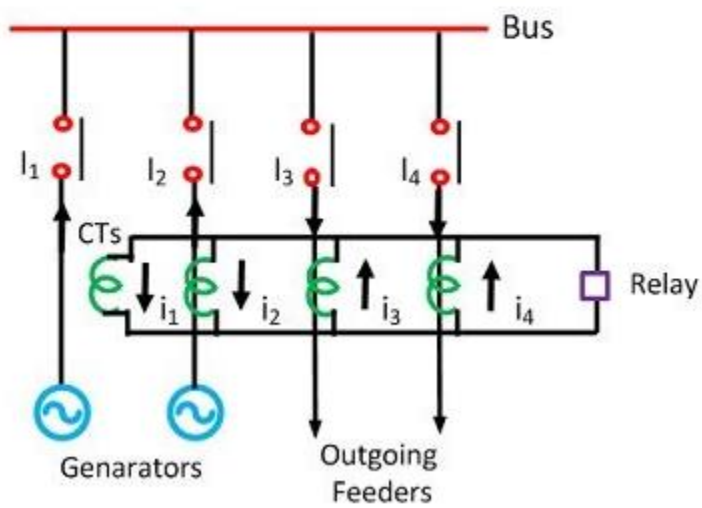


Figure 57: Schematic diagram for Bus Differential Protection

The summation current of the current transformer flows through the operating coil of the relay. The current flows through the relay coils indicates the short circuit current present on the secondary of the CTs. Thus, the relay sends the signal to the circuit breakers to open the contacts.

The drawback of such types of the scheme is that the iron cored current transformer causes the fault operation of the relay at the time of the external fault.

b)Voltage Differential Protection Relay

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

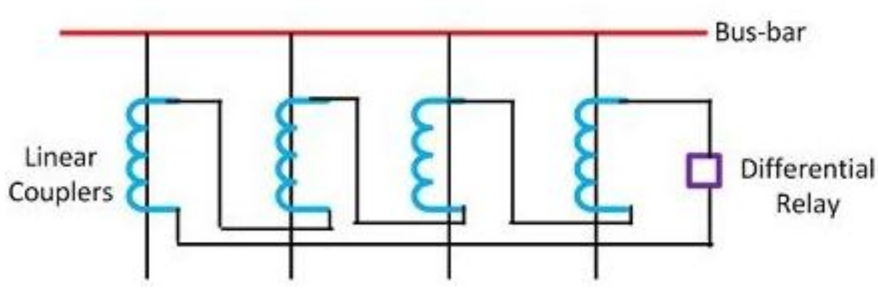


Figure 58: Voltage Differential Relay for Bus Bar

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

Unit 9: Feeder and Transmission Line Protection

Feeder protection is defined as the protection of the feeder from the fault so that the power grid continues supply the energy. The feeder injects the electrical energy from the substation to the load end. So, it is essential to protect the feeder from the various type of fault. The main requirement of the feeder protection are:

1. During the short circuit, the circuit breaker nearest to the fault should open and all other circuit breakers remain in a closed position.
2. If the breaker nearest to the fault fails to open then, backup protection should be provided by the adjacent circuit breaker.
3. The relay operating time should be small to maintain the system stability without necessary tripping of a circuit.

9.1 Time Graded Protection

This is a scheme in which the time setting of relays is so consecutive that in the event of a fault, the smallest possible part of the system is isolated. The applications of time graded are explained below.

9.1.1 Protection of Radial Feeders

The main characteristic of a radial system is that power flow only in one direction, i.e. from the generator or the supply end to the load end. It has the drawback that continuity of supply cannot be controlled at the load end in the occurrence of a fault.

In a radial system when the number of feeders is connected in series as shown in the figure. It is desired that the smallest possible part of the system should be off. This is conveniently achieved by employing time graded protection. The over current system should be adjusted in such a way that the longer the relay from the generating station the lesser the time of operation.

When the fault occurs on the SS_4, the relay OC_5 should operate first and not any other i.e. the time require to operate the relay OC_4 must be less than the time required for relay OC_3 and so on. This shows that the time setting required for these relays must be properly graded. The minimum interval of time which can be allowed for the two adjacent circuit breaker depends on its own clearance time, plus a small time for the safety margin.

With normal circuit breaker in use minimum, the discriminating time between adjustment breaker should be about 0.4 seconds. The time settings for relay OC_1, OC_2, OC_3, OC_4, and OC_5 will be 0.2 seconds, 1.5 seconds, 1.5 seconds, 1.0 seconds, 0.5 second and instantaneous respectively. Along with the grading system, it is also essential that the time of operation for the severe fault should be less. This can be done by using time limiting fuse in parallel with the trip coils.

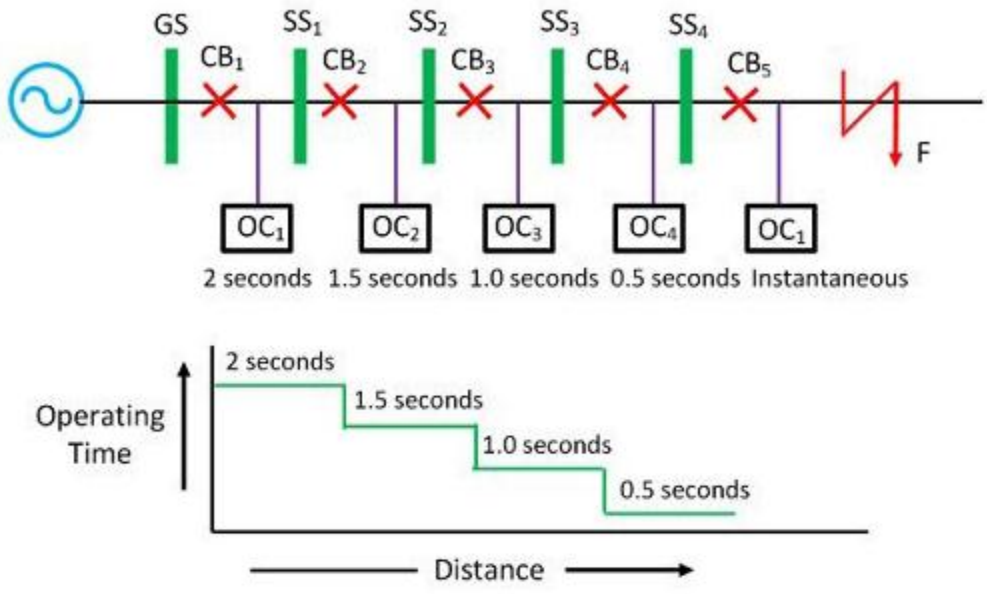


Figure 59: Time Graded Protection for Radial Feeder

9.1.2 Protection of Parallel Feeders

The parallel connection of the supply is mainly used for the continuity of the supply and for sharing the load. When the fault occurs on the protective feeder, the protective device will select and isolate the defective feeder while the other instantly assume the increased load.

One of the simplest methods for the protection of the relay is the time graded overload relay with inverse time characteristic at the sending end and instantaneous reverse power or directional relays at the receiving end as shown in the figure below.

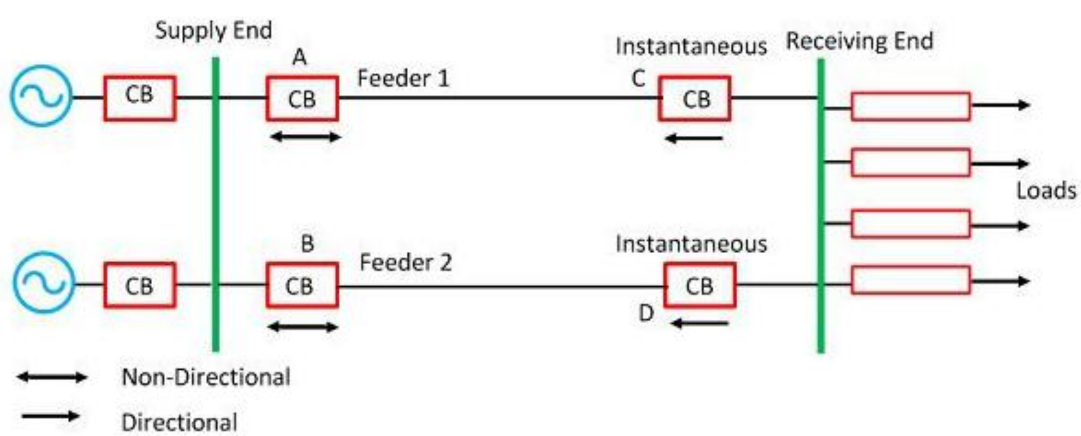


Figure 60: Protection of Parallel Feeder

When the heavy fault F occur on any one of the lines, then the power is fed into fault from the sending end as well as from the receiving end of the line. The direction of power flow will be reversed through the relay on D, which will be open.

The excess current is then restricted to B until its overload relay operates and trips the circuit breaker, thus completely isolating the faulty feeder and supplying power through the healthy feeder. This method is only satisfactory when the fault is heavy and reverse the power at D. Hence differential protection is also added along with the overloaded protection at both the end of the line.

9.1.3 Protection of Ring Main System

The ring main is a system of interconnection between a series of the power station by a different route. In the main ring system, the direction of power can be changed at will, particularly when the interconnection is used.

The elementary diagram of such a system is shown in the figure below where G is the generating station, and A, B, C, and Dare substations. At the generating station, the power flow only in one direction and hence no time lag overload relays are used. The time grade overload relay is placed at the end of the substation, and it will trip only when overload flows away from the substation which they protect.

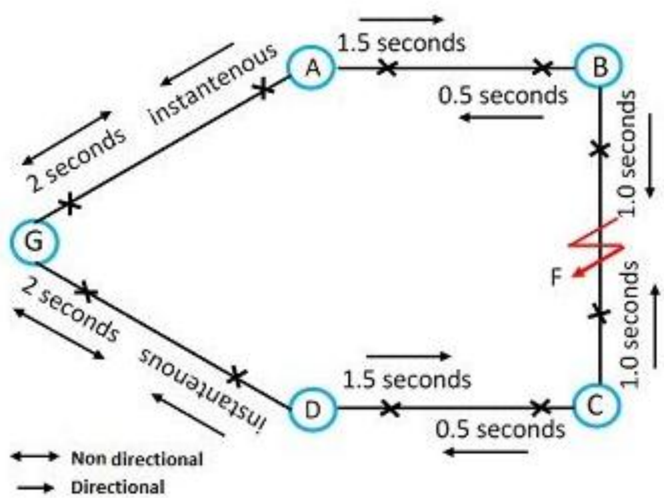


Figure 61: Protection of Ring Main System

Going round the ring in the direction GABCD the relay on the further side of each station are set with decreasing time lags. At generating station 2 seconds at station A, B, C and 1.5 seconds, 1.0 second, 0.5 second and instantaneous respectively. Similarly going round the ring in the opposite direction the relay on the outgoing sides would be set as follows.

If the fault occurs at point F, the power F is fed into the fault through two paths ABF and DCF. The relay to operate is that between substation B and fault point F and substation C and fault point F. Thus, the fault on any section will cause the relay on that section to operate, and the healthy section will be operating uninterruptedly.

9.2 Differential Pilot Wire Protection

This is simply a differential protection scheme applied to feeders. Several differential schemes are applied for protection of line but Merz Price Voltage balance system are most popularly used.

The working principle of Merz Price Balance system is quite simple. In this scheme of line protection, identical CT is connected to each of the both ends of the line. The polarity of the CTs is same. The secondary of these current transformer and operating coil of two instantaneous relays are formed a closed loop as shown in the figure below. In the loop pilot wire is used to connect both CT secondary and both relay coil as shown.

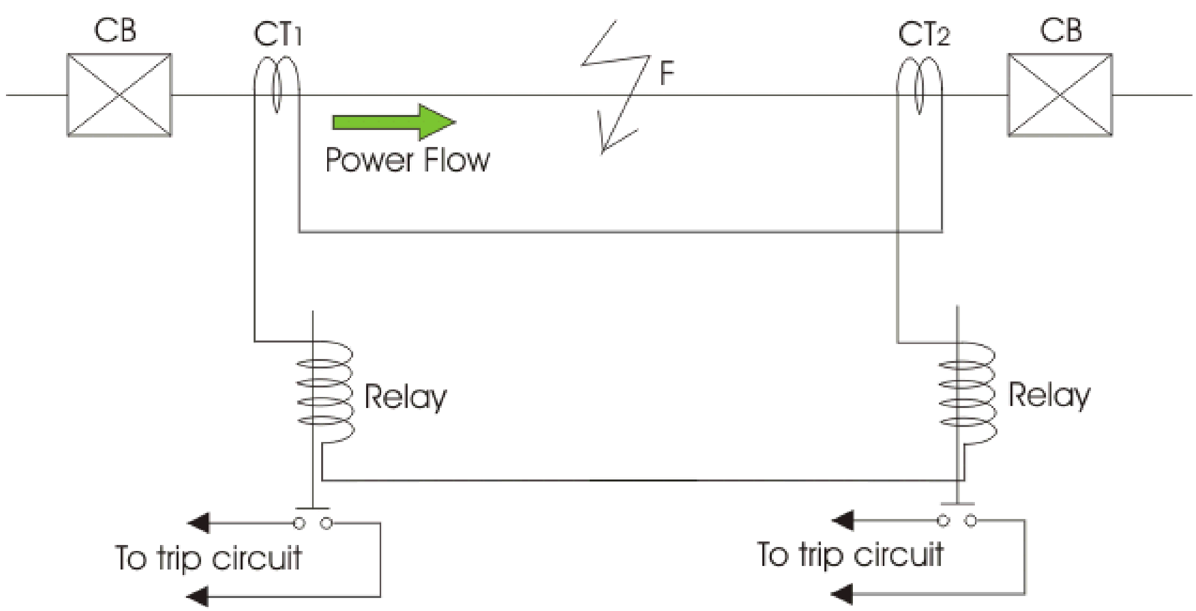


Figure 62: Differential Pilot Wire Protection

Now, from the figure it is quite clear that when the system is under normal condition, there would not be any current flowing through the loop as the secondary current of one CT will cancel out secondary current of other CT. Now, if any fault occurs in the portion of the line between these two CTs, the secondary current of one CT will no longer equal and opposite of secondary current of other CT. Hence there would be a resultant circulating current in the loop. Due to this circulating current, the coil of both relays will close the trip circuit of associate circuit breaker. Hence, the faulty line will be isolated from both ends.

9.3 Distance Protection of Transmission Line

Distance protection relay is the name given to the protection whose action depends on the distance of the feeding point to the fault. The time of operation of such protection is a function of the ratio of voltage and current, i.e., impedance. This impedance between the relay and the fault depends on the electrical distance between them. The principal type of distance relays is impedance relays, reactance relays, and the reactance relays.

Distance protection relay principle differs from other forms of protection because their performance does not depend on the magnitude of the current or voltage in the protective circuit but it depends on the ratio of these two quantities. It is a double actuating quantity relay with one of their coil is energized by voltage and the other coil is energized by the current. The current element produces a positive or pick-up torque while the voltages element has caused a negative and reset torque.

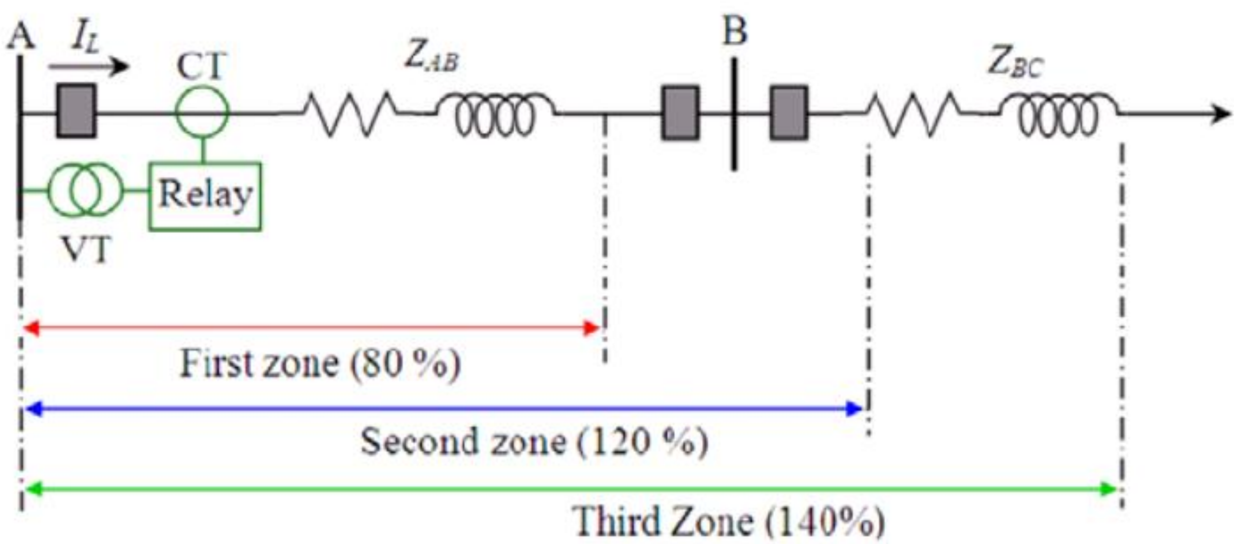


Figure 63: Setting Zone for Distance Protection

The relay operates only when the ratio of voltage and current falls below a set value. During the fault the magnitude of current increases and the voltage at the fault point decreases. The ratio of the current and voltage is measured at the point of the current and potential transformer. The voltage at potential transformer region depends on the distance between the PT and the fault.

If the fault is nearer, measured voltage is lesser, and if the fault is farther, measured voltage is more. Hence, assuming constant fault impedance each value of the ratio of voltage and current measured from relay location comparable to the distance between the relaying point and fault point along the line. Hence such protection is called the distance protection or impedance protection.

Distance zone is non-unit protection, i.e., the protection zone is not exact. The distance protection is high-speed protection and is simply to apply. It can be employed as a primary as well as backup protection. It is very commonly used in the protection of transmission lines.

Distance relays are used for both phase fault and ground fault protection, and they provide higher speed for clearing the fault. It is also independent of changes in the magnitude of the short circuits, current and hence they are not much affected by the change in the generation capacity and the system configuration. Thus, they eliminate long clearing times for the fault near the power sources required by overcurrent relay if used for the purpose.

Application of Distance Protection Relay

Distance protection relay is widely spread employed for the protection of high-voltage AC transmission line and distribution lines. They have replaced the overcurrent protection because of the following reasons.

- It provides faster protection as compared to overcurrent relay.
- It has a permanent setting without the need for readjustments.
- Direct protection relay has less effect of an amount of generation and fault levels.
- Their fault current magnitude permits the high line loading.

Distance protection schemes are commonly employed for providing the primary or main protection and backup protection for AC transmission line and distribution line against three phase faults, phase-to-phase faults, and phase-to-ground faults.

9.3.1 Adjustment of Distance Relay

All the relays are energised through CTs and PTs, the primary value of impedance must be converted to secondary values. For conversion of primary impedance to a secondary value for use in adjusting a phase or ground distance relay, the following relation is used.

Secondary impedance, $Z_{sec} = \frac{V_2}{I_2} = \frac{V_1}{PT\ Ratio} \times \frac{CT\ Ratio}{I_1} = \frac{V_1}{I_1} \times \frac{CT\ Ratio}{PT\ Ratio} = Z_{prim} \times \frac{CT\ Ratio}{PT\ Ratio}$

Where the CT ratio is the ratio of high-voltage phase current to the relay phase current and the PT ratio is the ratio of high-voltage phase to phase voltage and the relay phase to phase voltage all under balanced 3 phase condition.

Thus, for a 100 Km, 132 KV line with 600/5 Y-connected CTs and PT ratio 132KV/110 V the secondary positive phase sequence impedance

$=100\times 0.5 \times \frac{600}{5} \times \frac{110}{132000} = 5\Omega$

where average positive phase sequence reactance value is about 0.5 Ω/Km

first zone is usually covered to protect only 80% of first section. So, secondary positive phase sequence impedance to reach 80% length $=0.8\times 5=4\Omega$

This value of the secondary impedance should fall within the relay setting.

9.4 Numerical Solution

Example 14.1. A ring feeder with five sections and fed at one point is to be protected using directional overcurrent (DOC) relays and overcurrent (OC) relays with suitable time grading. Explain the working of the scheme. Show the location of DOCs and OCs and their time of operation. Assume a time grading of 5 ms between the relays. The fastest relay needs 5 ms for it to operate.

[U.P.S.C. I.E.S. Electrical Engineering-II, 2011]

Solution : A ring feeder with five sections and fed at one point is shown in Fig. 14.8 where G is the generating station and A, B, C and D

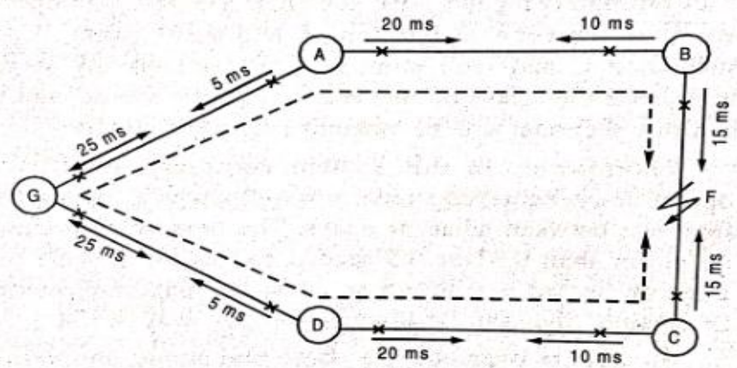


Fig. 14.8. ***Ring Feeder With Five Sections and Supplied at One Point***

are the substations. At the generating station, the power flows only in one direction *i.e.*, away from the bus-bars, so non-directional time lag overcurrent (OC) relays are used. The time graded directional relays are used at both sides of each substation and they are set so that they will only trip when an overload flows away from the substation which they protect. Going round the ring in the direction GABCD, the relays on the farther side of each section are set with decreasing time lags; for instance at generating station 25 ms and at substations A, B, C and D 20 ms, 15 ms, 10 ms and 5 ms respectively (providing time grading of 5 ms with the fastest relay with operating time of 5 ms at substation D). Similarly going round the ring in the opposite directions, the relays on the outgoing sides would be set as follows :

Generating station G = 25 ms; substations D = 20 ms; C = 15 ms; B = 10 ms and A 5 ms A study of the diagram will make it clear that a short circuit occurring at any point on the ring feeder will cause only the two immediately adjacent circuit breakers to operate.

If a fault occurs at point F, the power is supplied into the fault through two paths ABF and DCF. The relays to operate are that between substation B and the fault point F and substation C and fault point F. Thus, fault on any section will cause the relays on that section only to operate and the healthy sections will be operating uninterruptedly.

Unit 10: Digital Protection Device and Protection Scheme

With the rapid growth of electrical transmission and distribution systems during last fifty years and with the advent of much larger power stations and interconnected systems, the duty imposed upon protective gear become more and more severe. The basis of so called, static relaying is the use of circuit components to obtain a variety of functions and operating characteristics which for the protection purposes have traditionally been obtained using electromechanical devices. The need of fast and reliable protective schemes was realized because short circuit levels, circuit ratings and complexity of interconnection have increased. Shorter operating time have become more essential for preserving dynamic stability of the system. Experience shows that such requirements can readily be met by using static relays, which are capable of performing electronic circuit control functions in a manner similar to that of an electromagnetic relay without using moving parts.

10.1 Essential Component of Static Relay

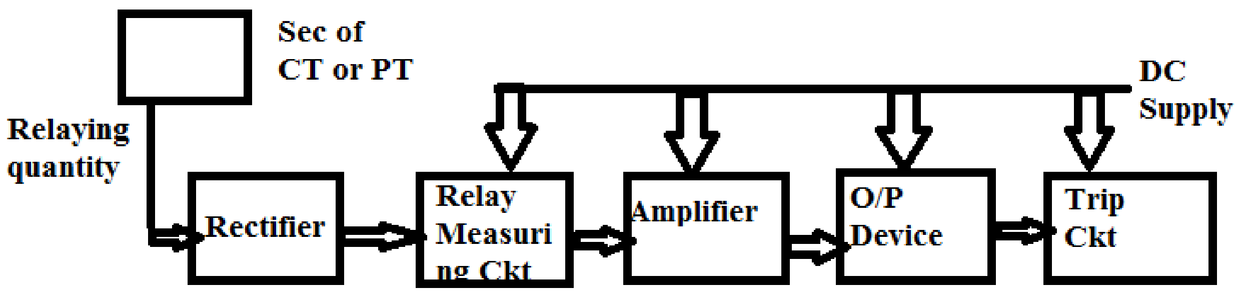


Figure 64: Block Diagram of Static Relay

The essential component of static relay is shown in the figure.

The relaying quantity i.e. output of CT or PT or transducer is rectified by a rectifier. The rectified output is supplied to measuring unit of comparators, level detector, filters or logic circuit. The output is actuated when the input attains the threshold value. This output is amplified by amplifier and fed to output device which is usually an electromagnetic one.

The relaying quantity such as voltage/current is rectified and measured. When the quantity under measurement attains certain well-defined value, the output device is triggered and thereby the circuit breaker trip circuit is energized.

10.2 Comparison of Static and Electromagnetic Relays

The static relay in comparison to electromagnetic relays have many advantages and few limitations.

Advantages of static Relay

1. The power consumption in case of static relays is usually much lower than that in case of electromagnetic relay. Hence the burden on CT and PT is reduced and their accuracy is increased.
2. Quick response, long life, high reliability and high degree of accuracy.

3. Absence of moving contacts and associated problem of arcing.
4. Use of printed circuit avoids the wiring errors.
5. Static relays are very compact. A single static relay can perform several functions. Space required for installation is reduced.
6. Ease of providing amplification enables greater sensitivity to be obtained.

Disadvantages of static Relay

1. Auxiliary DC supply is required.
2. Semiconductor components are sensitive to electrostatic discharge.
3. Static relays are sensitive to voltage spikes and voltage transients.
4. Characteristics of static relays are influenced by ambient temperature and ageing.
5. The static relay has low short time overload capacity compared to electromagnetic relay.
6. Highly trained persons are required for their servicing.

10.3 Static Over Current Relays

The block diagram of static over current relay is shown in the figure. The same construction may be used for under voltage and overvoltage.

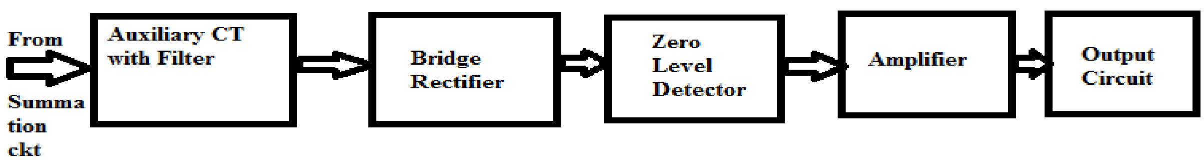


Figure 65: Block Diagram of Static Over Current Relays

The secondaries of the line CTs are connected to a summation circuit. The output of this summation is fed to an auxiliary CT, whose output is rectified, smoothened and supplied to the measuring unit (level detector). The measuring unit determines whether the quantity has attained the threshold value or not. When the input to measuring unit is less than the threshold value, the output of level detector is zero. For an over current relay

For $I_{input} < I_{threshold}$; $I_{0utput} = 0$

For $I_{input} \geq I_{threshold}$;I_{0utput} = present

After the operation of measuring unit, the output is amplified by the amplifier. The amplified output is given to output circuit to cause trip/alarm.

10.4 Directional Static Over Current Relay

Directional relay senses direction of power flow by means of phase angle between V and I. When the phase angle between V and I exceed certain predefined value, the directional relay operates with condition that the current is above pickup value. Thus directional relay is a double actuating quantity relay with one input as current from CT and the other input as V from PT.

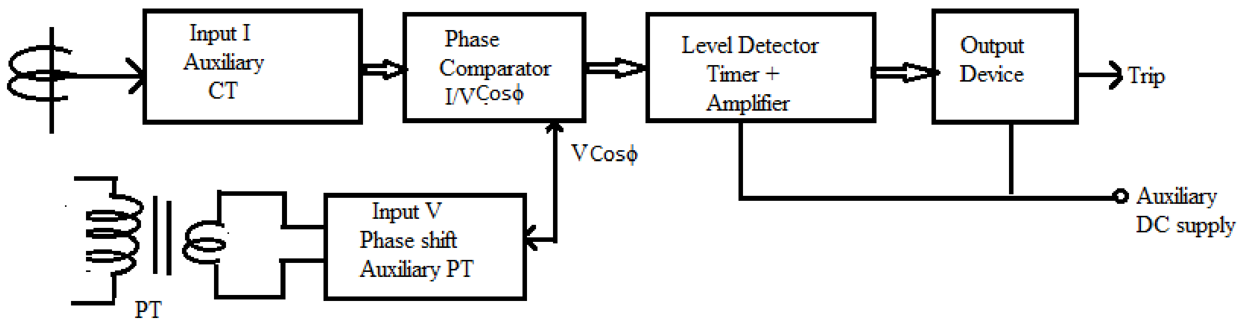


Figure 66:Block Diagram of Directional Static Over Current Relay

Figure shows the static directional relay with two input inputs (V and I). The inputs are supplied to the phase comparator. A phase shifter is included in the voltage input circuit, whose output is fed to the phase comparator; so that the output from phase comparator under phase faults/earth fault condition is maximum. The output of the level detector is amplified and in case a timer is necessary, the output is applied to the output device through timer.

Relay will operate when $I_s \leq I \cos(\phi - \theta)$.

Where I_s is the magnitude of set current, ϕ is the angle between V and I & θ is the relay characteristics angle. For maximum sensitivity of relay ϕ should be equal to θ.

10.5 Static Differential Relay

The differential relay measures the phasor difference between two similar electrical quantities (voltage-voltage or current-current). The rectifier bridge amplitude comparator is the most common static form for applications such as a differential relay element.

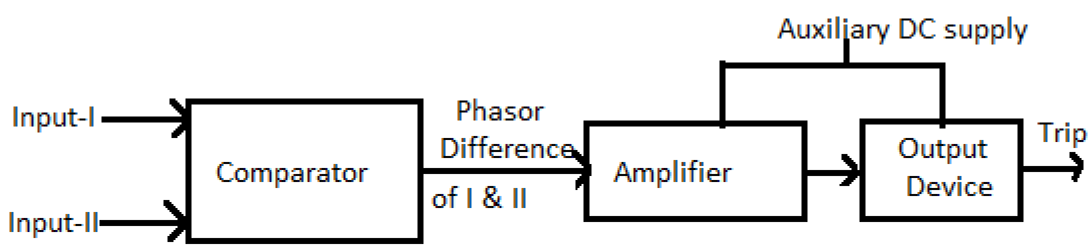


Figure 67: Block Diagram of Static Differential Relay

Input I and II are supplied to the comparator. The output of the comparator (phase difference of I and II) is amplified and used to operate relay. The static differential relays are most commonly used for protection of generators and transformers for any type of internal faults.

These relays are advantageous over electromagnetic differential relays as they are very compact, highly sensitive for internal faults and have absolute stability for heavy through faults, extremely short tripping times (20-50 ms) regardless the magnitude of auxiliary voltage.

Static type percentage difference relay is as shown in figure. The difference of current in the operating coil and restraining coil is fed to the output element for relay operation.

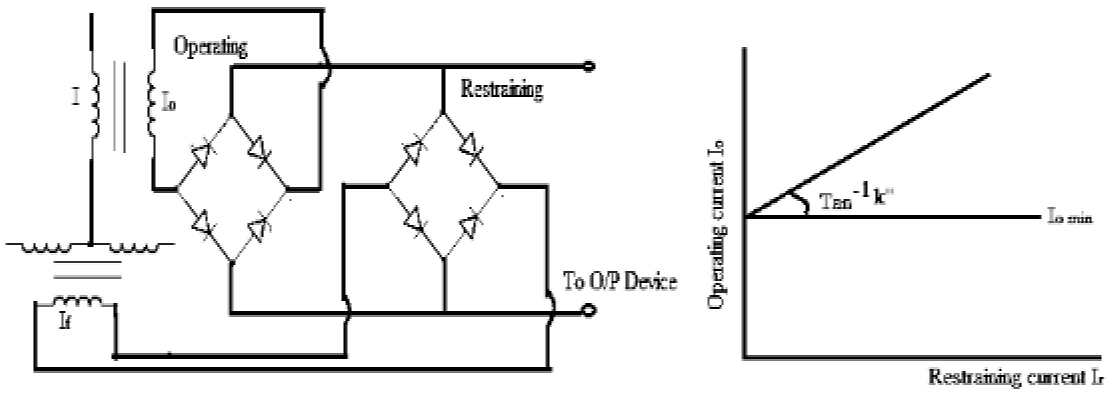


Figure 68: a) Differential Static Relay   b) Relay Characteristics

The relay operates when,

$K_0n_0I_0 > K_rn_rI_r + K'$

Where n_0 & n_r are then numbers of turns on the operating and restraining coils respectively and K_0 & K_r, the design constants and K', the spring control torque constant.

At threshold of operation $K' = K_0n_0I_{0min}$

Now the eqn under threshold becomes,

$K_0n_0I_0 = K_rn_rI_r + K_0n_0I_{0min}$

$I_0 = \frac{K_rn_rI_r}{K_0n_0} + I_{0min}$

$= K''I_r + I_{0min}$

Where $K'' = \frac{K_rn_r}{K_0n_0}$

The above equation is in the form of straight-line y= mx + c

$m = K''$ and $C = I_{0min}$

10.6 Static Distance Relays

a) Impedance Relay

Amplitude Comparison: Impedance relay is inherently an amplitude comparator and inputs are IZ_R and V.

For operation of relay

$|IZ_R| > |V|$

Or, $|Z| < |Z_R|$

Or, $R + jX < Z_R$

For threshold condition $R + jX = Z_R$

Which is an equation of a circle on impedance (R-X) diagram.

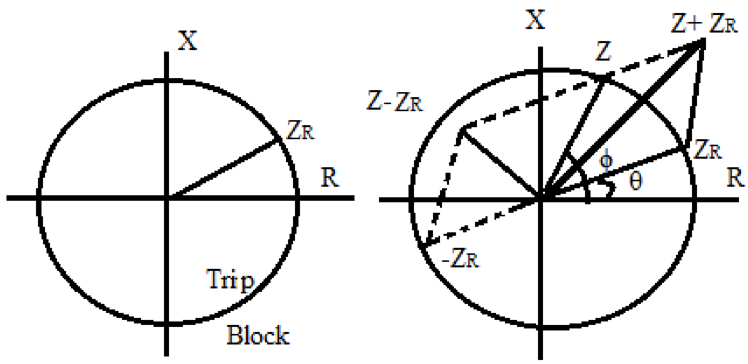


Figure 69:Impedance Relay Characteristics

Phase Comparison: The inputs are $(V + IZ_R)$ and $(V - IZ_R)$. The characteristics is given in figure. It can be seen that as long as Z_R lies along the circumference of the circle with radius Z_R, the two quantities $(Z + Z_R)$ and $(Z - Z_R)$ make an angle of +-90°.

b) Reactance Relay

Amplitude Comparison: This relay is a particular case of an angle impedance relay in which the reactance component of the impedance is measured and therefore, for operation of relay

$|2X_R - Z|>|Z|$

The two inputs are V and $(2IZ_R - 2I_R - V)$ where R_R is made equal to resistance of Z_R. Thus, leaving only its reactive component X_R.

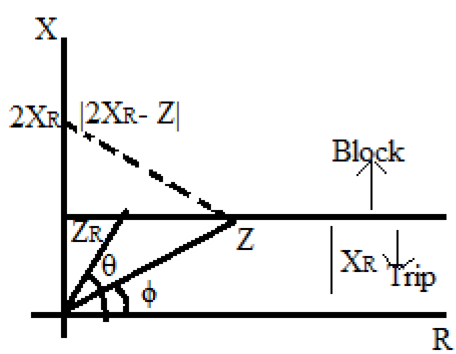


Figure 70: Reactance relay Characteristics

Phase Comparison: The two inputs are IZ_R and $(IZ_R – V)$ as in case of an angle impedance relay. The relay will trip when Z is below the characteristics i.e. when $(\psi + \theta) < 180°$. For Z to be purely reactive ψ would be 90° under threshold condition and the relay would trip when $Z\sin\phi$ is less than X_R on the R-X diagram.

c) Mho Relay

Amplitude Comparison: The two inputs are $|IZ_R|$ and $|2V - IZ_R|$. For relay operation.

$|2V - IZ_R| < |IZ_R|$

$|2V - Z_R| < |Z_R|$

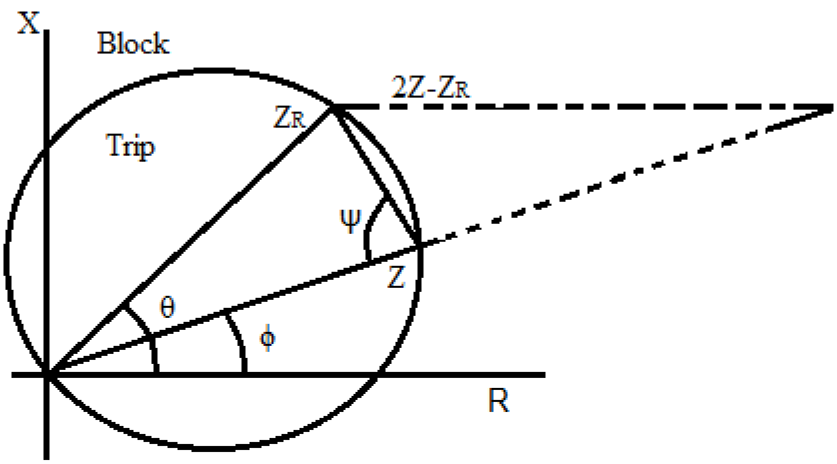


Figure 71:Mho Relay Characteristics

The characteristics is illustrated in figure. The relay will operate as long as the fault impedance Z lies within the circle having diameter Z_R

Phase Comparison: The two inputs are $| IZ_R – V |$ and V and the relay will operate when the phase angle between them is less than 90° i.e. when $90° > \psi > -90°$.

10.7 Microprocessor Based Relay

The above figure shows the block diagram of digital relay. Several components of the digital relays are described below:

The three phase AC input s derived from CTs and PTs are fed to Block 2. Block 2 comprises analog processing compensating circuits. In this block the measured currents and voltages are developed into a set of quantities required for the measurement processing and operation of the relay.

In Block 4 A/D conversion the phase information contained in these quantities are converted from the analog signals to representative square wave digital signals.

The equivalent digital signals from Block 4 fed Block 7 for digital processing. Block 7 consists of phase comparators, logic gates and other digital circuits required for signal processing. Block 7 also receives other external digital signals from Block 3. These include external data regarding back up breaker and other circuits which have an interface with the protective relay.

The digital processing carried out in Block 7 is controlled by current and voltage supervision functions carried out in Block 5.

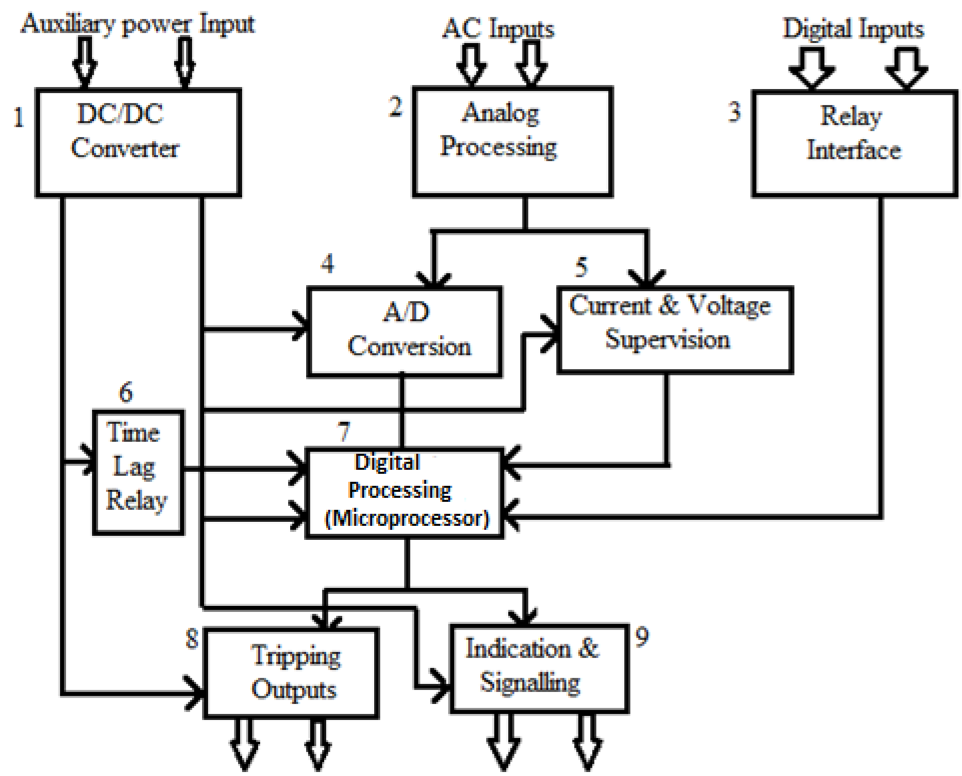


Figure 72: Block diagram of Microprocessor Based Relay

Block 8 provides an interface between relay and circuit breaker trio coils. Block 9 gives indication display on the front face of the relay and is called Man-Machine Interface. In the event of the power system disturbance, for which the relay reacts, the events are displayed on Block 9. Signaling contacts enable communication with peripheral devices like sequence of event recorders, reclosing relays etc. With digital relays there is a provision of fault recorder, fault locater etc.

Block 1 provides the galvanic separation between the station auxiliary DC system and protective relay. The time lag relays in Block 6 determine the operating time of the back-up function of the relay and therefore linked with Block 7.

10.8 Carrier Current Protection of Transmission Lines

Carrier current protection scheme is mainly used for the protection of the long transmission line. In the carrier, current protection schemes, the phase angle of the current at the two phases of the line are compared instead of the actual current. And then the phase angle of the line decides whether the fault is internal and external. The main elements of the carrier channel are a transmitter, receiver, coupling equipment, and line trap.

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

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

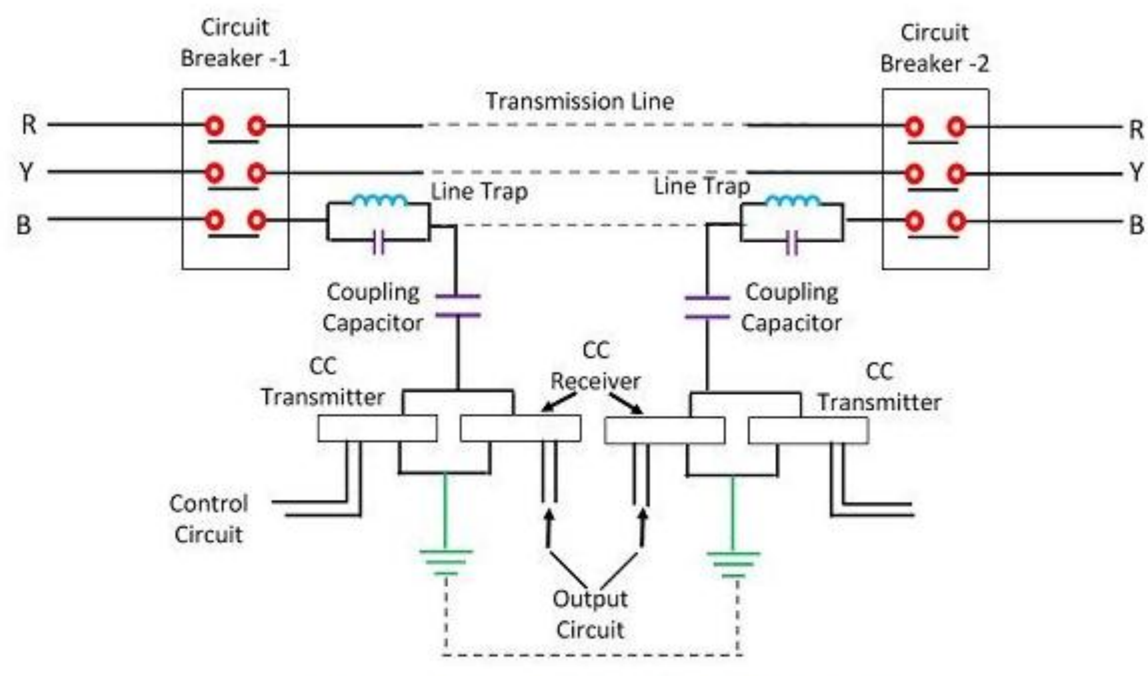


Figure 73: Carrier Current Transmission Line Protection Scheme

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

10.8.1 Methods of Carrier Current Protection

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

1. Directional Comparison protection
2. Phase Comparison Protection

These types are explained below in details

1. Directional Comparison Protection

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

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

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

- **Carrier Permitting Blocking Scheme**: The carrier, protective schemes allow the fault current to enter into the protected section of the system.

2. Phase Comparison Carrier Protection

This system compares the phase relation between the current enter into the pilot zone and the current leaving the protected zone. The current magnitudes are not compared. It provided only main or primary protection and backup protection must be provided also. The circuit diagram of the phase comparison carrier protection scheme is shown in the figure below.

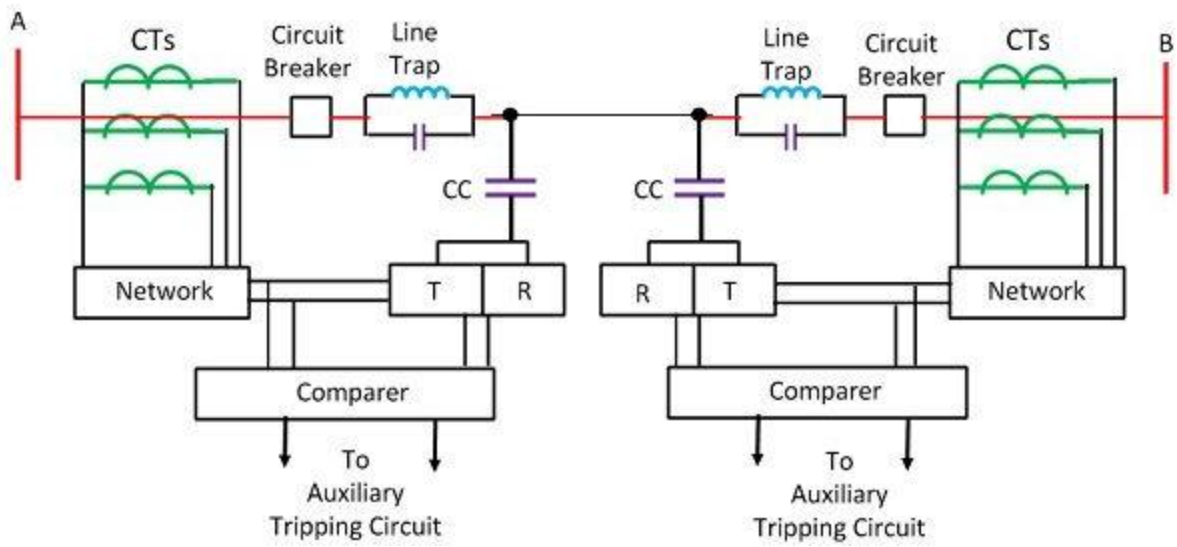


Figure 74:Phase Comparison Carrier Protection Scheme

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

10.8.2 Advantage of Carrier Current Protection

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

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

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

References

- A Course in Power Systems, J.B. Gupta, 2014, S.K. Kataria & Sons, New Delhi
- Switchgear And Protection, U.A.Bakshi, M.V.Bakshi
- Power system Protection and Switchgear, Badri Ram and D.N Vishwakarma, 2nd Edition, 2011, Tata McGraw- Hill
- Principle of Switchgear and Protection, Sandeep Neupane and Ganesh Bhandari, 2017
- A Complete note on Switchgear and Protection, Sandeep Neupane, 2018