Protection and Switchgear

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Chapter-9 Theory of Arc Quenching (9-1 to 9-48)

1 Protective Relaying

1.1 Introduction

Protective relaying is one of the several features of the power system design. Every part of the power system is protected. The factors affecting the choice of protection are type and rating of equipment, location of the equipment, types of faults, abnormal conditions and cost.

The protective relaying is used to give an alarm or to cause prompt removal of any element of power system from service when that element behaves abnormally. The abnormal behaviour of an element might cause damage or interference within effective operation of rest of the system. The protective relaying minimises the damage to the equipment and interruptions to the service when electrical failure occurs. Along with some other equipments the relays help to minimise damage and improve the service.

The relays are compact and self contained devices which can sense the abnormal conditions. Whenever an abnormal condition exists, the relay contacts get closed. This inturn closes the trip circuit of a circuit breaker. The circuit breakers are capable of disconnecting a faulty element, when they are called upon to do so by the relays. Thus entire process includes the operations like occurrence of fault, operation of relay, opening of a circuit breaker and removal of faulty element. This entire process is automatic and fast, which is possible due to effective protective relaying scheme.

The protective relaying scheme includes protective current transformers, voltage transformers, protective relays, time delay relays, auxiliary relays, secondary circuits, trip circuits etc. Each component plays its own role, which is very important in the overall operation of the scheme. The protective relaying is the team work of all these components. The protective relaying also provides the indication of location and type of the fault.

1.2 Functions of Protective Relaying

The various functions of protective relaying are :

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

The faults can not be completely avoided but can be minimised. Thus the protective relaying plays an important role in sensing the faults, minimizing the effects of faults and minimizing the damage due to the faults.

1.3 Protective Zones

In a protective relaying scheme, the circuit breakers are placed at the appropriate points such that any element of the entire power system can be disconnected for repairing work, usual operation and maintenance requirements and also under abnormal conditions like short circuits. Thus a protective covering is provided around each element of the system.

A **protective zone** is the separate zone which is established around each system element. The significance of such a protective zone is that any fault occurring within a given zone will cause the tripping of relays which causes opening of all the circuit breakers located within that zone. The various components which are provided with the protective zones are generators, transformers, transmission lines, bus bars, cables, capacitors etc. No part of the system is left unprotected. The Fig. 1.1 shows the various protective zones, used in a system

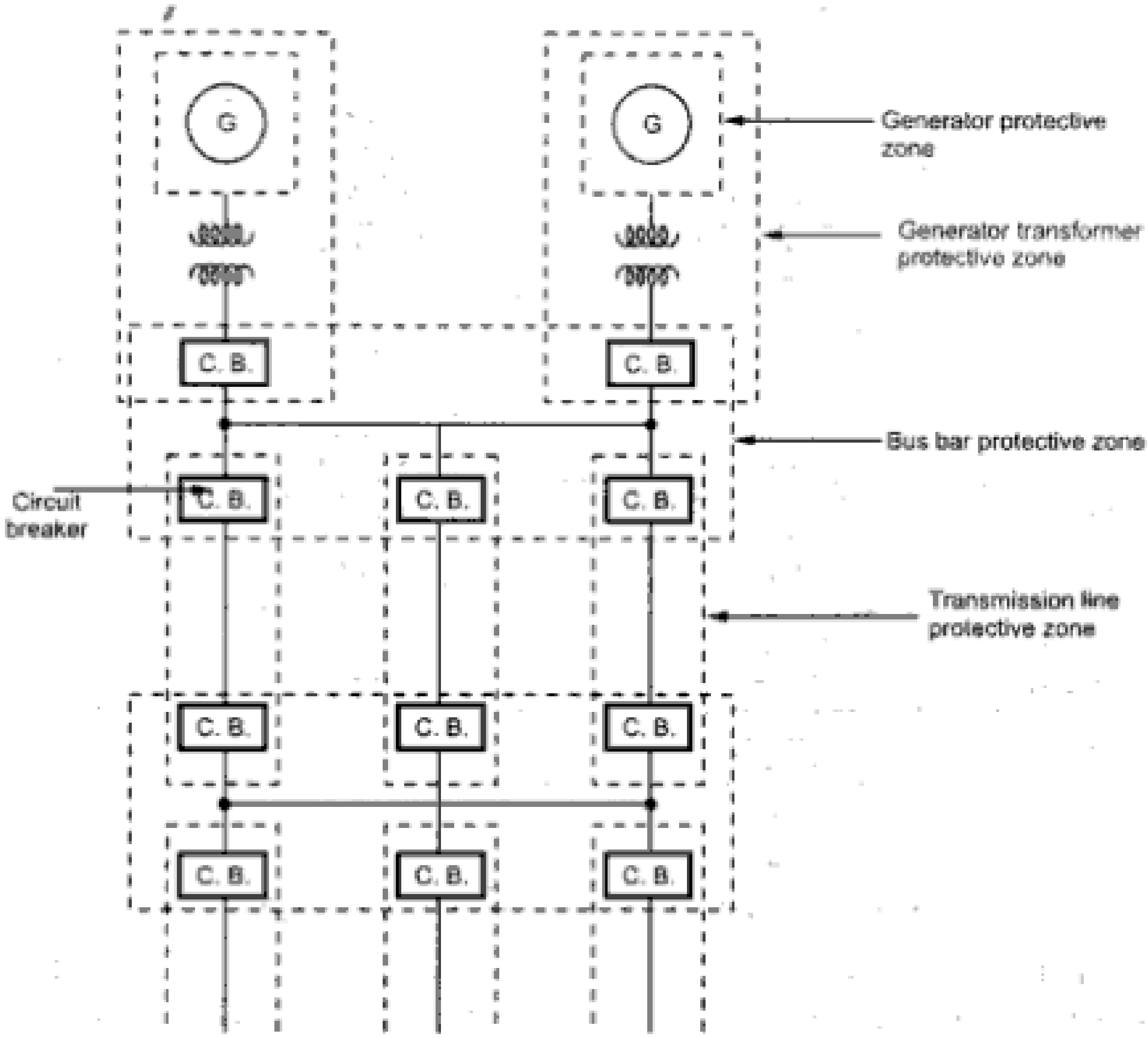


Fig. 1.1 Protective zones

The boundaries of protective zones are decided by the locations of the current transformers.

In practice, various protective zones are overlapped. The overlapping of protective zones is done to ensure complete safety of each and every element of the system. The zone which is unprotected is called dead spot. The zones are overlapped and hence there is no chance of existence of a dead spot in a system. For the failures within the region where two adjacent protective zones are overlapped, more circuit breakers get tripped than minimum necessary to disconnect the faulty element. If there are no overlaps, then dead spot may exist, means the circuit breakers lying within the zone may not trip eventhough the fault occurs. This may cause damage to the healthy system. The extent of overlapping of protective zones is relatively small. The probability of the failures in the overlapped regions is very low, consequently the tripping of too many circuit breakers will be also infrequent. The Fig. 1.2 shows the overlapping of protective zones in the primary relaying.

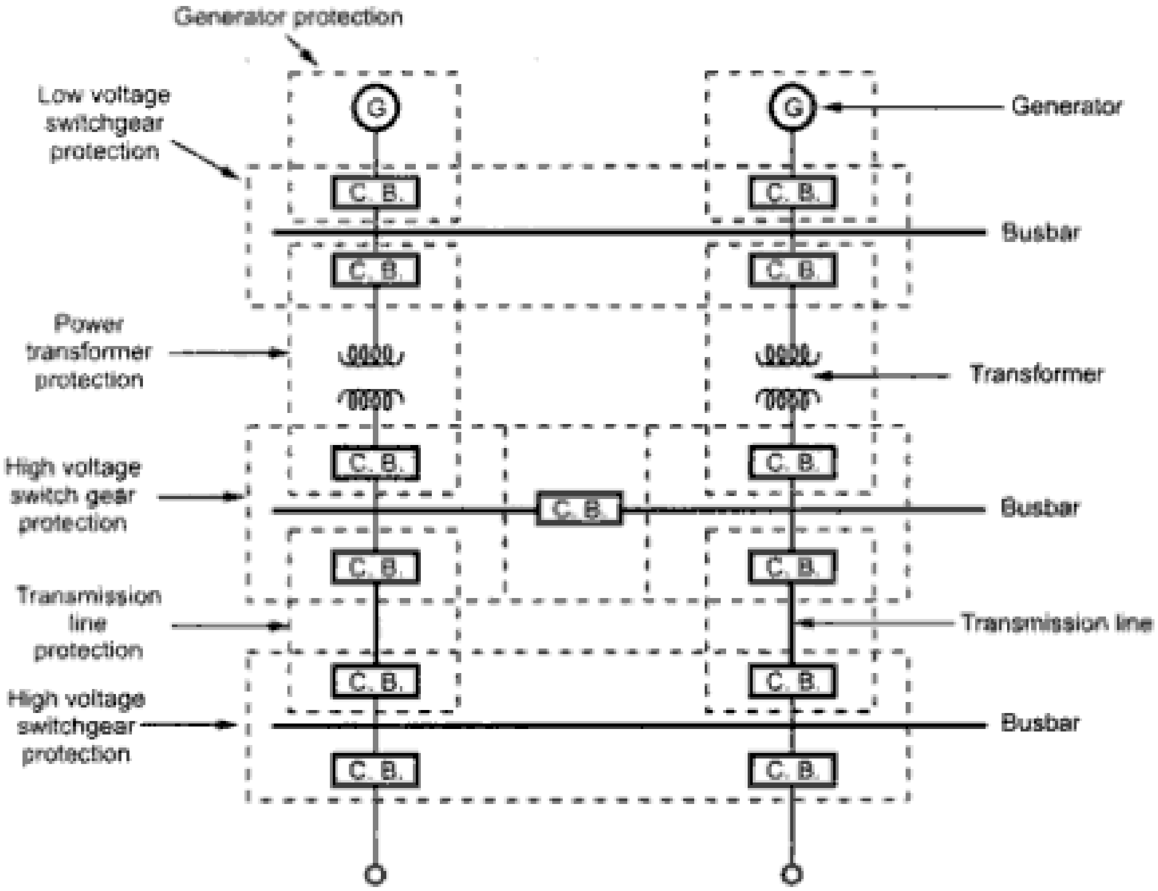


Fig. 1.2 Overlapping zones in primary relaying

It can be seen from the Fig. 1.2 that the circuit breakers are located in the connections to each power system element. This provision makes it possible to disconnect only the faulty element from the system. Ocassionally for economy in the number of circuit breakers, a breaker between the two adjacent sections may be omitted but in that case both the power system sections are required to be disconnected for the failure in either of the two.

Each protective zone has certain protective scheme and each scheme has number of protective systems.

1.4 Primary and Backup Protection

The protection provided by the protective relaying equipment can be categorised into two types as :

1. Primary protection
2. Backup protection

The primary protection is the first line of defence and is responsible to protect all the power system elements from all the types of faults. The backup protection comes into play only when the primary protection fails.

The backup protection is provided as the main protection can fail due to many reasons like,

1. Failure in circuit breaker
2. Failure in protective relay
3. Failure in tripping circuit
4. Failure in d.c. tripping voltage
5. Loss of voltage or current supply to the relay

Thus if the backup protection is absent and the main protection fails then there is a possibility of severe damage to the system.

When the primary protection is made inoperative for the maintenance purpose, the backup protection acts like a main protection. The arrangement of backup protective scheme should be such that the failure in main protection should not cause the failure in back up protection as well. This is satisfied if back up relaying and primary relaying do not have anything common. Hence generally backup protection is located at different stations from the primary protection. From the cost and economy point of view, the backup protection is employed only for the protection against short circuit and not for any other abnormal conditions.

1.4.1 Concept of Backup Relaying

Consider the backup relaying employed for the transmission line section EF as shown in the Fig. 1.3.

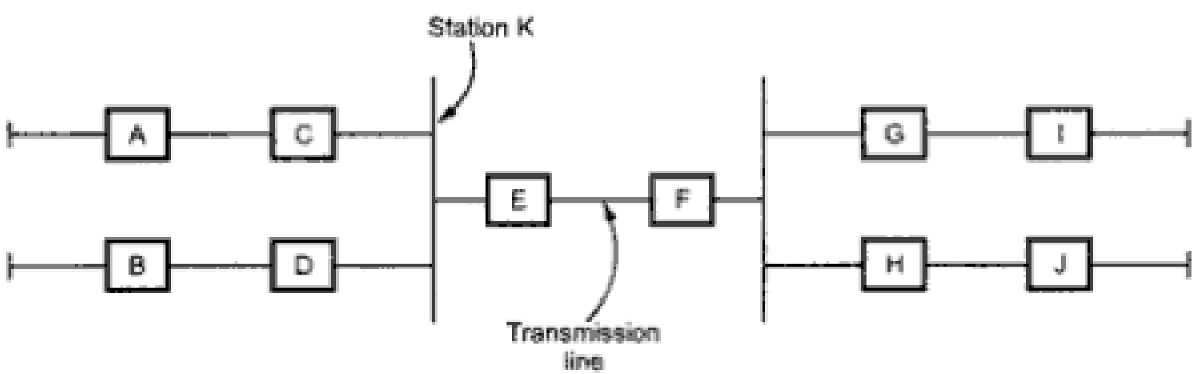


Fig. 1.3 Backup relaying

The relays C, D, G and H are primary relays while A, B, I and J are the backup relays.

Normally backup relays are tripped if primary relay fails. So if the primary relay E fails to trip, then backup relays A and B get tripped. The backup relays and associated backup relaying equipments are physically apart from the faulty equipment.

The backup relays A and B provide backup protection for fault at station K. Also the backup relays at A and F provide the backup protection for the faults in line DB.

The backup relaying often provides primary protection when the primary relays are out of service for repairs.

It is obvious that when the backup relay operates, the larger part of the system is disconnected.

The important requirement of backup relaying is that it must operate with sufficient time delay so that the primary relaying is given a chance to operate. When fault occurs, both the type of relays starts relaying operation but primary is expected to trip first and backup will then reset without having had time to complete its relaying operation.

When the given set of relays provides the backup protection for several adjacent system elements then the slowest primary relaying of any of those will determine the necessary time delay of the given backup relays.

1.4.2 Methods of Backup Protection

The various methods used for the backup protection are classified as,

1. **Relay Backup Protection :** In this scheme, a single breaker is used by both primary as well as backup protection but the two protective systems are different.
2. **Breaker Backup Protection :** In this method, separate breakers are provided for primary and backup protection. Both the types of breakers are at the same station.
3. **Remote Backup Protection :** In this method, separate breakers are provided for primary and backup protection. The two types of breakers are at the different stations and are completely isolated and independent of each other.
4. **Centrally Co-ordinated Backup Protection :** In this method, primary protection is at various stations. There is a central control room and backup protection for all the stations is at central control room. Central control continuously inspects the load flow and frequency in the system. If any element of any part of the system fails, load flow gets affected which is sensed by the control room. The control source consists of a digital computers which decides the proper switching action. The method is also called centrally controlled backup protection.

1.5 Nature and Causes of Faults

Any fault in electrical apparatus is nothing but the defect in its electrical circuit which makes current path directed from its intended path. Normally due to breaking of conductors or failure of insulation, these faults occur. The other reasons for occurance of fault include mechanical failure, accidents, excessive internal and external stresses. The impedance of the path in the fault is low and the fault currents are comparatively large. The reduction of the insulation is not considered as a fault until its shows some effect such as excessive current flow or reduction of impedance between conductors or between conductors and earth.

When a fault occurs on a system, the voltages of the three phases become unbalanced. As the fault currents are large, the apparatus may get damaged. The flow of power is diverted towards the fault which affects the supply to the neighbouring zone.

A power system consists of generators, transformers, switchgear, transmission and distribution circuits. There is always a possibility in such a large network that some fault will occur in some part of the system. The maximum possibility of fault occurance is on transmission lines due to their greater lengths and exposure to atmospheric conditions.

The faults can not be totally eliminated from the system but their occurance can be minimised by improving system design, quality of the equipment and maintenance.

The faults can be classified according to causes of their incidence. The breakdown may occur at normal voltage due to deterioration of insulation. The breakdown may also occur due to damage on account of unpredictable causes which include perching of birds, accidental short circuiting by snakes, kite strings, three branches etc. The breakdown may occur at abnormal voltages due to switching surges or surges caused by lighting.

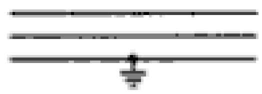
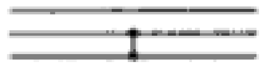
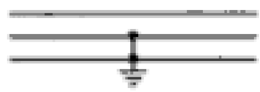
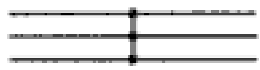
The AC faults can also be classified as single line to ground fault, double line to ground fault, three phase fault, that may occur in the system due to unbalance in current and voltage, over voltages, reversal of power, power swings, under frequency, temperature rise and instability.

It may be necessary to know the frequency of the fault occurance on various parts of the system which help in designing suitable protection circuit. Following table gives us an idea as to how the faults are distributed in the various parts of the system.

	Equipment	% of total faults
1)	Overhead lines	50
2)	Switchgear	15
3)	Transformer	12
4)	Cables	10
5)	Miscellaneous	8
6)	Control equipment	3
7)	CTs and PTs	2

Table 1.1

It can be seen from the above table that maximum number of faults are occuring on overhead lines. In case of three phase system, the breakdown of insulation between one of the phases and earth is known as line to ground fault. In line to line fault, there is insulation breakdown between either of the two phases. While the insulation breakdown between two phases and earth forms double line to ground fault. The breakdown of insulation between three phases is nothing but three phase fault. Following table gives occurance of these faults.

	Type of Fault	Representation	% occurance
1)	Line to Graound (L-G		85
2)	Line to Line (L-L)		8
3)	Line to Line to Ground (L-L-G)		5
4)	Line to Line to Line (L-L-L)		2 or Less

It can be seen from the above table that most of the faults are line to ground faults in case of overhead lines. A large number of these faults are transitory in nature. The word transitory refers to the fault which remains for short duration of time. The fault current varies with time. For example if a twig falls across a line and across arm and burns itself out or just falls down then the fault is transient as it vanishes after few cycles. During first one to three cycles, the fault current is very high but later on decreases very rapidly. This zone in which the current is very high but decreases very rapidly is called 'sub transient' state. After these first few cycles, the rate of current decrease is slower. This zone is called 'transient' state. This state remains for several cycles. After the transient state is over, steady state is reached. During the steady state, the rms value of short circuit current remains constant. The circuit breaker operates during transient state.

This fault current produced by line to ground fault has considerable magnitude. So the protective system must be properly designed so as to have reliable operation of relays under line to ground fault.

The Line to Line to Line (L-L-L) fault is nothing but symmetrical three phase fault which normally occurs due to carelessness of operating personnel. Usually the phase lines are tied together with the help of a bare conductor so as to protect the lineman working on the lines agains inadvertent charging of the line. Sometimes after the work, if lineman forgets to remove the tie up between phase lines and if the circuit breaker is closed then three phase symmetrical fault occurs.

The most serious effect of uncleared fault is nothing but fire which destroys the equipment, spreads up in the system and causes total failure. The most common type of fault which may prove to be dangerous is short circuit. Due to this fault, there is great reduction in line voltage over a major part of the power system. There is damage which may result to the elements of the system by electric arc which accompanies short circuit. The other apparatus in the system are damaged due to overheating and due to setting up of abnormal mechanical forces. The stability of the power system is disturbed which may sometimes result in complete shut down of the power system. Due to reduction in voltage, currents drawn by motors are abnormally high. This may result into loss of industrial production. So such faults are avoided from occuring by designing suitable and reliable but economical protective scheme.

1.6 Fault Current Calculation using Symmetrical Components

In case of three phase balanced system, currents and voltages are equal in magnitude and are displaced from each other by 120°. The currents and voltages are thus said to be symmetrical. The analysis of such system is easy which is done on per phase basis. But when the load is unbalanced, the analysis using normal techniques becomes difficult. Under such case, method of symmetrical components can be adopted as suggested by Fortescue. According to his theorem, the unbalanced phasors can be resolved into three balanced systems of phasors. The balanced sets of component can be given as (a) positive sequence component (b) negative sequence component (c) zero sequence component.

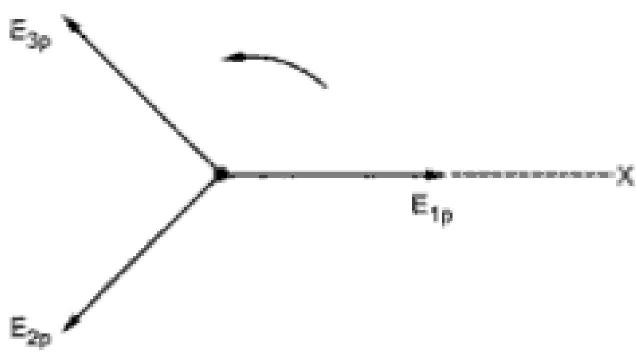


Fig. 1.4 Positive phase sequence with anticlockwise rotation of vectors (1-2-3)

A system of vectors is having positive phase sequence when it has all vectors having same magnitude and are displaced by 120°. They have same time interval to achieve fixed axis of reference as that of generated voltage. The positive sequence is designated by use of subscript P. It is shown in the Fig. 1.4 The vectors come to X axis in order of 1, 2 and 3.

A system of vector is having negative phase sequence when it has all vectors having same magnitude and are displaced by 120°. But arrive at the reference axis at a regular interval same as that of positive sequence but in reverse order i.e. in order of 1, 3, 2. It is shown in the Fig. 1.4 suffix n is used to designate negative sequence.

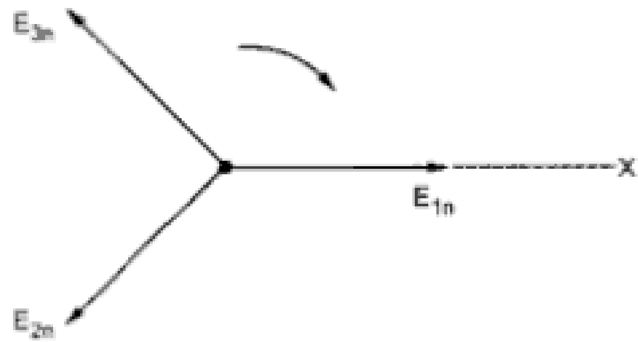


Fig. 1.5 Negative phase sequence with clockwise rotation of vectors (1-3-2)

Fig. 1.5(a) Zero phase sequence

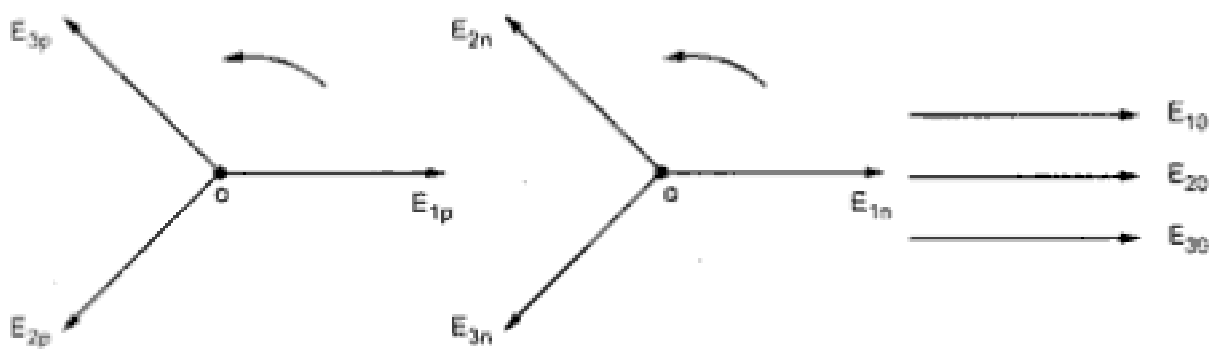
A system of vectors is having zero phase sequence if all the three vectos are not displaced in time from each other and there will be no phase sequence. In such cases the current or voltage in the 3 phase circuit will vary simultaneoulsy in all the 3 phases. Such a phase sequence is shown in the Fig. 1.5(a) suffix 0 is used to designate zero sequrnce.

Consider a system having three vectors and it can be resolved into positive, negative and zero phase sequence components as shown int the Fig. 1.6 It is possible to get 3 vectors by using following equations.

$$E_1 = E_{1p} + E_{1n} + E_{10}$$

$$E_2 = E_{2p} + E_{2n} + E_{20}$$

$$E_3 = E_{3p} + E_{3n} + E_{30}$$



i) Positive sequence of phase **ii) Negative sequence of phase** **iii) Zero sequence of phase**

Fig. 1.6

Consider in general a power system network as shown in the Fig. 1.7 suppose that fault occurs at point P in this system. Due to this currents I_r, I_y, I_b flow out of the system while V_r, V_y, V_b are the line voltages with respect to ground.

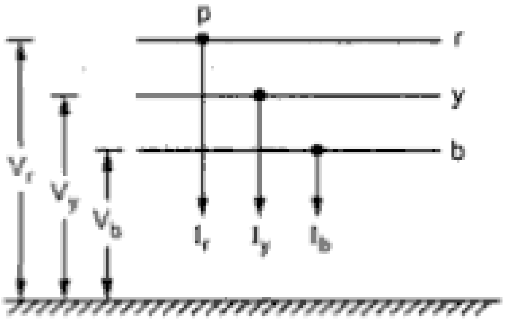


Fig. 1.7

If it is assumed that the system is operating at no load before occuring a fault, then the positive sequence voltages of all synchronous machines will be equal and has value same as prefault voltage at P. Let this voltage be E_r.

The voltage E_r is present only in the positive sequence network. There is no coupling between sequence network, the sequence voltages at P can be given in terms of sequence currents and Thevenin sequence impedance as

$$\begin{bmatrix} V_{rp} \\ V_{rn} \\ V_{r0} \end{bmatrix} = \begin{bmatrix} E_r \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_p & 0 & 0 \\ 0 & Z_n & 0 \\ 0 & 0 & Z_0 \end{bmatrix} \begin{bmatrix} I_{rp} \\ I_{rn} \\ I_{r0} \end{bmatrix}$$

Based on the types of fault, the sequence voltages and currents are constrained resulting to a particular connection of sequence networks. The sequence currents and voltages and fault currents and fault voltages can then be easily obtained.

1.7 Essential Qualities of Protective Relaying

A protective relaying scheme should have certain important qualities. Such an essential qualities of protective relaying are,

1. Reliability
2. Selectivity and Discrimination
3. Speed and Time
4. Sensitivity
5. Stability
6. Adequateness
7. Simplicity and Economy

1.7.1 Reliability

A protective relaying should be reliable is its basic quality. It indicates the ability of the relay system to operate under the predetermined conditions. There are various components which go into the operation before a relay operates. Therefore every component and circuit which is involved in the operation of a relay plays an important role. The reliability of a protection system depends on the reliability of various components like circuit breakers, relays, current transformers (C.T.s), potential transformers (P.T.s), cables, trip circuits etc. The proper maintenance also plays an important role in improving the reliable operation of the system. The reliability can not be expressed in the mathematical expressions but can be judged from the statistical data. The statistical survey and records give good idea about the reliability of the protective system. The inherent reliability is based on the design which is based on the long experience. This can be achieved by the factors like,

i) Simplicity ii) Robustness

iii) High contact pressure iv) Dust free enclosure

iv) Good contact material vi) Good workmanship and

vii) Careful maintenance

1.7.2 Selectivity and Discrimination

The selectivity is the ability of the protective system to identify the faulty part correctly and to disconnect that part without affecting the rest of the healthy part of system. The discrimination means to distinguish between. The discrimination quality of the protective system is the ability to distinguish between normal condition and abnormal condition and also between abnormal condition within protective zone and elsewhere. The protective system should operate only at the time of abnormal condition and not at the time of normal condition. Hence it must clearly discriminate between normal and abnormal condition. Thus the protective system should select the faulty part and disconnect only the faulty part without disturbing the healthy part of the system.

The protective system should not operate for the faults beyond its protective zone. For example, consider the portion of a typical power system shown in the Fig. 1.8.

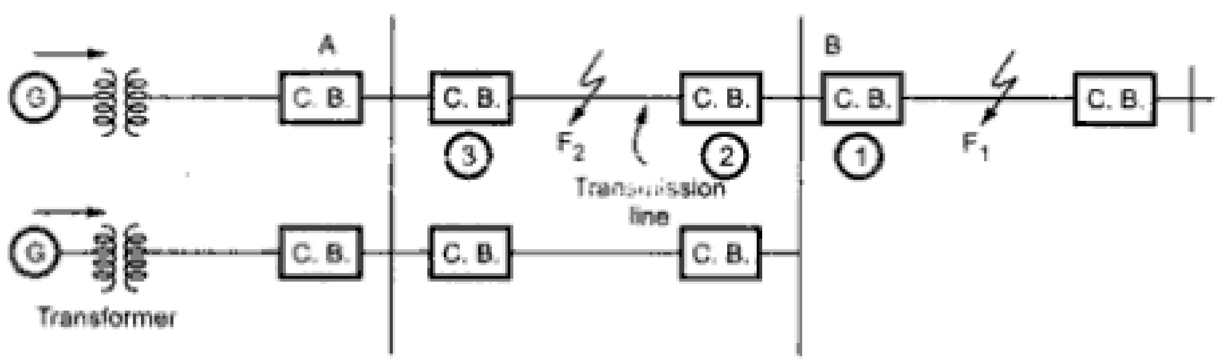


Fig. 1.8

It is clear from the Fig. 1.8 that if fault F_2 occurs on transmission line then the circuit breakers 2 and 3 should operate and disconnect the line from the remaining system. The protective system should be selective in selecting faulty transmission line only for the fault F_2 and it should isolate it without tripping the adjacent transmission line breakers or the transformer.

If the protective system is not selective then it operates for the faults beyond its protective zones and unnecessary the large part of the system gets isolated. This causes a lot of inconvenience to the supplier and users.

1.7.3 Speed and Time

A protective system must disconnect the faulty system as fast as possible. If the faulty system is not disconnected for a long time then,

1. The devices carrying fault currents may get damaged.
2. The failure leads to the reduction in system voltage. Such low voltage may affect the motors and generators running on the consumer side.
3. If fault persists for long time, then subsequently other faults may get generated.

The high speed protective system avoids the possibility of such undesirable effects.

The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is called fault clearing time. It is the sum of relay time and circuit breaker time. The relay time is the time between the instant of fault occurrence and the instant of closure of relay contacts. The circuit breaker time is the time taken by the circuit breaker to operate to open the contacts and to extinguish the arc completely. The fault clearing time should be as small as possible to have high speed operation of the protective system.

Though the small fault clearing time is preferred, in practice certain time lag is provided. This is because,

1. To have clear discrimination between primary and backup protection
2. To prevent unnecessary operation of relays under the conditions such as transients, starting inrush of current etc.

Thus fast protective system is an important quality which minimises the damage and it improves the overall stability of the power system.

1.7.4 Sensitivity

The protective system should be sufficiently sensitive so that it can operate reliably when required. The sensitivity of the system is the ability of the relay system to operate with low value of actuating quantity.

It indicates the smallest value of the actuating quantity at which the protection starts operating in relation with the minimum value of the fault current in the protected zone.

The relay sensitivity is the function of the volt-amperes input to the relay coil necessary to cause its operation. Smaller the value of volt-ampere input, more sensitive is the relay. Thus 1VA input relay is more sensitive than the 5VA input relay.

Mathematically the sensitivity is expressed by a factor called sensitivity factor K_S. It is the ratio of minimum short circuit current in the protected zone to the minimum operating current required for the protection to start.

$$K_S = \frac{I_s}{I_o}$$

where K_S = sensitivity factor

I_S = minimum short circuit current in the zone

I_o = minimum operating current for the protection

1.7.5 Stability

The stability is the quality of the protective system due to which the system remains inoperative and stable under certain specified conditions such as transients, disturbance, through faults etc. For providing the stability, certain modifications are required in the system design. In most of the cases time delays, filter circuits, mechanical and electrical bias are provided to achieve stable operation during the disturbances.

1.7.6 Adequateness

There are variety of faults and disturbances those may practically exists in a power system. It is impossible to provide protection against each and every abnormal condition which may exist in practice, due to economical reasons. But the protective system must provide adequate protection for any element of the system. The adequateness of the system can be assessed by considering following factors,

1. Ratings of various equipments
2. Cost of the equipments
3. Locations of the equipments
4. Probability of abnormal condition due to internal and external causes.
5. Discontinuity of supply due to the failure of the equipment

1.7.7 Simplicity and Economy

In addition to all the important qualities, it is necessary that the cost of the system should be well within limits. In practice sometimes it is not necessary to use ideal protection scheme which is economically unjustified. In such cases compromise is done. As a rule, the protection cost should not be more than 5% of the total cost. But if the equipments to be protected are very important, the economic constraints can be relaxed.

The protective system should be as simple as possible so that it can be easily maintained. The complex system are difficult from the maintenance point of view. The simplicity and reliability are closely related to each other. The simpler systems are always more reliable.

1.8 Classification of Protective Relays

All the relays consist of one or more elements which get energised and actuated by the electrical quantities of the circuit. Most of the relays used now a days are electro-mechanical type which work on the principles of electromagnetic attraction and electromagnetic induction.

1.8.1 Electromagnetic Attraction Type Relays

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

1. **Solenoid Type :** In this relay, the plunger or iron core moves into a solenoid and the operation of the relay depends on the movement of the plunger.
2. **Attracted Armature Type :** This relay operates on the current setting. When current in the circuit exceeds beyond the limit, the armature gets attracted by the magnetic force produced by the undesirable current. The current rating of the circuit in which relay is connected plays an important role in the operation of the relay.
3. **Balanced Beam Type :** In this relay, the armature is fastened to a balanced beam. For normal current, the beam remains horizontal but when current exceeds, the armature gets attracted and beam gets tilted causing the required operation.

1.8.2 Induction Type Relays

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

1. **Induction Disc Type :** In this relay, a metal disc is allowed to rotate between the two electromagnets. The electromagnets are energised by alternating currents. The two types of constructions used for this type are shaded pole type and watthour meter type.
2. **Induction Cup Type :** In this relay, electromagnets act as a stator and energised by relay coils. The rotor is metallic cylindrical cup type.

1.8.3 Directional Type Relays

These relays work on the direction of current or power flow in the circuit. The various types of these relays are,

1. **Reverse Current Type :** The relay is actuated when the direction of the current is reversed or the phase of the current becomes more than the predetermined value.
2. **Reverse Power Type :** The relay is actuated when the phase displacement between applied voltage and current attains a specified value.

1.8.4 Relays Based on Timing

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

1. **Instantaneous Type :** In this type no time is lost between operation of relay and tripping of contacts. No intentional time delay is provided.
2. **Definite Time Lag Type :** In this type intentionally a definite time lag is provided between operation of relay and tripping of contact.
3. **Inverse Time Lag type :** In this type, the operating time is approximately inversely proportional to the magnitude of the actuating quantity.

1.8.5 Distance Type Relays

These relays work on the principle of measurement of voltage to current ratio. In this type, there are two coils. One coil is energised by current while other by voltage. The torque produced is proportional to the ratio of the two quantities. When the ratio reduces below a set value, the relay operates. The various types of these relays are,

1. **Impedance Type :** In this type, the ratio of voltage to current is nothing but an impedance which is proportional to the distance of the relay form the fault point.
2. **Reactance Type :** The operating time is proportional to the reactance which is proportional to the distance of the relay from the fault point.
3. **Admittance Type :** This is also called mho type. In this type, the operating time is proportional to the admittance.

1.8.6 Differential Type Relays

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

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

1.8.7 Other Types of Relays

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

1. **Under voltage, current, power relay :** This relay operates when the voltage, current or power in a circuit falls below a set value.
2. **Over voltage, current, power relay :** This relay actuates when the voltage, current or power in a circuit rises above a set value.
3. **Thermal Relay :** This relay actuates due to the heat produced by the current in the relay coil.
4. **Rectifier Relay :** In this relay, the quantities to be sensed are rectified and then given to the moving coil unit of the relay.
5. **Permanent Magnet Moving Coil Relay :** In this relay, the coil carrying current is free to rotate in the magnetic field of a permanent magnet. This is used for d.c. only.
6. **Static Relay :** This relay uses some electronic method for sensing the actuating quantity. It uses a stationary circuit.
7. **Gas Operated Relay :** The gas pressure is adjusted according to the variations in the actuating quantity. This gas pressure is used to actuate the relay. Buchholz relay is an example of such type of relay.

1.9 Terminologies used in Protective Relaying

The various terminologies used in the protective relaying are,

1. **Protective Relay :** It is an electrical relay, which closes its contacts when an actuating quantity reaches a certain preset value. Due to closing of contacts, relay initiates a trip circuit of circuit breaker or an alarm circuit.
2. **Relay Time :** It is the time between the instant of fault occurrence and the instant of closure of relay contacts.
3. **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.

4. **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.

5. **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.

6. **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.

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

8. **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.

9. **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.

10. **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 tappings on the relay coil, which are brought out to a plug bridge as shown in the Fig. 1.9. The tap values are expressed in terms of percentage full load rating of current transformer (C.T.) with which relay is associated.

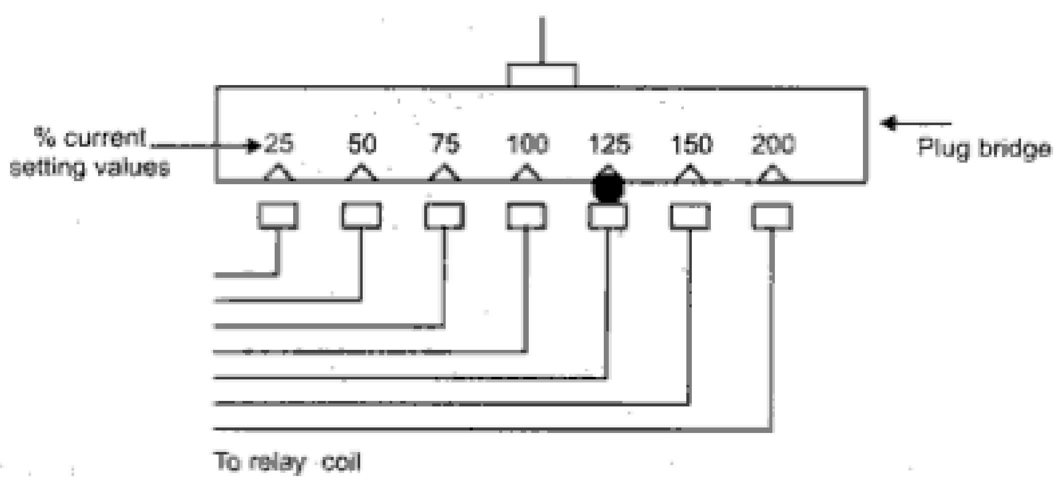


Fig. 1.9 Tapping for current setting

Thus the value of pickup current can be obtained as,

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

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

11. **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,

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

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

12. **Time/P.S.M. Curve :** For a relay, a curve showing relation between time and plug-setting multiplier is provided which is called time/P.S.M. curve. A typical curve for a relay is shown in the Fig. 1.10.

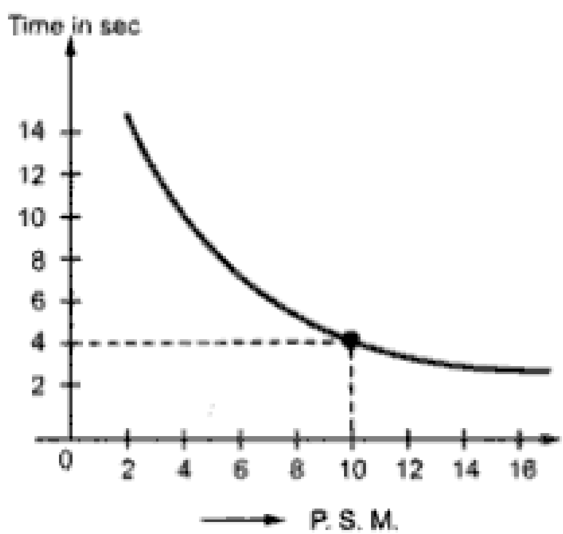


Fig. 1.10 Time / P.S.M. curve

It can be observed that for low values of overcurrents the operating time varies inversely with the current. But as the current increases and approaches upto 20 times its rated value then the time becomes almost constant. This type of characteristics is necessary to ensure discrimination on very high fault currents flowing through healthy part of the system.

Using this curve and time-setting multiplier, the actual time of operation of a relay can be obtained. For example, the time in seconds corresponding to P.S.M. of 10 is 4 seconds as shown in the Fig. 1.10. Multiplying this by a time-setting multiplier, actual time of operation can be obtained.

13. **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

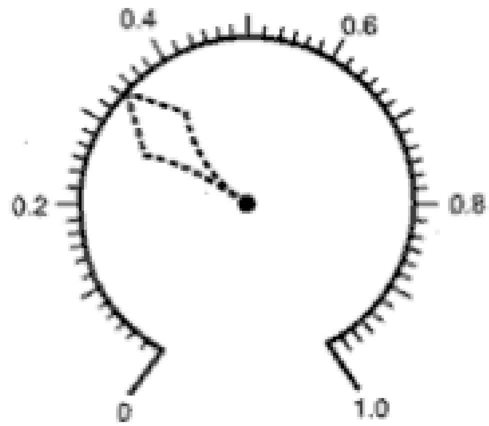


Fig. 1.11 Time-setting multiplier

known as time-setting multiplier. Its dial is calibrated from 0 to 1 in steps of 0.05 as shown in the Fig. 1.11.

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 × time-setting multiplier

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

14. **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.

15. **Earth Fault :** The fault involving earth is called earth fault. The examples of earth fault are single line to ground fault, double line to ground fault etc.

16. **Phase Fault :** The fault which does not involve earth is called phase fault. The example is line to line fault.

17. **Protective Scheme :** The combination of various protective systems covering a particular protective zone for a particular equipment is called protective scheme. For example a generator may be provided with protective systems like overcurrent, differential, earth fault etc. The combination of all these systems is called generator protective scheme.

18. **Protective System :** The combination of circuit breakers, trip circuits, C.T. and other protective relaying equipments is called protective system.

19. **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.

20. **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.

1.10 Instrument Transformers

In heavy currents and high voltage a.c. circuits, the measurement can not be done by using the method of extension of ranges of low range meters by providing suitable shunts. In such conditions, specially constructed accurate ratio transformers called **instrument transformers**. These can be used, irrespective of the voltage and current ratings of the a.c. circuits. These transformers not only extend the range of the low range instruments but also isolate them from high current and high voltage a.c. circuits. This makes their handling very safe. These are generally classified as (i) current transformers and (ii) potential transformers.

1.11 Current Transformers (C.T.)

The large alternating currents which can not be sensed or passed through normal ammeters and current coils of wattmeters, energymeters can easily be measured by use of current transformers along with normal low range instruments.

A transformer is a device which consists of two windings called primary and secondary. It transfers energy from one side to another with suitable change in the level of current or voltage. A current transformer basically has a primary coil of one or more turns of heavy cross-sectional area. In some, the bar carrying high current may act as a primary. This is connected in series with the line carrying high current.

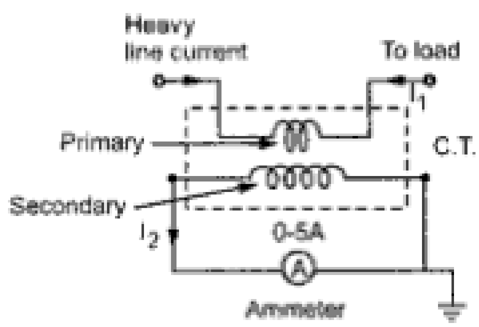


Fig. 1.12 Current transformer

The secondary of the transformer is made up of a large number of turns of fine wire having small cross-sectional area. This is usually rated for 5A. This is connected to the coil of normal range ammeter. Symbolic representation of a current transformer is as shown in the Fig. 1.12.

1.11.1 Working Principle

These transformers are basically step up transformers i.e. stepping up a voltage from primary to secondary. Thus the current reduces from primary to secondary. So from current point of view, these are step down transformers, stepping down the current value considerably from primary to secondary.

Let N_1 = Number of turns of primary

N_2 = Number of turns of secondary

I_1 = Primary current

I_2 = Secondary current

For a transformer,

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

As N_2 is very high compared to N_1, the ratio I_1 to I_2 is also very high for current transformers. Such a current ratio is indicated for representing the range of current transformer. For example, consider a 500 : 5 range then it indicates that C.T. Steps down the current from primary to secondary by a ratio 500 to 5.

$$\therefore \quad \frac{I_1}{I_2} = \frac{500}{2}$$

Knowing this current ratio and the meter reading on the secondary, the actual high line current flowing through the primary can be obtained.

➡ **Example 1.1 :** *A 250 : 5, current transformer is used along with an ammeter. If ammeter reading is 2.7 A, estimate the line current.*

Solution :

$$\frac{I_1}{I_2} = \frac{250}{5}$$

But as ammeter is in secondary, $I_2 = 2.7$ A

$$\therefore \quad \frac{I_1}{2.7} = \frac{250}{5}$$

$$\therefore \quad I_1 = 135 \text{ A}$$

So line current is 135 A.

1.12 Construction of Current Transformers

There are two types of constructions used for the current transformers which are,

1. Wound type
2. Bar type

1.12.1 Wound Type Current Transformer

In wound type construction, the primary is wound for more than one full turn, on the core. The construction is shown in the Fig. 1.13.

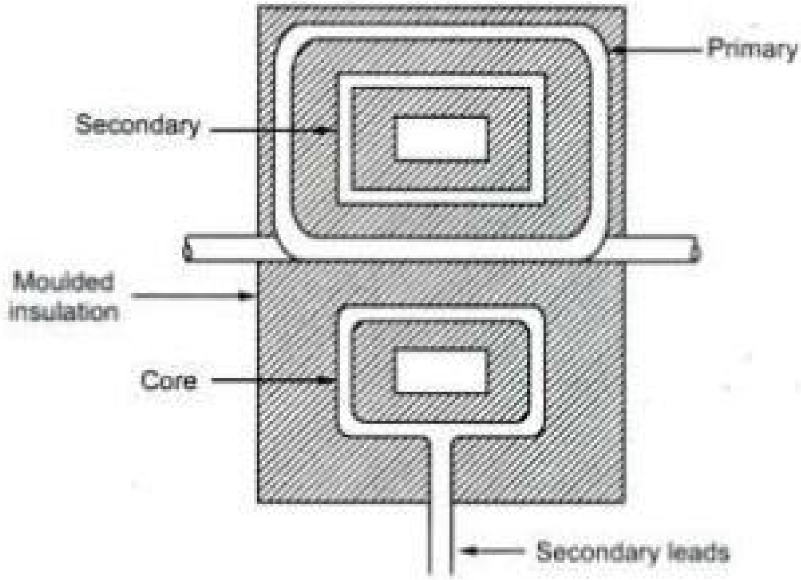
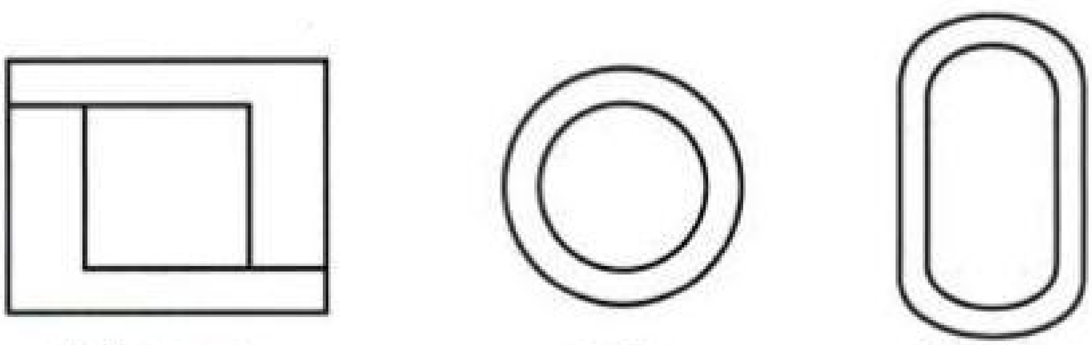


Fig. 1.13 Wound type current transformer

In a low voltage wound type current transformer, the secondary winding is wound on a bakelite former. The heavy primary winding is directly wound on the top of the secondary winding with a suitable insulation in between the two. Otherwise the primary is wound completely separately and then taped with suitable insulating material and assembled with the secondary on the core.

The current transformers can be ring type or window type. Some commonly used shapes for the stampings of window type current transformers are shown in the Fig. 1.14.



(a) Rectangular (b) Ring (c) Stadium

Fig. 1.14 Stampings for current transformers

The core material for wound type is nickel-iron alloy or an oriented electrical steel. Before installing the secondary winding on core it is insulated with the help of end collars and circumferential wraps of pressboards. Such pressboards provide additional insulation and protection to the winding from damage due to the sharp corners.

1.12.2 Bar Type Current Transformer

In this type of current transformer, the primary winding is nothing but a bar of suitable size. The construction is shown in the Fig. 1.15.

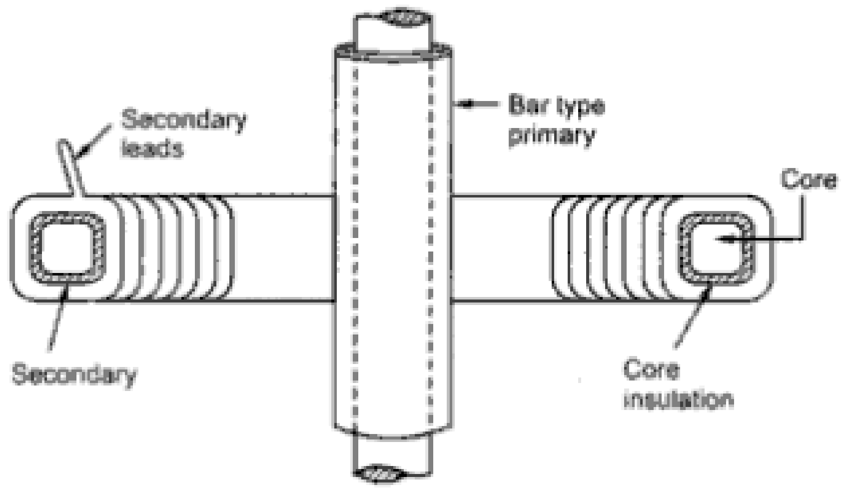


Fig. 1.15 Bar type current transformer

The insulation on the bar type primary is bakelized paper tube or a resin directly moulded on the bar. Such bar type primary is the integral part of the current transformer. The core and the secondary windings are same in bar type transformer.

The stampings used for the laminations in current transformers must have high cross-sectional area than the ordinary transformers. Due to this, the reluctance of the interleaved corners remains as low as possible. Hence the corresponding magnetizing current is also small. The windings are placed very close to each other so as to reduce the leakage reactance. To avoid the corona effect, in bar type transformer, the external diameter of the tube is kept large.

The windings are so designed that without damage, they can withstand short circuit forces which may be caused due to short circuit in the circuit in which the current transformer is inserted.

For small line voltages, the tape and varnish are used for insulation. For line voltages above 7 kV the oil immersed or compound filled current transformers are used.

1.13 Why Secondary of C.T. Should not be Open ?

It is very important that the secondary of C.T. should not be kept open. Either it should be shorted or must be connected in series with a low resistance coil such as current coils of wattmeter, coil of ammeter etc. If it is left open, then current through secondary becomes zero hence the ampere turns produced by secondary which generally oppose primary ampere turns becomes zero. As there is no counter m.m.f., unopposed primary m.m.f. (ampere turns) produce high flux in the core. This produces excessive core losses, heating the core beyond limits. Similarly heavy e.m.fs will be induced on the primary and secondary side. This may damage the insulation of the winding. This is danger from the operator point of view as well. It is usual to ground the C.T. on the secondary side to avoid a danger of shock to the operator.

Hence never open the secondary winding circuit of a current transformer while its primary winding is energised.

Thus most of the current transformers have a short circuit link or a switch at secondary terminals. When the primary is to be energised, the short circuit link must be closed so that there is no danger of open circuit secondary.

1.14 Potential Transformers (P.T.)

The basic principle of these transformers is same as current transformers. The high alternating voltage are reduced in a fixed proportion for the measurement purpose with the help of potential transformers. The construction of these transformers is similar to the normal transformer. These are extremely accurate ratio step down transformers. The windings are low power rating windings. Primary winding consists of large number of turns while secondary has less number of turns and usually rated for 110 V, irrespective of the primary voltage rating. The primary is connected across the high voltage line while secondary is connected to the low range voltmeter coil. One end of the secondary is always grounded for safety purpose. The connections are shown in the Fig. 1.16.

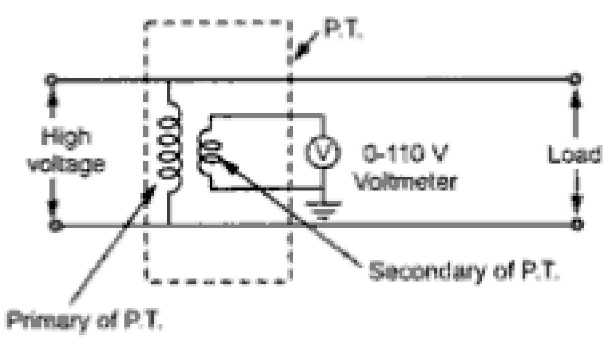


Fig. 1.16 Potential transformer

As a normal transformer, its ratio can be specified as,

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

So if voltage ratio of P.T. is known and the voltmeter reading is known then the high voltage to be measured, can be determined.

➡ **Example 1.2 :** *A 11000 : 110, potential transformer is used along with a voltmeter reading 87.5V. Estimate the value of line voltage.*

Solution : For a P.T.

$$\frac{V_1}{V_2} = \frac{11000}{110}$$

and $$V_2 = 87.5 \text{ V}$$

$$\therefore \quad \frac{V_1}{87.5} = \frac{11000}{110}$$

$$\therefore \quad V_1 = 8750 \text{ V}$$

This is the value of high voltage to be measured.

1.14.1 Construction

The potential transformer use larger core and conductor sizes compared to conventional power transformer. In potential transformer, economy of material is not an important consideration at the time of design. The accuracy is an important consideration.

The shell type or core type construction is preferred for potential transformer. The shell type is used for low voltage while core type for high voltage transformers. At the time of assembly special core is required to reduce the effect of air gap at the joints.

The coaxial primary and secondary windings are used, to reduce the leakage reactance. The secondary winding which is a low voltage winding is always next to the core. The primary winding is a single coil in low voltage transformers. For high voltages, insulation is the main problem. Hence in high voltage potential transformers, primary is divided into number of small sections of short coils to reduce the need of insulation between coil layers.

The cotton tape and varnished cambric are used as the insulations for windings. Hard fiber separators are used in between the coils. The oil immersed potential transformers are used for the voltage levels above 7 kV.

For oil filled potential transformers, oil filled bushings are used. Two bushings are required when no side of the line is at earth potential.

The overall construction of single phase, two winding potential transformer is shown in the Fig. 1.17.

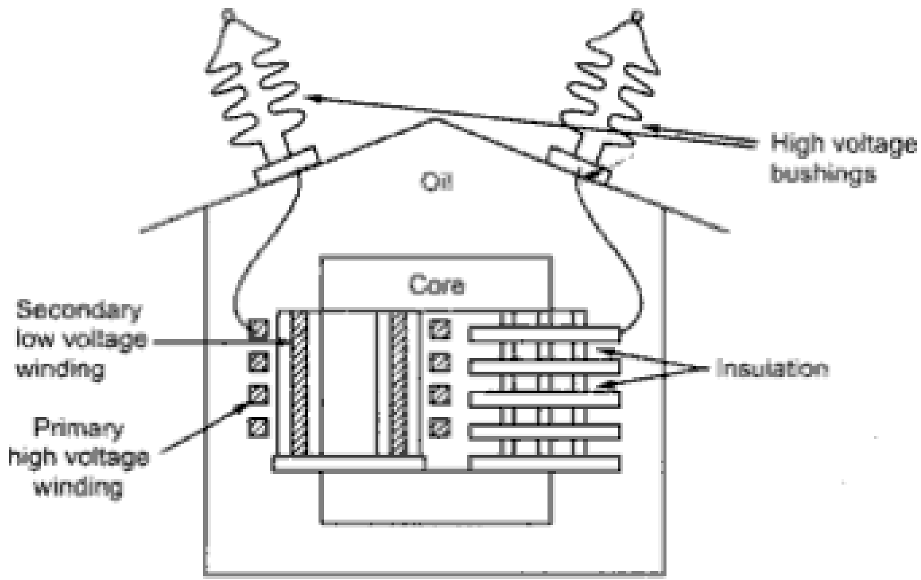


Fig. 1.17 Single phase potential transformer

1.15 Comparison of C.T. and P.T.

The comparison of C.T. and P.T. is given in the following table,

Sr. No.	Current Transformer	Potential Transformer
1.	It can be treated as series transformer under virtual short circuit conditions.	It can be treated as parallel transformer under open circuit secondary.
2.	Secondary must be always shorted	Secondary is nearly under open circuit conditions.
3.	A small voltage exists across its terminals as connected in series.	Full line voltage appears across its terminals
4.	The winding carries full line current.	The winding is impressed with full line voltage.
5.	The primary current and excitation varies over a wide range.	The line voltage is almost constant hence exciting current and flux density varies over a limited range.
6.	The primary current is independent of the secondary circuit conditions.	The primary current depends on the secondary circuit conditions.
7.	Needs only one bushing as the two ends of primary winding are brought out through the same insulator. Hence there is saving in cost.	Two bushings are required when neither side of the line is at ground potential.

Table 1.2

1.16 Errors in the Instrument Transformer

For an instrument transformers, it is necessary that the transformation ratio must be exactly equal to turns ratio and phase of the secondary terms (voltage and current) must be displaced by exactly 180° from that of the primary terms (voltage and current). Two types of errors affect these characteristics of an instrument transformer which are,

1. Ratio error
2. Phase angle error

1.16.1 Ratio Error

In practice it is said that current transformation ratio I_2 / I_1 is equal to the turns ratio N_1 / N_2. But actually it is not so. The current ratio is not equal to turns ratio because of magnetizing and core loss components of the exciting current. It also gets affected due to the secondary current and its power factor. The load current is not a constant fraction of the primary current. Similarly in case of potential transformers, the voltage ratio V_2 / V_1 is also not exactly equal to N_2 / N_1 due to the factors mentioned above. Thus the transformation ratio is not constant but depends on the load current, power factor of load and exciting current of the transformer. Due to this fact, large error is introduced in the measurements done by the instrument transformers. Such an error is called **ratio error**.

The ratio error is defined as,

$$\text{\% Ratio error} = \frac{\text{nominal ratio} - \text{actual ratio}}{\text{actual ratio}} \times 100$$

$$= \frac{K_n - R}{R} \times 100$$

where $$K_n = \frac{\text{rated primary current}}{\text{rated secondary current}} \quad \text{... for C. T.}$$

$$= \frac{\text{rated primary voltage}}{\text{rated secondary voltage}} \quad \text{... for P.T.}$$

and $$R = \frac{\text{actual primary current}}{\text{corresponding secondary current}} \quad \text{... for C.T.}$$

$$= \frac{\text{actual primary voltage}}{\text{corresponding secondary voltage}} \quad \text{... for P.T.}$$

The approximate formula to calculate R is given by,

$$R \approx n + \frac{I_c}{I_2}$$

where n = turns ratio

I_c = loss component of exciting current

I_2 = secondary current

Now $$I_2 = \frac{I_1}{n}$$

$$\therefore \quad R \approx n + \frac{n I_c}{I_1} \approx n\left(1 + \frac{I_c}{I_1}\right)$$

where I_1 = primary current

while precisely the formula to calculate R is,

$$R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_2}$$

where I_m = magnetising component of exciting current

δ = angle between secondary winding induced voltage and secondary winding current

δ is positive for lagging p.f. and negative for leading p.f.

1.16.2 Phase Angle Error

In the power measurements, it is must that the phase of secondary current is to be displaced by exactly 180° from that of primary current for C.T. While the phase of secondary voltage is to be displaced by exactly 180° from that of primary voltage, for P.T. But actually it is not so. The error introduced due to this fact is called **phase angle error**. It denoted by angle θ by which the phase difference between primary and secondary is different from 180°.

The precise expression to calculate the angle θ is,

$$\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{n I_2}\right] \text{degree}$$

While the approximate formula to calculate θ is,

$$\theta = \frac{180}{\pi}\left[\frac{Im}{n\, I_2}\right] = \frac{180}{\pi}\left[\frac{I_m}{n \times \frac{I_1}{n}}\right]$$

$$= \frac{180}{\pi}\left[\frac{I_m}{I_1}\right] \text{ degree}$$

Similar to ratio error, this error also depends on the components of exciting current (I_0), load current i.e. secondary current and power factor. This error does not affect the measurements of only current or voltage but do affect at the time of power and energy measurements.

The phase angle error for P.T. is defined as,

$$\theta = \frac{\frac{I_2}{n}[X_{1e}\cos\delta - R_{1e}\sin\delta] + I_C X_1 - I_m R_1}{n V_2} \text{ rad}$$

$$\theta = \frac{I_2}{V_2}(X_{2e}\cos\delta - R_{2e}\sin\delta] + \frac{I_c X_1 - I_m R_1}{n V_2}$$

where δ = secondary p.f. angle

R_{2e} = equivalent resistance of transformer referred to secondary $= R_2 + R_1' = R_2 + \frac{R_1}{n^2}$

X_{2e} = equivalent reactance of transformer referred to secondary $= X_2 + X_1' = X_2 + \frac{X_1}{n^2}$

X_1 = reactance of primary winding

R_1 = resistance of primary winding

V_1 = primary voltage

V_2 = secondary voltage

$I_c = I_o \cos\phi_o$ and $I_m = I_o \sin\phi_o$

where ϕ_o = no load power factor angle

X_{1e} = equivalent reactance of transformer referred to primary

$= X_1 + X_2' = X_1 + n^2 X_2$

R_{1e} = equivalent resistance of transformer referred to primary

$= R_1 + R_2' = R_1 + n^2 R_2$

and $n = \frac{V_1}{V_2} = \frac{N_1}{N_2}$ for potential transformer

1.16.3 Reduction of Ratio and Phase Angle Errors

The ratio and phase angle errors can be minimized by using following methods. :

1. As the errors depend on components of exciting current, reduce the magnetizing and loss components of exciting current. This requires to provide smaller magnetic path, good core material and low flux density in core.
2. Reduction of resistance and leakage reactance. The values decide the secondary circuit power factor which affects the errors. This can be achieved by providing thick conductors and smaller length of mean turn.
3. Providing turns compensation at no load the actual ratio exceeds the turns ratio thus the solution to this is to reduce primary turns or increasing secondary turns and to make actual ratio equal to nominal ratio for one particular value of load.

➠ **Example 1.3 :** *The no load current components of a current transformer are,*
magnetizing component = 102A
core loss component = 38A
The current transformation ratio is 1000 / 5 A. Calculate the approximate ratio error at full load.

Solution :

$$I_m = 102A,\ I_C = 38A$$

$$K_n = \text{nominal ratio} = \frac{1000}{5} = 200$$

At full load, $I_2 = 5A$

$$\therefore \quad R = n + \frac{I_c}{I_2} = 200 + \frac{38}{5}$$

$$= 207.6$$

$$\therefore \quad \%\ \text{Ratio error} = \frac{K_n - R}{R} \times 100 = \frac{200 - 207.6}{207.6} \times 100$$

$$= -3.66\%$$

➠ **Example 1.4 :** *A current transformer has a single turn primary and 400 secondary turns. The magnetizing current is 90A while core loss current is 40A. Secondary circuit phase angle is 28°. Calculate the actual primary current and ratio error when secondary carries 5A current.*

Solution :

$$I_m = 90A,\ I_c = 40A,\ \delta = 28^\circ,\ I_2 = 5A$$

$$n = \frac{400}{1} = 400$$

$$\therefore \quad K_n = n = 400$$

Now actual ratio $R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_2}$

$$= 400 + \frac{90 \times \sin 28 + 40 \times \cos 28}{5}$$

$$= 415.514.$$

Actual primary current = actual ratio × I_2

$$= 415.514 \times 5 = 2077.5703$$

∴ % Ratio error $= \frac{K_n - R}{R} \times 100 = \frac{400 - 415.514}{415.514} \times 100$

$$= -3.733\%$$

Example 1.5 : *A current transformer has turns ratio 1:399 and is rated as 2000/5A. The core loss component is 3A and magnetizing component is 8A, under full load conditions. Find the phase angle and ratio errors under full load condition if secondary circuit power factor is 0.8 leading.*

Solution : $I_C = 3A, I_m = 8A, \cos\delta = 0.8$ leading

$$n = \frac{399}{1} = 399$$

Nominal ratio $= K_n = \frac{2000}{5} = 400$

Actual ratio $= R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_2}$

Rated I_2 = 5A

$\delta = \cos^{-1} 0.8 = -36.86°$ ... negative as leading

∴ $\sin\delta = \sin(-36.86°) = -0.6$

∴ $R = 399 + \frac{8 \times (-0.6) + 3 \times 0.8}{5}$

$$= 398.52$$

∴ % Ratio error $= \frac{K_n - R}{R} \times 100 = \frac{400 - 398.52}{398.52} \times 100$

$$= 0.3713\%$$

And $\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_C \sin\delta}{n I_2}\right]$

$$= \frac{180}{\pi}\left[\frac{8\times0.8-3\times(-0.6)}{399\times5}\right]$$

$$= 0.2355^{\circ}$$

1.17 Advantages and Disadvantages of Instrument Transformers

The **advantages** of instrument transformers can be listed as,

1. The normal range voltmeter and ammeter can be used along with these transformers to measure high voltage and currents.
2. The rating of low range meter can be fixed irrespective of the value of high voltage or current to be measured.
3. These transformers isolate the measurement from high voltage and current circuits. This ensures safety of the operator and makes the handling of the equipments very easy and safe.
4. These can be used for operating many types of protecting devices such as relays or pilot lights.
5. Several instruments can be fed economically by single transformer.

Disadvantage :

The only disadvantage of these instrument transformers is that they can be used only for a.c. circuits and not for d.c. circuits.

Applications of C.T.s and P.T.s :

The C.T.s and P.T.s are used for,

1. Circulating current differential protection.
2. Over current phase fault protection.
3. Distance protection.
4. Intermediate CTs for feeding protective devices, measuring systems, relays etc.

Review Questions

1. *What is protective relaying ? What is a relay ?*
2. *Explain the various functions of protective relaying.*
3. *What is a protective zone ? With a simple diagram, show the various zones in a typical power system.*
4. *Why the protective zones are arranged in overlap fashion ? With the help of simple diagram, show how the zones are overlapped.*
5. *Explain what is meant by primary protection and backup protection.*
6. *State the various methods used to provide backup protection.*

7. *Discuss the basic action of a backup protection.*
8. *Discuss the quality of 'reliability' of a protective relaying. Which factors affect the reliability ?*
9. *Discuss in brief the various essential qualities of protective relaying.*
10. *Define and explain relay time, breaker time and fault clearing time.*
11. *Why time delay is intentionally provided in practical relays ?*
12. *Discuss the classification of protective relays.*
13. *Explain the following terms related to protective relaying :*

    i) Pickup *ii) Dropout or reset* *iii) Time delay*

    iv) Holding relay *v) Trip circuit* *vi) Protective scheme*

    vii) Protective system *viii) Current setting* *ix) Plug-setting multiplier*

    x) Time-setting multiplier
14. *What is time/P.S.M. curve ? How it can be used to obtain the actual operation time of a relay ?*

2 Electromagnetic Relays

2.1 Introduction

An important element of any protective relaying scheme is a relay. It is a device which detects the fault and is responsible to energize the trip circuit of a circuit breaker. This isolates the faulty part from rest of the system. In an electromagnetic relay, the driving torque is created based on an electrical or electronic principle. While the restraining torque is generally provided with the help of springs. The two torques are mechanically compared and the relay operates when driving or operating torque is more than the restraining torque. Thus,

$$T_d = \text{Driving torque or operating torque}$$
$$T_r = \text{Restraining torque}$$
$$T_R = \text{Resultant torque} = T_d - T_r$$

The relay operates when the resultant torque T_R is positive. Let us study the basic action of a trip circuit with a relay.

2.1.1 Basic Trip Circuit Operation

Consider a simplified circuit of a typical relay as shown in the Fig. 2.1. Usually the relay circuit is a three phase circuit and the contact circuit of relays is very much complicated. The Fig. 2.1 shows a single phase simplified circuit to explain the basic action of a relay. Let part A is the circuit to be protected. The current transformer C.T. is connected with its primary in series with the line to be protected. The secondary of C.T. is connected in series with the relay coil. The relay contacts are the part of a trip circuit of a circuit breaker. The trip circuit consists of a trip coil and a battery, in addition to relay contacts. The trip circuit can operate on a.c. or d.c.

If the fault occurs as shown in the Fig. 2.1, then current through the line connected to A increases to a very high value. The current transformer senses this current. Accordingly its secondary current increases which is nothing but the current through a relay coil. Thus the relay contacts get closed mechanically under the influence of such a high fault current. Thus the trip circuit of a circuit breaker gets closed and current starts flowing from battery, through trip coil, in a trip circuit. Thus the trip coil of a circuit breaker gets energised. This activates the circuit breaker opening mechanism, making the circuit breaker open. This isolates the faulty part from rest of the healthy system.

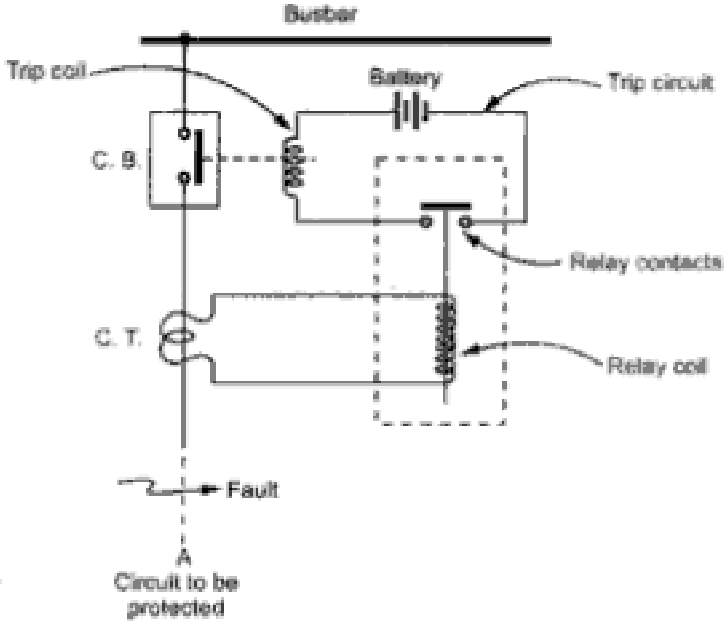


Fig. 2.1 Typical relay circuit

2.1.2 Auxiliary Switch

Another important device in the trip circuit is an auxiliary switch. It is a multipoint switch generally 4 point, 6 point, 12 point or 24 point. This switch is mechanically coupled with operating mechanism of the circuit breaker. Thus when circuit breaker opens, the switch also gets opened. The switch is in the trip circuit and hence when it opens, it breaks the current through the trip circuit. Once the current in the trip circuit is interrupted the relay contacts come to normal position. The advantage of an auxiliary switch is that the breaking of trip circuit takes place only across the switch and hence possible arcing due to current interruption across the relay contacts gets avoided. Such arcing is harmful for relay contacts as relay contacts are delicate and light. To interrupt a current through the inductive circuit like trip circuit a robust mechanical switch is necessary. This purpose is served by an auxiliary switch, protecting delicate relay contacts. In addition to this, indication circuits showing whether circuit breaker is open or close and some other control circuits also get connected or disconnected by an auxiliary switch.

The auxiliary switch is generally placed in the control cabinet of the circuit breaker.

2.2 Tripping Schemes in Circuit Breaker

Two schemes are very popularly used for tripping in circuit breakers which are,

1. Relay with make type contact 2. Relay with break type contact

The relay with make type contact requires auxiliary d.c. supply for its operation while the relay with break type contact uses the energy from the main supply source for its operation. Let us see the details of these two types of schemes.

2.2.1 Relays with Make Type Contact

The schematic diagram representing the arrangement of various elements in a relay with make type contact is shown in the Fig. 2.2.

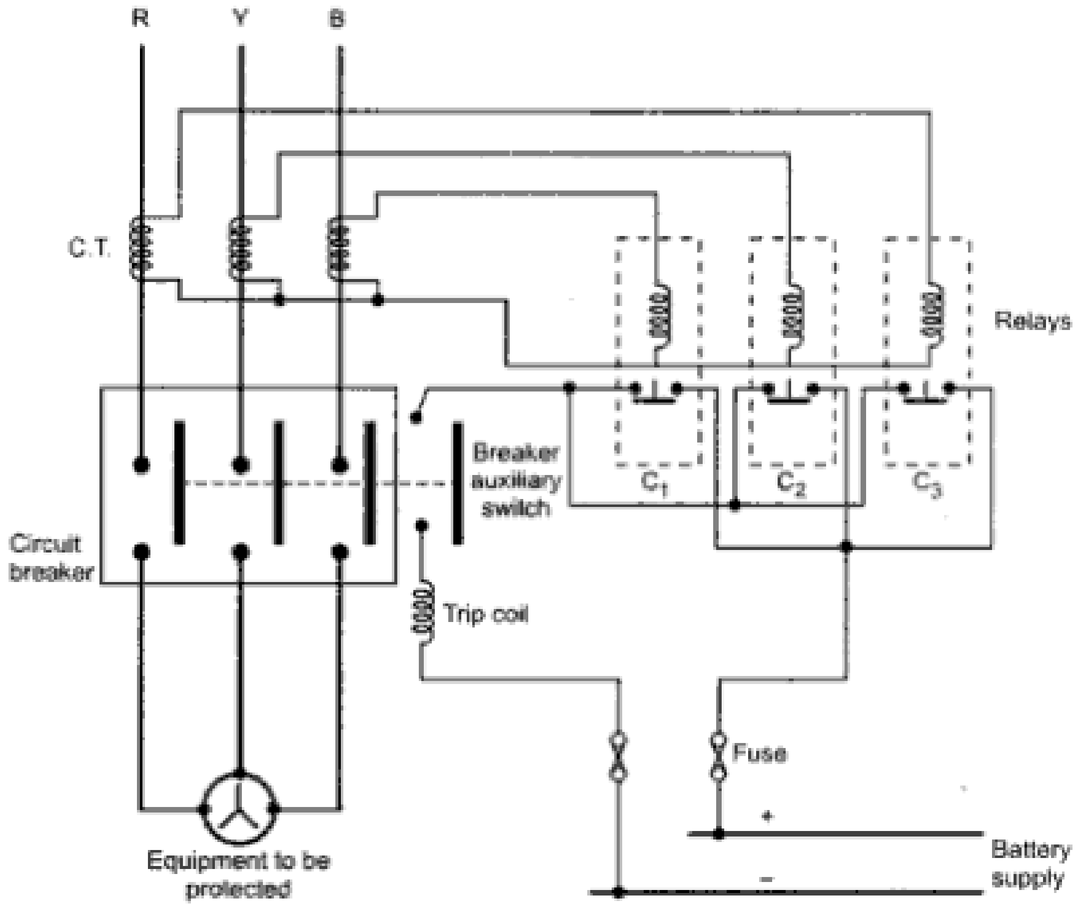


Fig. 2.2 Relay with make type contact

As mentioned earlier, a separate supply is necessary for the relay operation. The relays are connected in star while the relay contacts are connected in parallel. The entire relay contact unit is connected in series with the auxiliary switch, trip coil and the battery. Relay contacts are open in normal position.

Operation : When the fault occurs, the current through relay coils increases to a very high value. Due to this, the normally open relay contacts C_1, C_2 and C_3 get closed. This activates the trip coil of a circuit breaker. The auxiliary switch is initially closed along with the circuit breaker. So when contacts C_1, C_2 and C_3 are closed, the current flows through trip coil of circuit breaker. This activates the trip coil which opens the circuit breaker. As auxiliary switch is mechanically coupled with the circuit breaker, it also gets opened. This interrupts the current through trip coil. Thus supply to faulty part gets interrupted and trip coil also gets de-energized. This brings the relay contacts back to normal position. Due to auxiliary switch, arcing across relay contacts gets avoided. As relay contacts are normally open and they 'make' the circuit to open the circuit breaker hence called make type contact relay.

2.2.2 Relay with Break Type Contact

The schematic arrangement of various elements in a relay with break type contact is shown in the Fig. 2.3.

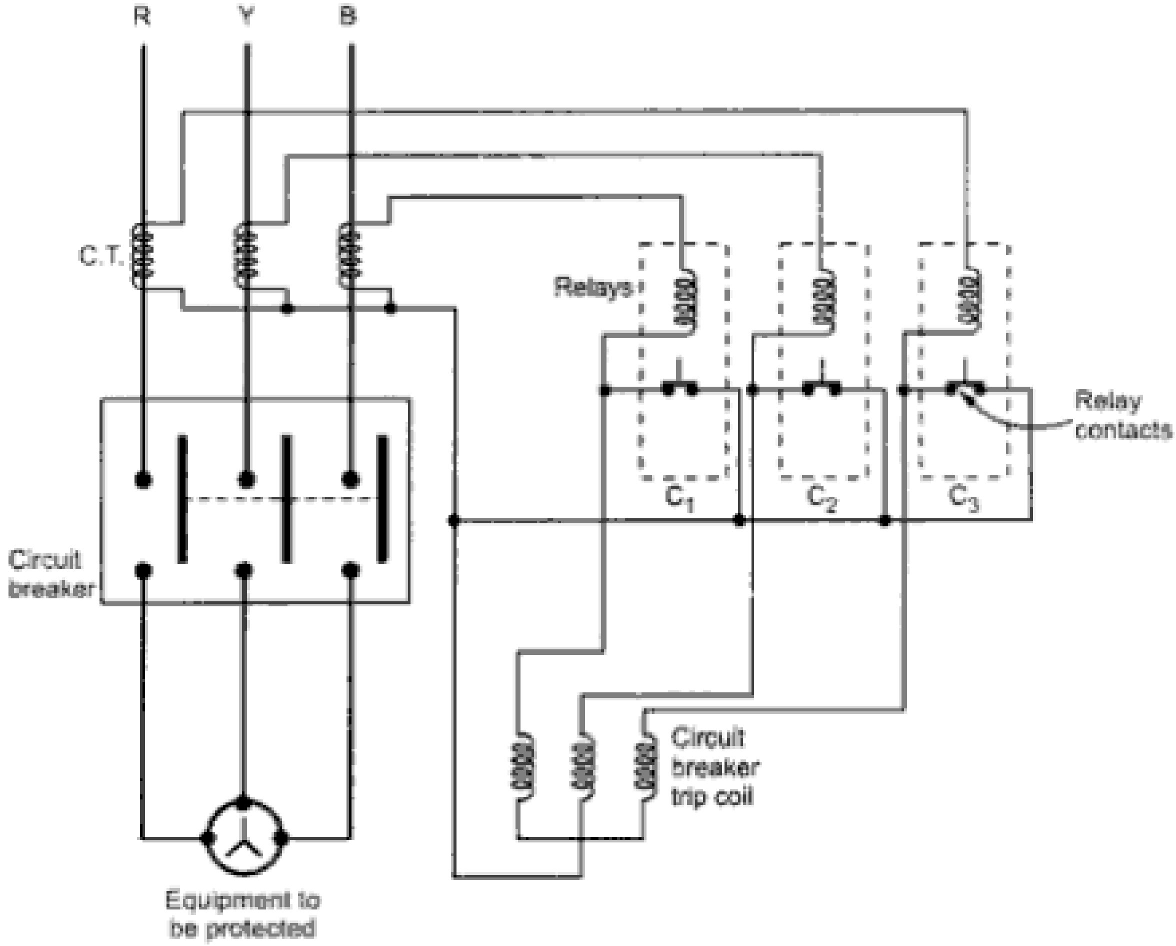


Fig. 2.3 Relay with break type contact (using C.T.s)

This type of relay does not require external battery supply for the tripping. The current transformers (C.T.s) or potential transformers (P.T.s) are used to derive the energy required for the relay from the main supply source. The relay using C.T.s to derive operating energy from the supply is shown in the Fig. 2.3.

In this scheme, the relay coil and trip coil of each phase are connected in series. The three phases are then connected in star. Under normal working, the relay contacts C_1, C_2 and C_3 are closed. The energy for relay coils is derived from supply using C.T.s. The trip coils of circuit breakers are de-energized under normal condition. When the fault occurs, heavy current flows through relay coils due to which relay contacts C_1, C_2 and C_3 break. Thus current flows through trip coils of circuit breaker due to which circuit breaker gets open.

The Fig. 2.4 shows the break type contact relay using P.T. to derive energy to keep relay coils energized.

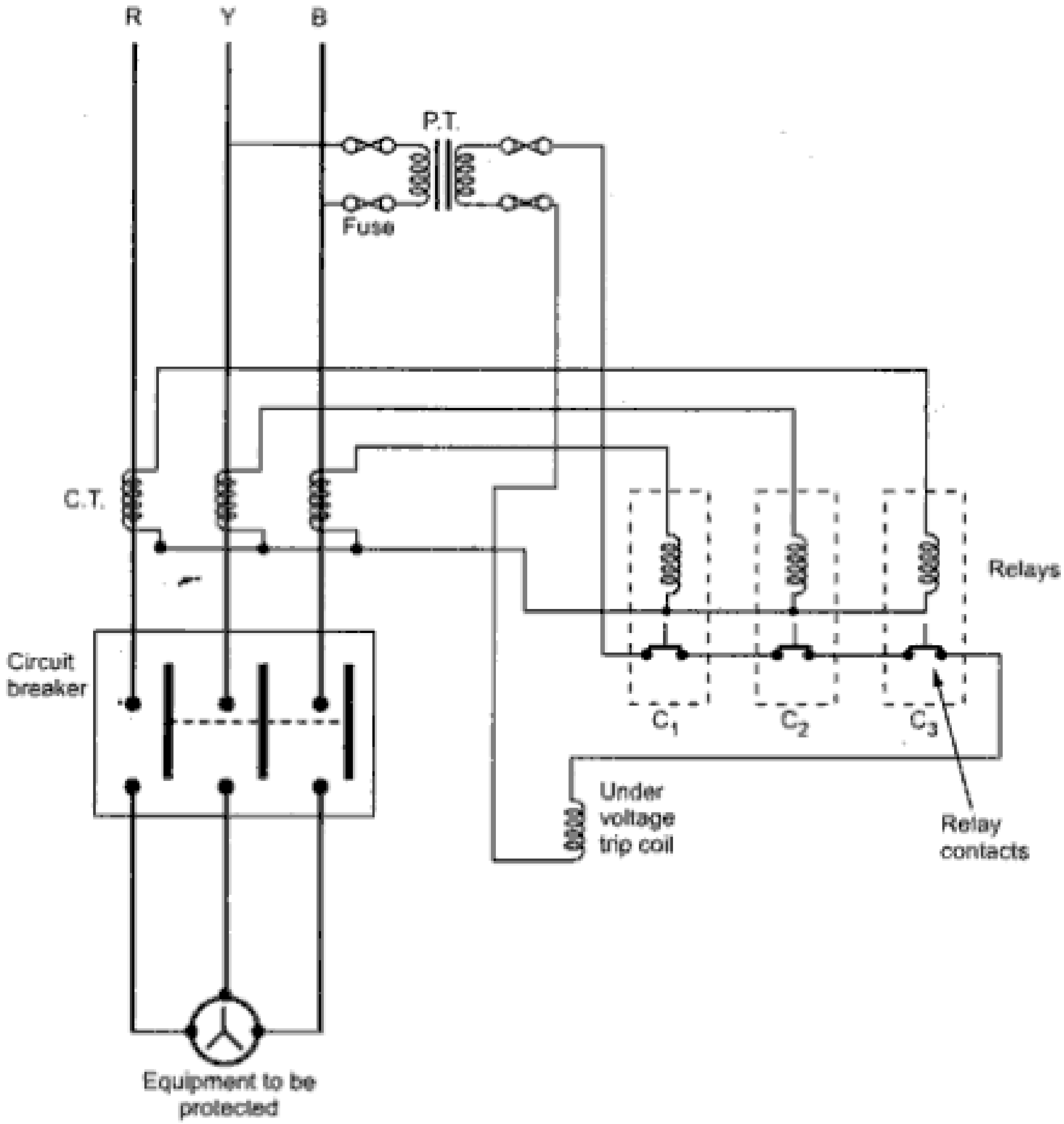


Fig. 2.4 Relay with break type contact (Using P.T.)

In this type, in addition to normal trip coils of circuit breaker, an additional undervoltage trip coil is used. All the relay contacts are in series with the undervoltage trip coil. Through potential transformer, for normal voltage, the undervoltage trip coil is kept energized. When the voltage becomes less than the normal value, the magnetic effect produced by undervoltage trip coil reduces which is responsible for the opening of the circuit breaker. When fault occurs, the normal trip coils of circuit breaker come into the picture and are responsible for the opening of the circuit breaker.

In both the types, relay contacts 'break' to cause the circuit breaker operation hence the relay is called break type contact relay.

2.3 Electromagnetic Attraction Relays

In these relays, there is a coil which enerzises an electromagnet . When the operating current becomes large, the magnetic field produced by an electromagnet is so high that it attracts the armature or plunger, making contact with the trip circuit contacts. These are simplest type of relays. The various types of electromagnetic attraction type relays are,

1. Attracted armature relay
2. Solenoid and plunger type relay

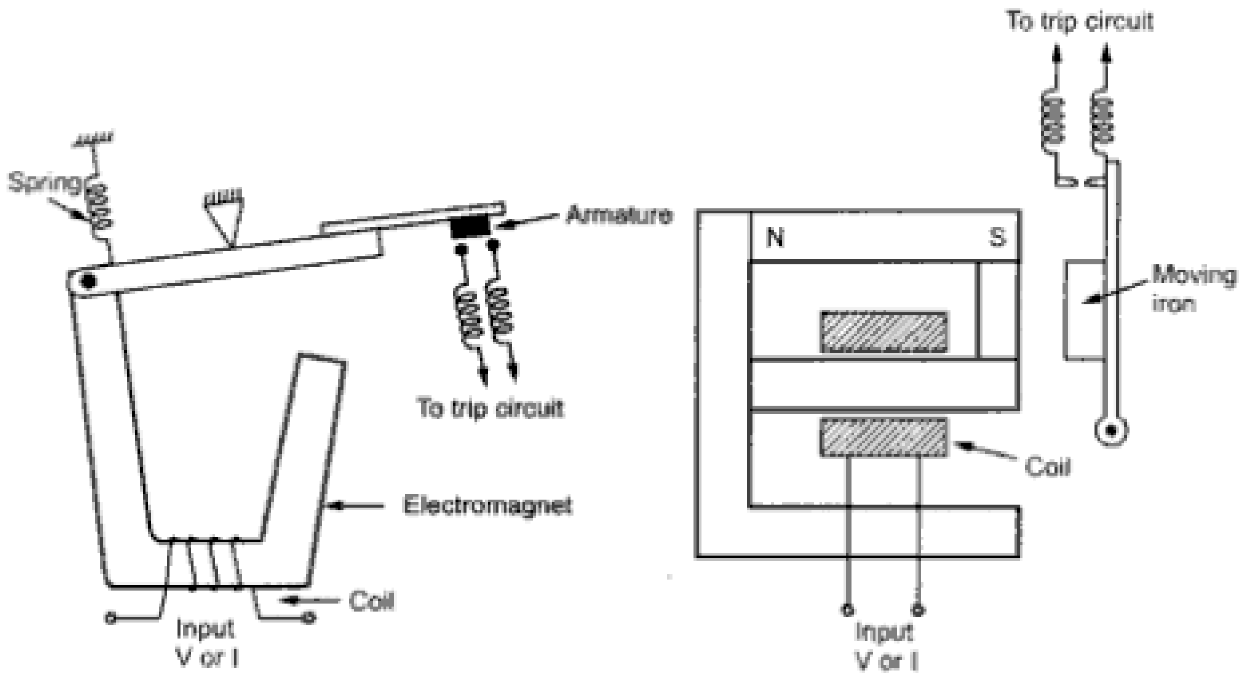
2.3.1 Attracted Armature Type Relay

There are two types of structures available for attracted armature type relay which are,

i) Hinged armature type

ii) Polarised moving iron type

The two types of attracted armature type relays are shown in the Fig. 2.5(a) and (b).



(a) Hinged armature type relay (b) Polarised moving iron type relay

Fig. 2.5

In attracted armature type, there exists a laminated electromagnet which carries a coil. The coil is energized by the operating quantity which is proportional to the circuit voltage or current. The armature or a moving iron is subjected to the magnetic force produced by the operating quantity. The force produced is proportional to the square of current hence these relays can be used for a.c. as well as d.c. The spring is used to produce restraining force. When the current through coil increases beyond the limit under fault conditions, armature gets attracted. Due to this it makes contact with contacts of a trip circuit, which results in an opening of a circuit breaker.

The minimum current at which the armature gets attracted to close the trip circuit is called **pickup current**.

Generally the number of tappings are provided on the relay coil with which its turns can be selected as per the requirement. This is used to adjust the set value of an operating quantity at which relay should operate.

An important advantage of such relays is their high operating speed. In modern relays an operating time as small as 0.5 msec is possible. The current-time characteristics of such relays is hyperbolic, as shown in the Fig. 2.6.

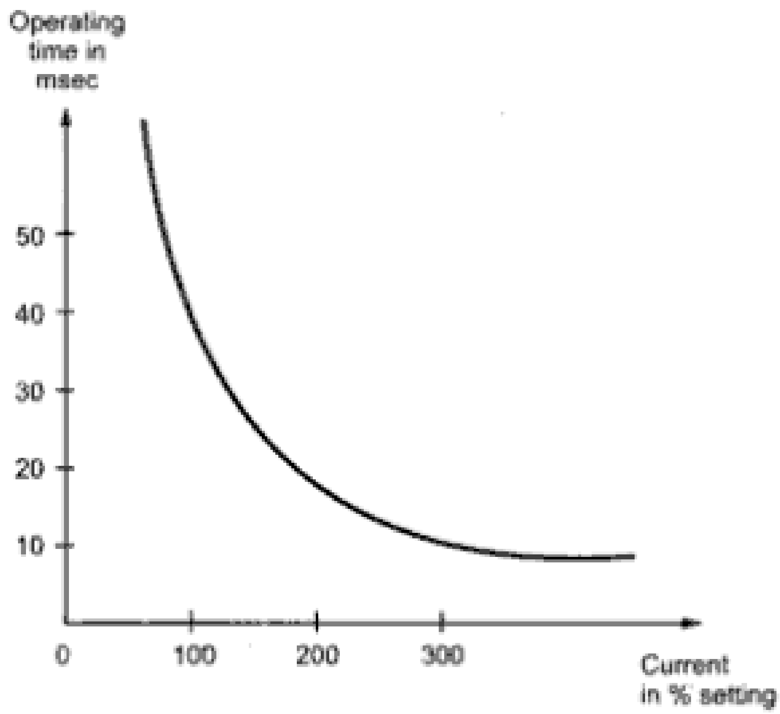


Fig. 2.6 Current-time characteristics

2.3.2 Solenoid and Plunger Type Relay

The Fig. 2.7 shows the schematic arrangement of solenoid and plunger type relay which works on the principle of electromagnetic attraction.

It consists of a solenoid which is nothing but an electromagnet. It also consists a movable iron plunger. Under normal working conditions, the spring holds the plunger in the position such that it cannot make contact with trip circuit contacts.

Under fault conditions when current through relay coil increases, the solenoid draws the plunger upwards. Due to this, it makes contact with the trip circuit contacts, which results in an opening of a circuit breaker.

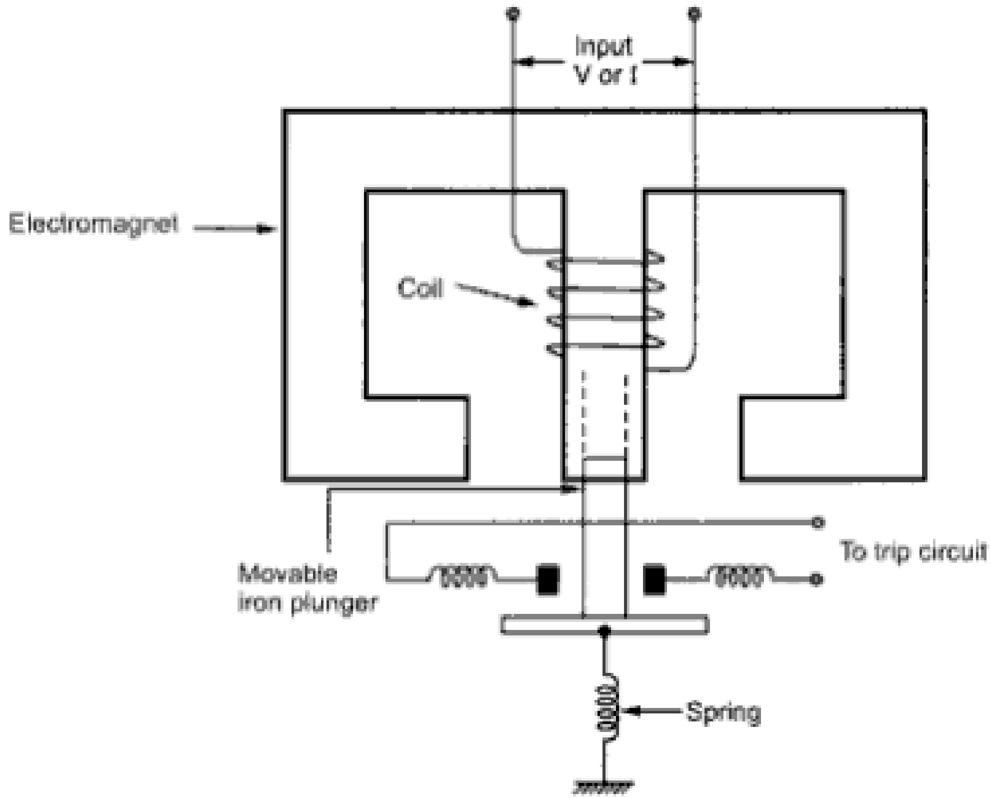


Fig. 2.7 Solenoid and plunger type relay

2.3.3 Operating Principle of Electromagnetic Attraction Relays

The electromagnetic force produced due to operating quantity which is exerted on armature, moving iron or plunger is proportional to the square of the flux in the air gap. Thus neglecting the saturation effect, the force is proportional to the square of the operating current. Hence such relays are useful for a.c. and d.c. both.

For d.c. operation : In d.c. operation, the electromagnetic force is constant. When this force exceeds the restraining force, the relay operates.

Now $F_e = K_1 I^2$

where F_e = Electromagnetic force

K_1 = constant

I = Operating current in a coil

And $F_r = K_2$

where F_r = Restraining force due to spring including friction

K_2 = Constant

On the verge of relay operating, electromagnetic force is just equal to the restraining force.

$$\therefore \quad K_1 I^2 = K_2$$

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

$$\therefore \quad I = \sqrt{\frac{K_2}{K_1}} = \text{constant}$$

This is the current at which relay operates in case of d.c. operation.

For a.c. operation : In a.c. electromagnetic relays, the electromagnetic force is proportional to square of the current but it is not constant. It is given by,

$$F_e = K I^2 = \frac{1}{2} K I_m^2 - \frac{1}{2} K I_m^2 \cos 2\omega t$$

where I_m = Maximum value of the operating current

K = constant

It shows that the electromagnetic force consists of two components,

i) Constant, independent of time.

ii) Pulsating at double the frequency of applied voltage.

The total force thus pulsates at double the frequency.

If the restraining force F_r which is produced by the spring is constant then the armature of relay will be picked up at time t_1 and it drops off at time t_2 as shown in the Fig. 2.8.

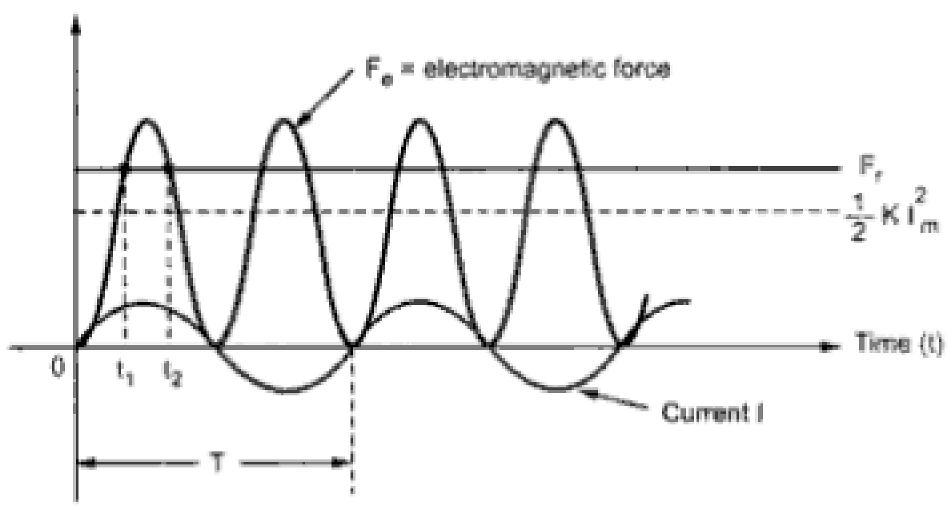


Fig. 2.8 Electromagnetic force and current curves

Thus relay armature pulsates at double frequency. This causes the relay to hum and produces a noise. It may cause damage to the relay contacts.

To overcome this difficulty, the air gap flux producing an electromagnetic force is divided into two fluxes acting simultaneously but differing in time phase. This causes resulting electromagnetic force to be always positive. If this is always greater than restraining force F_r then armature will not vibrate. The phase lag between the two components of flux can be easily produced using shading in a relay. The flux through the shaded pole lags behind the flux through the unshaded part.

2.3.4 Advantages of Electromagnetic Relays

The various advantages of electromagnetic relays are,

1. Can be used for both a.c. and d.c.
2. They have fast operation and fast reset.
3. These are almost instantaneous. Though instantaneous, the operating time varies with current. With extra arrangements like dashpot, copper ring etc. slow operating and resetting times can be obtained.
4. High operating speed with operating time in few milliseconds also can be achieved.
5. The pickup can be as high as 90-95% for d.c. operation and 60 to 90% for the d.c. operation.
6. Modern relays are compact, simple, reliable and robust.

2.3.5 Disadvantages of Electromagnetic Relays

The few disadvantages of these relays are,

1. The directional feature is absent.
2. Due to fast operation the working can be affected by the transients. As transients contain d.c. as well as pulsating component, under steady state value less than set value, the relay can operate during transients.

2.3.6 Applications of Electromagnetic Relays

The various applications of these relays are,

1. The protection of various a.c. and d.c. equipments.
2. The over/under current and over/under voltage protection of various a.c. and d.c. equipments.
3. In the definite time lag over current and earth fault protection along with definite time lag over current relay.
4. For the differential protection.
5. Used as auxiliary relays in the contact systems of protective relaying schemes.

2.4 Induction Type Relays

The induction type relays are also called magnitude relays. These relays work on the principle of the induction motor or an energy meter. In these relays a metallic disc is allowed to rotate between the two electromagnets. The coils of the electromagnets are energized with the help of alternating currents. The torque is produced in these relays due to the interaction of one alternating flux with eddy currents induced in the rotor by another alternating flux. The two fluxes have same frequency but are displaced in time and space. As the interaction of alternating fluxes is the base of operation of these relays, these are not used for the d.c. quantities. These are widely used for protective relaying involving only a.c. quantities.

Based on the construction, the various types of the induction type relays are,

1. Shaded pole type
2. Watt hour meter type
3. Induction cup type

Before studying these types in detail, let us derive the torque equation for the induction type relays, which is same for all the three types of relays.

2.4.1 Torque Equation for Induction Type Relays

As mentioned earlier, the alternating currents supplied to two electromagnets produce the two alternating fluxes ϕ_1 and ϕ_2. These two fluxes have same frequency but they have a phase difference of α in between them such that ϕ_2 leads ϕ_1. Thus the two fluxes can be mathematically expressed as,

$$\phi_1 = \phi_{1m} \sin \omega t \quad \ldots (1)$$

$$\phi_2 = \phi_{2m} \sin (\omega t + \alpha) \quad \ldots (2)$$

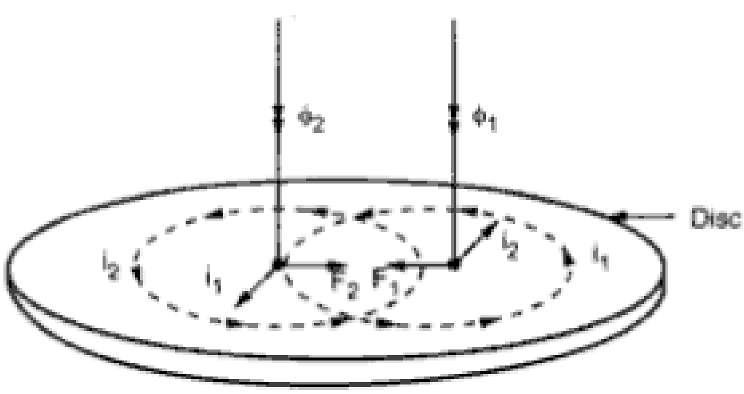


Fig. 2.9 Torque production

These alternating fluxes cause the induced e.m.f.s in the rotor. Due to the induced e.m.f.s, the eddy currents i_1 and i_2 are circulated in the disc. The two eddy currents react with each other to produce a force which acts on the rotor.

The Fig. 2.9 shows how the forces are produced in a section of rotor due to the alternating fluxes. The instant considered to show the various quantities is when both the fluxes are directed downwards and are increasing in magnitude. The induced eddy currents lag behind the respective fluxes by 90°.

Assumption : The parts of rotor in which rotor currents flow have negligible self inductance and hence the rotor currents are in phase with the respective induced voltages.

The induced voltages are proportional to the rate of change of fluxes and hence the eddy currents also are proportional to the rate of change of fluxes. Hence we can write,

$$i_1 \propto \frac{d\phi_1}{dt} \quad \text{... (3)}$$

$$i_2 \propto \frac{d\phi_2}{dt} \quad \text{... (4)}$$

Substituting ϕ_1 and ϕ_2 from (1) and (2) we get,

$$i_1 \propto \frac{d(\phi_{1m} \sin \omega t)}{dt} \propto \phi_{1m} \cos \omega t \quad \text{... (5)}$$

$$i_2 \propto \frac{d[\phi_{2m} \sin(\omega t + \alpha)]}{dt} \propto \phi_{2m} \cos(\omega t + \alpha) \quad \text{... (6)}$$

The forces are produced due to the interaction of ϕ_1 with i_2 and ϕ_2 with i_1.

$$\therefore \quad F_1 \propto \phi_1 i_2 \quad \text{... (7)}$$

and

$$F_2 \propto \phi_2 i_1 \quad \text{... (8)}$$

The directions of F_1 and F_2 can be obtained by Flemings left hand rule. It can be seen from the Fig. 2.9 that the two forces are acting in the opposite directions and hence the net force acting on the disc is proportional to the difference between the two forces.

$$\therefore \quad F \propto F_2 - F_1$$

$$\therefore \quad F \propto \phi_2 i_1 - \phi_1 i_2 \quad \text{...(9)}$$

Substituting the proportional expressions of ϕ_1, ϕ_2, i_1, i_2 from (1), (2), (5) and (6) in the equation (9) we get,

$$\therefore \quad F \propto [\phi_{2m} \sin(\omega t + \alpha)\, \phi_{1m} \cos \omega t - \phi_{1m} \sin \omega t\, \phi_{2m} \cos(\omega t + \alpha)]$$

$$\propto \phi_{1m}\, \phi_{2m}\, [\sin(\omega t + \alpha) \cos(\omega t) - \sin(\omega t) \cos(\omega t + \alpha)]$$

$$\propto \phi_{1m}\, \phi_{2m}\, [\sin(\omega t + \alpha - \omega t)]$$

$$\therefore \quad F \propto \phi_{1m}\, \phi_{2m} \sin \alpha \quad \text{... (10)}$$

The equation (10) gives the net force acting on the disc which is proportional to sin α.

Substituting the r.m.s. values of the fluxes instead of maximum values we get,

$$\boxed{F \propto \phi_1 \phi_2 \sin\alpha} \quad \ldots (11)$$

It is important to note that the net force or torque acting on the disc is same at every instant. The action of relay under such force is free from vibrations.

It can be observed from the equation (10) that if α is zero then the net force is zero and disc cannot rotate. Hence there must exist a phase difference between the two fluxes. The torque is maximum when the phase difference α is 90°.

The direction of the net force which decides the direction of rotation of disc depends on which flux is leading the other. In practice various constructions are used to produce phase displacement between the two fluxes.

2.4.2 Shaded Pole Type Induction Relay

The construction of shaded pole induction relay is shown in the Fig. 2.10.

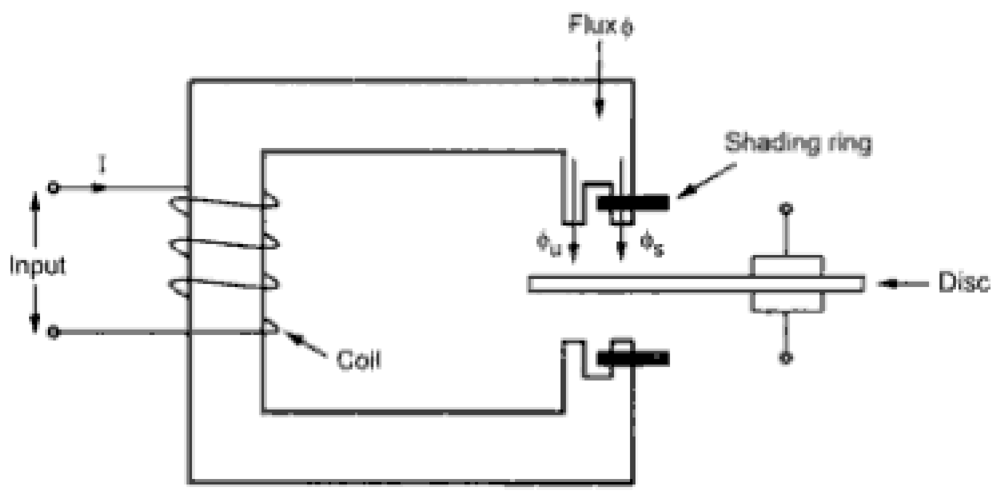


Fig. 2.10 Shaded pole type induction relay

It consists of an aluminium disc which is free to rotate in an air gap of an electromagnet. The part of pole face of each pole is shaded with the help of copper band or ring. This is called shading ring. The total flux ϕ produced due to the alternating current split into two fluxes displaced in time and space due to the shading ring.

Due to the alternating flux, e.m.f. gets induced in the shading ring. This e.m.f. drives the currents causing the flux to exist in shaded portion. This flux lags behind the flux in the unshaded portion by angel α.

Let ϕ_s = Flux in shaded portion

ϕ_u = Flux in unshaded portion

E_s = E.M.F. induced in the disc due to ϕ_s

E_u = E.M.F. induced in the disc due to ϕ_u

I_s = Induced current due to E_s

I_u = Induced current due to E_u

E_u lags behind ϕ_u by 90° while E_s lags behind ϕ_s by 90°. The current I_s lags E_s by small angle β while I_u lags E_u by small angle β. This angle is generally neglected and I_s and I_u are assumed to be in phase with E_s and E_u respectively, in practice. The phasor diagram is shown in the Fig. 2.11.

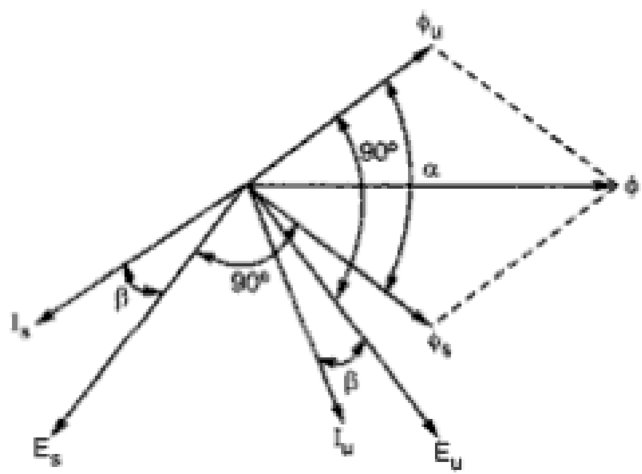


Fig. 2.11 Phasor diagram

As proved in the previous section, neglecting β we get,

$$T \propto \phi_s \phi_u \sin \alpha$$

where T = Torque

Assuming fluxes ϕ_s and ϕ_u to be proportional to the current I in the relay coil we can write,

$$T \propto I^2 \sin \alpha$$

$$\therefore \quad \boxed{T = kI^2} \quad \text{... k = constant}$$

As sin α is constant for the given design. Thus the torque is proportional to the square of the current through the coil.

2.4.3 Watthour Meter Type Induction Relay

The construction of this type of relay is similar to the watthour meter which is very popularly used everywhere. Thus relay has double winding structure. The arrangement is shown in the Fig. 2.12.

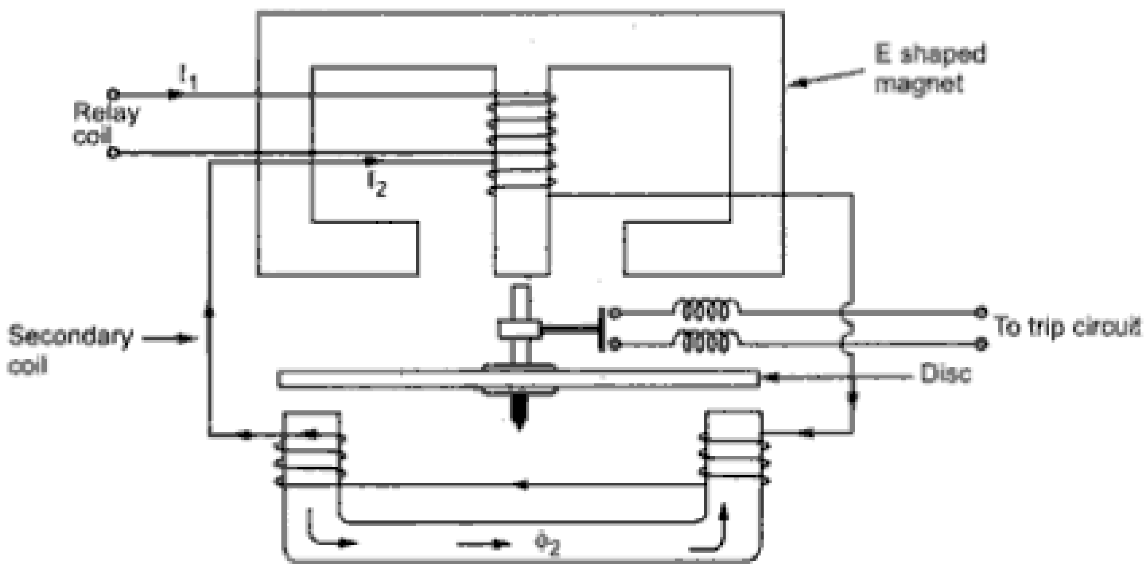


Fig. 2.12 Watthour meter type induction relay

It consists of two magnets, one E shaped magnet and other U shaped magnet. The disc is free to rotate in between these two magnets. The upper E shaped magnet carries both primary winding which is relay coil and the secondary winding. The primary carries the relay current I_1 which produces the flux ϕ_1. The e.m.f. gets induced in the secondary due to this flux. This drives current I_2 through secondary. Due to this current I_2, flux ϕ_2 gets produced in the lower magnet. This flux lags behind the main flux ϕ_1 by an angle α. Due to the interaction of these two fluxes, the torque is exerted on the disc and disc rotates.

Assuming that the entire flux ϕ_1 enters the disc from upper magnet and entire flux ϕ_2 enters the disc from lower magnet, we can write,

$$T \propto \phi_1 \phi_2 \sin \alpha$$

In this relay, the tapping can be provided on the primary. With the help of this suitable number of primary turns can be selected and hence current setting can be adjusted.

Most of the induction relays are of this type. An important feature of this relay is that its operation can be controlled by opening or closing of the secondary winding. It is opened, no current can flow through secondary hence flux ϕ_2 cannot be produced and hence no torque can be produced. Thus relay can be made inoperative opening the secondary winding.

2.4.4 Induction Cup Type Relay

The construction of this type of relay is very similar to an induction motor. The arrangement is shown in the Fig. 2.13.

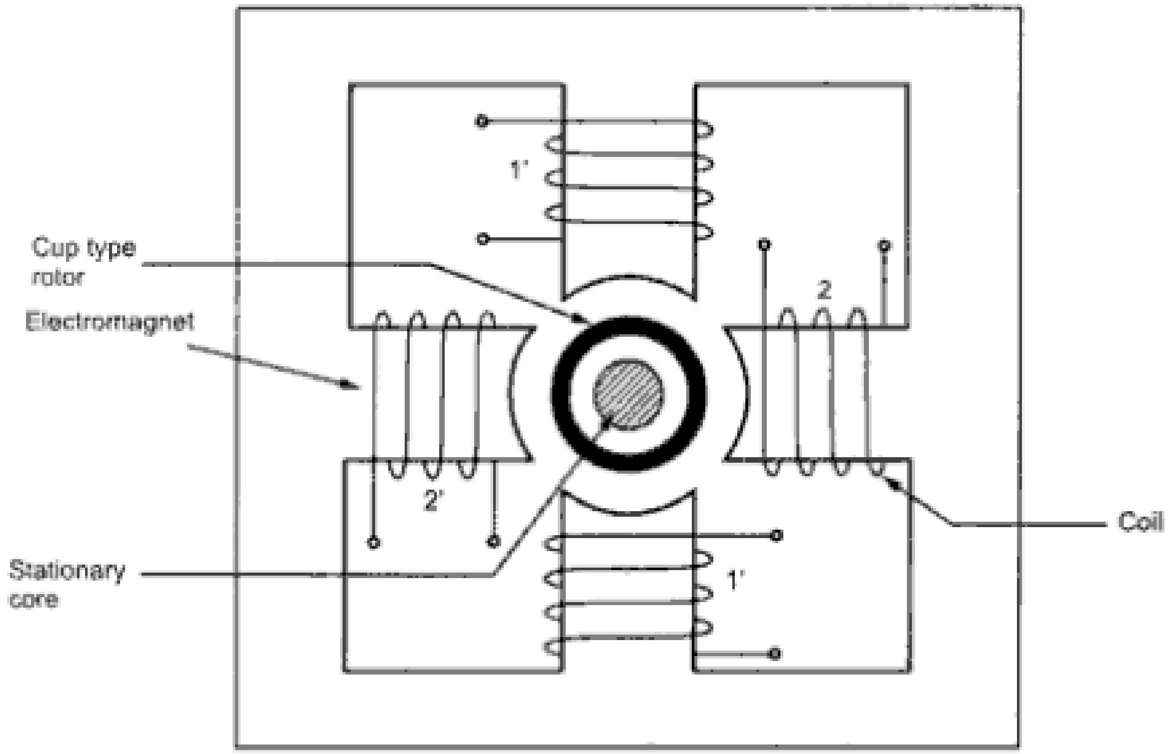


Fig. 2.13

The stator consists of two, four or more poles. These are energized by the relay coils. The Fig. 2.13 shows 4 pole structure and the two pairs of coils. The coils 1 and 1' are connected while the coils 2 and 2' are connected to form two pairs of coils. The rotor is hollow cyclindrical cup type in structure. Compared to induction motor the difference is that in this relay the rotor core is stationary and only rotor conductor portion is free to rotate about its axis.

The currents and respective fluxes produced by the two pairs of coils are displaced from each other by angle α. Thus the resultant flux in the air gap is rotating. So rotating magnetic field is produced by two pairs of coils. Due to this, eddy currents are induced in the cup type rotor. These currents produce the flux. The interaction of the two fluxes produce the torque and the rotor rotates in the same direction as that of rotating magnetic field. A control spring and the back stop carried on an arm attached to the spindle of the cup, are responsible to prevent continuous rotation.

These relays are very fast in operation. The operating time of the order of 10 milliseconds is possible with this type. This is because the rotor is light having very low moment of inertia. The induction cup structure can be used for two quantity or

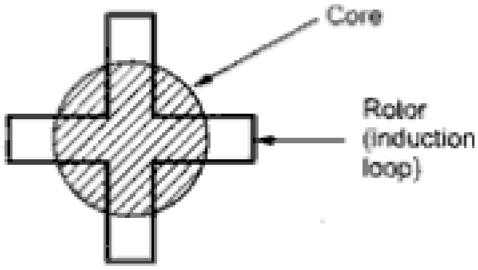


Fig. 2.14 Double induction loop structure

single quantity relays. A single quantity relay means both the coils are fed by the same actuating quantity with a fixed phase angle shift in between them. To reduce the rotor inertia and to make the operation more fast, double induction loop structure is used. Such a structure is shown in the Fig. 2.14.

In all, the induction relays are widely used for protective relays involving a.c. quantities. High, low and adjustable speeds are possible in these relays. Various shapes of time against operating quantity curves can be obtained.

2.5 Nondirectional Induction Type Overcurrent Relay

This relay is also called earth leakage induction type relay.

The overcurrent relay operates when the current in the circuit exceeds a certain preset value. The induction type nondirectional overcurrent relay has a construction similar to a watthour meter, with slight modification. The Fig. 2.15 shows the constructional details of nondirectional induction type over current relay.

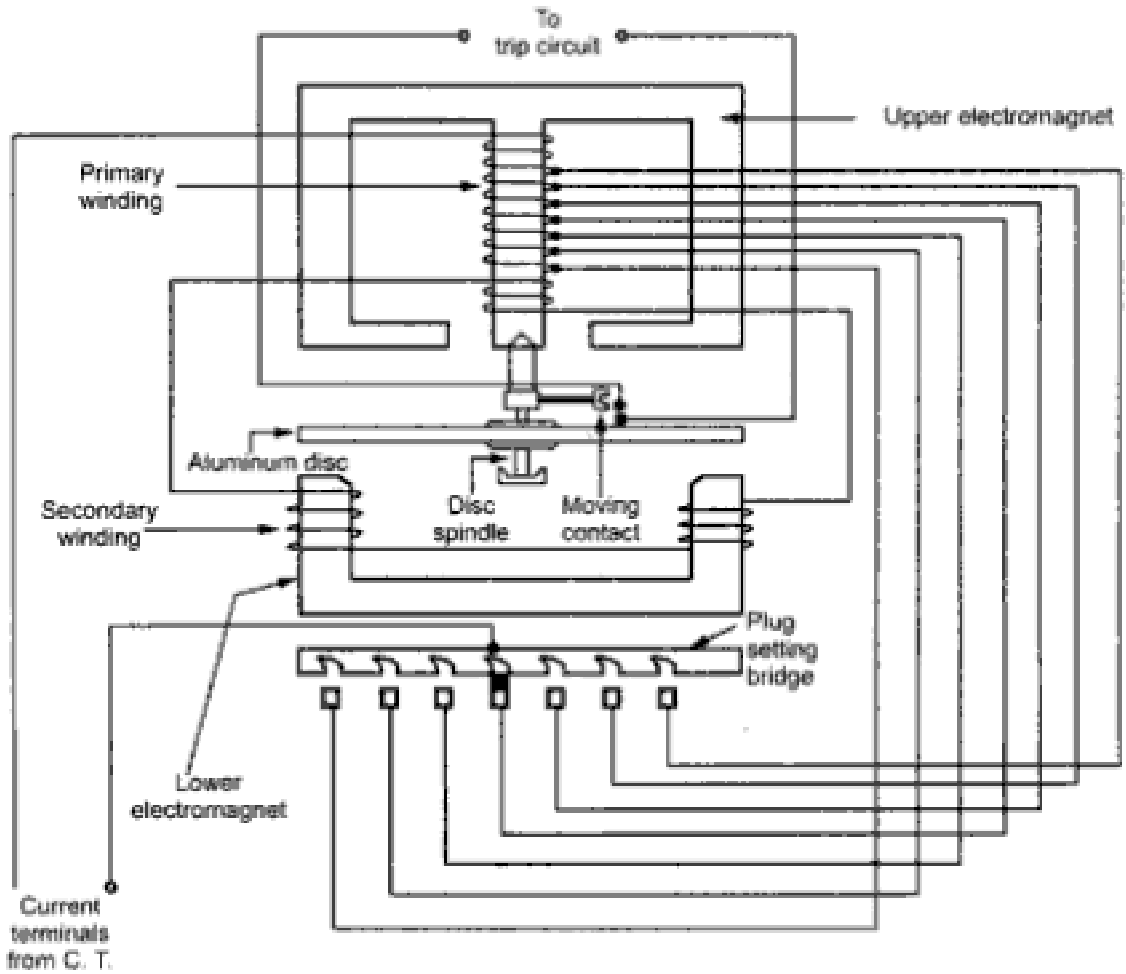


Fig. 2.15 Nondirectional induction over current relay

It consists of two electromagnets. The upper is E shaped while the lower is U shaped. The aluminium disc is free to rotate between the two magnets. The spindle of the disc carries moving contacts and when the disc rotates the moving contacts come in contact with fixed contacts which are the terminals of a trip circuit.

The upper magnet has two windings, primary and secondary. The primary is connected to the secondary of C. T. on the line to be protected. This winding is tapped at intervals. The tappings are connected to plug setting bridge.

With the help of this bridge, number of turns of primary winding can be adjusted. Thus the desired current setting for the relay can be obtained. There are usually seven sections of tappings to have the overcurrent range from 50% to 200% in steps of 25%. These values are percentages of the current rating of the relay. Thus a relay current rating may be 10A i.e. it can be connected to C.T. with secondary current rating of 10A but with 50% setting the relay will start operating at 5A. So adjustment of the current setting is made by inserting a pin between spring loaded jaw of the bridge socket, at the proper tap value required. When the pin is withdrawn for the purpose of changing the setting while relay is in service then relay automatically adopts a higher current setting thus secondary of C.T. is not open circuited. So relay remains operative for the fault occurring during the process of changing the setting.

The secondary winding on the central limb of upper magnet is connected in series with winding on the lower magnet. This winding is energized by the induction from primary. By this arrangement of secondary winding, the leakage fluxes of upper and lower magnets are sufficiently displaced in space and time to produce a rotational torque on the aluminium disc. The control torque is provided by the spiral spring.

When current exceeds its preset value, disc rotates and moving contacts on spindle make connection with trip circuit terminals. Angle through which the disc rotates is between 0° to 360°. The travel of the moving contacts can be adjusted by adjusting angle of rotation of disc. This gives the relay any desired time setting which is indicated by a pointer on a time setting dial. The dial is calibrated from 0 to 1. This does not give direct operating time but it gives multiplier which can be used along with the time-plug setting multiplier curve to obtain actual operating time of the relay. The time-plug setting multiplier curve is provided by the manufacturer.

2.5.1 Time-Current Characteristics

Time required to rotate the disc depends on a torque. The torque varies as current in the primary circuit. More the torque, lesser is the time required hence relay has inverse time characteristics. The Fig. 2.16 (see on next page) shows the time-current characteristics for the overcurrent relay. Such characteristics are called Inverse Definite Minimum Type (I.D.M.T.) characteristics. This is because, the characteristics shows inverse relation between time and current for small values of currents. But as current

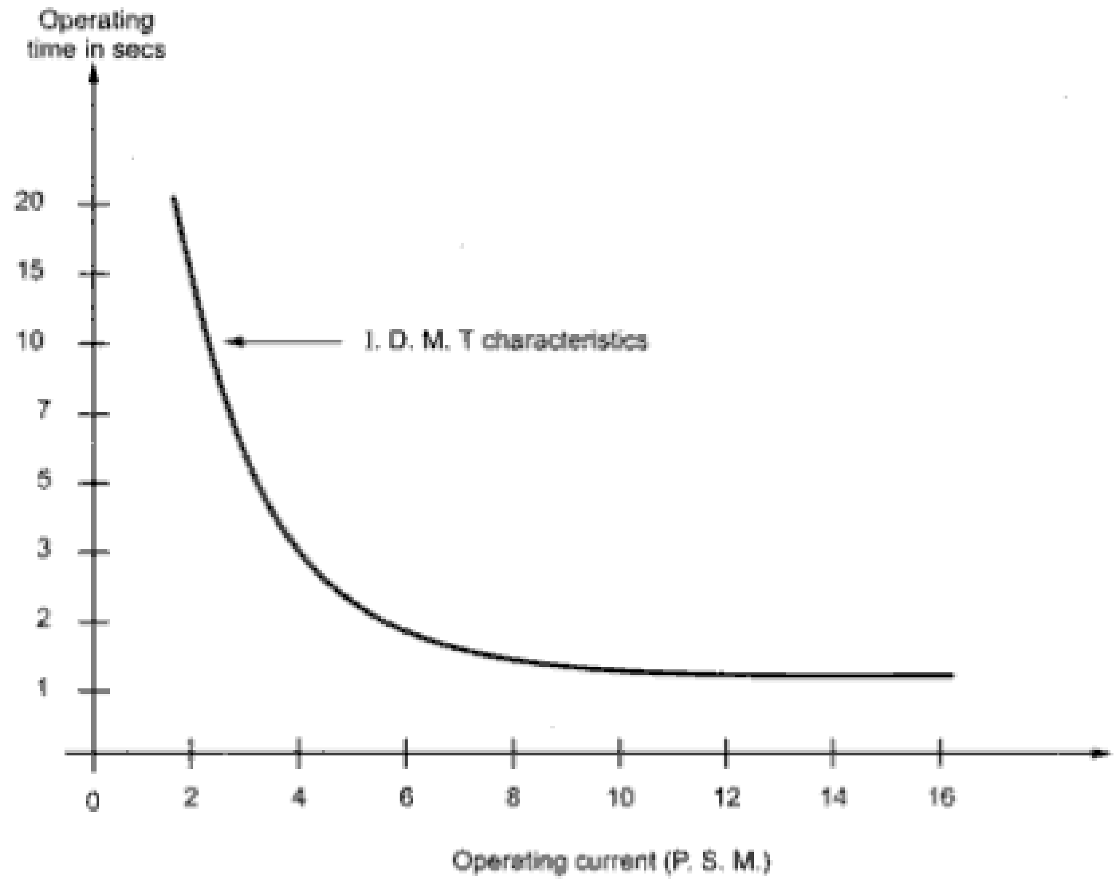


Fig. 2.16 Time-current characteristics

increases, some definite time is required by the relay. So the characteristics becomes straight line for higher values of currents. Such I.D.M.T. characteristics can be obtained by saturating the iron in the upper magnet so that there cannot be increase in the flux once current achieves certain high value.

The P.S.M. can be obtained as,

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

$$\text{Fault current in relay coil} = \text{Line fault current} \times \text{C.T. ratio}$$

2.5.2 Operation

The torque is produced due to induction principle, as explained in the section 2.4.1. This torque is opposed by restraining force produced by spiral springs. Under normal conditions the restraining force is more than driving force hence disc remains stationary. Under fault conditions when current becomes high, the disc rotates through the preset angle and makes contact with the fixed contacts of trip circuit. The trip circuit opens the circuit breaker, isolating the faulty part from rest of the healthy system.

Example 2.1 : *An I.D.M.T. overcurrent relay has a current setting of 150% and a time multiplier setting of 0.6. The primary of relay is connected to secondary of C.T. having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 5000 A. The time-current characteristics of the relay is shown in the Fig. 2.17.*

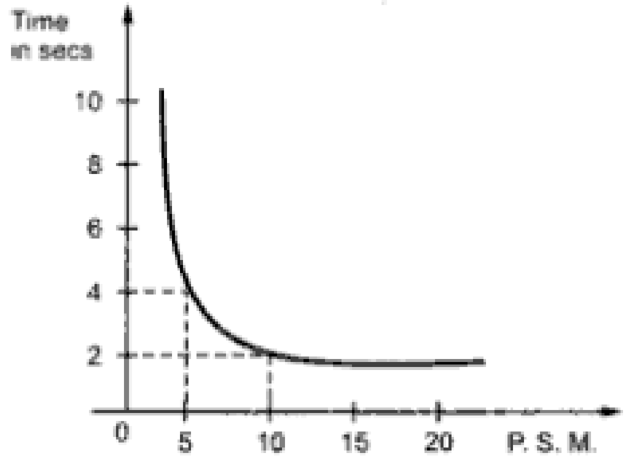


Fig. 2.17

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

$$\text{Fault current in relay coil} = \text{actual fault current} \times \text{C.T. ratio}$$

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

$$= 62.5 \text{ A}$$

$$\text{Rated secondary of C.T.} = 5 \text{ A}$$

$$\text{Current setting} = 150\% = 1.5$$

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

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

$$\therefore \quad \text{Actual operation time} = 1.8 \times \text{time setting multiplier}$$

$$= 1.8 \times 0.6$$

$$= 1.08 \text{ seconds}$$

Example 2.2 : *The Fig. 2.18 shows the part of a typical power system. If for the discrimination, the time grading margin between the relays is 0.6 sec, calculate the time of operation of relay 1 and time setting multiplier for relay 2. Refer to characteristics given in the Fig. 2.17. The time setting multiplier of relay 1 is 0.3.*

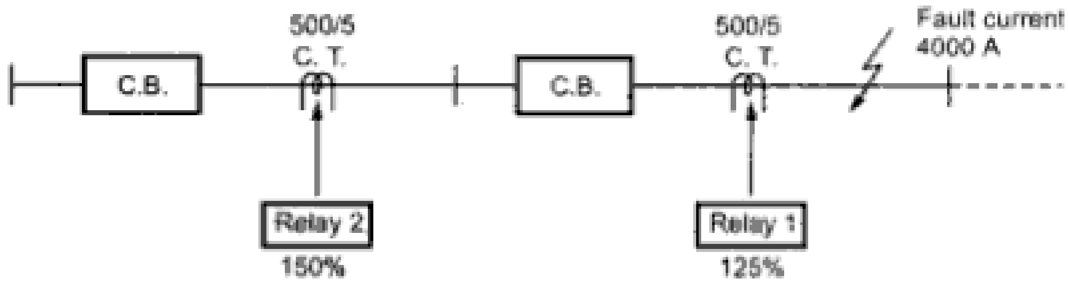


Fig. 2.18

Solution : **For relay 1 :** Current setting = 125 % = 1.25

Fault current = 4000 A

C.T. ratio = 500/5

$\therefore$ Fault current in relay coil $= 4000 \times \dfrac{5}{500}$

$= 40$ A

$\therefore$ $$\text{P.S.M.} = \frac{40}{5 \times 1.25} = 6.4$$

From the Fig. 2.17, the corresponding time for 6.4 P.S.M. is approximately 3 sec.

$\therefore$ Actual time of operation = 3 × time setting multiplier = 3 × 0.3

= 0.9 sec

For relay 2 : Current setting = 150% = 1.5

Actual time of operation = time of operation of relay 1 + time margin

= 0.9 + 0.6 = 1.5 sec

$$\text{Fault current} = 4000 \times \frac{5}{500} = 40 \text{ A}$$

$\therefore$ $$\text{P.S.M.} = \frac{\text{Fault current}}{\text{C.T. secondary rating} \times \text{current setting}}$$

$$= \frac{40}{5 \times 1.5} = 5.33$$

From the Fig. 2.17, the corresponding time for 5.33 P.S.M. is approximately 3.8 sec.

$\therefore$ $$\text{Time setting multiplier} = \frac{\text{Actual time of operation}}{\text{Time for P.S.M. obtained}}$$

$$= \frac{1.5}{3.8} = 0.395 \approx 0.4$$

This is the required time setting multiplier for the relay 2.

2.6 Directional Power Relay

The directional relay means the relay operates for the specific direction of the actuating quantity in the circuit. The directional power relay operates when power in the circuit flows in the specific direction. The construction and principle of operation of this relay is similar to the induction type watthour meter relay. The difference is that in watthour meter type relay the torque is produced due to interaction of the fluxes produced by only the current derived from secondary of C.T. while in directional power relay the torque is produced due to interaction of the fluxes produced from both voltage and current of the circuit. The relay has two windings, one acts as voltage coil while other as current coil, similar to a wattmeter. The upper magnet carries a voltage coil or potential coil which is energized from P.T. while the lower magnet carries a current coil which is energized from C.T. in the line to be protected. The construction is shown in the Fig. 2.19.

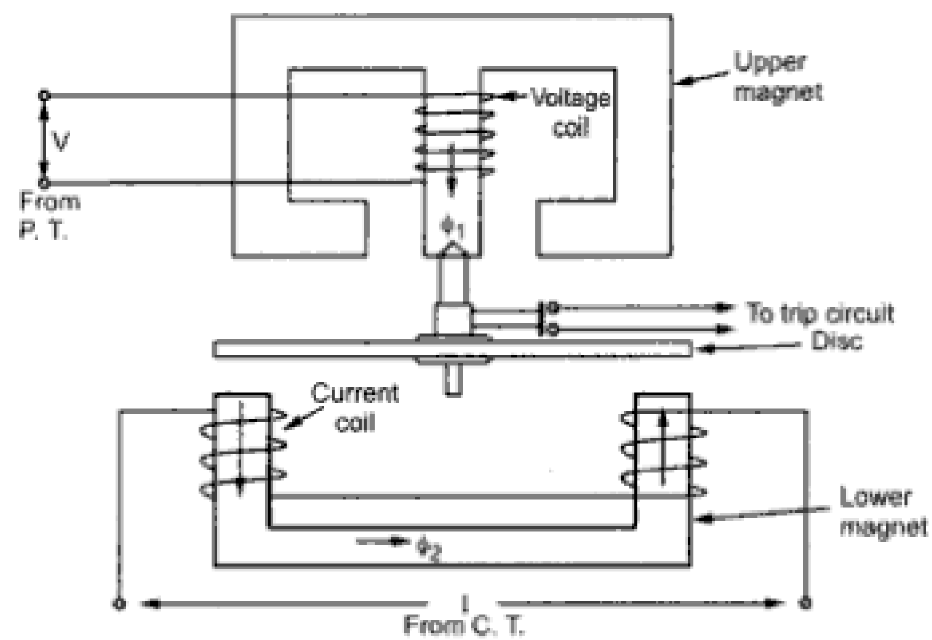


Fig. 2.19 Directional power relay

The number of tappings are provided to the current coil with which desired current setting can be achieved. The restraining torque is provided by the spiral spring. The spindle of disc carries the moving contacts which make contact with tripping circuit terminals when the disc rotates. The voltage coil provided on the upper magnet produces the flux ϕ_1. This lags the voltage V by 90°. The current I is sensed by the current coil on lower magnet which produces the flux ϕ_2. This is in phase with current I. The current I lags voltage V by an angle ϕ. The angle between ϕ_1 and ϕ_2 is α as shown in the phasor diagram in the Fig. 2.20.

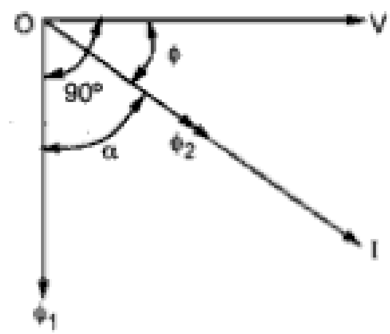


Fig. 2.20

The interaction of fluxes ϕ_1 and ϕ_2 produces the torque. Hence we can write,

$$T \propto \phi_1 \phi_2 \sin \alpha$$

But $\phi_1 \propto V$ and $\phi_2 \propto I$

while $\alpha = 90 - \phi$

$\therefore$ $T \propto V I \sin (90 - \phi)$

$\therefore$ $T \propto V I \cos \phi \propto$ power in circuit

Under normal working conditions, the driving torque acts in the same direction as that of restraining torque. This moves the moving contacts away from the fixed tripping circuit contacts. Thus relay remains inoperative as long as power flow is in one particular direction.

But when there is a current reversal and hence the power reversal then the driving torque acts in opposite direction to the restraining torque in such a manner that the moving contacts close the tripping circuit contacts. This opens the circuit breaker to isolate the faulty part.

This relay is used for providing the reverse power protection to synchronous machines. The relay can be single phase or three phase.

2.7 Directional Induction Type Overcurrent Relay

The directional power relay is not suitable to use as a protective relay under short circuit conditions. This is because under short circuit conditions the voltage falls drastically and such a reduced voltage may not be sufficient to produce the driving torque required for the relay operation. Hence in practice, directional induction type overcurrent relay is used. This relay operates almost independent of system voltage and power factor.

The directional induction type overcurrent relay uses two relay elements mounted on a common case. These elements are,

1. Directional element which is directional power relay
2. Nondirectional element which is nondirectional overcurrent relay

The schematic arrangement of such a directional relay is shown in the Fig. 2.21.

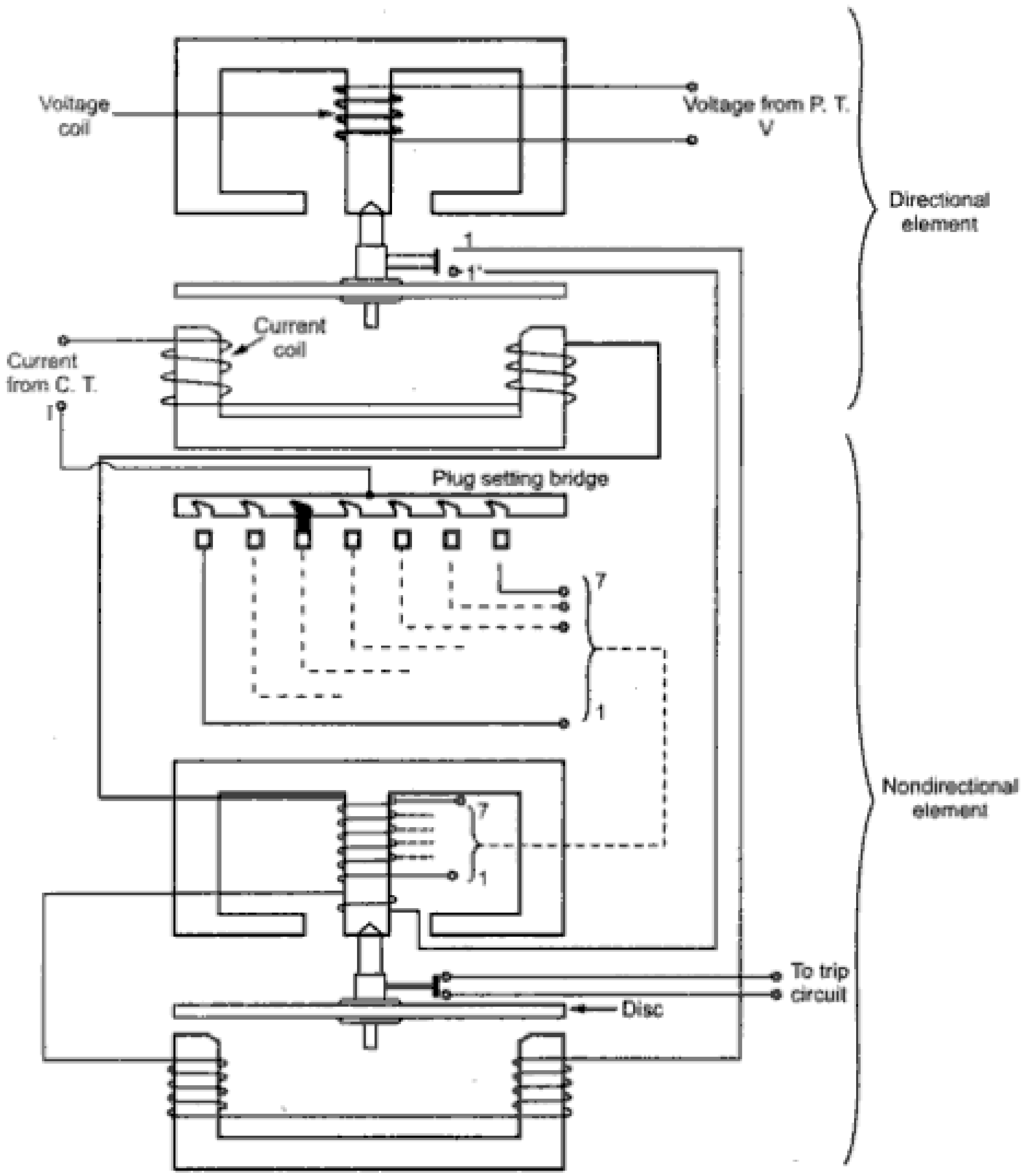


Fig. 2.21 Directional overcurrent relay

Directional element : The directional element is nothing but a directional power relay which operates when power in the circuit flows in a particular direction. The voltage coil of this element is energized by a system voltage through a potential transformer. The current coil on the lower magnet is energized by the system current through a current transformer. The trip contacts of this relay (1 – 1') are connected in series with the secondary winding of nondirectional element.

Nondirectional element : The current coil of the directional element is connected in series with the primary winding of nondirectional element. The plug setting bridge is provided in this element to adjust current setting as per the requirement. The trip contacts (1 – 1') are in series with winding on lower magnet of nondirectional element. So unless and until trip contacts (1 – 1') are closed by the movement of the disc of directional element, the nondirectional element cannot operate. Thus the movement of the nondirectional element is controlled by the directional element.

2.7.1 Operation

Under normal conditions, power flows in the proper direction and hence directional element of the relay is inoperative. Thus the secondary winding on lower magnet of nondirectional element is open and hence nondirectional element is also inoperative.

When the fault takes place, the current or power in the circuit has a tendency to flow in reverse direction. The current flows through current coil of directional element which produces the flux. The current in the voltage coil produces another flux. The two fluxes interact to produce the torque due to which the disc rotates. As disc rotates, the trip contacts (1 – 1') get closed. Note that the design of directional element is such that it is very sensitive and though voltage falls under short circuit, the current coil is responsible to produce sufficient torque to have disc rotation. It is so sensitive that it can operate even at 2 % of power flow in reverse direction.

The current also flows through the primary winding on the upper magnet of nondirectional element. Thus energizes the winding to produce the flux. This flux induces the e.m.f. in the secondary winding of the nondirectional element according to induction principle. As the contacts (1 – 1') are closed, the secondary winding has a closed path. Hence the induced e.m.f. drives the current through it, producing the another flux. The two fluxes interact to produce the driving torque which rotates the disc. Thus the contacts of trip circuit get closed and it opens the circuit breaker to isolate the faulty section.

So directional element must operate first to have the operation of the nondirectional element.

The following **conditions** must be satisfied to have the operation of the entire relay :

1. The direction of current in the circuit must reverse to operate directional element.
2. The current value in the reverse direction must be greater than the current setting.
3. The high value of current must persist for a time period which is greater than the time setting of the relay.

2.7.2 Directional Characteristics

Let us study the phasor diagram to understand the directional characteristics of the relay.

Let V = Relay voltage through P.T.

I = Relay coil current through C.T.

θ = Angle between V and I

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

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

So current I leads voltage V by angle θ.

ϕ_V = Flux produced by voltage V

This flux ϕ_V lags voltage V by an angle ϕ.

ϕ_I = Flux produced by current I

The flux ϕ_I is in phase with the current I.

The phasor diagram is shown in the Fig. 2.22. The voltage V is taken as reference.

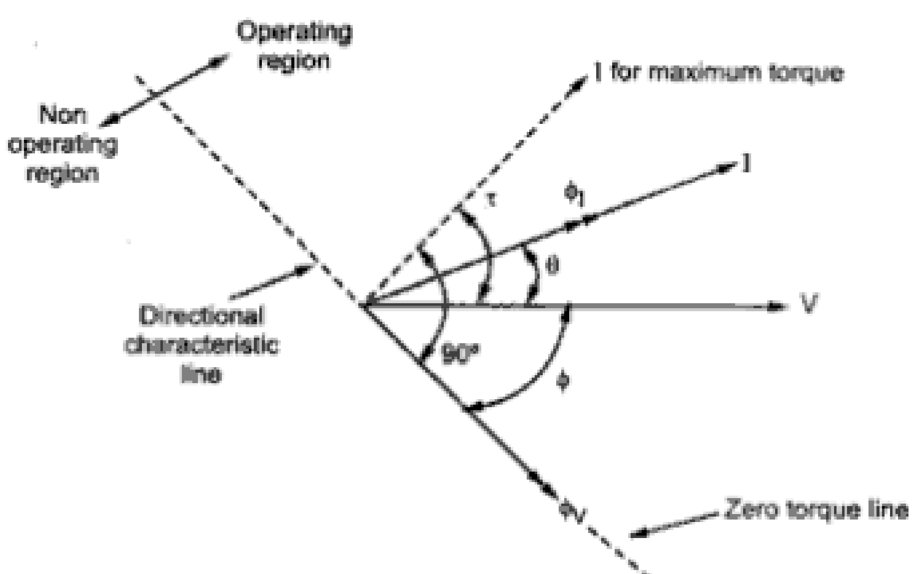


Fig. 2.22 Phasor diagram and directional characteristic

The torque is proportional to the fluxes ϕ_V, ϕ_I and sine of the angle between the two fluxes.

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

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

Now $\quad \phi_V \propto V \quad$ and $\quad \phi_I \propto I$

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

where $\quad K = $ constant

Maximum torque occurs when $\sin(\theta + \phi)$ is 1 i.e.

$$\theta + \phi = 90^\circ$$

The condition for the maximum torque is shown dotted in the Fig. 2.22.

The torque is zero when $\sin(\theta + \phi) = 0$ i.e.

$$\theta + \phi = 0^\circ \text{ or } 180^\circ$$

This will be satisfied when the relay current I phasor lies along the ϕ_V phasor or in antiphase with ϕ_V. The corresponding line is called zero torque line and is shown in the Fig. 2.22. This line is at right angles to the maximum torque condition line.

Thus the directional element operates, provided that the current phasor lies within $\pm 90^\circ$ of the maximum torque line. If it is displaced more than 90° then the element will restrain. Both operating as well as nonoperating regions are shown in the Fig. 2.22.

Maximum torque angle : The angle by which the current supplied to the relay leads the voltage supplied to the relay so as to obtain the maximum torque is called maximum torque angle (M.T.A.). It is denoted as τ in the Fig. 2.22.

From the Fig. 2.22, we can write,

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

Substituting in the torque equation,

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

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

This is the torque equation interms of maximum torque angle τ. The typical values of the maximum torque angle are 0°, 30°, 45° etc.

2.8 Thermal Relays

Thermal relays work on the principle of heating effect of an electric current in the relay coil. Instead of the measurement of temperature, these relays sense the temperature rise produced by the current.

In a simplest thermal relay, a bimetallic strip is used. The strip is mounted above a resistance coil carrying current to produce necessary heating effect. The spring is used to make the connection between contacts and the strip. The insulated lever arm is used to carry the contact which is pivoted. To have variable settings, the tension in the spring can be adjusted. The Fig. 2.23 shows the schematic diagram of thermal relay.

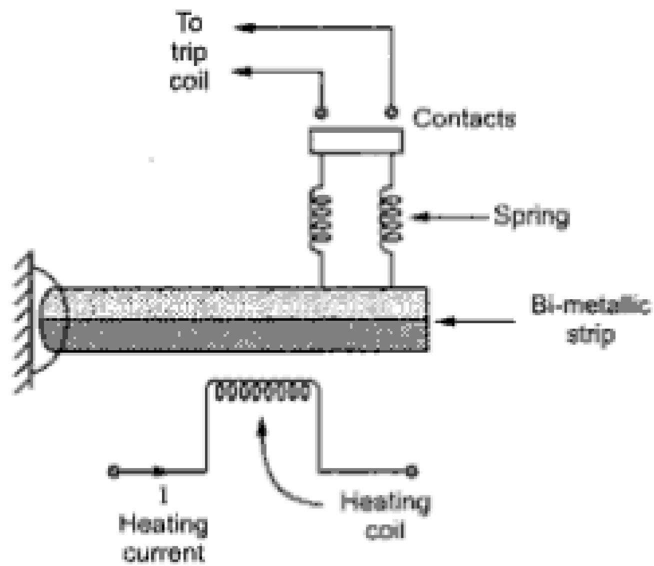


Fig. 2.23

Under normal conditions, the heating due to current I is not enough to heat the strips and contacts remain closed as strip remains straight.

When there is overloading, then the current I increases beyond safe value producing very high I^2R losses and corresponding large heat. Thus the strip gets heated up and bends. Due to the bending of the strip, the spring opens the contacts and current is interrupted.

In some cases, the bimetallic strips themselves carry the current without using a heater coil. These relays are commonly used in protection of low voltage a.c. and d.c. motors. In case of large motors, the bimetallic strip is connected through current transformer.

2.9 Universal Relay Torque Equation

Most of the protection relays consist of some arrangement of electromagnets with armature or induction disc, which carry contacts. The relays also carry the closing or opening of contacts control devices like trip coils of circuit breaker. The electromagnets have current, voltage or both the types of windings. Currents through windings produce magnetic fluxes and torque is developed by the interaction between the fluxes of same windings or between the fluxes of both the windings. In general the torque produced by current winding is proportional to square of the current the torque produced by voltage winding is proportional to square of the voltage, and the torque produced by both the windings is proportional to product of voltage and the current. Mathematically we can write,

Torque produced by current coil, $= K_1 I^2$

Torque produced by voltage coil $= K_2 V^2$

Torque produced by both the coils $= K_3 VI \cos(\theta - \tau)$

where K_1, K_2 and K_3 = constant θ = angle between V and I

τ = maximum torque angle

Torque produced by control spring = K_4

The control springs are used as restraining elements

If all the elements are present in a relay then total torque produced by all the causes can be expressed by a general equation as,

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

This equation is called universal relay torque equation the term K_4 can be a restraining torque due to springs or gravity.

By assigning positive and negative signs to certain constants and lets other constants to be zero and sometimes by adding similar other terms, the operating characteristics equation of all the types of protective relays can be obtained from universal equation.

For example, for overcurrent relay $K_2 = K_3 = 0$ and the spring torque is negative so we get,

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

For the directional relay $K_1 = K_2 = 0$ and the spring torque is negative .

So we get,

$$T = K_3 VI \cos(\theta - \tau) - K_4$$

Review Questions

1. *Explain the operation of basic trip circuit*
2. *Explain the following schemes used in circuit breakers.*
   i) Relay with make type contact
   ii) Relay with break type contact
3. *Describe any one type of electromagnetic attracted armature relay*
4. *Describe with neat sketch the operation of solenoid and plunger type relay*

5. *Derive the torque equating for electromagnetic attraction relays when used for,*

   i) a.c. operation

   ii) d.c. operation

6. *State the advantages, disadvantages and applications of electromagnetic relays*

7. *Derive the torque equation for the induction type relays*

8. *Describe the operation of following relays with neat sketches,*

   i) Shaded pole type induction relay

   ii) Watthour meter type induction relay

   iii) Induction cup type relay

9. *Explain with the help of a neat diagram, the construction and working of a nondirectional induction type overcurrent relay. Draw and explain its time-current characteristics.*

10. *What is I.D.M.T characteristics of a relay?*

11. *Explain the working principle of directional power relay.*

12. *What is the procedure of setting I.D.M.T. relay ? What initial data is required ? How is the directional relay different than simple I.D.M.T relay ?*

13. *Explain with the help of neat sketch, the construction and working of directional induction type overcurrent relay.*

14. *State the conditions to be satisfied by a directional relay before its operation*

15. *Draw the directional characteristics and explain what is maximum torque angle*

16. *What is universal relay torque equation ? What is its use ?*

17. *An I.D.M.T. overcurrent relay has a current setting of 150% and has a time multiplier setting of 0.5 . The relay is connected in the circuit with the help of C.T. having ratio 500 : 5 A. Calculate the time of operation of the relay if circuit carries a fault current of 6000 A. The relay characteristics are given in the Fig. 2.24.*

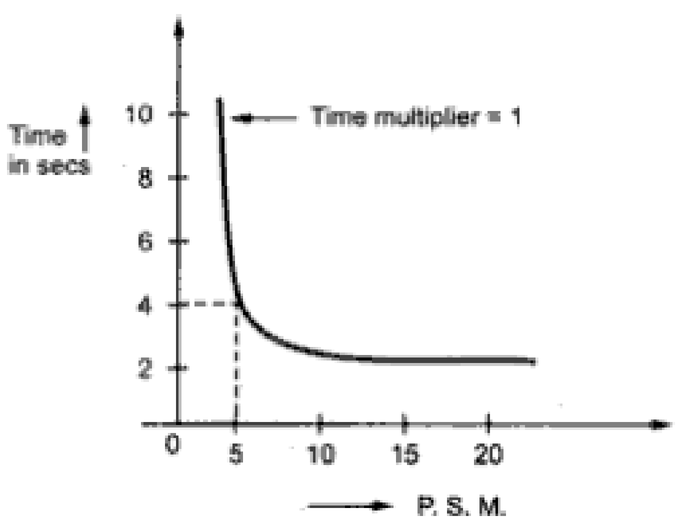


Fig. 2.24 Relay characteristics

18. *For a particular transmission line, relays are used as shown in the Fig. 2.25.*

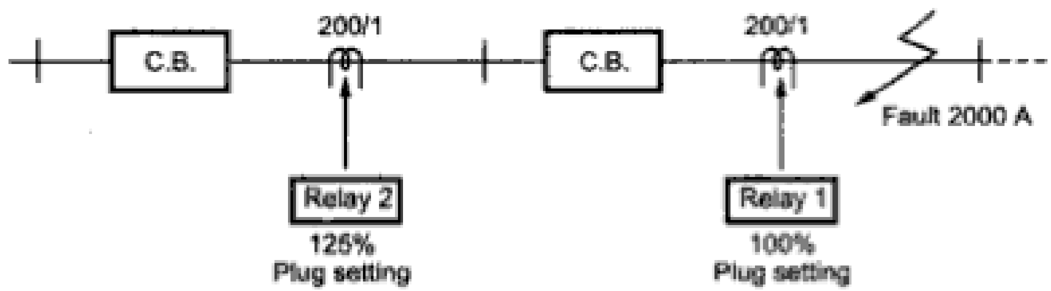


Fig. 2.25

For discrimination, the time grading margin is 0.5 sec.

Determine the time of operation of the two relays assuming that both the relays have characteristics as shown in the Fig. 2.25. The relay 1 has time setting multiplier of 0.2. Find the time setting multiplier of relay 2. **(Ans. : 0.56 sec, 1.06 sec, 0.3364)**

19. *Write a note on thermal relays.*

❑❑❑

3 Differential Protection

3.1 Introduction

In the overcurrent relays, a current is sensed but such relays are not very sensitive as these relays cannot distinguish between heavy loads and minor fault conditions. In such cases, differential relays can be used.

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

Thus a current differential relay operates on the result of comparison between the phase angle and magnitudes of the currents entering and leaving the system to be protected. Under normal conditions, the two currents are equal in phase and magnitude hence relay is inoperative. But under fault conditions, this condition no longer exists. The relay is connected in such a manner that the difference between current entering and current leaving flows through the operating coil. If this difference current exceeds a preset value then the relay operates and opens the circuit breaker.

Almost any type of relay when connected in a certain way can be made to operate as a differential relay.

3.2 Types of Differential Relays

The various types of differential relays are,

1. Current differential relay
2. Biased beam relay or percentage differential relay
3. Voltage balance differential relay

3.2.1 Current Differential Relay

Most of the differential relays are of current differential type. Consider an over current relay connected in the circuit so as to operate as the current differential relay. This is shown in the Fig. 3.1.

Two current transformers are used having same ratio are connected on the either side of the section to be protected. The secondaries of current transformers are connected in series, so they carry induced currents in the same direction. Let current I

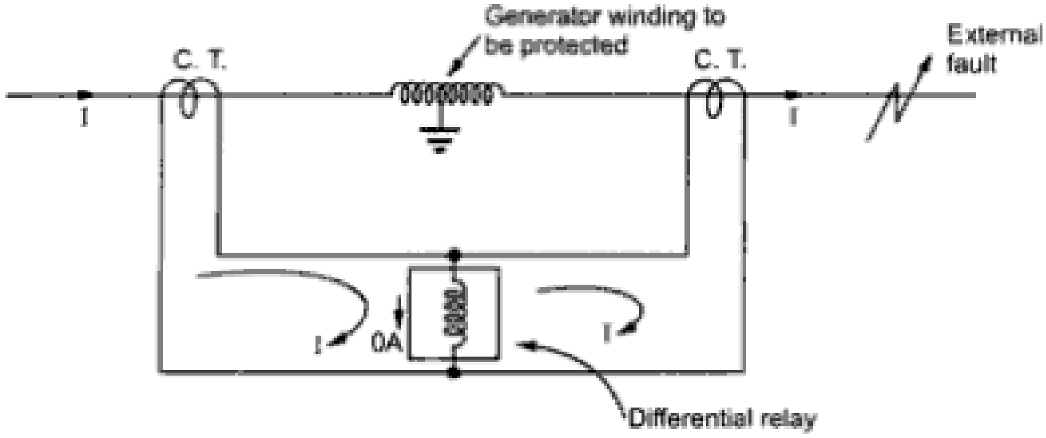


Fig. 3.1 Current differential relay

is flowing through the primary of current transformers towards the external fault. As the current transformers are identical, the secondaries of current transformers will carry equal currents. Due to the connection of relay, no current will flow through the operating coil for the relay. Hence relay will remain inoperative. So relay cannot operate if there is an external fault.

Consider now that an internal fault occurs at point A, as shown in the Fig. 3.2.

The current flows through the fault from both sides. The two secondary currents through C.T.s are not equal. The current flowing through the relay coil is now $I_1 + I_2$. This high current causes the relay to operate.

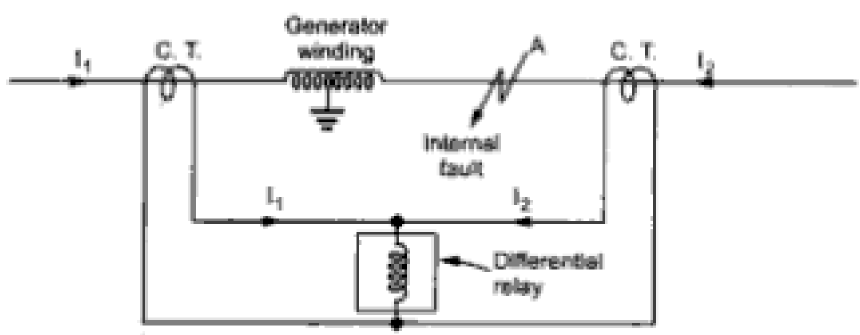


Fig. 3.2 Action of differential relay

It should be noted that the fault current need not always flow to the fault from both sides. A flow on one side only or even some current flowing out of one side while a large current entering the other side can cause differential relay to operate. Thus the amount of current flowing through a relay coil depends upon the way the fault is being fed.

This relay suffers from the following **disadvantages,**

1. The current transformers are connected through cables called pilot cables. The impedance of such pilot cables generally causes a slight difference between the currents at the ends of the section to be protected. A sensitive relay can operate to a very small difference in the two currents, though there is no fault existing.

2. The relay is likely to operate inaccurately with heavy through current flows. This is because the assumed identical current transformers may not have

identical secondary currents due to the constructional errors and pilot cable impedances.

3. Under severe through fault conditions, the current transformers may saturate and cause unequal secondary currents. The difference between the currents may approach the pick value to cause the inaccurate operation for the relay.

4. Under heavy current flows, pilot cable capacitances may cause inaccurate operation of the relay.

All these disadvantages are overcome in biased beam relay.

3.2.2 Biased Beam Relay or Percentage Differential Relay

As the name suggests, this relay is designed to operate to the differential current in terms of its fractional relation with the actual current flowing through the protected circuit.

The Fig. 3.3 shows the arrangement of a biased beam relay.

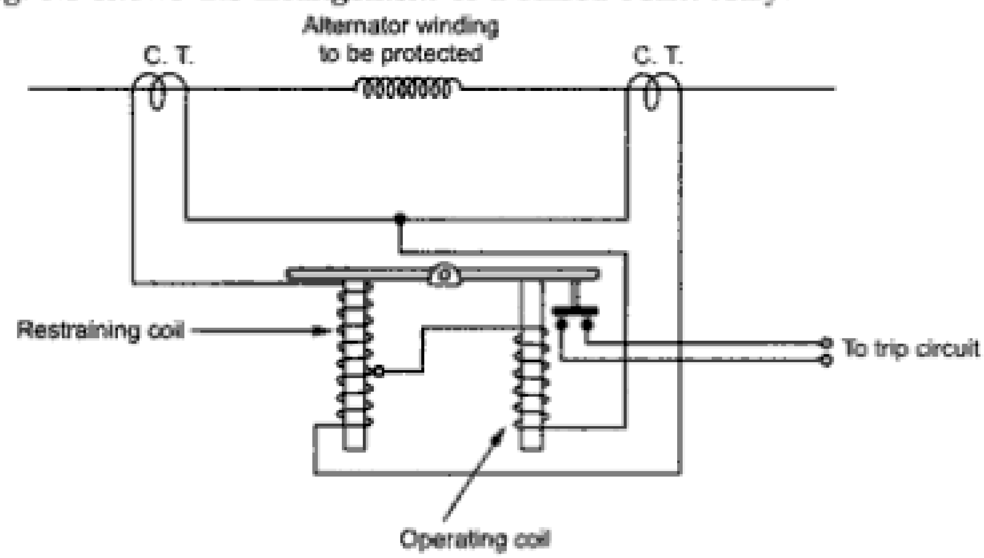


Fig. 3.3 Biased beam relay

The simple circuit connection of this type of relay is shown in the Fig. 3.4.

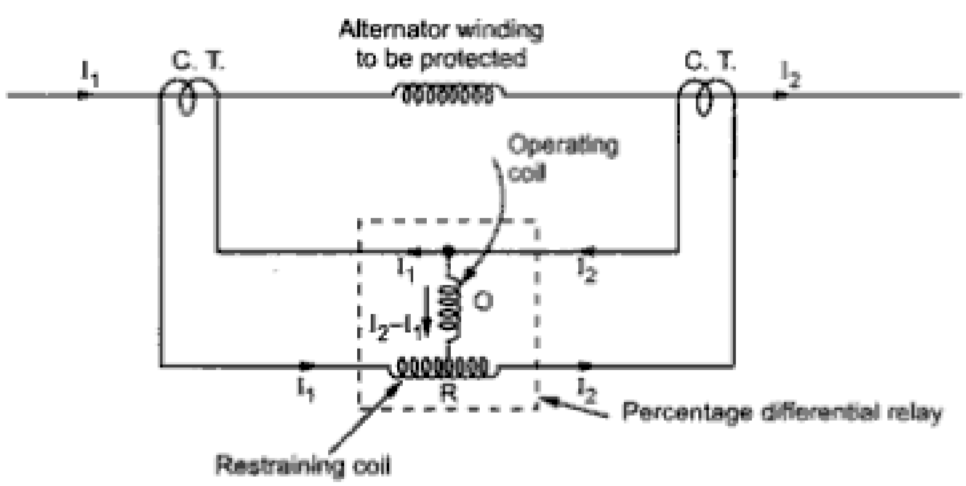


Fig. 3.4 Simple circuit of biased beam relay

The operating coil O of the relay carries a differential current $(I_2 - I_1)$ while the restraining coil R carries the current proportional to $\left(\frac{I_1 + I_2}{2}\right)$ as the operating coil is connected at the midpoint of the restraining coil. This can be explained as,

Let N = Total number of turns of restraining coil

So current I_1 flows through $\frac{N}{2}$ turns while current I_2 flows through $\frac{N}{2}$.

$$\text{Effective ampere turns} = \frac{I_1 N}{2} + \frac{I_2 N}{2} = N\left(\frac{I_1 + I_2}{2}\right)$$

Thus it can be assumed that the current $\left(\frac{I_1 + I_2}{2}\right)$ flows through the entire N turns of the restraining coil.

Under normal and through load conditions, the bias force produced due to the restraining coil is greater than the operating force produced by operating coil hence relay is inoperative. When internal fault occurs, the operating force becomes more than the bias force. Due to this, beam moves and the trip contacts are closed to open then circuit breaker.

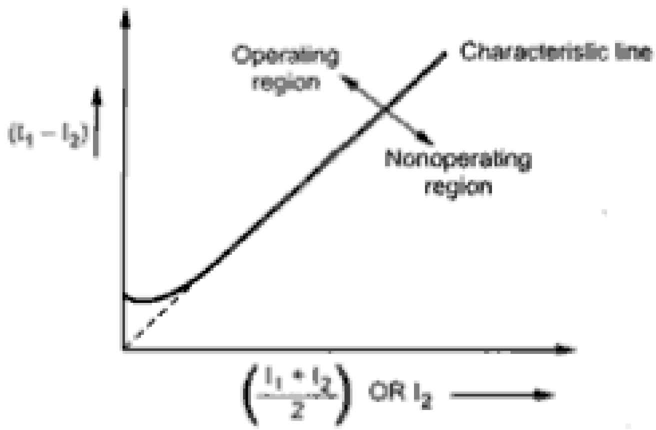


Fig. 3.5 Operating characteristics

The operating characteristics of this type of relay is shown in the Fig. 3.5.

It can be seen that except at low currents, the characteristics is a straight line.

Thus the ratio of the differential operating current to the average restraining current is a fixed percentage. Hence the relay name is percentage differential relay.

The relays with constant slope characteristics are called constant slope percentage differential relays.

In some relays, the slope of the characteristics increases as the short circuit current increases. Such characteristics is shown in the Fig. 3.6.

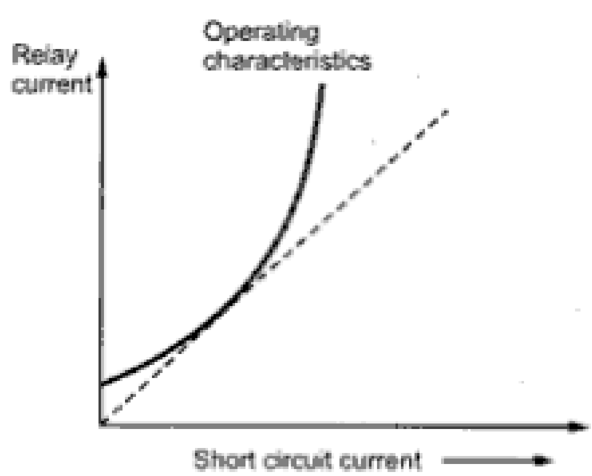


Fig. 3.6 Increase in slope characteristic

Such relays are called increasing slope percentage differential relays.

The important fact about increasing slope type relays is that their cost is more but require less accuracy in the performance of their current transformers. Constant slope type relays require good accuracy in the performance of the current transformers.

3.2.3 Voltage Balance Differential Relay

This is also called opposed voltage method. In this type, the over current relay is connected in series with the secondaries of the current transformers. This is shown in the Fig. 3.7.

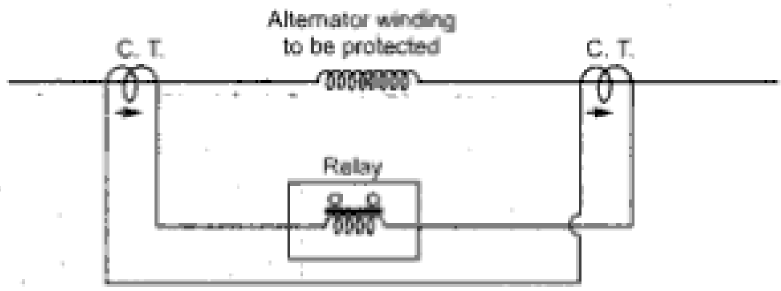


Fig. 3.7 Voltage balance differential relay

Under normal conditions, the current at the two ends of the section to be protected is same. Hence there is no voltage drop across the relay to cause the current to flow.

Under fault conditions, the currents in the two secondaries of current transformers are different. This causes a large voltage drop across the relay. Thus the voltage balance of the circuit gets disturbed. Hence large current flows through the relay due to which the relay operates to open the circuit breaker.

3.3 Busbar Protection

The busbar plays an important role in the supply system. The busbar faults are rare but if occurs there can be interruption of supply, considerable damage and loss. Hence busbar protection is must and it must be fast, stable and reliable. The busbar protection needs to protect not only the busbar but the apparatus associated with it such as circuit breakers, isolating switches, instrument transformers etc.

3.3.1 Busbar Faults

The various busbar faults can be classified as,

1. Failure of insulation due to material deterioration.
2. Failure of circuit breaker.
3. Earth fault due to failure of support insulator.
4. Flashover due to sustained excessive over voltages.
5. Errors in the operation and maintenance of switchgear.
6. Earthquake and mechanical damage.
7. Accidents due to foreign bodies falling across the busbars.
8. Flashover due to heavily polluted insulator.

3.4 Frame Leakage Protection of Busbar

All busbar protection schemes are mostly designed for earth faults. Each conductor is surrounded by the earthed metal barrier. All the metal frameworks are bonded together and insulated from earth. The switchgear framework is also insulated from lead cable sheaths.

The arrangement of frame leakage protection to a single busbar substation with a switchgear unit is shown in the Fig. 3.8.

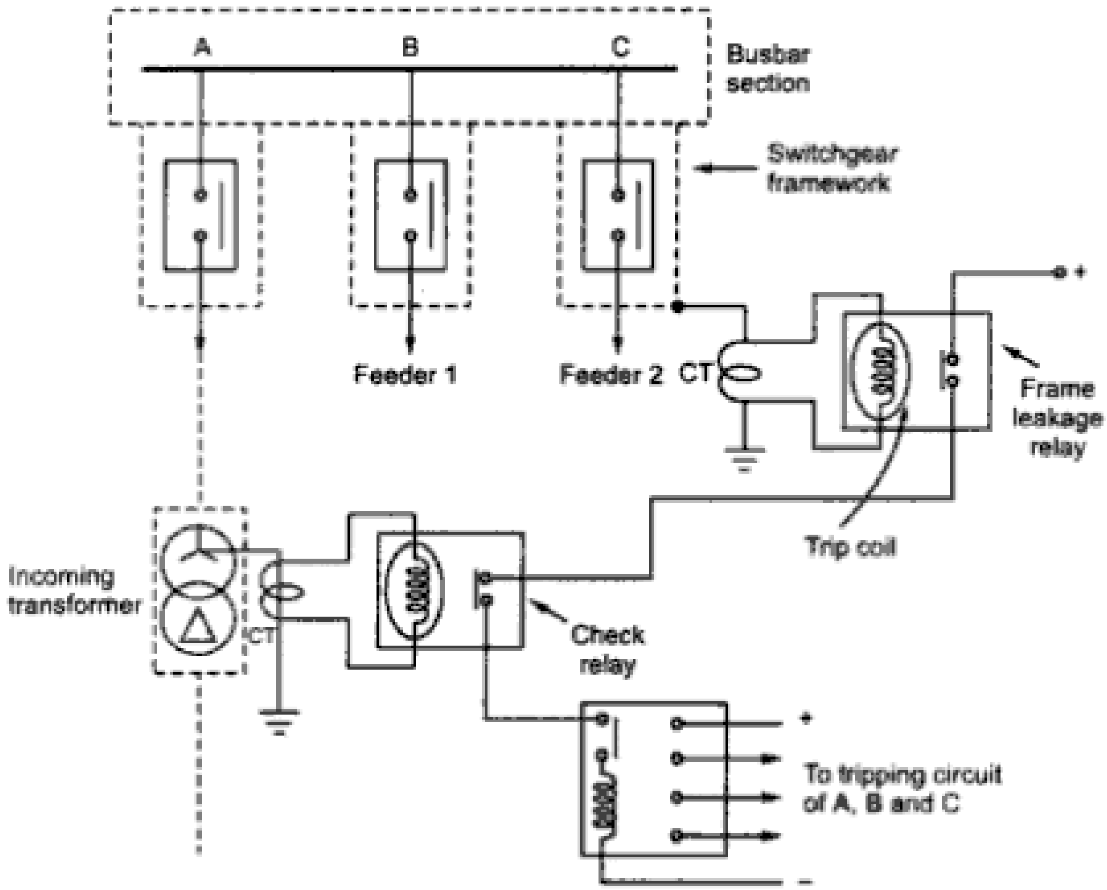


Fig. 3.8 Frame leakage protection of busbar

Metal supporting frame work known as fault bus is earthed through a CT. When the fault is there, a contact between conductor and earth results. This drives current through this CT. This energizes the frame leakage relay.

The CT energizing the check relay is mounted in neutral earth of the transformer. The contacts of check relay and frame leakage relay are in series.

Thus before tripping circuit gets energized both the relays must operate. Once both the relays operate due to earth fault, all the breakers will trip connecting the equipment to the busbar. Due to check relay, accidental operation of single relay to trip the circuit gets avoided.

3.5 Circulating Current Protection of Busbar

This is nothing but the differential scheme of the protection of busbar. The circulating current principle states that under normal working conditions or external fault conditions, sum of the currents entering the bus equals sum of the currents leaving the bus. Under any abnormal conditions in the protected zone i.e. short circuit or phase to phase faults, the current condition gets disturbed and sensing this the relay can be operated.

The Fig. 3.9 shows the principle of circulating current protection of busbar.

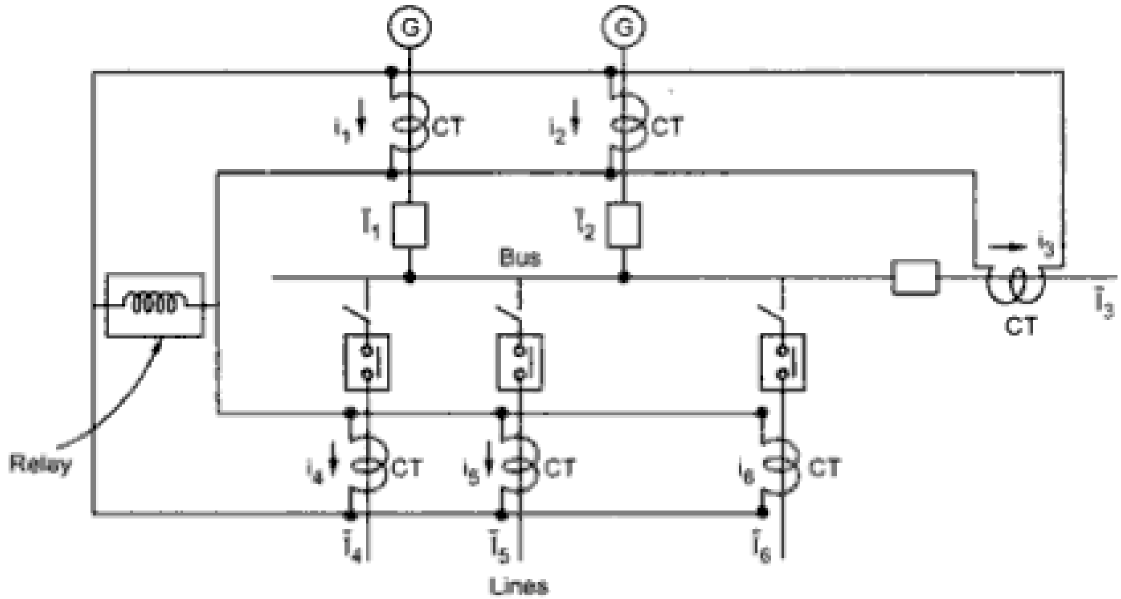


Fig. 3.9 Circulating current protection of busbar

I_1, I_2 ...... I_6 are the currents in the circuits connected to the busbar.

Under normal condition, $\sum I = 0$.

i.e. $\bar{I}_1 + \bar{I}_2 + \bar{I}_3 + \bar{I}_4 + \bar{I}_5 + \bar{I}_6 = 0$ (vector sum)

No current flows through the relay and hence remains inoperative.

Under fault conditions,

$\bar{I}_1 + \bar{I}_2 + \bar{I}_3 + ... + \bar{I}_6 = \bar{I}_f$

where $\bar{I}_f$ = Fault current = unbalanced current.

The unbalanced current flows through the relay and the relay operates.

Under normal conditions, currents in the secondaries of CT balance each other and no current flows through the relay. Thus relay is inoperative. Under any fault conditions, the fault current flows through relay coil to activate it.

To obtain exact balance of currents, all current transformers must have same ratio. But in practice there exists a difference in the magnetic conditions of iron cored current transformers and false operation of the relay is possible, at the time of external faults. For large fault currents there is a possibility of saturation of the cores of current transformers. To overcome such difficulties, a special type of C.T. having no iron core is used. It is called **linear coupler.**

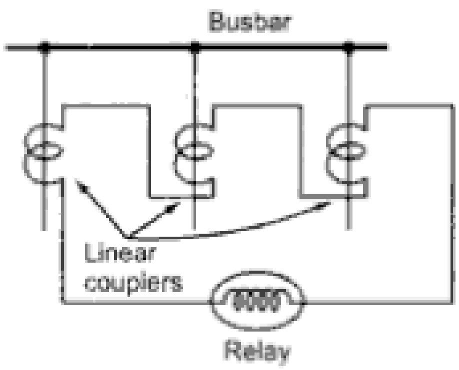


Fig. 3.10

The linear coupler has a property that its secondary voltage is proportional to the primary current and the secondary windings of all the linear couplers are connected in series to the relay. This is shown in the Fig. 3.10.

The sum of the voltage outputs of linear couplers is equal to the vector sum of the voltages in the circuits connected to the busbars. Hence under normal conditions overall voltage in the secondary circuit is zero and relay is inoperative. Under fault conditions, there is resultant voltage in the secondary and the relay operates.

A high impedance relay can differentiate properly the internal and external faults compared to normal low impedance relay. Hence in circulating current protection, high impedance relays are used. A high resistance is connected in series with relay operating coil to get high impedance relay. This resistance is called **stabilising resistance**.

3.6 High Impedance Differential Protection of Busbar

Another method to provide differential protection to busbar is based on sensing a voltage drop across a high impedance, under fault conditions. The scheme is shown in the Fig. 3.11.

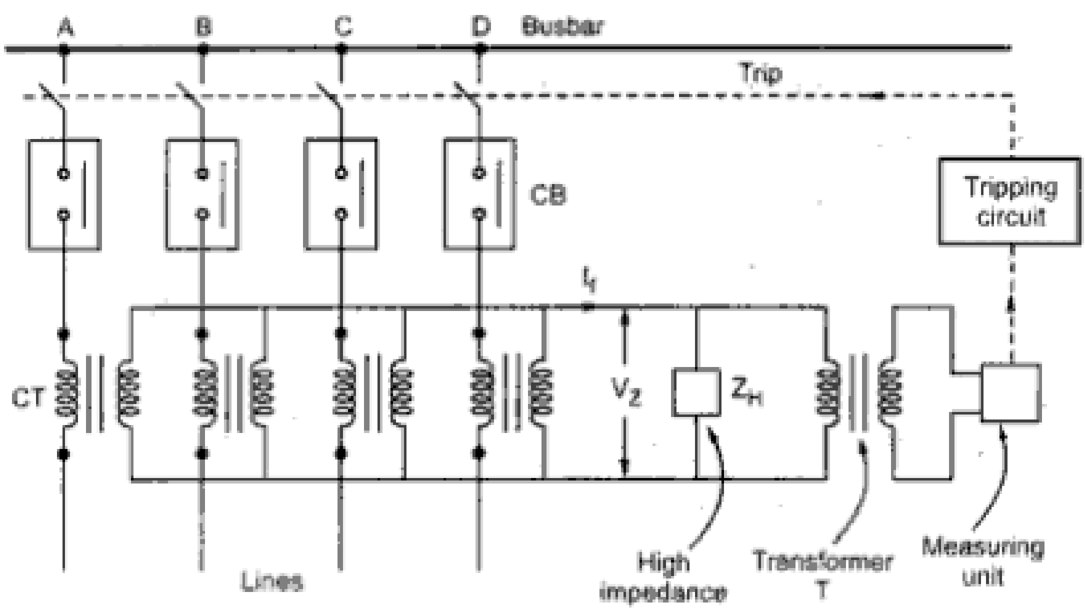


Fig. 3.11 High impedance busbar protection

The basic principle remains same as differential scheme. Under normal conditions vector sum of the currents in the lines is zero. Hence I_f i.e. current flowing through high impedance Z_H is zero. And the relay is inoperative.

During fault conditions, unbalanced current exists. Such an out of balance current I_f flows through Z_H causing a high voltage drop V_r across it. It is given to a transformer. A measuring unit is connected to the secondary of this transformer which measures this drop and trips the relay accordingly. Main advantage is that as voltage drop is sensed, saturation of core of one of the current transformers has no effect on the protection scheme.

3.7 Difficulties in Busbar Protection

The various difficulties in the busbar protection are,

1. Current levels for different circuits are different.
2. Large number of circuits to be protected.
3. Saturation of cores of current transformers due to d.c. component in short circuit current is possible which produces ratio error.
4. Due to various bus sections, the scheme becomes complicated.
5. With large load changes, relay settings need to be changed.

Review Questions

1. *What are differential relays ? How they are classified ?*
2. *Explain the working of following differential relays,*
   i) Current differential relay
   ii) Percentage differential relay
   iii) Voltage balance differential relay
3. *Explain the need of busbar protection and difficulties in bus bar protection.*
4. *Explain frame leakage protection of busbar.*
5. *Explain current circulating protection of busbar.*
6. *Explain high impedance differential protection of busbar.*

❑❑❑

4

Distance Protection

4.1 Distance Relays

In the relays discussed uptil now, the operation of the relays is dependent on the magnitude of the current or voltage of the circuit to be protected. In distance relays, the operation is dependent on the ratio of the voltage and current, which is expressed interms of an impedance. Hence basically distance relays are called impedance relays. The impedance is nothing but an electrical measure of distance along a transmission line. The relay operates when the ratio V/I i.e. impedance is less than a predetermined value. As the ratio V/I affects the performance of these relays, the relays are also called ratio relays. Dependent on the ratio of V and I there are three types of distance relays which are,

1. Impedance relay which is based on measurement of impedance Z.
2. Reactance relay which is based on measurement of reactance X.
3. Admittance or Mho relay which is based on measurement of component of admittance Y.

In short, a distance relay is one whose performance is based on the measurement of impedance, reactance or admittance of line between the location of relay and the point where fault occurs.

4.2 Impedance Relay

The impedance relay works corresponding to the ratio of voltage V and current I of the circuit to be protected. There are two elements in this relay, the one produces a torque proportional to current while the other produces a torque proportional to voltage. The torque produced by the current element is balanced against torque produced by the voltage element. Thus the current element produces operating torque, pickup torque which can be said to be positive torque. The voltage element produces restraining torque, reset torque which can be said to be negative torque. So this relay is voltage restrained overcurrent relay.

The Fig. 4.1 shows the basic operating principle of an impedance relay.

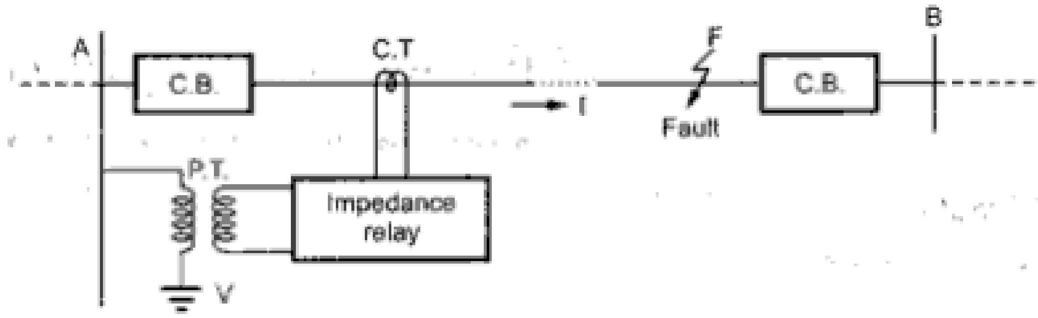


Fig. 4.1 Basic operation of impedance relay

The current element is energized by current through C.T. while voltage element is energized by voltage through P.T. The section AB of the line is protected zone.

Under normal conditions, the ratio of voltage V and current I is denoted as Z_L which is impedance of line. The relay is inoperative under this condition.

When the fault occurs at point F in the protected zone then the voltage drops while current increases. Thus the ratio V/I i.e. the impedance reduces drastically. This is the impedance of line between the point at which relay is connected and the point F at which fault occurs. So when the impedance reduces than its predetermined value Z_L, it trips and makes the circuit breaker open.

4.2.1 Torque Equation

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

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

Hence the torque equation becomes,

$$T = K_1 I^2 - K_2 V^2 - K_3 \qquad \text{... (1)}$$

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

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

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

$$\therefore \quad K_2 V^2 = K_1 I^2 - K_3 \qquad \text{... (2)}$$

Dividing both sides by $K_2 I^2$,

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

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

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

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

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

$$= \frac{V}{I} = \text{constant} \quad \ldots (4)$$

4.2.2 Operating Characteristics

As seen from the equation (4), it can be stated that the impedance relay is on the verge of operating at a given constant value of the ratio V/I, which can be expressed as an impedance.

For a particular fault position, the ratio V/I i.e. impedance is constant. It changes if the fault position changes. If fault is nearer to relay, this ratio will be low and as fault position moves away from the relay the ratio becomes higher and higher. So it can be installed to operate for the section to be protected and once installed and adjusted for a particular section, it is inoperative beyond that section.

The operating characteristics of the relay is shown in the Fig. 4.2.

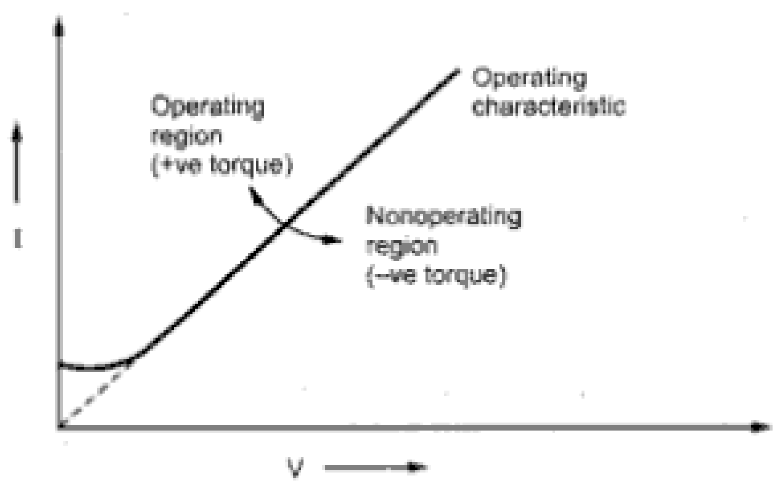


Fig. 4.2 Operating characteristics

As the effect of spring is dominating for the lower values of currents, the characteristics shows a noticiable bend at lower currents.

But for all practical purposes, the dotted line, which represents a constant value of Z may be considered as an operating characteristics.

The impedance Z which is predetermined set value is given by,

$$Z = \frac{1}{\text{slope of characteristics}}$$

The relay will pickup for any combination of V and I represented by any point above the line in the positive torque region. In other words for any value of Z less than the constant value represented by the line, the relay will operate.

By adjustments, the slope of the characteristics can be changed so that the relay will respond to all the values of impedance less than any desired upper limit.

4.2.3 Operating Characteristics on R-X Diagram

The operating characteristics of an impedance relay can be more easily represented by a diagram called R-X diagram. The diagram is shown in a plane having X-axis as R (resistance) while the Y-axis as X (reactance). This plane is called R-X plane. The impedance Z can be expressed as,

$$Z = R + jX$$

$$\therefore \quad |Z| = \sqrt{R^2 + X^2}$$

$$\therefore \quad Z^2 = R^2 + X^2 \qquad \ldots (1)$$

Mathematically $x^2 + y^2 = r^2$ represents an equation of circle where x and y are vertical and horizontal co-ordinates while r is the radius. Similarly the equation (1) represents circle where R and X are vertical and horizontal co-ordinates and magnitude of impedance $|Z|$ is the radius of the circle. The centre of this circle is at point where R and X axes intersect each other i.e. origin.

From equation (1) we can write,

$$\tan\phi = \frac{X}{R}$$

$$\therefore \quad \phi = \tan^{-1}\frac{X}{R} \qquad \ldots (2)$$

The numerical values of ratio V and I determine the length of the radius vector Z while the phase angle ϕ between V and I determines the exact position of the vector Z.

If I is in phase with V then the Z vector lies along R-axis. If I lags vector V then X is negative while if I leads vector V then X is positive.

The operation of the relay is independent of phase angle ϕ and hence the operating characteristic is a circle with radius equal to magnitude of Z which is predetermined set value.

At any value of Z less than the radius of the circle, the relay operates. Hence the entire portion inside the circle is **positive torque region** i.e. operating region of the relay while the portion exterior to the circle is **negative torque region** i.e. nonoperative region, as shown in the Fig. 4.3.

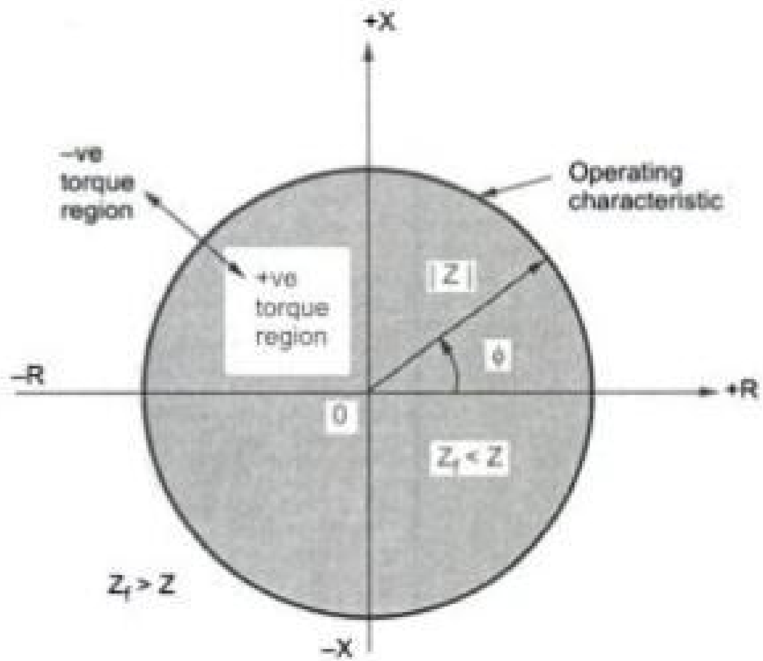


Fig. 4.3 Characteristic on R-X diagram

If Z_f = Impedance between relay and fault point

Z = Set value for impedance = Radius of circle

Then for, $Z_f < Z$ ... relay operates

$Z_f > Z$ ... relay is inoperative

Such a relay is nondirectional and can operate for faults on either side of a point where relay is installed.

4.2.4 Disadvantages of Plain Impedance Relay

The plain impedance relay suffers from following disadvantages,

1. It is nondirectional and can operate for faults on both sides of a point where relay is connected. Hence it fails to discriminate between internal and external faults.

2. When fault occurs, an arc exists. The arc resistance of line fault affects the performance of this relay.
3. As a large area is covered by the circle on each side on R-X plane, the power swings also can affect the performance of this relay.

The nondirectional performance can be made directional by adding a directional element in the plain impedance relay.

4.2.5 Directional Impedance Relay

The directional impedance relay can be obtained by adding a directional element in the basic impedance relay. The element can sense the direction of power or current flow and relay can operate only if the direction of power flow is in one particular direction with respect to the point where relay is installed.

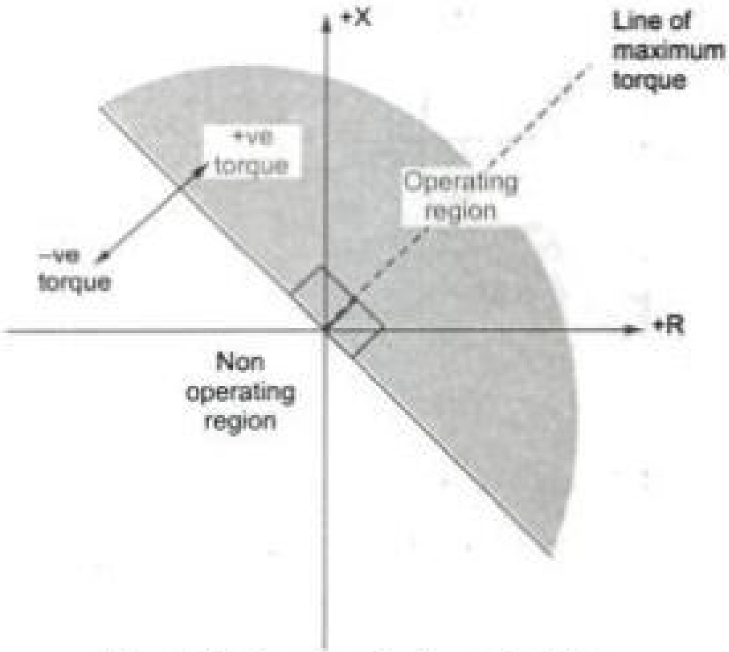


Fig. 4.4 Directional characteristics

The characteristics of a directional element is a tilted straight line passing through origin, which can be shown in R-X diagram as represented in the Fig. 4.4. The dotted line indicates the line of maximum torque. While the dotted portion shown above the line indicates the opering region of the directional element.

Now such a pure directional element is added to the impedance relay, we get the resultant characteristics which is a combination of a straight line and a circle of radius $|Z|$. Thus the resultant characteristics obtained by superimposing the straight line characteristics of directional element on the circle of the impedance relay is shown in the Fig. 4.5. The relay trips for the points which are within the circle and above the directional characteristics. The operating region is just a **semicircle.** The shaded portion shown in the Fig. 4.5 is a positive torque region i.e. the operating region of the relay.

Modified Characteristics : By supplying additional voltage to the voltage coils of an impedance relay, the torque equation of the relay can be modified. The additional voltage supplied is proportional to the line current and is called current bias. The modified torque equation is,

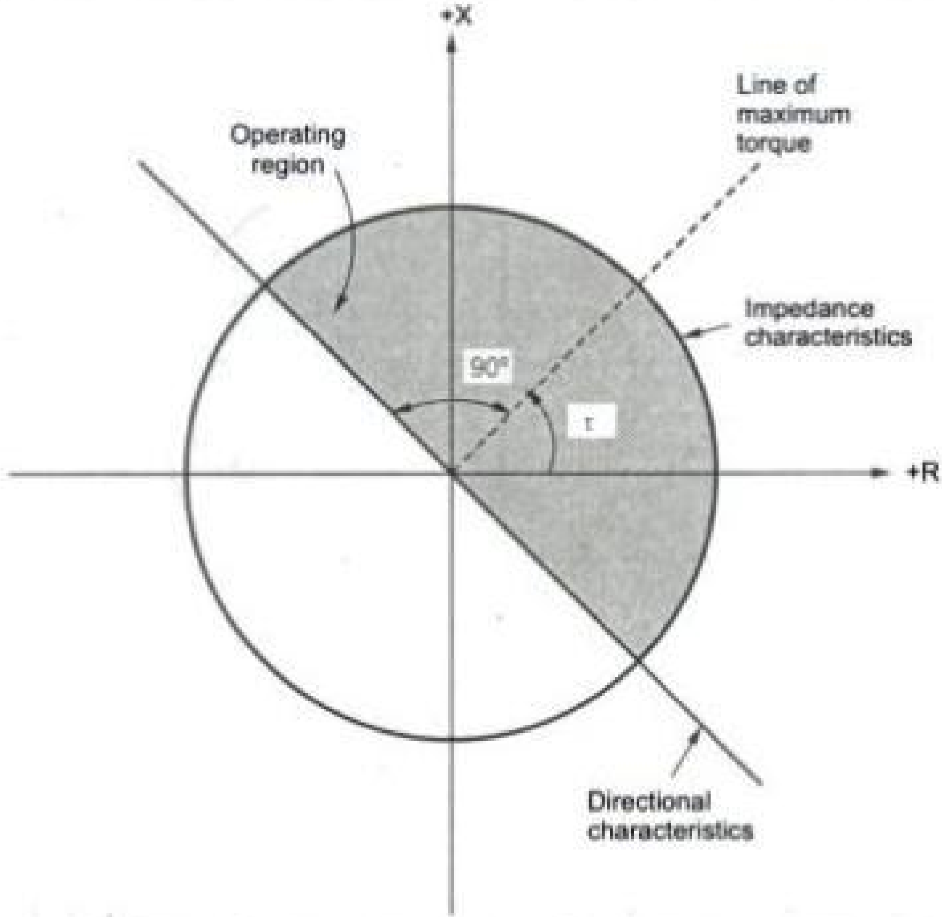


Fig. 4.5 Directional impedance relay characteristics

$$T = K_1 I^2 - K_2 (V + K_3 I)^2$$

where $(V + K_3 I)$ = voltage supplied to voltage coil

Due to this additional current bias, the circle representing impedance characteristics on R-X diagram shifts. The radius of circle remains same as V/I but its centre gets shifted from origin. This is shown in the Fig. 4.6. By controlling current bias, shift of the circle can be adjusted as per the requirement. (See Fig. 4.6 on next page.)

4.2.6 Use of Impedance Relay for Transmission Line Protection

Let us see how an impedance relay can be used for the transmission line protection. The scheme is called distance protection for the transmission line. The voltage coil of the relay is fed from P.T. while its current coil is fed from C.T. as shown in the Fig. 4.7.

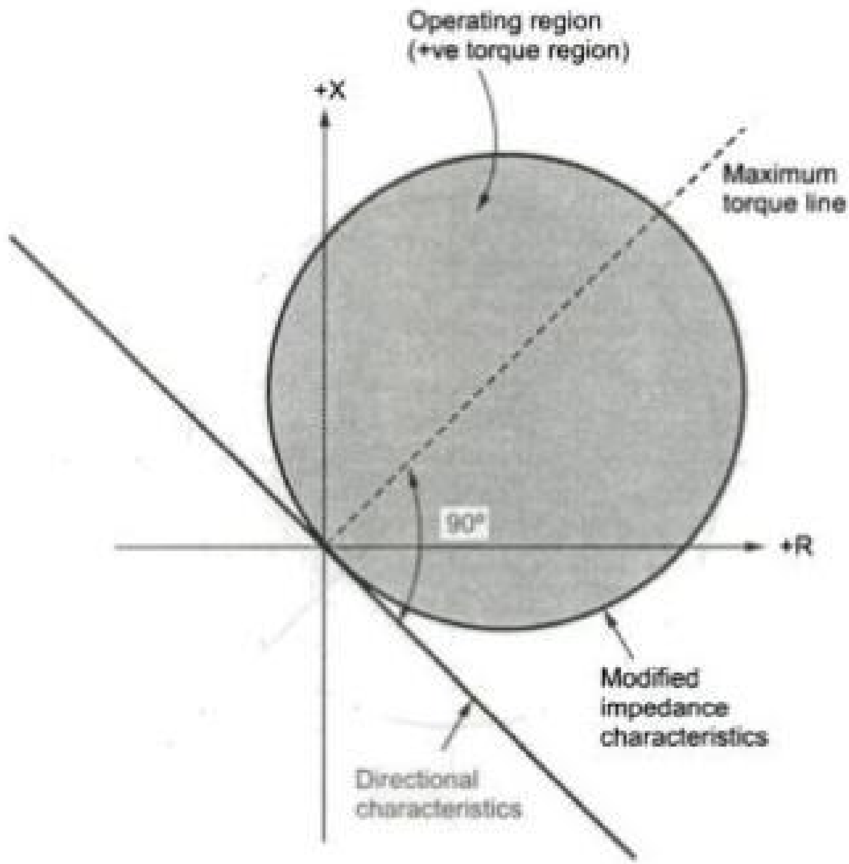


Fig. 4.6 Modified directional impedance relay characteristics

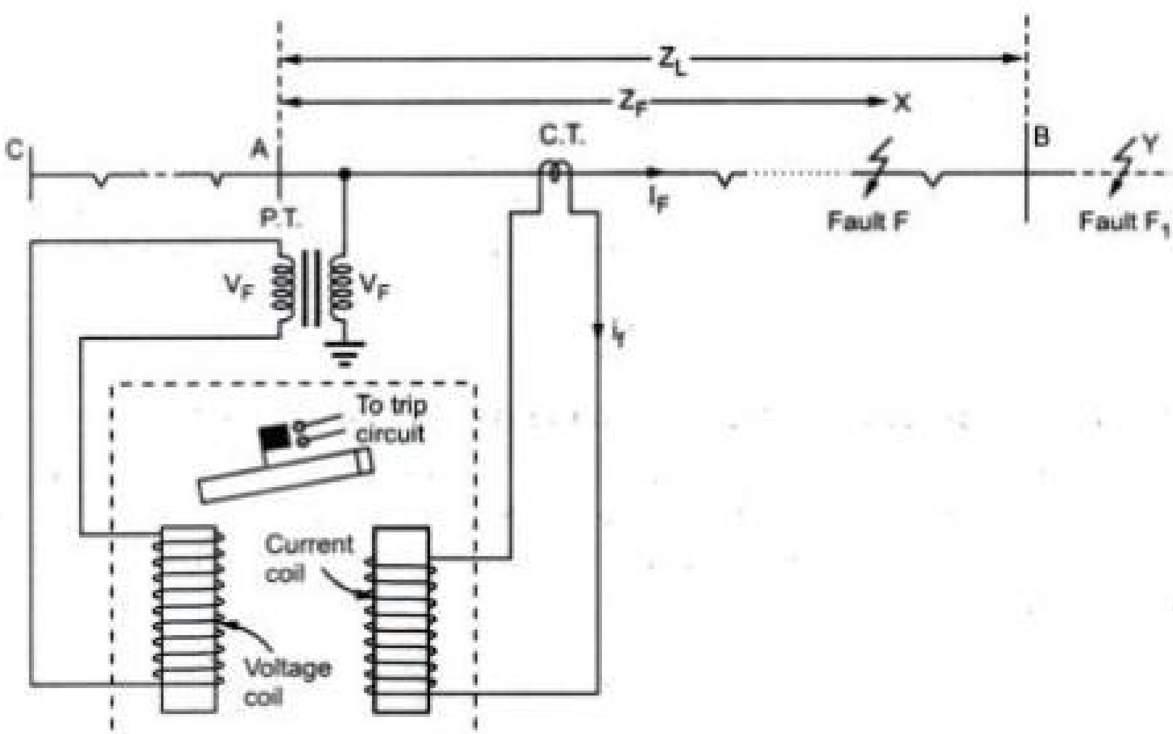


Fig. 4.7 Use of impedance relay

Let

I_F = Line current when fault occurs at point X

V_F = Supply voltage when fault occurs at point X

i_F = Current supplied to current coil when fault occurs

V_F = Voltage supplied to voltage coil when fault occurs

V = Normal supply voltage

I = Normal line current

$Z_L = \frac{V}{I}$ = impedance of healthy section

$Z_F = \frac{V_F}{I_F}$ = impedance when fault occurs

The relay is connected at point A. The fault occurs at point X. The voltage coil of relay receives voltage V_F and current coil receives current i_F, when fault occurs. The setting of the relay is selected, such that it protects the transmission line upto point B. Thus for any fault between A-B similar to that shown at point X, the impedance under fault condition will be less than the predetermined value of impedance Z_L and the relay will operate.

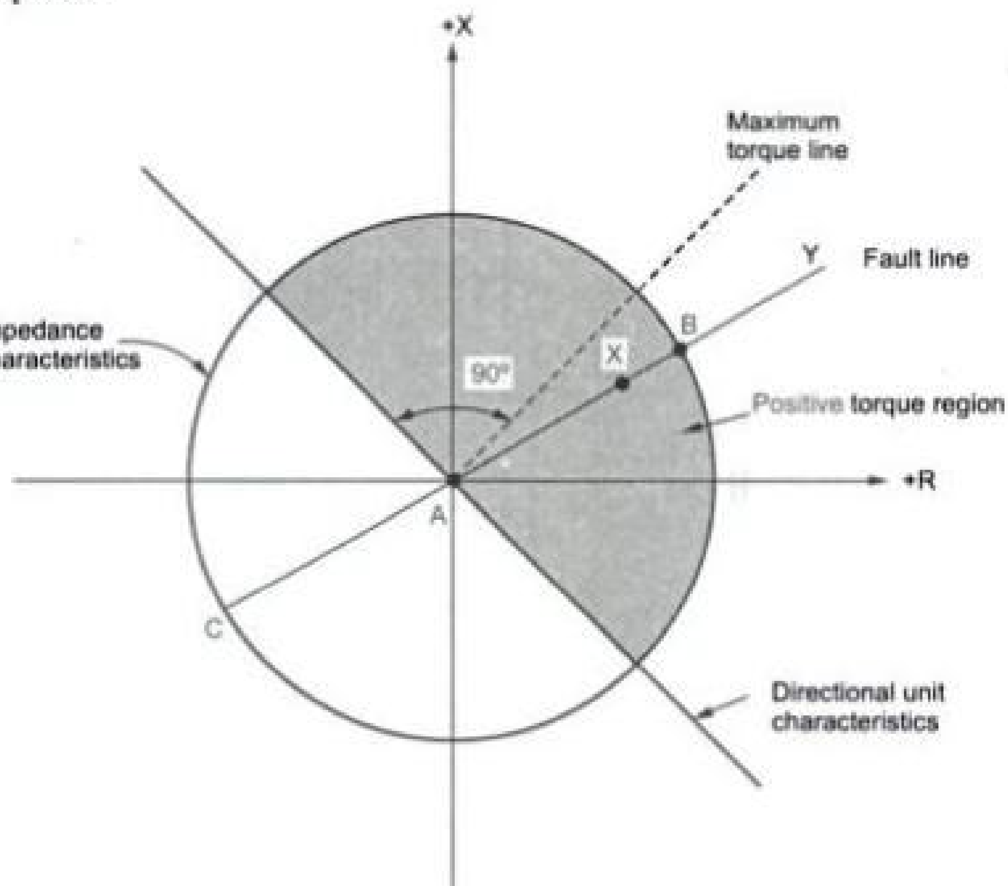


Fig. 4.8

If the impedance relay used is nondirectional, it can protect the line from faults for all fault positions within the section AC too. So nondirectional relay provides protection on either side of the point where relay is located. But if the portion of line AB only is to be protected, then the directional impedance relay can be used. As directional unit permits tripping only in one direction, the section AB will be protected but relay will not operate for any fault positions between section AC.

Whether the relay is directional or nondirectional, if its setting is such that for impedance less than Z_L defined upto point B, the relay should operate then for any fault positions to the right of point B like point Y the relay will not operate.

The characteristics of the directional distance scheme discussed above can be shown on R-X diagram. It is shown in the Fig. 4.8 (See Fig. on previous page). The various sections of the line are represented by straight lines on the R-X diagram.

For fault at X, $Z_f < Z_L$ hence point X is in the operating region and relay will trip. So for any fault position along line AB, relay will trip as the entire section AB is in the protected zone. For fault at Y, it can be seen that the impedance $Z_f > Z_L$ hence point lies outside the circle hence in the negative torque region and relay remains inoperative.

4.3 Reactance Relay

In this relay the operating torque is obtained by current while the restraining torque due to a current-voltage directional relay. The overcurrent element develops the positive torque and directional unit produces negative torque.

Thus the reactance relay is an overcurrent relay with the directional restraint.

- The directional element is so designed that the maximum torque angle is 90°.

4.3.1 Construction

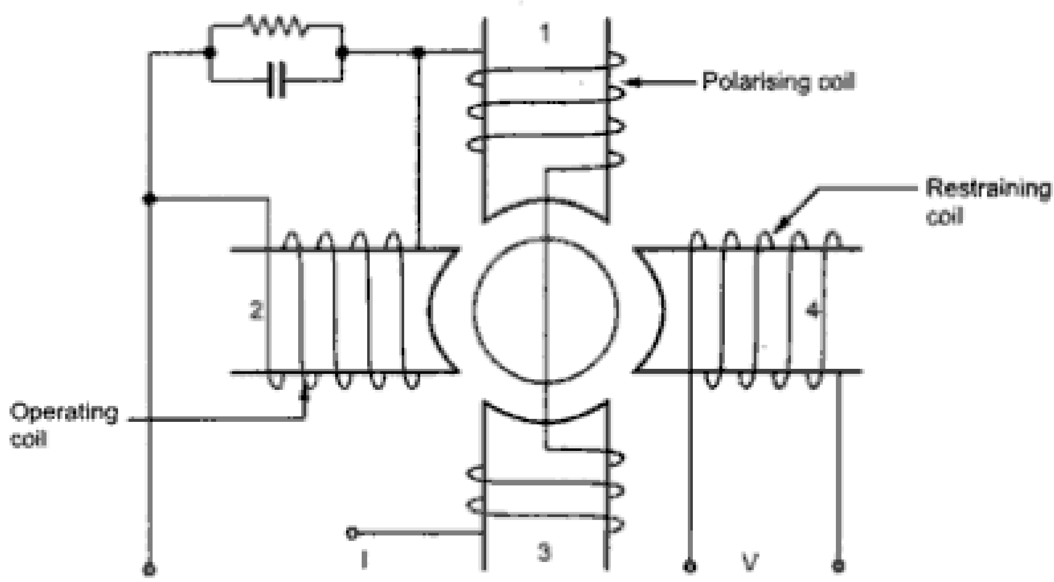


Fig. 4.9 Schematic arrangement of reactance relay

The structure used for the reactance relay can be of induction cup type. It is a four pole structure. It has operating coil, polarizing coil and a restraining coil. The schematic arrangement of coils for the reactance relay is shown in the Fig. 4.9.

The current I flows from pole 1, through iron core stacking to lower pole 3. The winding on pole 4 is fed from voltage V. The operating torque is produced by interaction of fluxes due to the windings carrying current coils i.e. interaction of fluxes produced by poles 1, 2 and 3. While the restraining torque is developed due to interaction of fluxes due to the poles 1, 3 and 4. Hence the operating torque is proportional to the square of the current (I^2) while the restraining torque is proportional to the product of V and I (VI). The desired maximum torque angle is obtained with the help of RC circuit, shown in the Fig. 4.9.

4.3.2 Torque Equation

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

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

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

At the balance point net torque is zero,

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

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

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

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

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

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

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

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

Consider an impedance triangle shown in the Fig. 4.10.

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

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

$$\therefore \quad X = \frac{K_1}{K_2} = \text{constant}$$

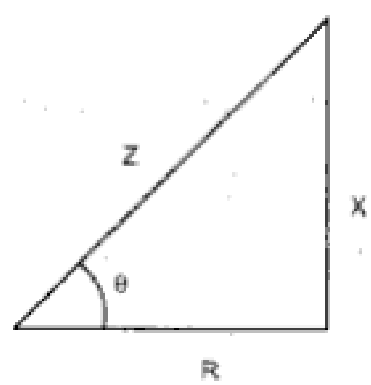


Fig. 4.10

Thus the relay operates on the reactance only. The constant X means a straight line parallel to X-axis on R-X diagram. For the operation of the relay, the reactance seen by the relay should be smaller than the reactance for which the relay is designed.

4.3.3 Operating Characteristics

The operating characteristics of such relay is a straight line parallel to the x-axis i.e R-axis on R-X diagram. All the impedance vectors have their tips lying on the straight line representing constant reactance. The resistance component of the impedance has no effect on the operation of the relay. It responds only to the reactance component of the impedance. The characteristics is shown in the Fig. 4.11.

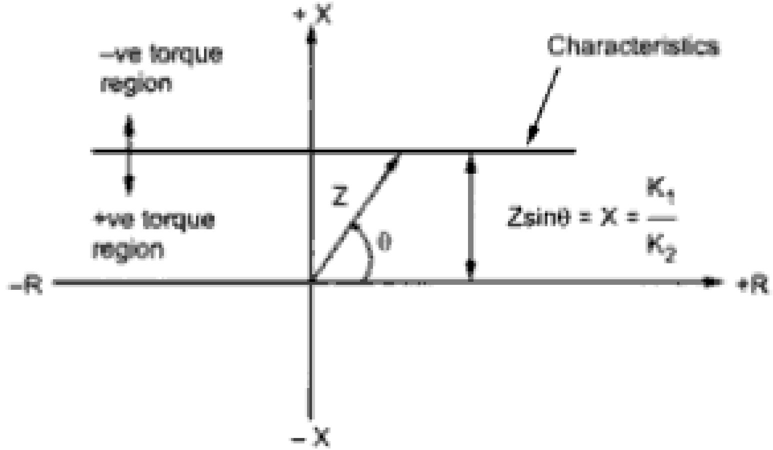


Fig. 4.11 Operating characteristics of reactance relay

The relay will operate for all the impedances whose heads lie below the operating characteristics, whether below or above the R-axis.

4.3.4 Disadvantages

This relay as can be seen from the characteristics is a nondirectional relay. This will not be able discriminate when used on transmission line, whether the fault has taken place in the section where relay is located or it has taken place in the adjoining section. It is not possible to use a directional relay of the type used with basic impedance relay because in that case the relay will operate even under normal load conditions if the system is operating at or near unity p.f. conditions. The reactance relay with directional feature is called mho relay or admittance relay.

4.4 Mho Relay or Admittance Relay

In the impedance relay a separate unit is required to make it directional while the same unit can not be used to make a reactance relay with directional feature. The mho relay is made inherently directional by adding a voltage winding called polarizing winding. This relay works on the measurement of admittance $Y \angle \theta$. This relay is also called angle impedance relay.

4.4.1 Construction

This relay also uses an induction cup type structure. It also has an operating coil, polarizing coil and restraining coil. The schematic arrangement of all the coils is shown in the Fig. 4.12.

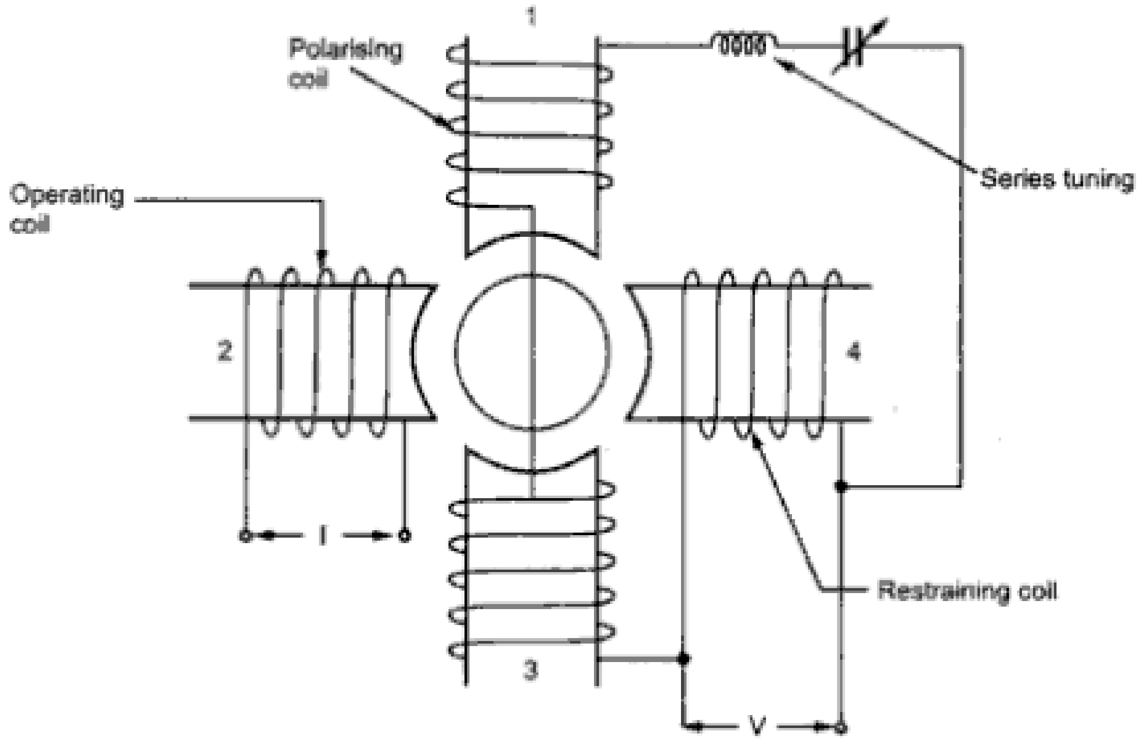


Fig. 4.12 Schematic arrangement of admittance relay

In this relay the operating torque is obtained by V and I element while the restraining torque is obtained by a voltage element. Thus an admittance relay is a voltage restrained directional relay.

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

Thus the restraining torque is proportional to the square of the voltage (V^2) while the operating torque is proportional to the product of voltage and current (VI). The torque angle is adjusted using series tuning circuit.

4.4.2 Torque Equation

The operating torque is proportional to VI while restraining torque is proportional to V^2. Hence net torque is given by,

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

where K_3 = control spring effect

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

And at balance net torque is also zero.

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

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

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

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

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

This is the equation of a circle having diameter K_1/K_2 passing through origin. And this constant K_1/K_2 is the ohmic setting of this relay.

4.4.3 Operating Characteristics

As seen from the torque equation, the characteristics of this relay is a circle passing through origin with diameter as K_1/K_2.

Let $\frac{K_1}{K_2} = Z_R$ = ohmic setting of relay = diameter

The circle is shown in the Fig. 4.13.

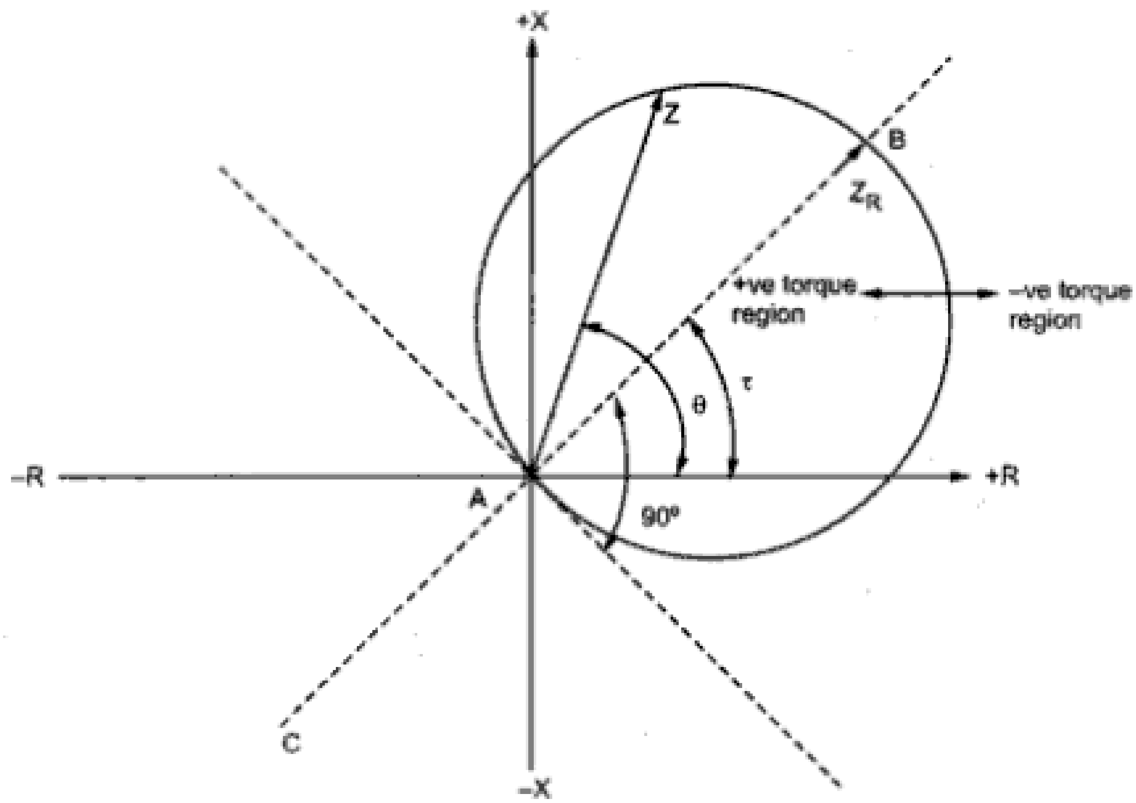


Fig. 4.13 Operating characteristics of mho relay

The relay operates when the impedance seen by the relay falls within this circle. Consider two lines AB and AC with mho relay located at the point A. The relay will operate for the faults occurring in the section AB only and not for the faults occurring in the section AC. This shows that this relay is inherently directional without any additional directional unit required.

The angle τ can be adjusted to be 45°, 60°, 75° and so on. This angle is maximum torque angle. The setting of 45° is used for high voltage (33 or 11 kV) distribution lines, the setting of 60° is used for 66 or 132 kV lines while the setting of 75° is used for 275 and 400 kV lines.

Example 4.1 : *On a R-X diagram show a line having an impedance of 3 + j 4 Ω. On the same diagram show the operating characteristics of,*

1. Impedance relay

2. Reactance relay

3. Mho relay

Assume that these relays are adjusted to just operate for a zero impedance short circuit at the end of the line section.

If an arcing short circuit fault having an arc impedance of 1 + j0 Ω occurs anywhere on the line, find for each type of distance relay, the maximum portion of the line that can be protected.

Solution : The line OA is the impedance vector with impedance 3 + j 4 Ω

$$OB = 3$$

$$BA = 4$$

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

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

Draw the circle with OA as the diameter, passing through O and A represents characteristics of mho relay.

The characteristics are shown in the Fig. 4.14. (See on next page)

The impedance of arcing fault is 1 + j 0, is represented by OD.

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

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

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

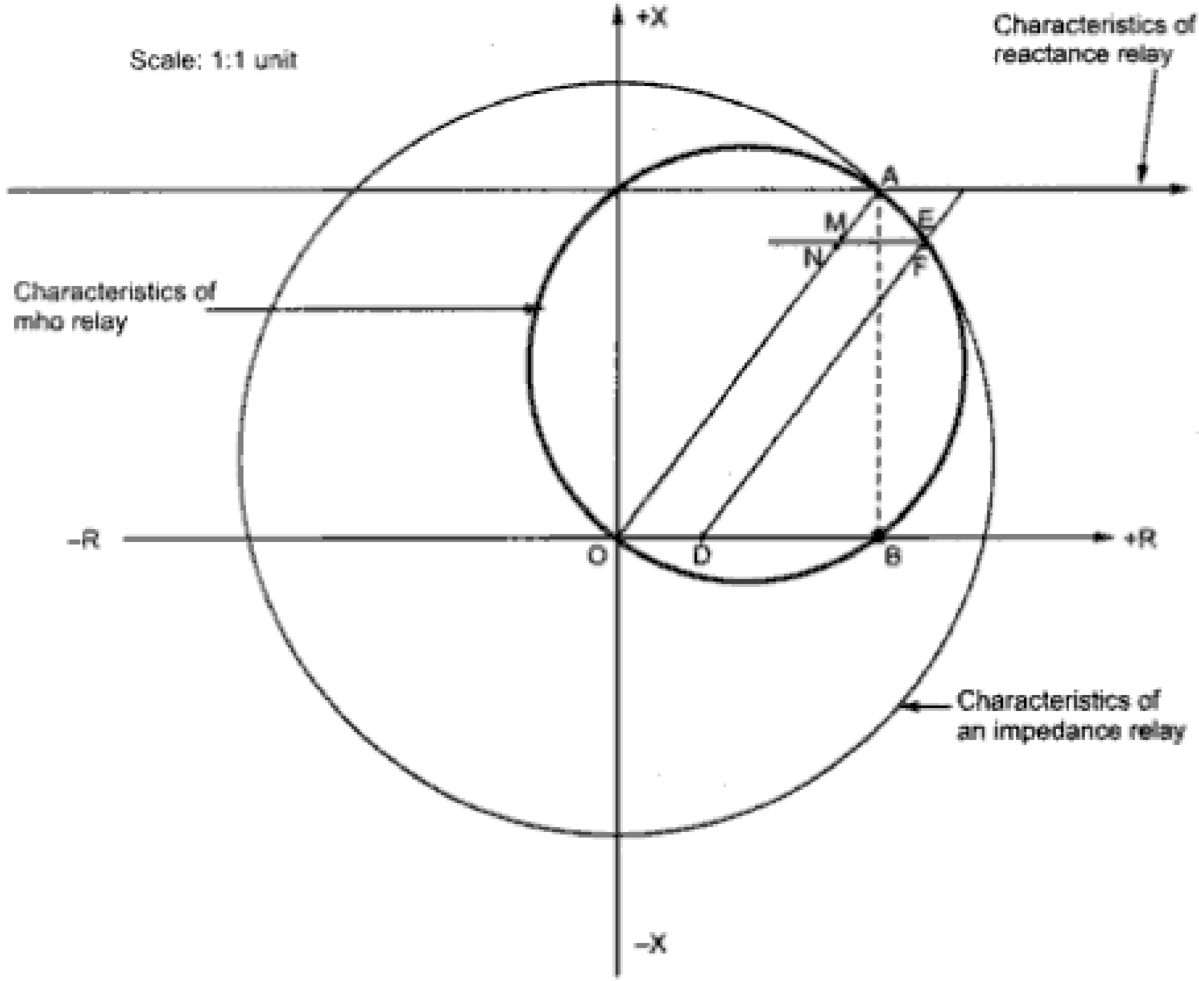


Fig. 4.14

$$\therefore \quad \frac{ON}{OA} \times 100 = \text{\% of line protected by mho relay}$$

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

$$= 80\%$$

While the ratio OM/OA represents the line protected by impedance relay.

$$\therefore \quad \frac{OM}{OA} \times 100 = \text{\% of line protected by impedance relay}$$

$$= \frac{4.25}{5} \times 100$$

$$= 85\ \%$$

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

4.5 Classification of Distance Relays

We have seen that the distance relay basically measures ohmic values and operates when the impedance is below the preset value. The distance relays are classified as,

1. **Definite distance relays :** These can be of impedance type, reactance type or mho type. This operates instantaneously for the faults upto certain predetermined distance from the relay.
2. **Distance time relays :** These can be also of impedance type, reactance type or mho type. In these relays the time of operation is proportional to the distance of the fault from the point where relay is installed. The fault nearer to the relay operates it faster than for the faults further away from the relay.

Let us discuss the construction and operation of these two types of distance relays.

4.5.1 Definite Distance Type Impedance Relay

The construction of this relay can be balanced beam type or induction disc type. The balanced beam type construction of definite distance impedance relay is shown in the Fig. 4.15.

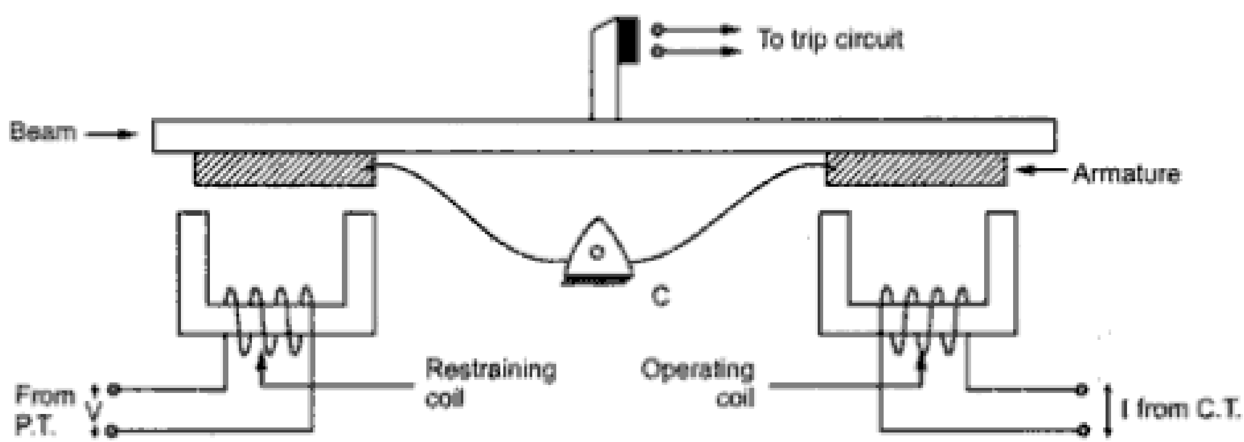


Fig. 4.15 Definite distance type impedance relay

It consists of a balanced beam pivoted at the central point C. The beam carries the armatures of the two electromagnets. The two electromagnets are energized by a current from C.T. and voltage from P.T., which are located in the circuit to be protected. The voltage coil acts as restraining coil while the current coil acts as operating coil. The beam also carries the moving contacts which can bridge the two fixed contacts of a trip circuit when the relay operates.

Operation : The torque produced by voltage coil is proportional to square of the voltage ($K_1 V^2$) while the torque produced by current coil is proportional to the square of the current ($K_2 I^2$). Under normal operating conditions, the torque produced by voltage coil is more than the torque produced by the current coil. Thus restraining torque is more than the operating torque and hence the relay is inoperative. On the occurrence of any fault, the voltage of system decreases and current increases. Thus the ratio V/I which is impedance also decreases. It falls below its preset value. The torque produced by current coil becomes greater than the torque produced by the voltage coil. Hence beam experiences a pull on the current coil side. As the beam tilts, the moving contacts of beam bridges the fixed contacts of the trip circuit. This operates the trip circuit and opens the circuit breaker.

Torque Equation : The torque by voltage coil is proportional to V^2 while that by current coil is I^2.

The relay will operate when torque produced by voltage coil is less than that produced by current coil. So we can write,

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

where K_1, K_2 = constants

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

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

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

So for impedance value less than $\sqrt{K_2/K_1}$, the relay operates.

The constants K_1 and K_2 are dependent on the ampere turns of the two electromagnets. By providing tappings on the coils, K_1 and K_2 can be changed and hence any preset value for the impedance can be adjusted as per the requirement.

Characteristics : The Fig. 4.16 shows the characteristics of the definite distance type impedance relay. The Y-axis represents time for operation while the X-axis represents distance which is measured interms of impedance between fault position and the point where relay is installed.

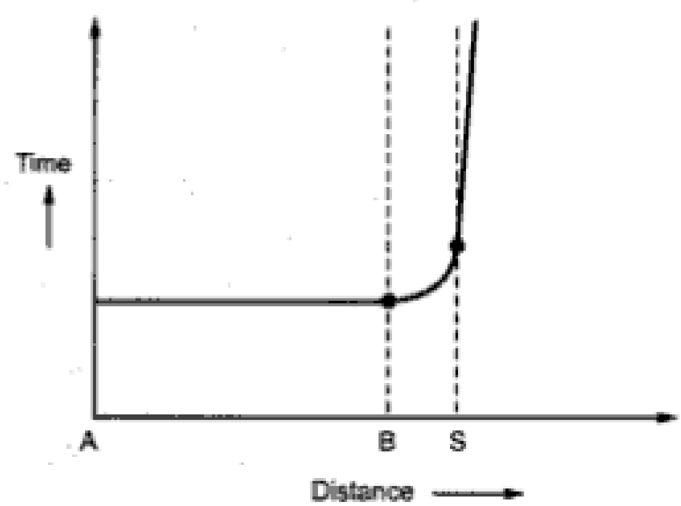


Fig. 4.16 Characteristics of definite distance impedance relay

For the entire length AB of the line, the time of operation remains constant, irrespective of distance. But if fault occurs in the section of line which is not protected, the operating time becomes suddenly infinite as shown in the Fig. 4.16. Towards end of the protected zone, the curve rises gradually.

Its advantages are,

1. Superior to the time graded over current relay
2. Number of feeders in series which can be protected is unlimited as the relay time is constant.

The one limitation of these relays is the absence of back up protection.

4.5.2 Distance Time Impedance Relay

This relay adjusts automatically, its time or operation corresponding to the distance of the fault from the relay.

$$\text{Operating time} \propto Z \propto \text{distance}$$

The Fig. 4.17 shows the schematic arrangement of distance time impedance relay.

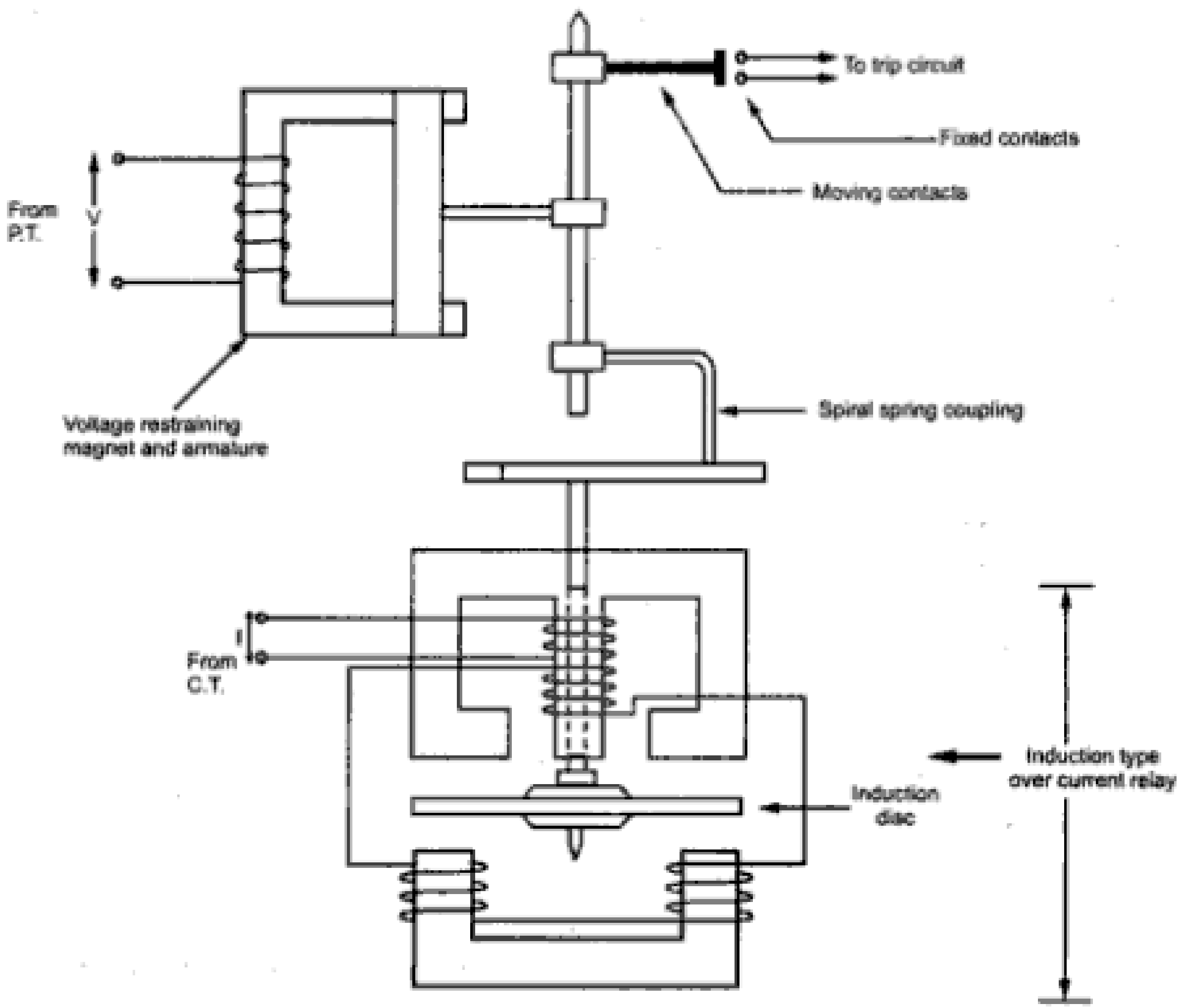


Fig. 4.17 Distance time impedance relay

It consists of an induction type over current relay unit which is a current driven element. The spindle which is carrying the disc of the element is connected to a second spindle with the help of spiral spring coupling. This second spindle carries moving contacts which is nothing but a bridging piece which can bridge the trip contacts when relay operates. The trip contacts are normally open and spindle is held in this position by an armature held against the pole face of an electromagnet. This electromagnet is energized by the voltage of the circuit to be protected.

Operation : Under normal conditions, the force exerted by voltage restraining magnet is more than that produced by an overcurrent induction element. Thus the trip contacts remain open and the relay is inoperative.

When the fault occurs, the induction disc starts rotating. The speed of the disc is proportional to the operating current, neglecting the spring effect. Hence the time which the disc requires to turn through the given angle varies inversely with current. As the disc rotates, spiral spring is wound. This exerts a force on armature so as to pull it away from the voltage restrained magnet. The disc continues to rotate till the tension of the spring is sufficient to overcome the restraining force produced by voltage restraining magnet on the armature. Immediately the moving contacts bridge the fixed contacts of tripping circuit. This opens the circuit breaker to isolate the faulty section.

The angle through which the disc must rotate to close the trip contacts depends on the pull required by armature which is restrained by voltage restraining magnet. This pull is thus proportional to the voltage of system. Greater this pull, greater will be travel of the disc. So travel for the disc is proportional to the voltage V. But the time which disc takes to rotate through certain required angle varies inversely with current (1/I). Thus effectively,

$$\text{Time of operation of relay} \propto \frac{V}{I} \propto Z \propto \text{distance}$$

In actual practice the pull on armature is proportional to the V^2 while the torque on disc is proportional to the I^2. Hence the time distance characteristics of this relay is nonlinear in nature, as shown in the Fig. 4.18. The exact curve is shown dotted while the assumed line is shown thick. The minimum operating time for the relay is generally 0.2 seconds.

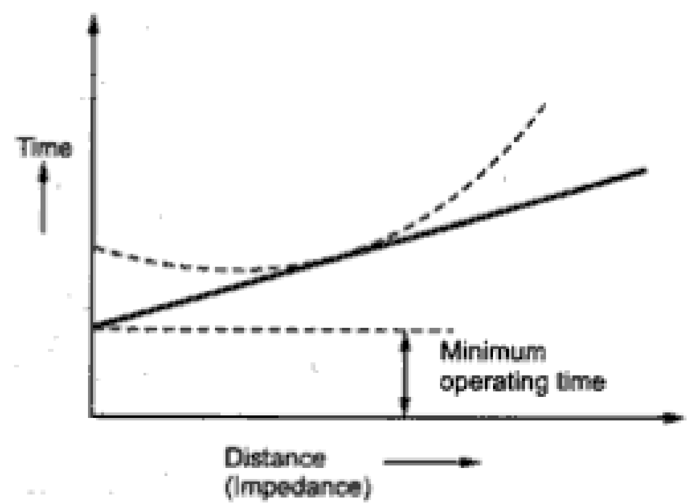


Fig. 4.18 Time-distance characteristics of distance time impedance relay

4.5.3 Applications and Advantages of Distance Relays

The various advantages of the distance relays are.

1. Gives faster operation
2. Simpler to co-ordinate
3. Less effect of fault levels and fault current magnitudes
4. Permits high line loading.
5. With the need at readjustments, permanent settings can be done.

Thus the distance relays are used for providing the primary i.e. main protection and backup protection for a.c. transmission and distribution lines against the following faults,

1. Three phase faults
2. Phase to phase faults
3. Phase to earth faults.

4.6 Frequency Relay

The frequency of the induced e.m.f. is related to the speed of the synchronous generators by the relation,

$$f = \frac{N_s P}{120}$$

where f = frequency

N_s = synchronous speed of generator

P = number of poles

If the load is reduced, the speed of the synchronous generator increases and frequency increases. While if load increases, the speed decreases and the frequency decreases. Hence frequency relays are required if frequency changes from its normal value and are used in the generator protection and for load frequency control.

The frequency relays can be electromagnetic or static relays. These can be **under frequency** or **over frequency** relays.

Constructionally it consists of two pairs of coils and a cup type rotor as shown in the Fig. 4.19.

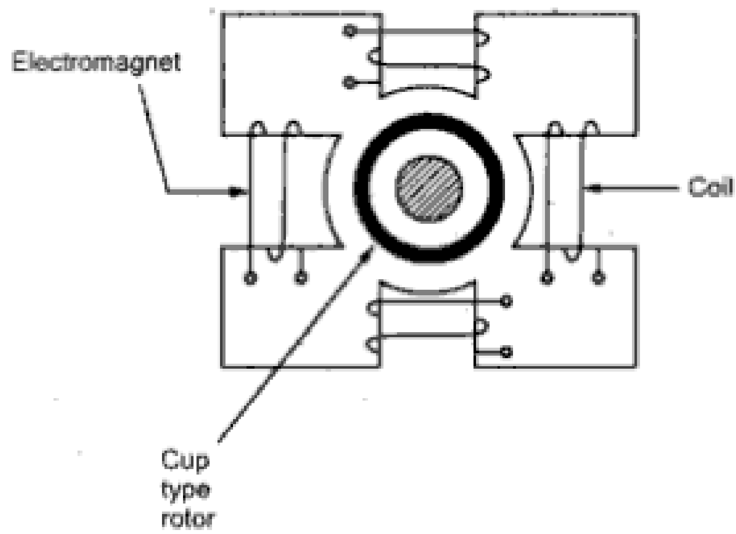


Fig. 4.19

It uses a Ferraris measuring system. The frequency relays are connected to the secondary of voltage transformer. The two pairs of coils are connected in parallel to the supply voltage through the impedances.

Now impedances are functions of frequency. At normal frequency the impedances are tuned balancing each other. Thus no torque is experienced by the cup type rotor at normal rated frequency.

If frequency increases then there is unbalance in the impedances and torque say clockwise in nature is exerted on the rotor. This operates the relay if frequency increases beyond the setting. This is over frequency relay.

If frequency decreases then again there is unbalance in the impedances. But now torque exerted on the rotor is anticlockwise. This operates the relay if frequency decreases beyond the setting. This is under frequency relay.

By varying the position of sliding resistor the frequency setting can be adjusted. The pickup sensitivity can be controlled by adjusting the restraining spring.

Review Questions

1. *Explain fully how an impedance relay is used for distance protection obtain its operating characteristic. Draw its operating characteristics on R-X diagram.*
2. *State the disadvantages of basic impedance relay.*
3. *Explain the operation of directional impedance relay. Draw its characteristics on R-X diagram. How these characteristics can be modified, similar to that of mho relay ?*
4. *Draw and explain the full scheme of protecting a transmission line using an impedance relay.*

5. *Explain the construction, working, torque equation and characteristics of following distance relays*

   i) Reactance relay

   ii) Mho relay

6. *Explain the construction and working of,*

   i) Definite distance type impedance relay

   ii) Distance time impedance relay

7. *State the advantages and applications of distance relays*

8. *A line section has an impedance of $2.8 + j\,5\ \Omega$. Show this on R-X diagram, as impedance vector. If the relay is adjusted to operate for a zero impedance short circuit at the end of the line section, show on the same R-X diagram the characteristics of,*

   1. Impedance relay

   2. Reactance relay

   3. Mho relay

   Assume that centre of mho relay characteristics lies on an impedance vector. If the arching fault occurs with an impedance of $1.5 + j0\ \Omega$ anywhere along the line, find for each type of distance relay the maximum portion of the line that can be protected. **(Ans. : 82%, 100% and 85%)**

❑❑❑

5 Generator Protection

5.1 Introduction

The generators used in the power system are the alternators which produce very high a.c. voltages. The protection of generators is very much complex due to the following reasons,

1. The generators are very large machines producing very high voltages and are connected to busbars.
2. Various other equipments are always associated with the generators. Such equipments are prime movers, excitation systems, voltage regulators, cooling systems etc. Thus protection of generators must consider the presence of these other equipments also.
3. The generators are very costly, expensive and very important factor in a power system. The protection scheme must be such that it should not shut off the generators as far as possible. The shut off generators result in a power shortage.

All these factors make the design of protection scheme for the generator, very much complex.

Before studying the various protection schemes for the generators, let us discuss various faults which can occur associated with the generators.

5.2 Generator Faults

The various faults which can occur associated with a generator can be classified as,

1. Stator faults : The faults associated with the stator of the generator.
2. Rotor faults : The faults associated with the rotor of the generator.
3. Abnormal running conditions : This includes number of abnormal conditions which may occur in practice, from which the generator must be protected.

Let us discuss these faults in detail.

5.2.1 Stator Faults

The stator faults means faults associated with the three phase armature windings of the generator. These faults are mainly due to the insulation failure of the armature windings. The main types of stator faults are,

1. Phase to earth faults
2. Phase to phase faults
3. Inter-turn faults involving turns of same phase winding.

The most important and common fault is phase to earth fault. The other two are not very common while inter-turn fault is very difficult to detect.

5.2.1.1 Phase to Earth Faults

These faults mainly occur in the armature slots. The faults are dangerous and can cause severe damage to the expensive machine. The fault currents less than 20 A cause negligible burning of core if machine is tripped quickly. But if the fault currents are high, severe burning of stator core can take place. This may lead to the requirement of replacing the laminations which is very costly and time consuming. So to avoid the damage due to phase to earth faults, a separate, sensitive earth fault protection is necessary for the generators alongwith the earthing resistance.

5.2.1.2 Phase to Phase Faults

The phase to phase faults means short circuit between two phase windings. Such faults are uncommon because the insulation used between the coils of different phases in a slot is large. But once phase to earth fault occurs, due to the over heating phase to phase fault also may occur. This fault is likely to occur at the end connections of the armature windings which are overheating parts outside the slots. Such a fault causes severe arcing with very high temperatures. This may lead to melting of copper and fire if the insulation is not fire resistant.

5.2.1.3 Stator Inter-Turn Faults

The coils used in the alternators are generally multiturn coils. So short circuit between the turns of one coil may occur which is called an inter-turn fault. This fault occurs due to current surges with high value of (L di/dt) voltage across the turns. But if the coils used are single turn then this fault can not occur. Hence for the large machines of the order of 50 MVA and more, it is a normal practice to use single turn coils. But in some countries, multiturn coils are very commonly used where protection against inter-turn faults is must.

5.2.2 Rotor Faults

The rotor of an alternator is generally a field winding as most of the alternators are of rotating field type. The field winding is made up of number of turns. So the conductor to earth faults and short circuit between the turns of the field winding, are the commonly occurring faults with respect to a rotor. These faults are caused due to the severe mechanical and thermal stresses, acting on the field winding insulation.

The field winding is generally not grounded and hence single line to ground fault does not give any fault current. A second fault to earth will short circuit the part of the field winding and may there by produce an unsymmetrical field system. Such an unsymmetrical system gives rise to the unbalanced forces on the rotor and results in excess pressure on the bearings and the shaft distortion, if such a fault is not cleared very early. So it is very much necessary to know the existence of the first occurrence of the earth fault so that corrective measures can be taken before second fault occurs.

The unbalanced loading on the generator is responsible to produce the negative sequence currents. These currents produce a rotating magnetic field which rotates in opposite direction to that of rotor magnetic field. Due to this field, there is induced e.m.f. in the rotor winding. This causes overheating of the rotor.

Rotor earth fault protection and rotor temperature indicators are the essential and are provided to large rating generators.

5.2.3 Abnormal Running Conditions

In practice there are number of situations in which generator is subjected to some abnormal running conditions. The protection must be provided against the abnormal conditions. These abnormal conditions include,

1. Overloading
2. Overspeeding
3. Unbalanced loading
4. Overvoltage
5. Failure of prime mover
6. Loss of excitation (Field failure)
7. Cooling system failure

5.2.3.1 Overloading

Due to the continuous overloading, the overheating of the stator results. This may increase the winding temperature. If this temperature rise exceeds certain limit, the insulation of the winding may get damaged. The degree of overloading decides the effects and temperature rise. The overcurrent protection is generally set to very high value hence continuous overloads of less value than the setting cannot be sensed by overcurrent protection.

5.2.3.2 Overspeeding

In case of hydraulic generators a sudden loss of load results in overspeeding of the generator. This is because the water flow to the turbine cannot be stopped or reduced instantly. Generally a turbogovernor is provided to prevent the ovespeeding. But if there is any fault in the turbine governor then the dangerous overspeeding may take place. Hence it is necessary to supervise the working of turbine governor and take some corrective measures if there is some fault in the governor.

5.2.3.3 Unbalanced Loading

The unbalanced loading of the generator results in the circulation of negative sequence currents. These currents produce the rotating magnetic field. This rotating magnetic field rotates at the synchronous speed with respect to rotor. The direction of rotation of this magnetic field is opposite to that of rotor. Hence effectively the relative speed between the two is double the synchronous speed.

Thus the e.m.f. gets induced, having double the normal frequency, in the rotor winding. The circulating currents due to the induced e.m.f. are responsible to overheat the rotor winding as well as rotor stampings. Continuous unbalanced load more than 10% of the rated load causes tremendous heating which is dominant incase of cylindrical rotor of truboalternators.

The reasons for the unbalanced load conditions are,

1. Occurrence of unsymmetrical faults near the generating station.
2. The failure of circuit breaker near the generating station in clearing all the three phases.

Negative sequence protection is important to prevent dangerous situations due to negative sequence currents which are because of unbalanced load conditions.

5.2.3.4 Overvoltage

The overvoltages are basically due to the overspeeding of generators. Another reason for the overvoltages is the faulty operation of voltage regulators. Not only the internal overvoltages are dangerous but atmospheric surge voltages can also reach to the generators. Such atmospheric surge voltages are generated by direct lighting strokes to the aerial lines of high voltage system. Inductively and capacitively, these surges can get transferred to the generator. To protect the generators from surge voltages, the surge arresters and surge capacitors are often used.

At the time of restriking across the contacts of circuit breakers, the transient over voltages get generated. Such surges are called switching surges and can be limited by the uses of modern circuit breakers. R-C surge suppressors also help in reducing switching surges. Another situation, when the transient overvoltages are generated, is when the arcs are grounded. During arcing grounds, the transient voltages having amplitudes five times more than the normal line to neutral peak amplitude are generated. Such transient voltages are dangerous and can be reduced by using resistance earthing.

5.2.3.5 Failure of Prime Mover

The failure of prime mover results in motoring operation of synchronous generator. The generator draws active power from the network and continues to run at synchronous speed as a synchronous motor. This may lead to dangerous mechanical conditions if allowed to persist for more than twenty seconds. The serious overheating of the steam turbine blades may result. To prevent this the reverse power protection achieved by directional power relays is used.

5.2.3.6 Loss of Excitation

The loss of excitation or reduced excitation is possible due to the field failure i.e. opening of field winding or due to short circuit in field or due to some fault in exciter system.

Such loss of excitation results in loss of synchronism within a second and this causes the increase in speed of the generator. Since power input to the machine remains same, the generator starts working as an induction generator, drawing the reactive power from the bus. The machine starts drawing an exciting current from the system, which is equal to the full load rated value. This leads to the overheating of the stator winding and the rotor body due to induced currents. The loss of excitation may also lead to the pole slipping condition which results in the voltage reduction for the output above half the rated load.

Loss of excitation should not persist for long and corrective measures like disconnection of alternator should be taken immediately. For this a tripping scheme can be used which can trip the generator circuit breaker immediately when there is a field failure.

5.2.3.7 Cooling System Failure

The failure of cooling system also causes severe overheating to rise the temperature above safe limit. This may lead to insulation failure, causing some other faults to occur. The thermocouples or resistance thermometers are used in large machines to sense the temperature. The corrective measures are taken whenever the temperature exceeds the limit.

Apart from the above dominant abnormal conditions, some conditions may exist which are rare in practice. Such conditions are, wrong synchronization, local overheating, leakage in hydrogen circuit, moisture in the generator winding, oxygen in pure water circuit, vibrations, bearing currents, excessive bearing temperature etc.

5.3 Basic Differential Protection Scheme for Generators

A basic differential protection scheme used for the generators is shown in the Fig. 5.1. It is known that the differential relay operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined value.

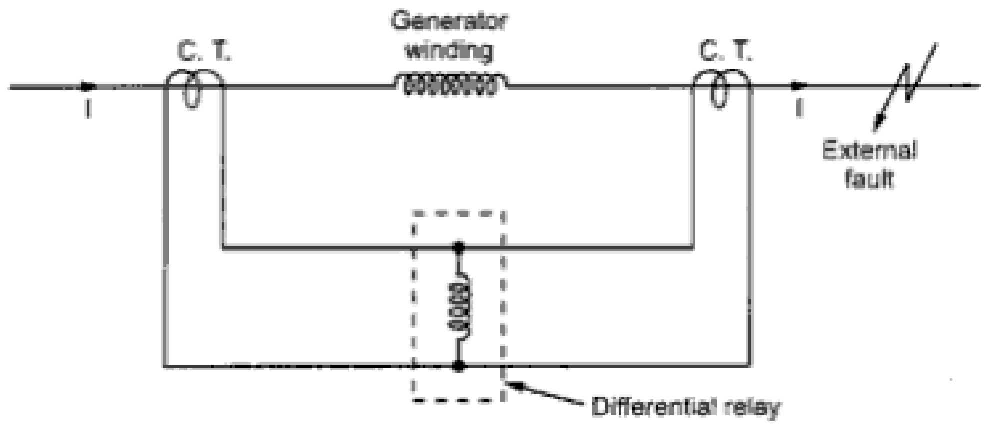


Fig. 5.1

Suppose the current I flows through the primary of C.T.s to the external fault. If the two C.T.s have same ratio, then no current will flow through the relay and it remains inoperative.

But now if an internal fault occurs at point X as shown in the Fig. 5.2, the current flows through the fault from both the sides. The primary currents are I_1 and I_2 while the secondary currents are i_1 and i_2. So the current flowing through the relay will be $i_1 + i_2$. Even some current flowing out of one side while a large current entering the other side will cause the differential current. Such a current is responsible to operate the relay.

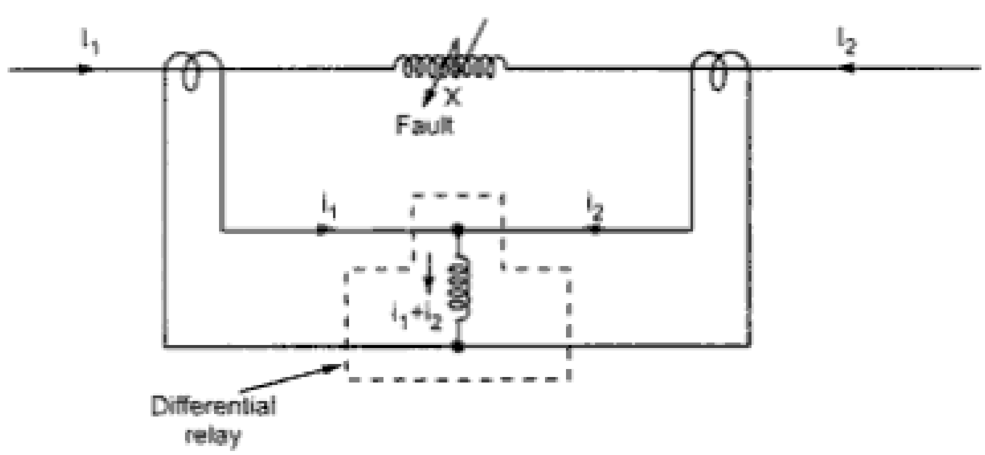


Fig. 5.2

Thus the relay current is proportional to the phasor difference between the currents entering and leaving the protected circuit and if the differential current exceeds the pickup value, the relay operates.

This basic differential scheme has following disadvantages :

1. This circuit operates inaccurately with heavy external faults.
2. The C.T.s may saturate and cause unequal secondary currents and the difference of secondary currents may approach the pickup value to operate the relay unnecessarily.

These disadvantages are overcome in the percentage differential relay.

5.4 Basic Percentage Differential Protection Scheme for Generators

This protection scheme is also called biased differential protection scheme. The Fig. 5.3 shows the connections of the percentage differential relay, in such a protection scheme.

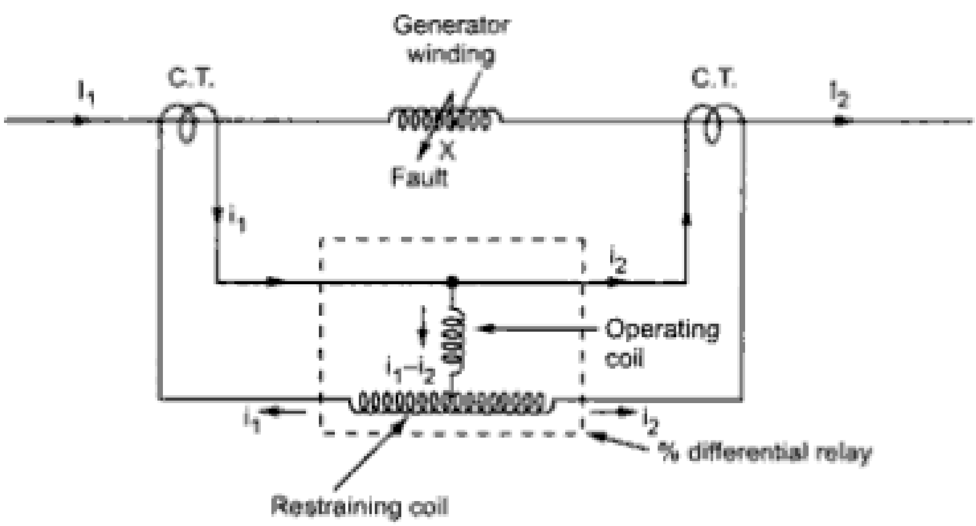


Fig. 5.3 Percentage differential protection scheme

The fault occurs at point X and the primary currents in the circuit are I_1 and I_2. The C.T. secondary currents are i_1 and i_2. The current flowing through the operating coil of the relay is $i_1 - i_2$. While the current flowing through the restraining coil of the relay is $\left(\frac{i_1 + i_2}{2}\right)$. This is because the operating coil is connected to the midpoint of the restraining coil.

Thus if the number of turns of the restraining coil is N then i_1 flows through $\frac{N}{2}$ and i_2 flows through remaining $\frac{N}{2}$. The total ampere turns are $\frac{i_1 N}{2}+\frac{i_2 N}{2}$ i.e. N

$\left(\frac{i_1 + i_2}{2}\right)$. This is as good as the flow of current $\left(\frac{i_1 + i_2}{2}\right)$ through the entire restraining coil.

The operating characteristics of such a biased differential relay is shown in the Fig. 5.4. The characteristics shows that except at low currents, ratio of differential operating current to average restraining current is a fixed percentage. Hence the relay is called the percentage differential relay.

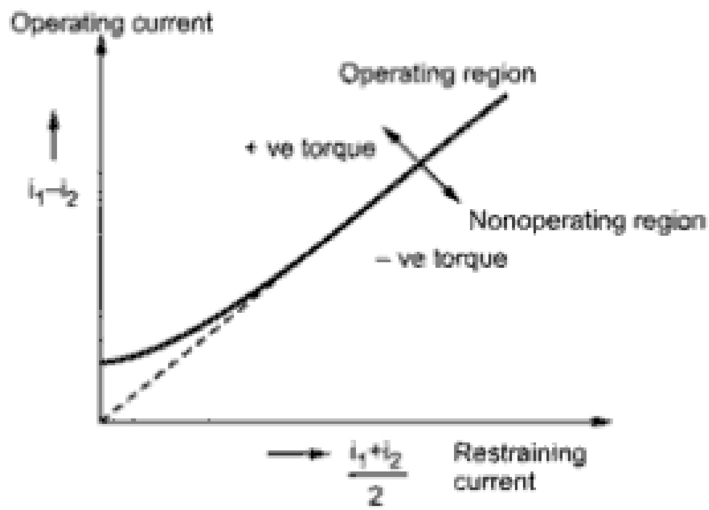


Fig. 5.4

This basic percentage differential protection scheme forms the basis of the practically very commonly used percentage differential protection scheme for alternator stator windings. This popular scheme is known as Biased differential protection or Merz-Price protection.

Let us discuss the details of Merz-Price protection scheme for the three phase alternator stator windings.

5.5 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 generator circuit breaker to isolate the faulty section. The field is also disconnected and is discharged through a suitable impedance.

The Fig. 5.5 shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator.

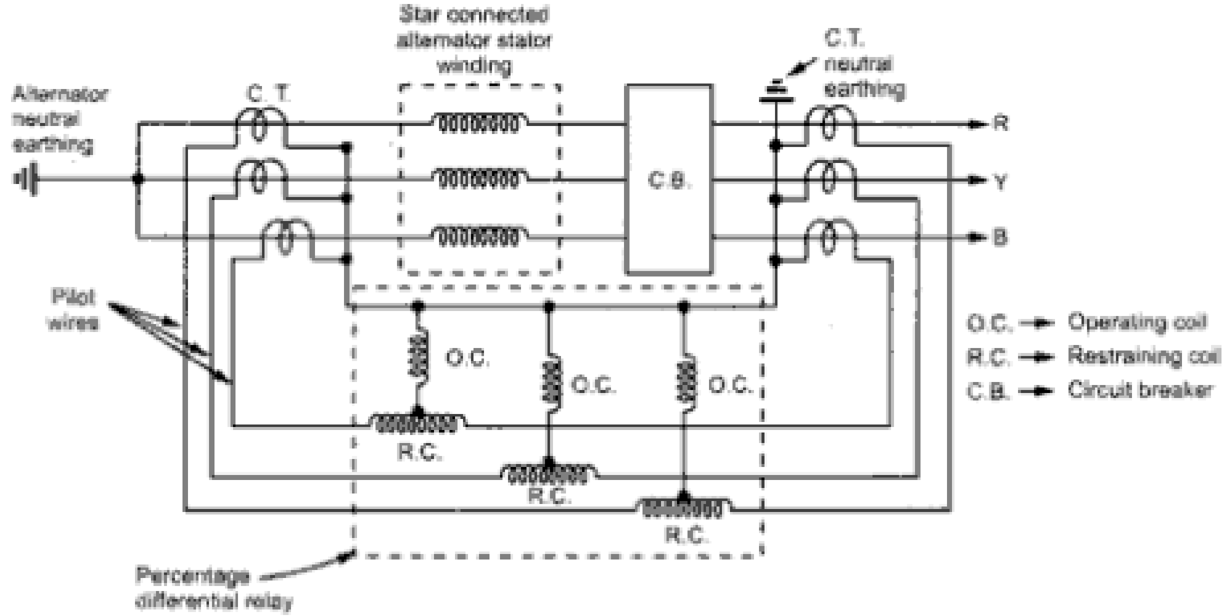


Fig. 5.5 Merz-Price protection for star connected alternator

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 tappings from restraining coils and the C.T. neutral earthing connection.

The similar arrangement is used for the delta connected alternator stator winding, as shown in the Fig. 5.6.

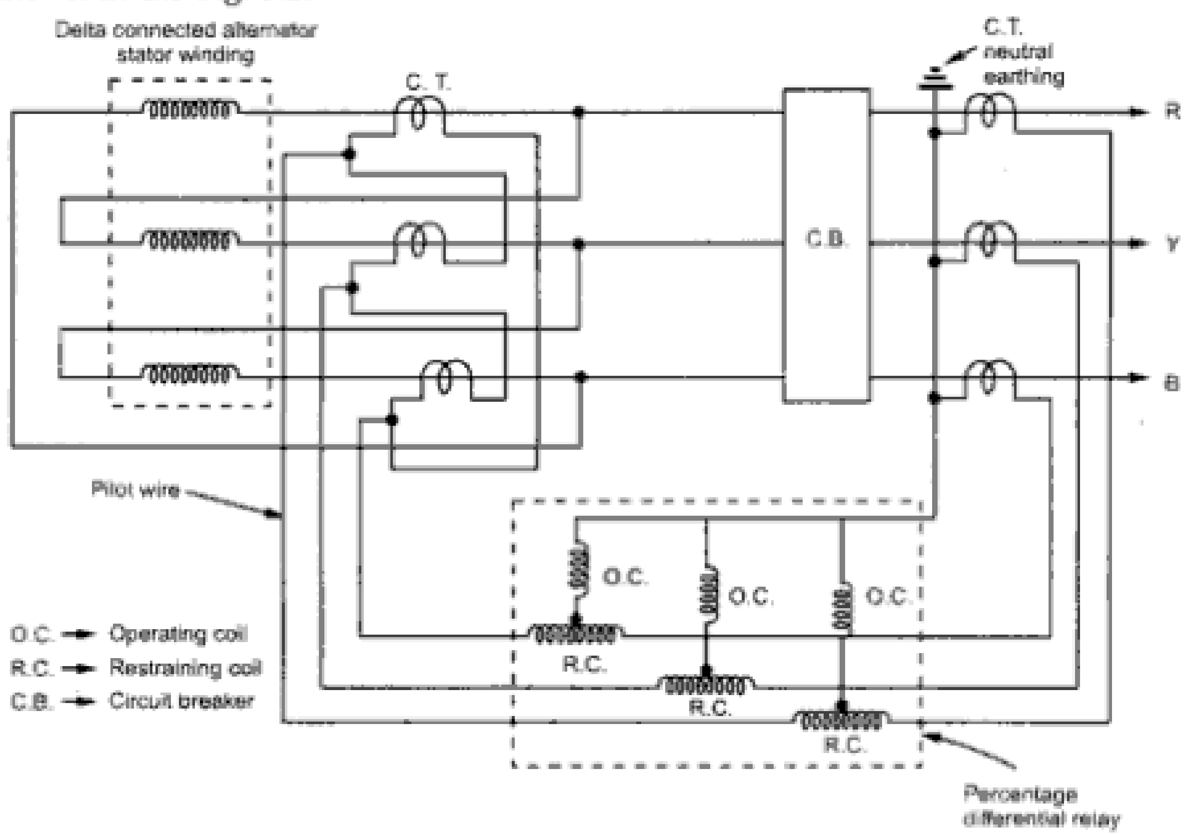


Fig. 5.6 Merz-Price protection for delta connected alternator

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 tappings 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 of the two current transformers. Thus, under fault conditions, a differential current flows 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.

In addition to the tripping of circuit breaker, the percentage differential relay trip a hand reset multicontact auxiliary relay. This auxiliary relay simultaneously initiates the following operations,

1. Tripping of the main circuit breaker of generator
2. Tripping of the field circuit breaker
3. Tripping of the neutral circuit breaker if it is present
4. Shut down of the prime mover
5. Turn on of CO_2 gas if provided for safety of generator under faulty conditions.
6. Operation of alarm and /or annunciator to indicate the occurrence of the fault and the operation of the relay the field must be opened immediately otherwise it starts feeding the fault.

When differential relaying is used for the protection, C.T.s at both the ends of generator must be of equal ratio and equal accuracy otherwise if the error is excessive, wrong operation of the relay may result. The causes of unequal currents on both the sides of C.T.s without any fault are ratio errors, unequal lengths of the leads, unequal secondary burdens etc.

This scheme provides very fast protection to the stator winding against phase to phase faults and phase to ground faults. If the neutral is not grounded or grounded through resistance then additional sensitive earth fault relay should be provided.

The **advantages** of this scheme are,

1. Very high speed operation with operating time of about 15 msec.
2. It allows low fault setting which ensures maximum protection of machine windings.
3. It ensures complete stability under the most severe through and external faults.

4. It does not require current transformers with air gaps or special balancing features.

5.6 Restricted Earth Fault Protection of Generator

Generally Merz-Price protection based on circulating current principle provides the protection against internal earth faults. But for large generators, as these are costly, an additional protection scheme called restricted earth fault protection is provided.

When the neutral is solidly grounded then the generator gets completely protected against earth faults. But when neutral is grounded through earth resistance, then the stator windings get partly protected against earth faults. The percentage of winding protected depends on the value of earthing resistance and the relay setting.

In this scheme, the value of earth resistance, relay setting, current rating of earth resistance must be carefully selected. The earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less. But when earth fault occurs near the neutral point then the insufficient voltage across the fault drives very low fault current than the pick up current of relay coil. Hence the relay coil remains inoperative. Thus 15 to 20% winding from the neutral side remains unprotected in this scheme. Hence it is called restricted earth fault protection. It is usual practice to protect 85% of the winding.

The restricted earth fault protection scheme is shown in the Fig. 5.7.

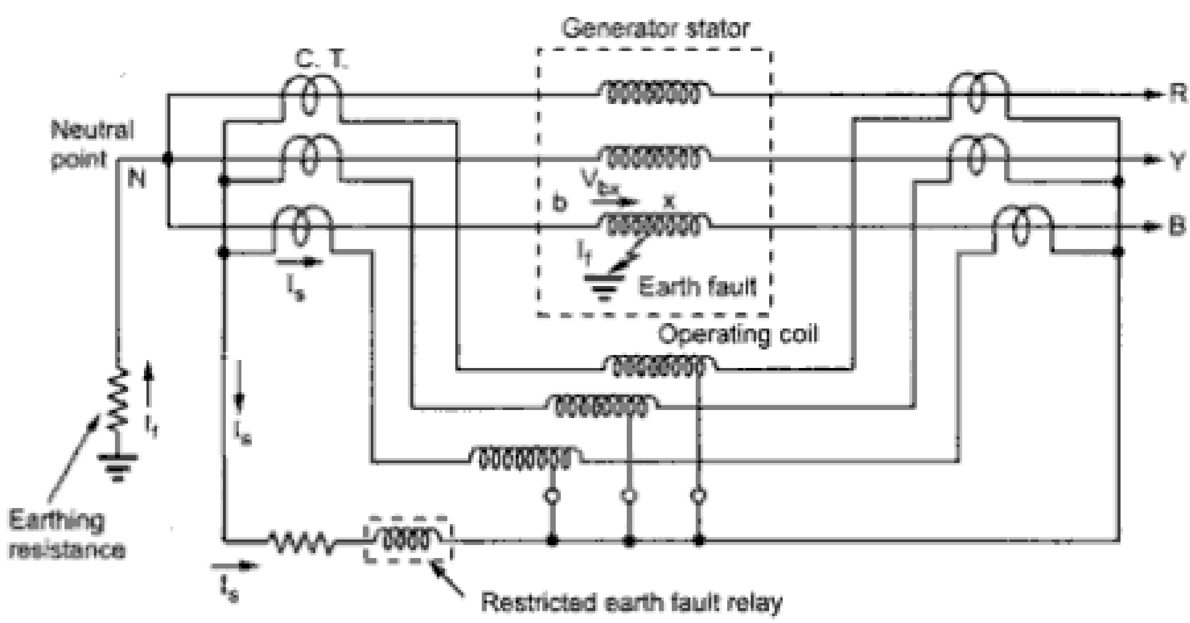


Fig. 5.7 Restricted earth fault protection

Consider that earth fault occurs on phase B due to breakdown of its insulation to earth, as shown in the Fig. 5.7. The fault current I_f will flow through the core, frame of machine to earth and complete the path through the earthing resistance. The C.T. secondary current I_s flows through the operating coil and the restricted earth fault relay coil of the differential protection. The setting of restricted earth fault relay and setting of overcurrent relay are independent of each other. Under this secondary current I_s, the relay operates to trip the circuit breaker. The voltage V_{bx} is sufficient to drive the enough fault current I_f when the fault point x is away from the neutral point.

If the fault point x is nearer to the neutral point then the voltage V_{bx} is small and not sufficient to drive enough fault current I_f. And for this I_f, relay cannot operate. Thus part of the winding from the neutral point remains unprotected. To overcome this, if relay setting is chosen very low to make it sensitive to low fault currents, then wrong operation of relay may result. The relay can operate under the conditions of heavy through faults, inaccurate C.T.s, saturation of C.T.s etc. Hence practically 15% of winding from the neutral point is kept unprotected, protecting the remaining 85% of the winding against phase to earth faults.

5.6.1 Effect of Earth Resistance on % of Winding Unprotected

Let us see the effect of earth resistance on the % of the winding which remains unprotected.

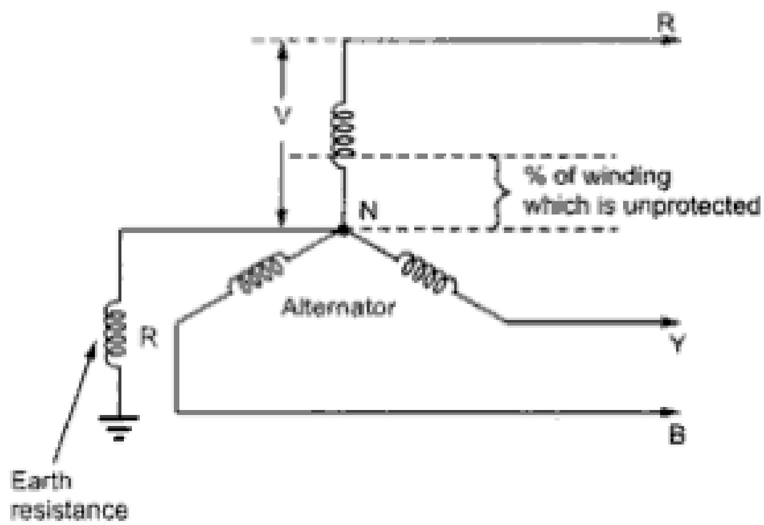


Fig. 5.8

Consider the earth resistance R used to limit earth fault current as shown in the Fig. 5.8.

The value of the resistance R limits the earth fault current.

If the resistance R is very small i.e. the neutral is almost solidly grounded, then the fault current is very high. But high fault currents are not desirable hence small R is not preferred for the large machines.

For low resistance R, the value of R is selected such that full load current passes through the neutral, for a full line to neutral voltage V.

In medium resistance R, the earth fault current is limited to about 200A for full line to neutral voltage V, for a 60 MW machine.

In high resistance R, the earth fault current is limited to about 10 A. This is used for distribution transformers and generator-transformer units.

Now higher the value of earth resistance R, less is the earth fault current and less percentage of winding gets protected. Large percentage of winding remains unprotected.

Let V = Full line to neutral voltage

I = Full load current of largest capacity generator

R = Earth resistance

Then the value of the resistance R is,

$$R = \frac{V}{I}$$

And the percentage of winding unprotected is given by,

$$\text{\% of winding } \textbf{unprotected} = \frac{RI_o}{V} \times 100$$

where I_o = Minimum operating current in the primary of C.T.

If relay setting used is 15% then I_o is 15% of the full load current of the **largest machine** and so on.

Greater percentage of windings of small capacity machines running parallel get protected.

➡ **Example 5.1 :** *A generator is protected by restricted earth fault protection. The generator ratings are 13.2 kV, 10 MVA. The percentage of winding protected against phase to ground fault is 85%. The relay setting is such that it trips for 20% out of balance. Calculate the resistance to be added in the neutral to ground connection.*

Solution : The given values,

V_L = 13.2 kV Rating = 10 MVA

From rating, calculate the full load current,

$$I = \frac{\text{Rating in VA}}{\sqrt{3}\, V_L} = \frac{10 \times 10^6}{\sqrt{3} \times 13.2 \times 10^3}$$

$$= 437.386 \text{ A}$$

Relay setting is 20% out of balance i.e. 20% of the rated current activates the relay.

$$\therefore \quad I_o = 4387.386 \times \frac{20}{100} = 87.477 \text{ A}$$

= Minimum operating current

$$V = \text{Line to neutral voltage} = \frac{V_L}{\sqrt{3}}$$

$$= \frac{13.2 \times 10^3}{\sqrt{3}} = 7621.02 \text{ V}$$

% of winding unprotected = 15% as 85% is protected

$$\therefore \quad 15 = \frac{RI_0}{V} \times 100$$

$$\therefore \quad 15 = \frac{R \times 87.477}{7621.02} \times 100$$

$$\therefore \quad R = 13.068 \ \Omega$$

Example 5.2 : *A star connected 3 phase, 12 MVA, 11 kV alternator has a phase reactance of 10%. It is protected by Merz-Price circulating current scheme which is set to operate for fault current not less than 200 A. Calculate the value of earthing resistance to be provided in order to ensure that only 15% of the alternator winding remains unprotected.*

Solution : The given values are,

$$V_L = 11 \text{ kV} \qquad \text{Rating} = 12 \text{ MVA}$$

$$\text{Rating} = \sqrt{3} V_L I_L$$

$$\therefore \quad 12 \times 10^6 = \sqrt{3} \times 11 \times 10^3 \times I_L$$

$$\therefore \quad I_L = \frac{12 \times 10^6}{\sqrt{3} \times 11 \times 10^3}$$

$$= 629.8366 \text{ A} = I = \text{rated current}$$

$$V = \frac{V_L}{\sqrt{3}} = \frac{11 \times 10^3}{\sqrt{3}} = 6350.8529 \text{ V}$$

$$\% \text{ Reactance} = \frac{IX}{V} \times 100$$

where X = reactance per phase

and I = rated current

$$\therefore \quad 10 = \frac{629.8366 X}{6350.8529} \times 100$$

$$\therefore \quad X = 1.0083 \ \Omega$$

$\therefore$ Reactance of unprotected winding

$$= (\% \text{ of unprotected winding}) \times (X)$$

$$= \frac{15}{100} \times 1.0083$$

$$= 0.1512\ \Omega$$

$$v = \text{voltage induced in unprotected winding}$$

$$= \frac{15}{100} \times V = 0.15 \times 6350.8529$$

$$= 952.6279\ V$$

$$i = \text{Fault current}$$

$$= 200\ A$$

$$Z = \text{Impedance offered to the fault}$$

$$= \frac{v}{i} = \frac{952.6279}{200}$$

$$= 4.7631\ \Omega \qquad \ldots (1)$$

Now

$$Z = r + j\ (\text{reactance of unprotected winding})$$

$$Z = r + j\ (0.1512)\ \Omega$$

$$\therefore \quad |Z| = \sqrt{r^2 + (0.1512)^2} \qquad \ldots (2)$$

Equating (1) and (2),

$$4.7631 = \sqrt{r^2 + (0.1512)^2}$$

$$\therefore \quad 22.6875 = r^2 + 0.02286$$

$$\therefore \quad r^2 = 22.6646$$

$$\therefore \quad r = 4.7607\ \Omega$$

This is the earthing resistance required.

5.7 Unrestricted Earth Fault Protection

The unrestricted earth fault protection uses a residually connected earth fault relay. It consists of three C.T.s, one in each phase. The secondary windings of these C.T.s are connected in parallel. The earth fault relay is connected across the secondaries which carries a residual current. The scheme is shown in the Fig. 5.9.

When there is no fault, under normal conditions, vector sum of the three line currents is zero. Hence the vector sum of the three secondary currents is also zero.

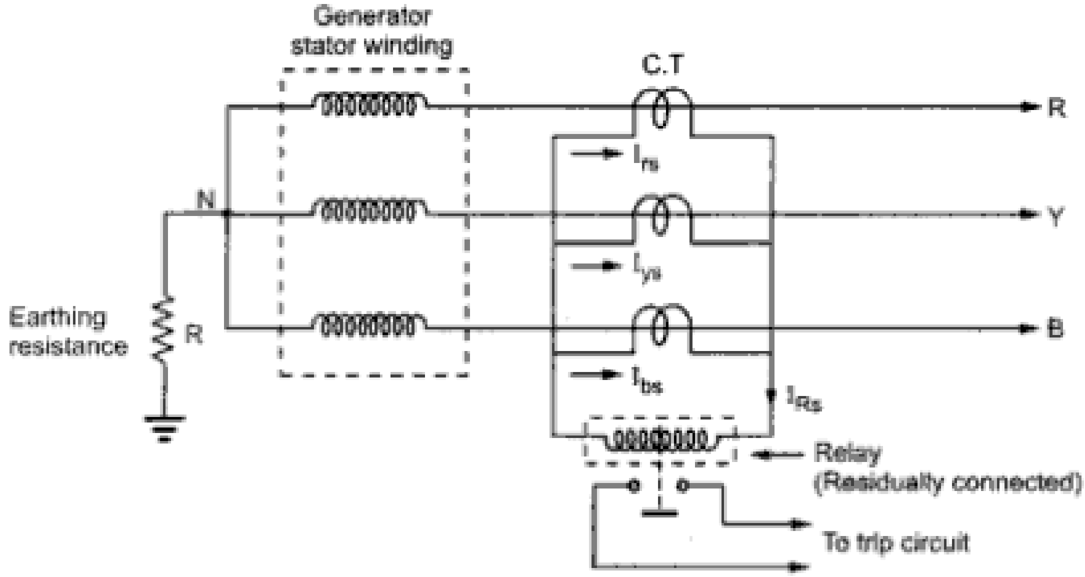


Fig. 5.9 Unrestricted earth fault protection

So if I_{rs}, I_{ys} and I_{bs} are C.T. secondary currents then under normal conditions we can write,

$$\bar{I}_{rs} + \bar{I}_{ys} + \bar{I}_{bs} = 0$$

The sum of the three currents is residual current I_{Rs} which is zero under normal conditions.

The earth fault relay is connected in such a way that the residual current flows through the relay operating coil. Under normal condition, residual current is zero so relay does not carry any current and is inoperative. However in presence of earth fault condition, the balance gets disturbed and the residual current I_{RS} is no more zero. If this current is more than the pickup value of the earth fault relay, the relay operates and opens the circuit breaker through tripping of the trip circuit.

In the scheme shown in the Fig. 5.9, the earth fault at any location near or away from the location of C.T.s can cause the residual current. Hence the protected zone is not definite. Such a scheme is hence called unrestricted earth fault protection.

5.8 Balanced Earth Fault Protection

In practice for small rating alternators, the neutral ends of the three phases are connected to a single point. Hence it is not possible to introduce C.T. in each phase on neutral side as required in Merz-Price protection. In such cases, the balanced earth fault protection can be used.

The balanced earth fault protection is shown in the Fig. 5.10.

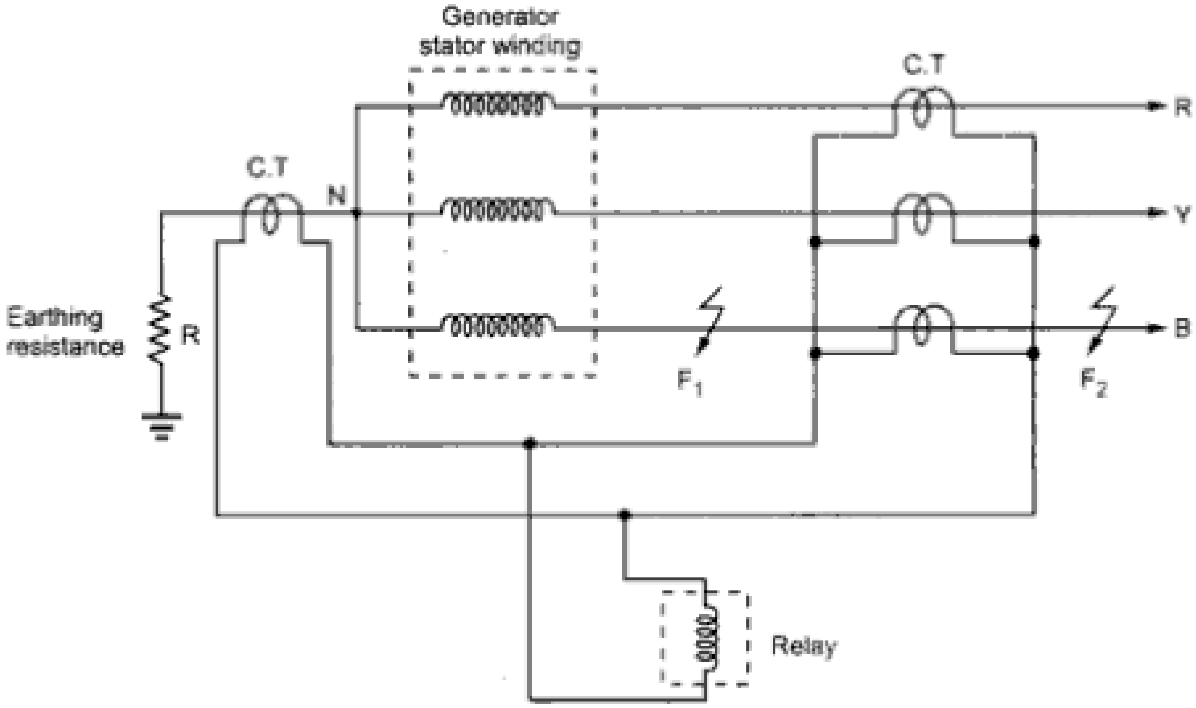


Fig. 5.10 Balanced earth fault protection

At the outgoing side, the three C.T.s are connected in parallel as are connected in unrestricted earth fault protection. A single C.T. is connected on the neutral side in the pilot wire connecting neutral of alternator to earth. The neutral earthing is achieved through the earthing resistance. A relay is connected across the C.T. secondaries.

Under normal conditions, the alternator line currents add to zero. Hence the vector sum of the currents through the secondaries of C.T. is also zero. Thus no current flows through the relay and as neutral carries zero current hence no current is supplied to relay from neutral side. So relay is inoperative.

If the fault appears at F_2, at a position outside the protected zone then the sum of the alternator line currents is exactly equal to the current in the neutral. Thus zero current flows through the relay is inoperative.

But if the fault occurs at F_1 which is the protected zone then vector sum of alternator line currents is different than the current through neutral side current transformer. Hence a residual current flows through the relay. If this is greater than the pickup value of the relay, the relay operates. This trips the tripping circuit, opening the circuit breaker.

By this scheme, the protection against earth faults is restricted to the region between the neutral and the position where line current transformers are installed.

5.9 100% Earth Fault Protection

As seen uptill now, no protection scheme is in a position to give complete protection to the stator of generator against earth faults. The maximum protection achieved is upto 85 to 90% from the schemes discussed uptill now.

But in modern days it is possible to provide 100% earth fault protection to the stator of the generator. It uses a coupling transformer and the coded signal current. The scheme is shown in the Fig. 5.11.

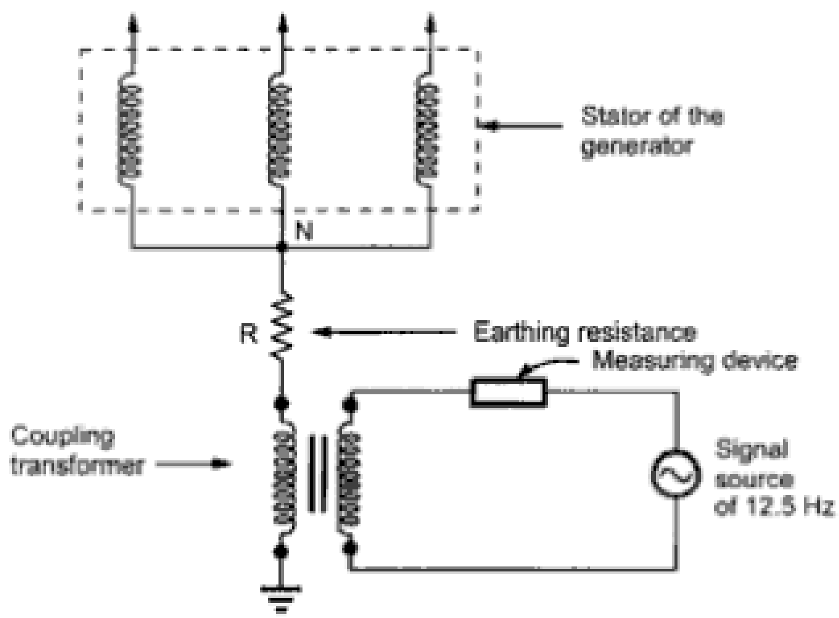


Fig. 5.11 100% earth fault protection

A coupling transformer is connected between the earth and the earthing resistance R i.e. in neutral to ground circuit. The primary of the coupling transformer is excited by coded signal current source. This coded signal current has a frequency of 12.5 Hz. This current is continuously injected into the generator stator winding through the secondary of the coupling transformer.

During the normal condition the signal current injected into the stator flows through stray capacitance of the generator and directly connected system. But when earth fault occurs, the stray capacitance is bypassed. This increases the monitoring current. This increase is measured by a measuring device. Depending upon this measurement an immediate corrective action is taken.

This scheme gives the protection of 15 to 20% of stator winding from the neutral side, the portion which is unprotected by Merz-Price protection. The remaining portion is protected by Merz-Price protection. Overall 100% of stator winding gets protected against earth faults.

5.10 Stator Protection Against Interturn Faults

The Merz-Price protection system gives protection against phase to phase faults and earth faults. It does not give protection against interturn faults. The interturn fault is a short circuit between the turns of the same phase winding. Thus the current produced due to such fault is a local circuit current and it does not affect the currents entering and leaving the winding at the two ends, where C.T.s are located. Hence Merz-Price protection cannot give protection against interturn faults.

In single turn generator, there is no question of interturn faults but in multiturn generators, the interturn fault protection is necessary. So such interturn protection is provided for multiturn generators such as hydroelectric generators. These generators have double winding armatures. This means, each phase winding is divided into two halves, due to the very heavy currents which they have to carry. This splitting of single phase winding into two is advantageous in providing interturn fault protection to such hydroelectric generators.

The Fig. 5.12 shows the interturn fault protection scheme used for the generator with double winding armatures.

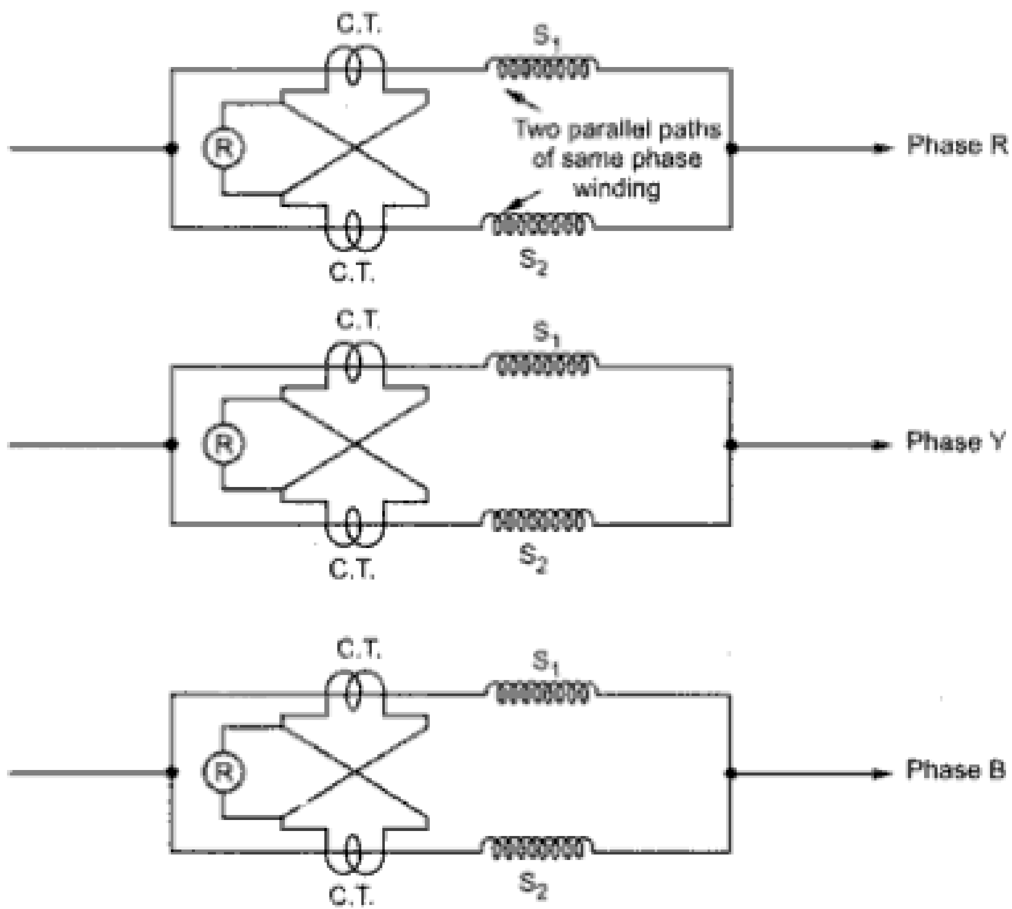


Fig. 5.12 Interturn fault protection

The scheme uses cross differential principle. Each phase of the generator is doubly wound and split into two parts S_1 and S_2 as shown in the Fig. 5.12. The current transformers are connected in the two parallel paths of the each phase winding. The secondaries of the current transformers are cross connected. The current transformers work on circulating current principle. The relay is connected across the cross connected secondaries of the current transformers.

Under normal operating conditions, when the two paths are sound then currents in the two parallel paths S_1 and S_2 are equal. Hence currents in the secondaries of the current transformers are also equal. The secondary current flows round the loop and is same at all the points. Hence no current flows through the relay and the relay is inoperative.

If the short circuit is developed between the adjacent turns of the part S_1 of the winding say then currents through S_1 and S_2 no longer remain same. Thus unequal currents will be induced in the secondaries of the current transformers. The difference of these currents flows through the relay R. Relay then closes its contacts to trip the circuit breaker which isolates the generator from the system.

Such an interturn fault protection system is extremely sensitive but it can be applied to the generators having doubly wound armatures.

5.11 Rotor Earth Fault Protection

The rotor circuit of the alternator is not earthed and d.c. voltage is imposed on it. And hence single ground fault in rotor does not cause circulating current to flow through the rotor circuit. Hence single ground fault in rotor does not cause any damage to it. But single ground fault causes an increase in the stress to ground at other points in the field winding when voltages are induced in the rotor due to transients. Thus the probability of second ground fault increases.

If the second ground fault occurs then part of the rotor winding is bypassed and the currents in the remaining portion increase abruptly. This causes the unbalance of rotor circuit and hence the mechanical and thermal stresses on the rotor. Due to this, rotor may get damaged. Sometimes damage of bearings and bending of rotor shaft takes place due to the vibrations. Hence the rotor must be protected against earth fault.

Method 1 : In this method a high resistance is connected across the rotor circuit. It is provided with centre tap and the centre tap point is connected to the ground through a sensitive earth fault relay as shown in the Fig. 5.13.

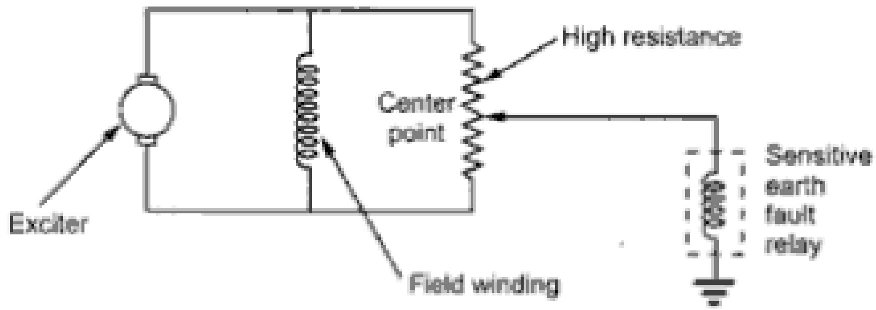


Fig. 5.13 Rotor earth fault protection

Except the centre point, the earth fault relay detects the earth faults for most of the rotor circuit. Thus most of the rotor winding part is protected against the earth faults.

Method 2 : The modern method of providing earth fault protection includes d.c. injection or a.c. injection. The scheme is shown in the Fig. 5.14.

A small d.c. power supply is connected to the field circuit. A fault detecting sensitive relay and the resistance are also connected in series with the circuit. This high resistance limits the current through the circuit.

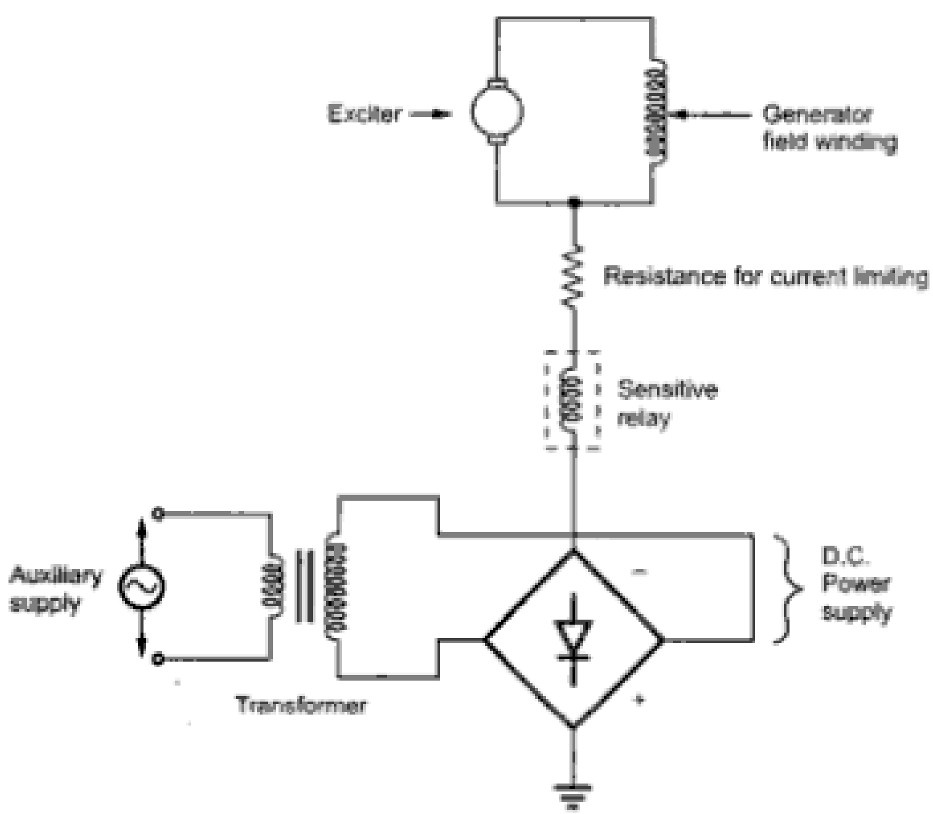


Fig. 5.14 Rotor earth fault protection

A fault at any point on the field circuit will pass a current of sufficient magnitude through the relay to cause its operation. The d.c. supply is preferred and simple to use and it has no problem of the leakage currents. In case of a.c. injection, the high resistance is replaced by a capacitor.

The earth fault relays are instantaneous in operation and are connected to an alarm circuit for indication and to take the proper action. This is because, a single ground fault does not require an immediate action of isolating the generator.

5.12 Protection Against Loss of Excitation

The loss of excitation of the generator may result in the loss of synchronism and slightly increase in the generator speed. The machine starts behaving as an induction generator. It drawn reactive power from the system which is undesirable. The loss of excitation may lead to the pole slipping condition. Hence protection against loss of excitation must be provided.

The protection is provided using directional distance type relay with the generator terminals.

When there is loss of excitation, the equivalent generator impedance varies and traces a curve as shown in the Fig. 5.15. This Fig. 5.15 shows the loss of excitation characteristics alongwith the relay operating characteristics, on R-X diagram.

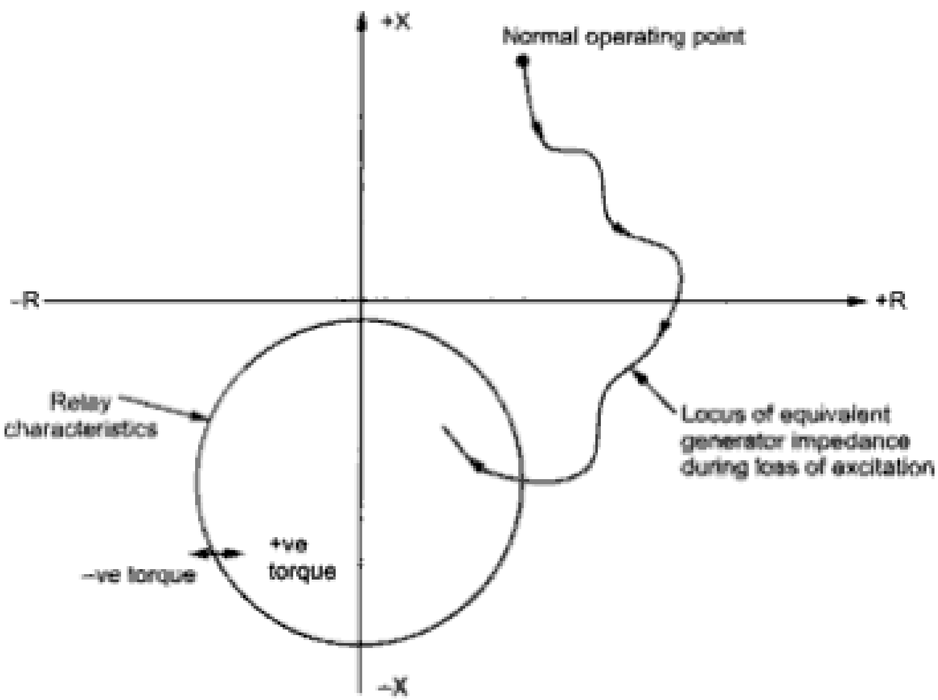


Fig. 5.15 Loss of excitation characteristics

The equivalent generator impedance locus traces a path from first quadrant of R-X diagram to the fourth quadrant. The distance relay is used which covers the portion of the fourth quadrant where impedance locus path exists. Thus when the impedance takes value in the region covered by the relay characteristics, the relay operates. The relay operates when generator first starts to slip poles. Then relay trips the field circuit breaker. And it disconnects the generator from the system, too. When the excitation is regained and becomes normal, the generator can then be returned to service instantly.

5.13 Negative Sequence Relays

The negative relays are also called phase unbalance relays because these relays provide protection against negative sequence component of unbalanced currents existing due to unbalanced loads or phase-phase faults. The unbalanced currents are dangerous from generators and motors point of view as these currents can cause overheating. Negative sequence relays are generally used to give protection to generators and motors against unbalanced currents.

A negative sequence relay has a filter circuit which is operative only for negative sequence components. Low order of over current also can cause dangerous situations hence a negative sequence relay has low current settings. The earth relay provides protection for phase to earth fault but not for phase to phase fault. A negative sequence relay provides protection against phase to phase faults which are responsible to produce negative sequence components.

The Fig. 5.16 shows the schematic arrangement of negative phase sequence relay.

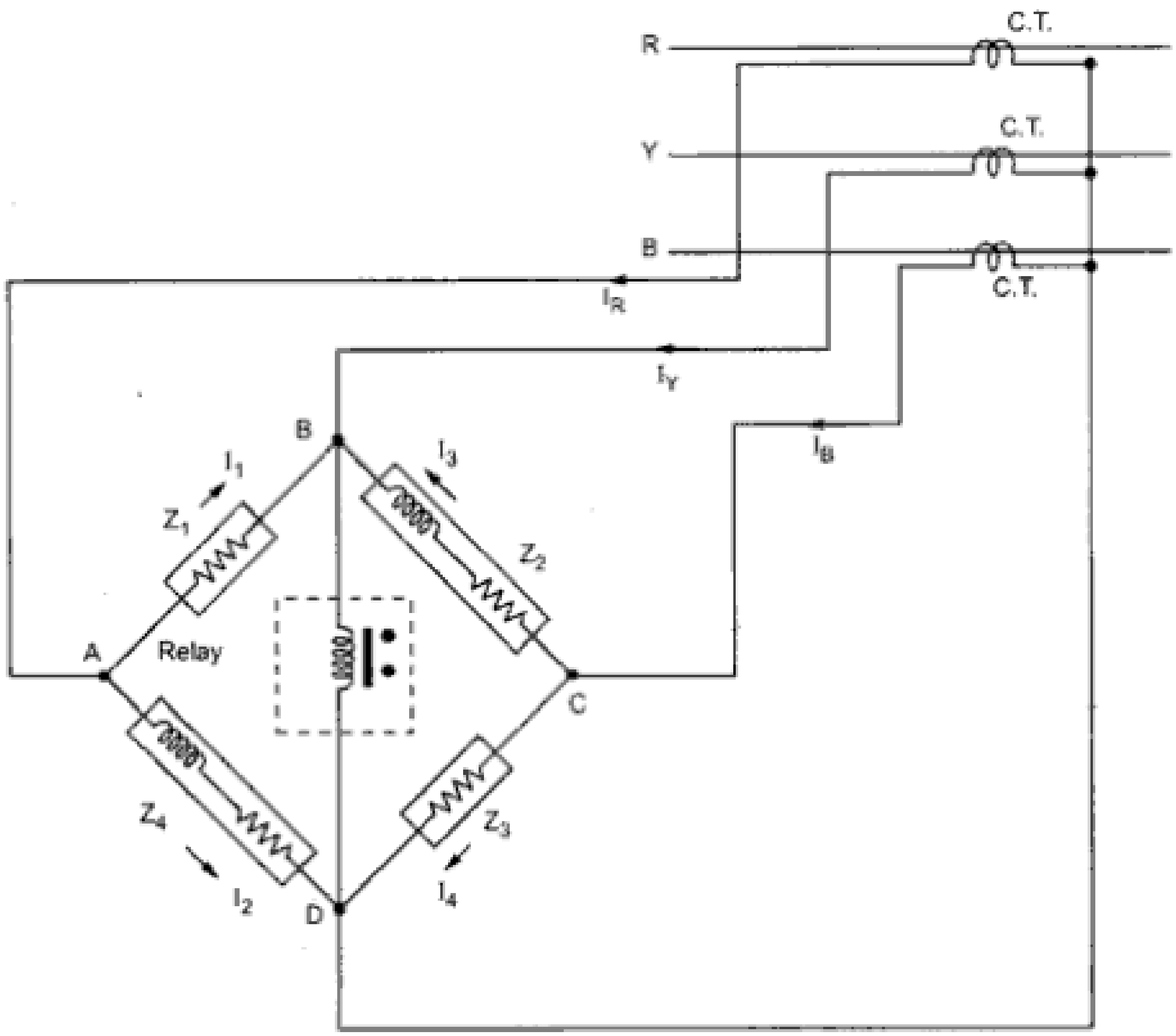


Fig. 5.16 Negative phase sequence relay

Basically it consists of a resistance bridge network. The magnitudes of the impedances of all the branches of the network are equal. The impedances Z_1 and Z_3 are purely resistive while the impedances Z_2 and Z_4 are the combinations of resistance and reactance. The currents in the branches Z_2 and Z_4 lag by 60° from the currents in the branches Z_1 and Z_3. The vertical branch B-D consists of inverse time characteristics relay. The relay has negligible impedance.

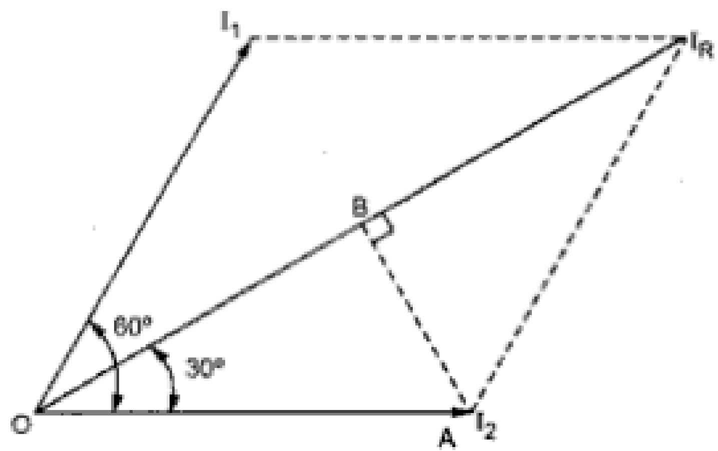


Fig. 5.17

The current I_R gets divided into two equal parts I_1 and I_2. And I_2 lags I_1 by 60°. The phasor diagram is shown in the Fig. 5.17.

$$\bar{I_1} + \bar{I_2} = \bar{I_R}$$

Let $$I_1 = I_2 = I$$

The perpendicular is drawn from point A on the diagonal meeting it at point B, as shown in the Fig. 5.17. This bisects the diagonal.

$$\therefore \quad OB = \frac{I_R}{2}$$

Now in triangle OAB,

$$\cos 30 = \frac{OB}{OA}$$

$$\therefore \quad \frac{\sqrt{3}}{2} = \frac{\left(\frac{I_R}{2}\right)}{I}$$

$$\therefore \quad I = \frac{I_R}{\sqrt{3}} = I_1 = I_2 \qquad \ldots (1)$$

Now I_1 leads I_R by 30° while I_2 lags I_R by 30°.

Similarly the current I_B gets divided into two equal parts I_3 and I_4. The current I_3 lags I_4 by 60°. From equation (1) we can write,

$$\frac{I_B}{\sqrt{3}} = I_3 = I_4 \qquad \ldots (2)$$

The current I_4 leads I_B by 30° while current I_3 lags I_B by 30°.

The current entering the relay at the junction point B in the Fig. 5.16 is the vector sum of I_1, I_3 and I_Y.

$$\therefore \quad I_{relay} = \overline{I_1} + \overline{I_3} + \overline{I_Y}$$

$$= I_Y + \frac{I_R}{\sqrt{3}} \text{ (leads } I_R \text{ by } 30°) + \frac{I_B}{\sqrt{3}} \text{ (lags } I_B \text{ by } 30°)$$

The vector sum is shown in the Fig. 5.18 when the load is balanced and no negative sequence currents exist.

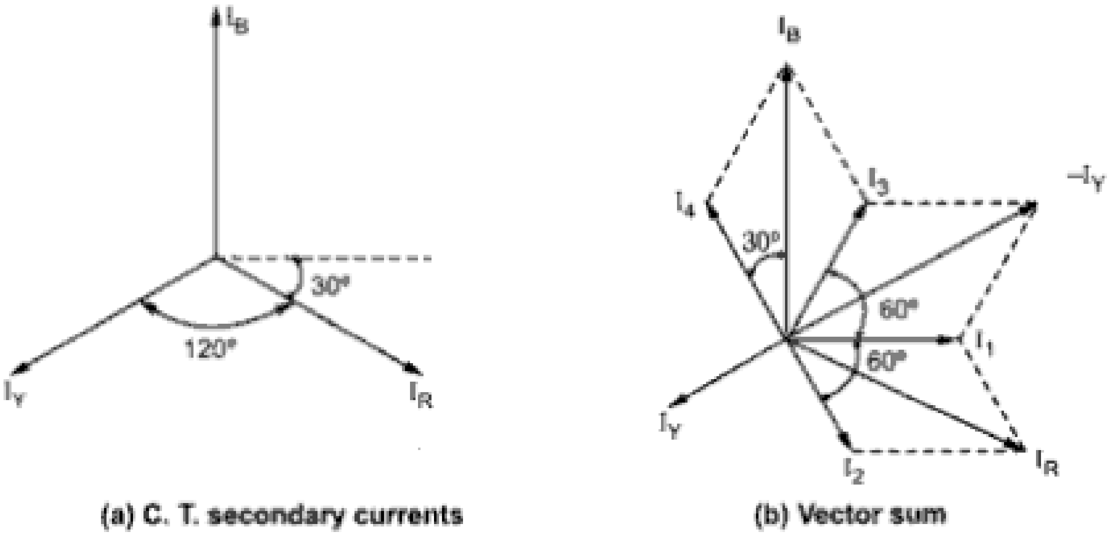


Fig. 5.18

It can be seen from the Fig. 5.18 that,

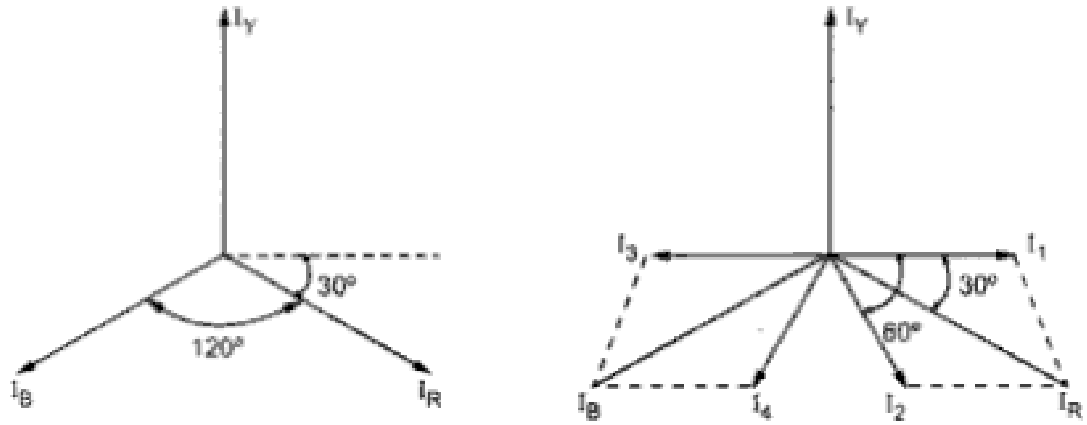
$$\overline{I_1} + \overline{I_3} = -\overline{I_Y}$$

$$\therefore \quad \overline{I_1} + \overline{I_3} + \overline{I_Y} = 0$$

Thus the current entering the relay at point B is zero. Similarly the resultant current at junction D is also zero. Thus the relay is inoperative for a balanced system.

Now consider that there is unbalanced load on generator or motor due to which negative sequence currents exist. The phase sequence of C.T. secondary currents is as shown in the Fig. 5.19 (a). The vector diagram of I_1, I_3 and I_Y is shown in the Fig. 5.19 (b) under this condition.

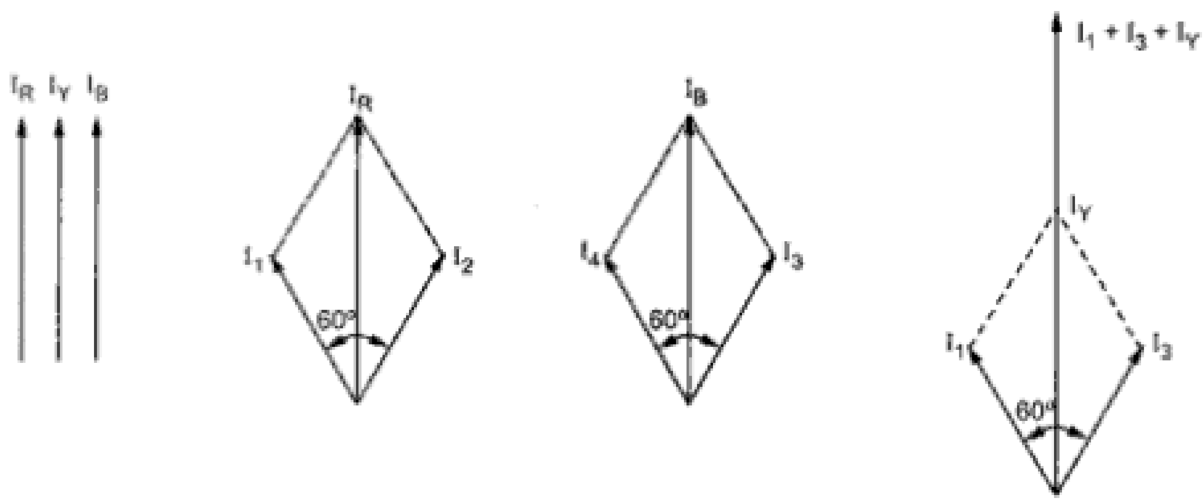
The components I_1 and I_3 are equal and opposite to each other at the junction point B. Hence I_1 and I_3 cancel each other. Now the relay coil carries the current I_Y and when this current is more than a predetermined value, the relay trips closing the contacts of trip circuit which opens the circuit breaker.



(a) C.T. secondary currents (b) Vector sum

Fig. 5.19 Negative sequence currents

Zero Sequence Currents : The zero sequence components of secondary currents are shown in the Fig. 5.20 (a). We know that,



(a) (b) (c) (d)

Fig. 5.20 Zero sequence currents

$$\overline{I_R} = \overline{I_1} + \overline{I_2}$$

$$\overline{I_B} = \overline{I_3} + \overline{I_4}$$

These sums are shown in the Fig. 5.20 (b) and (c). It can be seen from the Fig. 5.20 (d) that,

$$\overline{I_1} + \overline{I_3} = \overline{I_Y} \text{ in phase with } I_Y$$

The total current through relay is $\overline{I_1} + \overline{I_3} + \overline{I_Y}$. Thus under zero sequence currents the total current of twice the zero sequence current flows through the relay. Hence the relay operates to open the circuit breaker.

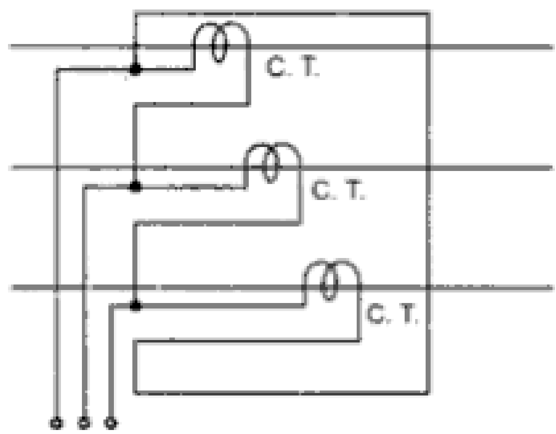


Fig. 5.21 Delta connection of C.T.s

To make the relay sensitive to only negative sequence currents by making it inoperative under the influence of zero sequence currents is possible by connecting the current transformers in delta as shown in the Fig. 5.21. Under delta connection of current transformers, no zero sequence current can flow in the network.

5.13.1 Induction Type Negative Sequence Relay

Another commonly used negative sequence relay is induction type. Its construction is similar to that of induction type over current relay. The schematic diagram of this type of relay is shown in the Fig. 5.22.

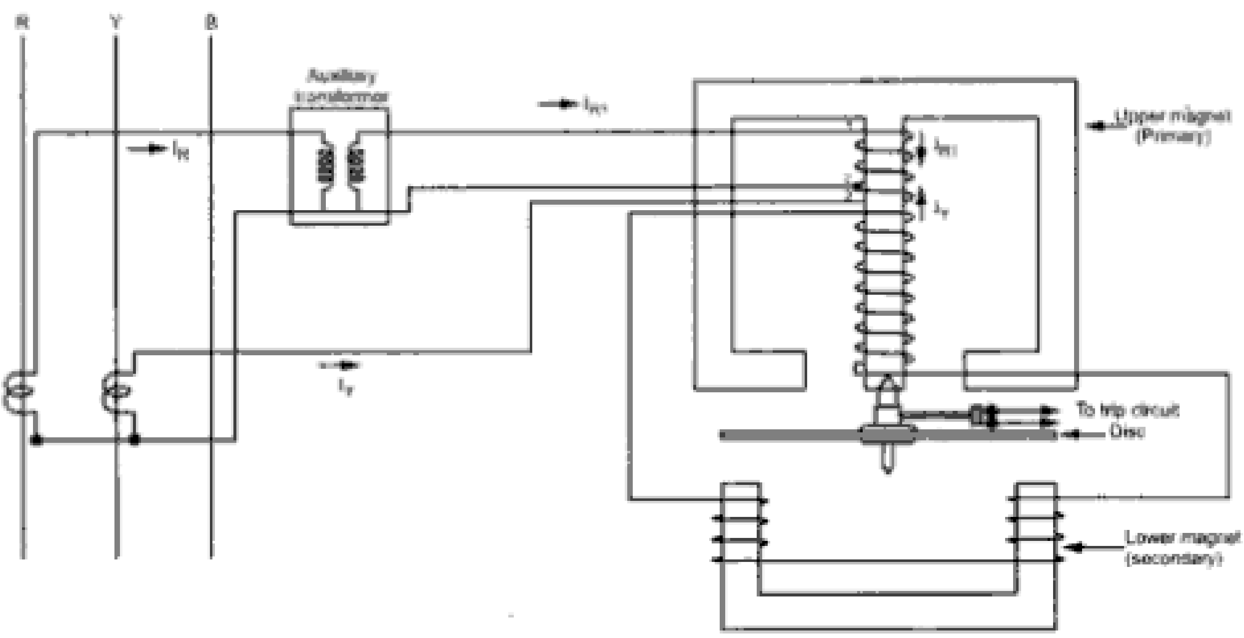


Fig. 5.22 Induction type negative sequence relay

The central limb of upper magnet carries the primary which has a centre tap. Due to this, the primary winding has three terminal 1, 2, and 3. The section 1-2 is energized from the secondary of an auxiliary transformer to R-phase. The section 2-3 is directly energized from the Y-phase current.

The auxiliary transformer is a special device having an air gap in its magnetic circuit. With the help of this, the phase angle between its primary and secondary can be easily adjusted. In practice it is adjusted such that output current lags by 120° rather than usual 180° from the input.

So, I_R = Input current of auxiliary transformer

I_{R1} = Output current of auxiliary transformer

and I_{R1} lags I_R by 120°

Hence the relay primary carries the current which is phase difference of I_{R1} and I_Y.

Positive Sequence Currents : The C.T. secondary currents are shown in the Fig. 5.23 (a). The Fig. 5.23 (b) shows the position of vector I_{R1} lagging I_R by 120°. The Fig. 5.23 (c) shows the vector sum of I_{R1} and $-I_Y$.

The phase difference of I_{R1} and I_Y is the vector sum of I_{R1} and $-I_Y$. It can seen from the Fig. 5.23 (c) that the resultant is zero. Thus the relay primary current is zero and relay is inoperative for positive sequence currents.

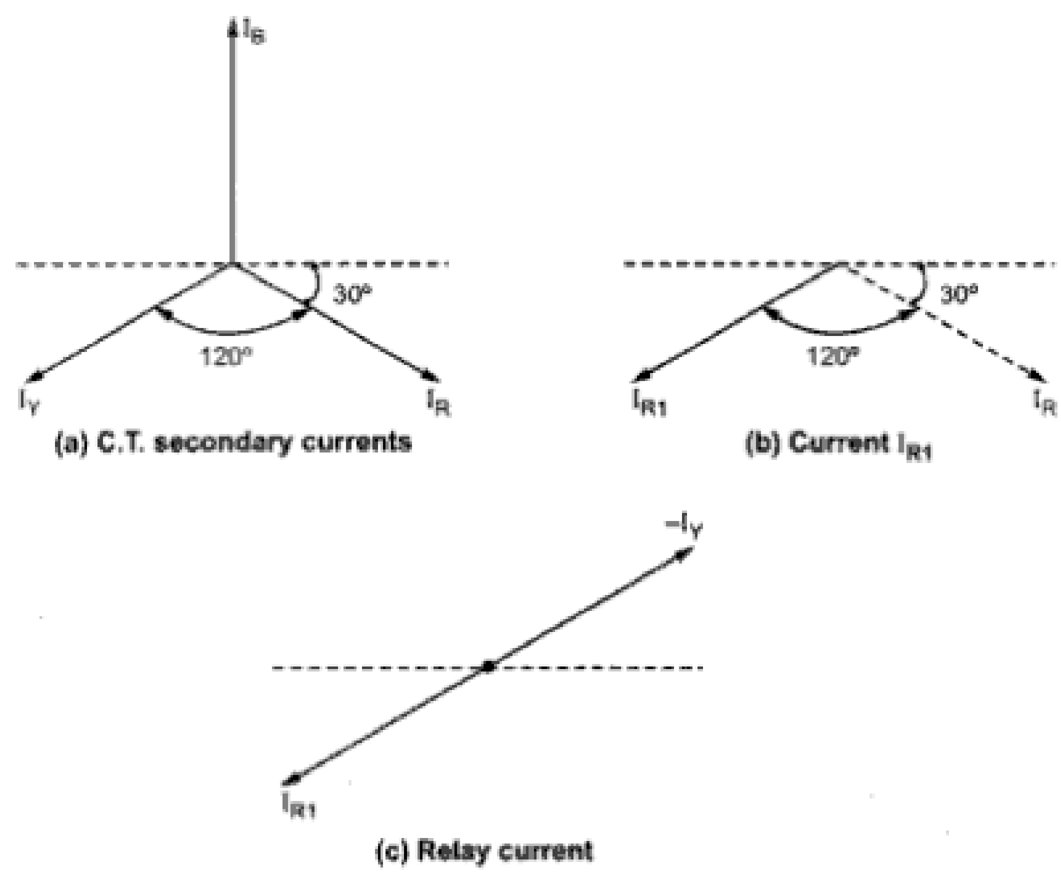


Fig. 5.23 Positive sequence currents

Negative sequence currents : The C.T. secondary currents are shown in the Fig. 5.24 (a). The Fig. 5.24 (b) shows the position of I_{R1} lagging I_R by 120°. The Fig. 5.24 (c) shows the vector difference of I_{R1} and I_Y which is the relay current.

Under negative sequence currents, the vector difference of I_{R1} and I_Y results into a current I as shown in the Fig. 5.24 (c). This current I flows through the primary coil of the relay.

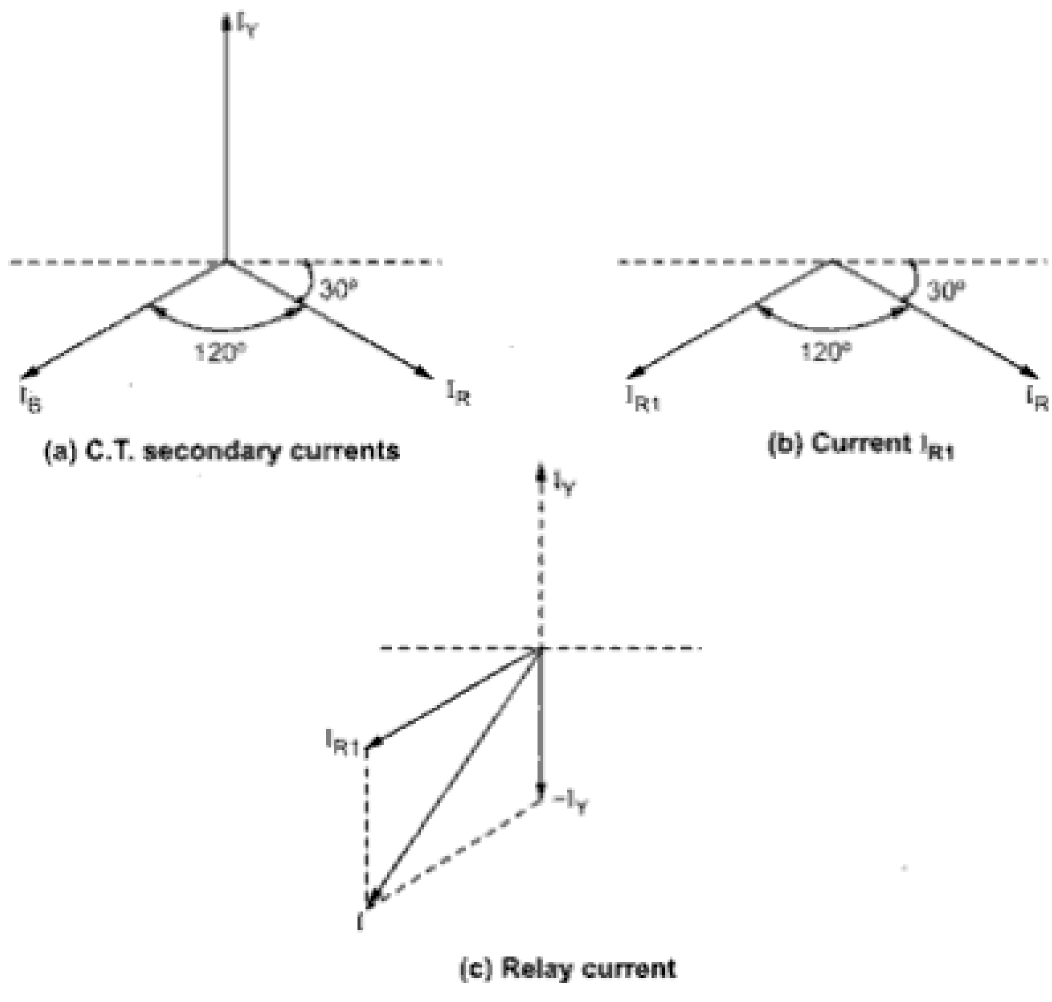


Fig. 5.24 Negative sequence currents

Under the influence of current I, the relay operates. The disc rotates to close the trip contacts and it opens the circuit breaker.

This relay is inoperative for zero phase sequence currents. But the relay can be made operative for the flow of zero sequence currents also by providing an additional winding on the central limb of the upper magnet of the relay. This winding is connected in the residual circuit of the three line C.T.s. This relay is called induction type negative and zero sequence relay.

The schematic arrangement of induction type negative and zero sequence relay is shown in the Fig. 5.25.

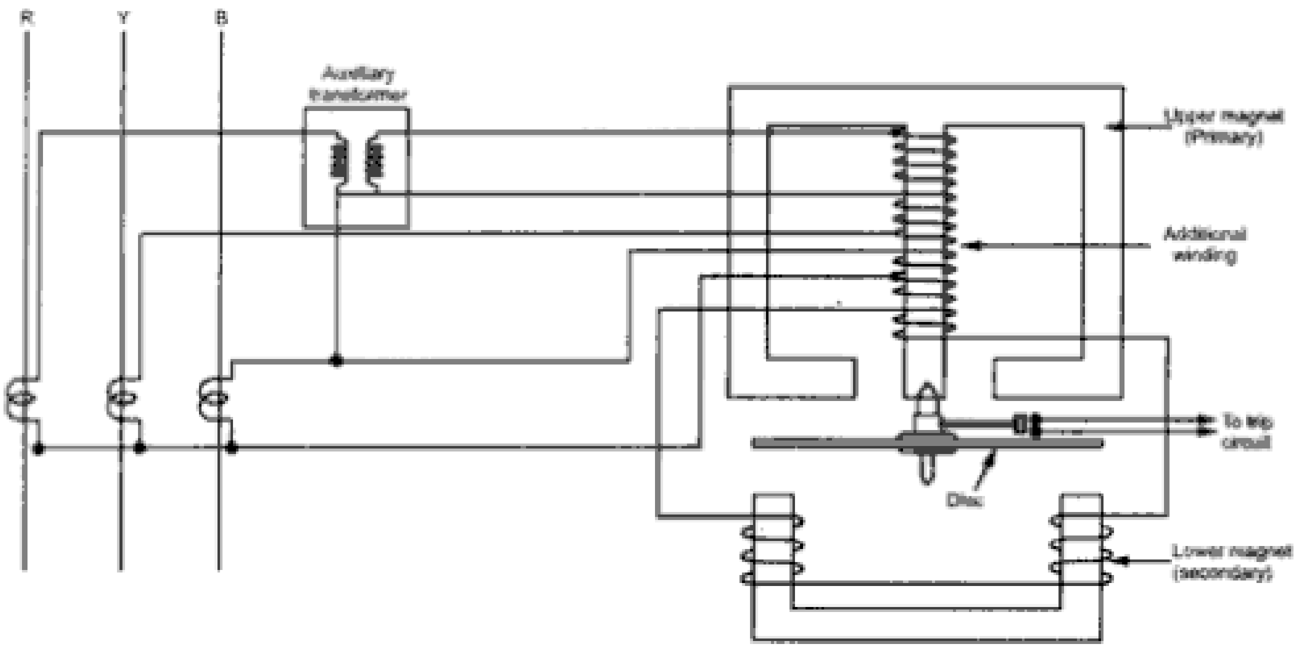


Fig. 5.25 Induction type negative and zero sequence relay

5.14 Protection Against Unbalanced Loading

When the load on the generator becomes unbalanced, negative phase sequence currents flow. The negative sequence components produce a rotating magnetic field which rotates at synchronous speed in a direction opposite to the direction of rotor field. Hence effectively the relative speed between the two is double the synchronous speed. Thus double frequency currents are induced in the rotor. These currents cause severe heating of the rotor and can cause damage to the rotor. The unbalanced stator currents also cause severe vibrations and heating of stator. Hence it is necessary to provide the negative sequence protection to the generators against the unbalanced load conditions.

The negative phase sequence filter alongwith the overcurrent relay provides the necessary protection against the unbalanced loads.

The relative asymmetry of a three phase generator is given by the ratio of negative sequence current to the rated current. Mathematically it can be expressed as,

$$\% S = \frac{I_n}{I} \times 100$$

where $\% S$ = percentage asymmetry

I_n = Negative sequence current

I = Rated current

The negative sequence protection scheme is shown in the Fig. 5.26.

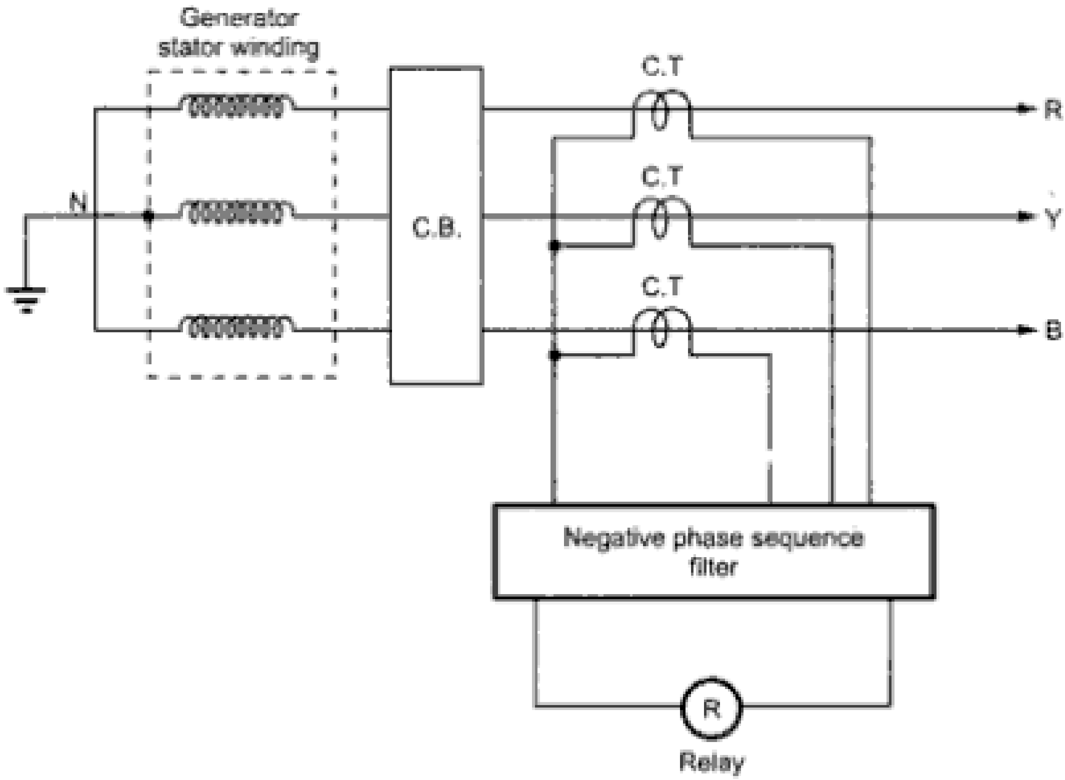


Fig. 5.26 Negative sequence protection

A negative phase sequence filter is connected to the secondaries of the current transformers. A negative phase sequence filter consists of resistors and inductors. These are so arranged that under normal operating conditions, the relay is inoperative. The filter circuit is stable for the symmetrical overloads up to about three times the rated full load.

When unbalanced load occurs, the negative phase sequence filter circuit produces an output proportional to the negative phase sequence components. This is directed through the relay coil. Hence the relay operates to open the circuit breaker to isolate the generator.

Examples with Solutions

➡ **Example 5.3 :** *The neutral point of a 11 kV alternator is earthed through a resistance of 12 Ω, the relay is set to operate when there is out of balance current of 0.8 A. The C.T.s have a ratio of 200/5. What percentage of the winding is protected against earth faults. What must be the minimum value of earthing resistance required to give 90% of protection to each phase ?*

Solution : The given values are,

$$V_L = 11 \text{ kV} \qquad R = 12\ \Omega \qquad \text{C.T. ratio} = 2000/5$$

$$i_o = \text{relay current} = 0.8 \text{ A}$$

$$\therefore \quad I_o = \text{minimum operating line current (C.T. primary)}$$

$$= i_o \times \frac{2000}{5} = \frac{0.8 \times 2000}{5}$$

$$= 320 \text{ A}$$

$$V = \text{line to neutral voltage} = \frac{V_L}{\sqrt{3}}$$

$$= \frac{11 \times 10^3}{\sqrt{3}} = 6350.8529 \text{ V}$$

$$\therefore \% \text{ Winding unprotected} = \frac{R I_o}{V} \times 100 = \frac{12 \times 320}{6350.8529} \times 100$$

$$= 60.46\ \%$$

$$\therefore \quad \% \text{ Winding protected} = 100 - 60.46 = 39.53\ \%$$

Thus with R = 12 Ω only 39.53 % winding is protected.

It is necessary to give 90% protection.

$$\therefore \quad \% \text{ Winding unprotected} = 100 - 90 = 10\%$$

$$\therefore \quad 10\% = \frac{R \times I_o}{V} \times 100$$

$$\therefore \quad 10 = \frac{R \times 320}{6350.8529} \times 100$$

$$\therefore \quad R = 1.9846\ \Omega$$

This is the minimum value of resistance to give 90% protection to the **largest** machine.

Example 5.4 : *A 50 MVA, 3 phase, 33 kV synchronous generator is protected by the Merz-Price protection using 1000/5 ratio C.T.s. It is provided with restricted earth fault protection with the earthing resistance of 7.5 Ω . Calculate the percentage of winding unprotected in each phase against earth faults if the minimum operating current of the relay is 0.5 A.*

Solution : The given values are,

$$V_L = 33 \text{ kV} \qquad \text{C. T. ratio} = 1000/5 \qquad R = 7.5\ \Omega$$

$$i_o = 0.5 \text{ A} = \text{relay current}$$

$\therefore$ $$I_o = \text{minimum operating current (primary)}$$

$$= i_o \times \frac{1000}{5} = \frac{0.5 \times 1000}{5}$$

$$= 100 \text{ A}$$

$$V = \frac{V_L}{\sqrt{3}} = \frac{33 \times 10^3}{\sqrt{3}}$$

$$= 19052.55 \text{ V}$$

$\therefore$ % Winding unprotected $= \frac{R I_o}{V} \times 100$

$$= \frac{7.5 \times 100}{19052.55} \times 100$$

$$= 3.936\%$$

Example 5.5 : *A 13.2 kV, 3 phase, 100 MW at 0.8 p.f. lag, alternator has reactance of 0.2 p.u. If it is equipped with a circulating current differential protection set to operate at least at 500 A fault current, determine the magnitude of the neutral grounding resistance that leaves the 10% of the winding unprotected.*

Solution : The given values are,

$$V_L = 13.2 \text{ kV} \quad \cos\phi = 0.8 \quad P = 100 \text{ MW} \quad X = 0.2 \text{ p.u.}$$

Now $$P = \sqrt{3}\, V_L\, I_L \cos\phi$$

$\therefore$ $$100 \times 10^6 = \sqrt{3} \times 13.2 \times 10^3 \times I_L \times 0.8$$

$\therefore$ $$I_L = 5467.33 \text{ A} = I = \text{full load current}$$

The p.u. reactance is given by,

$$\text{p.u. } X = \frac{I X}{V} \quad \text{where } X = \text{reactance per phase}$$

$\therefore$ $$0.2 = \frac{5467.33\, X}{\left(\frac{13.2 \times 10^3}{\sqrt{3}}\right)} \quad \text{where } V = \frac{V_L}{\sqrt{3}}$$

$\therefore$ $$X = 0.2787\ \Omega \text{ per phase}$$

% of unprotected winding = 10%

$\therefore$ Reactance of unprotected winding $= \frac{10}{100} \times 0.2787$

$$= 0.02787\ \Omega$$

Voltage induced in 10% of unprotected winding

$$= \frac{10}{100} \times V = \frac{10}{100} \times \frac{13.2 \times 10^3}{\sqrt{3}} = 762.1023\ V$$

Let this voltage be $v = 762.1023\ V$

$$Z = \sqrt{r^2 + x^2}$$

where Z = Impedance offered to the fault

r = Resistance in neutral

x = Reactance of 10% of winding

Now $Z = \frac{v}{i}$

where v = Voltage induced in 10% winding

= 762.1023 V

i = Fault current = 500 A

$$\therefore \quad \sqrt{r^2 + x^2} = \frac{762.1023}{500}$$

$$\therefore \quad \sqrt{r^2 + (0.02787)^2} = 1.5242$$

$$\therefore \quad r^2 + (0.02787)^2 = 2.3232$$

$$\therefore \quad r^2 = 2.3224$$

$$\therefore \quad r = 1.524\ \Omega$$

This is the required resistance in neutral earthing.

Example 5.6 : *An alternator stator winding protected by a percentage differential relay is shown in the Fig. 5.27. The relay has 15% slope of characteristics* $(I_1 - I_2)$ *against* $(I_1 + I_2/2)$. *The high resistance ground fault has occurred near the grounded neutral end of the generator winding while the generator is carrying load. The currents flowing at each end of the generator winding are also shown. Assuming C.T. ratio to be 500/5 A, will the relay operate to trip the circuit breaker ?*

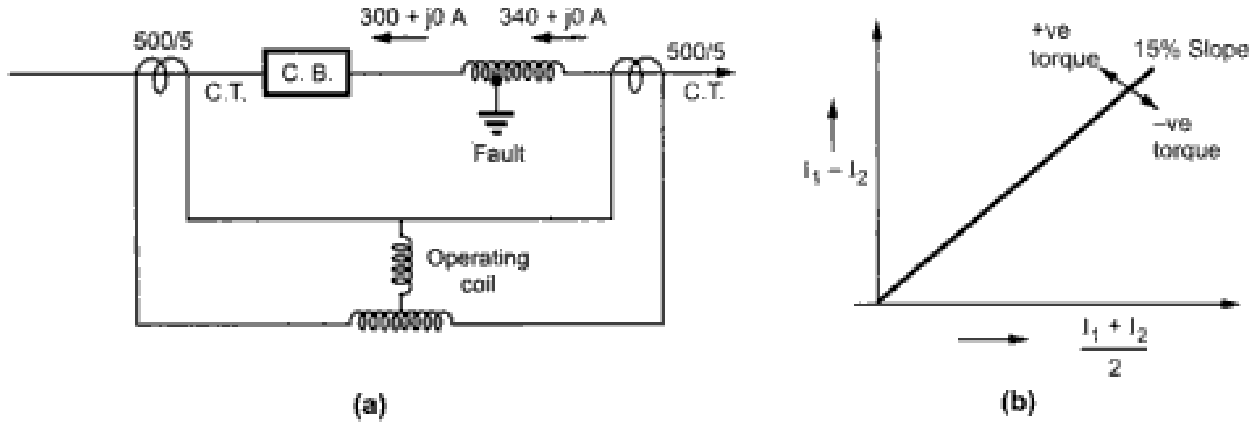


Fig. 5.27

Solution : From the given current at two ends, let us calculate C.T. secondary currents at two ends,

$$\therefore \quad i_1 = (300 + j\,0) \times \frac{5}{500} = 3 \text{ A}$$

$$\text{and} \quad i_2 = (340 + j\,0) \times \frac{5}{500} = 3.4 \text{ A}$$

The directions of currents are shown in the Fig. 5.28.

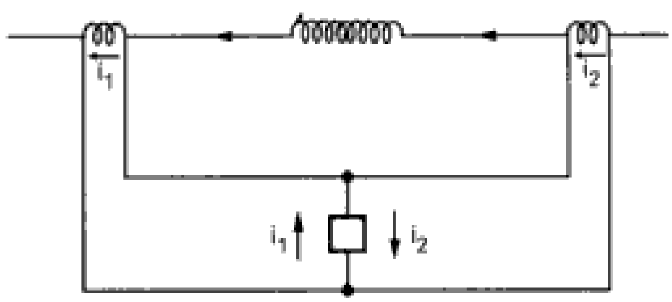


Fig. 5.28

The current flowing through the relay coil is $i_1 - i_2$.

$$\therefore \quad i_1 - i_2 = 3 - 3.4 = -0.4 \text{ A}$$

$$\text{While} \quad \frac{i_1 + i_2}{2} = \frac{3+3.4}{2} = 3.2 \text{ A}$$

From the characteristics of 15 % slope, corresponding to $\frac{i_1 + i_2}{2}$ the out of balance current required is,

$$i_1 - i_2 = \text{Slope} \times \left(\frac{i_1 + i_2}{2}\right)$$

$$= 0.15 \times 3.2$$

$$= 0.48 \text{ A}$$

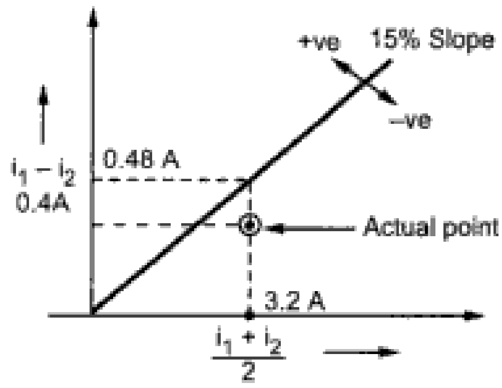


Fig. 5.29

This is shown in the Fig. 5.29.

Thus $i_1 - i_2$ must be more than 0.48 A i.e. above the line to operate the relay but actual point is located below the line in negative torque region.

Hence the **relay will not operate.**

Example 5.7 : *A 6.6 kV, star connected alternator has a transient reactance of 2 Ω per phase and negligible winding resistance. It is protected by circulating current Merz-Price protection. The alternator neutral is earthed through the resistance of 7.5 Ω. The relays are set to operate when there is out of balance current of 1 A in secondary of 500/5 A current transformers. How much % of winding is protected against earth fault?*

Solution : The given values,

$$V_L = 6.6 \text{ kV} \quad X = 2\ \Omega/\text{phase} \quad r = 7.5\ \Omega \quad \text{C.T.} = 500/5$$

Let the x % of winding is unprotected.

Reactance of unprotected winding $= \frac{x}{100} \times 2 = 0.02\ x\ \Omega$

$$V = \frac{V_L}{\sqrt{3}} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810.511 \text{ V} \qquad \text{... full voltage}$$

V = Voltage across unprotected winding

$$= \frac{x}{100} \times 3810.511 = 38.10511\ x\ \text{V}$$

$$r = 7.5\ \Omega$$

Z = Impedance offered to the fault

$$= r + j\,(0.02\ x)$$

$$= 7.5 + j\,(0.02\ x)\ \Omega$$

$$\therefore \quad |Z| = \sqrt{(7.5)^2 + (0.02\,x)^2}$$

i = fault current

= out of balance secondary current × C.T. ratio

$$= 1 \times \frac{500}{5}$$

$$= 100 \text{ A}$$

$$\therefore \quad |Z| = \frac{V}{i}$$

$$\therefore \quad \sqrt{(7.5)^2 + (0.02x)^2} = \frac{38.10511x}{100}$$

$$\therefore \quad (7.5)^2 + (0.02\ x)^2 = 0.1452\ x^2$$

$$\therefore \quad 56.25 + 4 \times 10^{-4} x^2 = 0.1452\ x^2$$

$$\therefore \quad 0.1448\ x^2 = 56.25$$

$$\therefore \quad x^2 = 388.4668$$

$$\therefore \quad x = 19.7\%$$

This is % of winding unprotected.

$$\therefore \quad \%\text{ of winding protected} = 100 - 19.7$$

$$= 80.29\ \%$$

Example 5.8 : *A synchronous generator rated at 20 kV protected by circulating current system having neutral grounded through a resistance of 15 Ω. The differential protection relay is set to operate when there is an out of balance current of 3 A. The C.T.s have ratio of 1000/5 A. Determine,*

i) The % of winding remains unprotected

ii) Value of earth resistance to achieve 75% protection of winding :

Solution : The given values are,

$$V_L = 20 \text{ kV}, \quad i_o = 3 \text{ A}, \quad R = 15\ \Omega, \quad \text{C.T. ratio} = 1000/5$$

i)

$$I_o = \text{minimum line operating current (C.T. primary)}$$

$$= i_o \times \frac{1000}{5} = \frac{3 \times 1000}{5}$$

$$= 600 \text{ A}$$

$$V = \frac{V_L}{\sqrt{3}} = \frac{20 \times 10^3}{\sqrt{3}}$$

$$= 11547 \text{ V}$$

$$\therefore \quad \%\ X = \%\text{ of winding unprotected}$$

$$= \frac{R\ I_o}{V} \times 100 = \frac{15 \times 600}{11547} \times 100$$

$$= 77.94\ \%$$

ii) We want 75% protection.

$$\therefore \quad \%\ X = 100 - 75 = 25\ \%$$

Remaining conditions are same except R.

$$\therefore \quad 25 = \frac{R\ I_o}{V} \times 100$$

$$\therefore \quad 25 = \frac{R \times 600}{11547} \times 100$$

$$\therefore \quad R = \frac{25 \times 11547}{600 \times 100}$$

$$= 4.811\ \Omega$$

This is the required earth resistance.

➡ **Example 5.9 :** *The Fig. 5.30 shows the percentage differential relay used for the protection of an alternator winding. The relay has minimum pickup current of 0.25 A and has a % slope of 10%. A high resistance ground fault occurs near the grounded neutral end of the generator winding with the current distribution as shown in the Fig. 5.30. Assume a C.T. ratio of 400 : 5, determine if relay will operate.*

Fig. 5.30

Solution : For the given current at the two ends, the C.T. secondary currents can be obtained using C.T. ratio as,

$$i_1 = (380 + j\,0) \times \frac{5}{400} = 4.75\ A$$

$$i_2 = (340 + j\,0) \times \frac{5}{400} = 4.25\ A$$

$$\therefore \quad i_1 - i_2 = 4.75 - 4.25 = 0.5\ A$$

$$\frac{i_1 + i_2}{2} = \frac{4.75 + 4.25}{2}$$

$$= 4.5\ A$$

So $i_1 - i_2$ current flows through operating coil while 4.5 A flows through the restraining coil.

With the minimum pickup current of 0.25 A, and slope 10%, the operating characteristics is as shown in the Fig. 5.31.

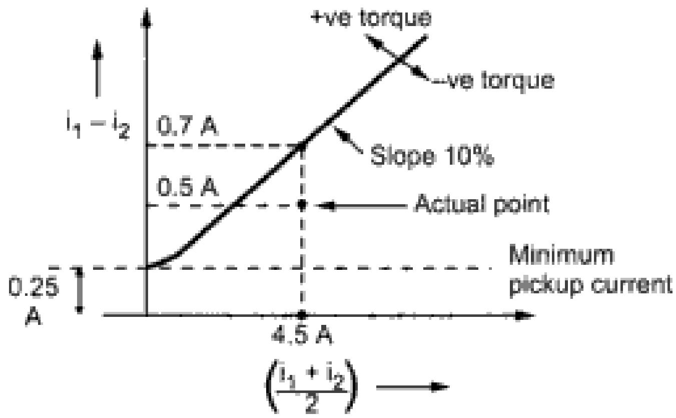


Fig. 5.31

The equation of the characteristics is,

$$y = m x + c$$

At origin, x = 0 but y = 0.25

$$\therefore \quad y = c = 0.25$$

Hence characteristic equation is,

$$(i_1 - i_2) = m\frac{i_1 + i_2}{2} + 0.25 \qquad \text{where m = slope = 0.1}$$

$$\therefore \quad (i_1 - i_2) = 0.1\left(\frac{i_1 + i_2}{2}\right) + 0.25$$

For $\frac{i_1 + i_2}{2} = 4.5$ we get,

$$i_1 - i_2 = (0.1 \times 4.5) + 0.25$$

$$= 0.7 \text{ A}$$

Thus to operate the relay, $i_1 - i_2$ must be greater than 0.7 A when $\frac{i_1 + i_2}{2}$ is 4.5 A. But actually $i_1 - i_2 = 0.5$ A as shown. It is located below the line in negative torque region hence relay will not operate.

Example 8.10 : *An alternator rated 10 kV protected by 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 amperes in the pilot wires which are connected to the secondary of current transformers with ratio 1000/5.*

Determine :

i) The percentage winding which remains unprotected.

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

(V.T.U August-2002)

Solution : $V_L = 10$ kV, $R = 10\ \Omega$, C.T. ratio = 1000/5, $i_o = 1.8$ A

I_o = minimum operating line current (C.T. primary)

$$= i_o \times \frac{1000}{5} = 1.8 \times \frac{1000}{5} = 360 \text{ A}$$

$$V = \text{line to neutral voltage} = \frac{V_L}{\sqrt{3}} = \frac{10 \times 10^3}{\sqrt{3}} = 5773.5026 \text{ V}$$

$$\text{i) \% Winding unprotected} = \frac{RI_o}{V} \times 100 = \frac{10 \times 360}{5773.5026} \times 100$$

$$= \mathbf{62.3538\ \%}$$

ii) It is necessary to give 80 % protection.

∴ % Winding unprotected = 100 − 80 = 20 %

$$\therefore \quad 20 = \frac{R \times 360}{5773.5026} \times 100$$

∴ $R = \mathbf{3.2075\ \Omega}$ ... Minimum earthing resistance required

Example 5.11 : *An alternator stator winding protected by a percentage differential relay is shown in Fig. 5.32(a). The relay has 0.15 amp minimum pick up and a 12% slope of characteristics* $(i_1 - i_2)$ V_s $\left(\frac{i_1 + i_2}{2}\right)$. *A high resistance ground fault has occured near the grounded neutral end of the generator winding while generator is carrying load. The currents flowing at each end of the generator winding are shown in Fig. 5.32. Assuming that the CT's have 400/5 amps ratio and no inaccuracies will the relay trip the generator CB under this fault condition.*

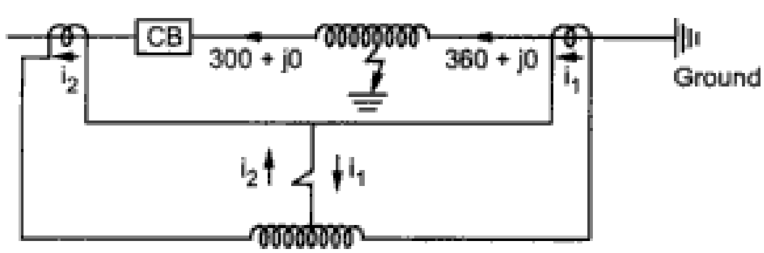


Fig. 5.32(a)

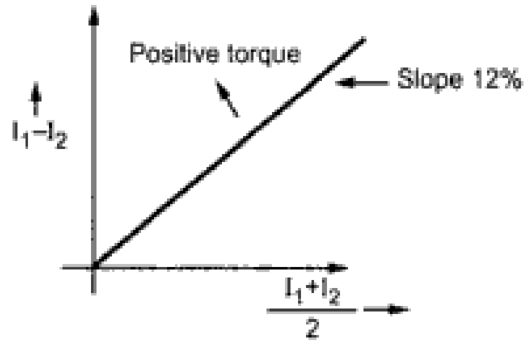


Fig. 5.32(b)

(AU-April-2004)

Solution : From the given current at two ends, let us calculate C.T. secondary curents at two ends,

$$i_2 = (300 + j0) \times \frac{5}{400} = 3.75 \text{ A}$$

$$i_1 = (300 + j0) \times \frac{5}{400} = 4.5 \text{ A}$$

$$\text{The relay coil current} = i_1 - i_2 = 0.75 \text{ A}$$

$$\frac{i_1 + i_2}{2} = 4.125 \text{ A}$$

From the characteristics of 12 % slope, corresponding to $\left(\frac{i_1 + i_2}{2}\right)$, the out of balance current required is,

$$i_1 - i_2 = \text{slope} \times \left(\frac{i_1 + i_2}{2}\right) = 0.12 \times 4.125 = 0.495 \text{ A}$$

Thus $i_1 - i_2$ must be more thatn 0.495 A for relay to operate. And actually it is 0.75 A. Hence **the relay will operate :**

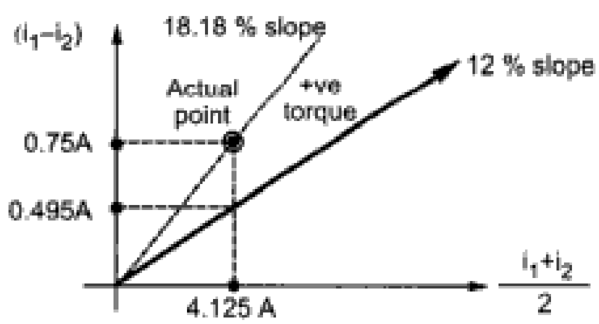


Fig. 5.33

Actual point is located in positive torque region. Slope of line through actual point is

$$= \frac{(i_1 - i_2)}{\left(\frac{i_1 + i_2}{2}\right)} = \frac{0.95}{4.125} \times 100$$

$$= 18.18 \%$$

As this slope is more than 12% of the characteristics given, **relay will operate.**

Example 5.12 : *A 3 phase, 10 MVA, 6.6 kV alternator supplies a load of 8 MVA at 0.8 p.f. and is being protected through Merz-price circulating current system and its relays are so set that they do not operate until the out of balance current ocurs at 20% of full load current. Calculate the value of earth resistance to be provided in order to ensure that only 10% of alternator winding remains unprotected. Assume alternator reactance of 10% Neglect resistance of the alternator.* **(AU-Dec.-2004)**

Solution : $V_L = 6.6$ kV, Rating = 10 MVA, $V = V_L/\sqrt{3} = 3810.5117$ V.

$\therefore$ $$\text{Rating} = \sqrt{3}\, V_L I_L$$

$\therefore$ $$I_L = \frac{10 \times 10^8}{\sqrt{3} \times 6.6 \times 10^3} = 874.7731 \text{ A}$$ ...Full load current

$\therefore$ $$\% \text{ Reactance} = \frac{IX}{V} \times 100$$ ...X = Reactance per phase

$\therefore$ $$10 = \frac{874.7731X}{3810.5117} \times 100$$

$\therefore$ $$X = 0.4356\ \Omega$$

Reactance of unprotected winding $= \frac{10}{100} \times 0.4356 = 0.04356\ \Omega$

$$v = \text{Voltage induced in unprotected winding}$$

$$= \frac{10}{100} \times V = 381.05117 \text{ V}$$

$$i = \text{Fault current} = 20\% \text{ of } I_L = 174.954 \text{ A}$$

$\therefore$ $$Z = \frac{v}{i} = \text{impedance offered to fault} = 2.178\ \Omega$$

But $$Z = A + j\, 0.04356\ \Omega$$

$\therefore$ $$|Z| = \sqrt{R^2 + (0.04356)^2}$$

$\therefore$ $$(2.178)^2 = R^2 + (0.04356)^2$$

$\therefore$ $$R = \mathbf{2.177\ \Omega}$$ ...Earth resistance required

➡ **Example 5.13 :** *Current transformers of current ratio of 1000/5 A are used for protection of a star connected 3 phase, 10 MVA, 6.6 kV alternator. If the relay is set to operates for a minimum current of 0.5 A, Calculate the percentage of each phase stator winding which is unprotected agains earth fault when the machine operates at normal voltage. Assume that star point of alternator is earthed through a resistance of 7.5 Ω.*

(AU-April-2005)

Solution : $V_L = 6.6 \times 10^3$ V, $R = 7.5\ \Omega$, C.T. ratio = 1000/5, $i_o = 0.5$A

$$\therefore \quad I_o = i_o \times \text{C.T. ratio} = 0.5 \times \frac{1000}{5} = 100 \text{ A}$$

$$V = \frac{V_L}{\sqrt{3}} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810.5117 \text{ V}$$

$$\therefore \text{ \% winding unprotected} = \frac{RI_o}{V} \times 100 = \frac{7.5 \times 100}{3810.5117} \times 100$$

$$= \mathbf{19.682\%}$$

➡ **Example 5.14 :** *A 500 kVA, 6.6 kV star connected alternator has a synchronous reactance of 1.0 Ω per phase and negligible resistance. The differential relay operates if the out of balance current through it exceeds 30% of the normal full load current of the alternator. The star point of the alternator is earthed through a resistance of 5 Ω . What percent of the stator winding is left unprotected ? Show that the effect of the alternator reactance can be neglected.*

(AU-Dec.-2005)

Solution : The full load current,

$$I_L = \frac{V_A}{\sqrt{3}\, V_L} = \frac{500 \times 10^3}{\sqrt{3} \times 6.6 \times 10^3} = 43.738 \text{ A}$$

Out of balance curent = 30% I_L = 0.3 × 43.738 = 13.1214 A

Let winding unprotected = x %

Impedance of x% winding = $\frac{x}{100}(0 + j1)$

Value of earthing resistance = 5 Ω

∴ Total impedance at fault of the fault circuit.

$$= [5 + j\, 0.01\, x]$$

Voltage induced in x % of winding

$$= \frac{6.6 \times 10^3}{\sqrt{3}} \times \frac{x}{100} = \frac{66x}{\sqrt{3}}$$

$$\therefore \text{ Out of balance current} = \frac{\text{Voltage induced}}{\text{Impedance}}$$

$$\therefore \quad 13.1214 = \frac{\frac{66x}{\sqrt{3}}}{5 + j\,0.01x} \qquad \ldots(1)$$

This is to be solved by trial and error method. Hence effect of alternator reactance can be neglected.

$$\therefore \quad 13.1214 = \frac{66x}{5\sqrt{3}}$$

$$\therefore \quad x = \mathbf{1.7217\ \%} \qquad \ldots\text{Winding unprotetced}$$

The equation (1) can be solved as,

$$13.1214 = \frac{\frac{66x}{5\sqrt{3}}}{\sqrt{(5)^2 + (0.01x)^2}} \qquad \ldots \text{ Considering magnitude.}$$

$$\therefore \quad \sqrt{25 + (0.01x)^2} = 2.904\ x$$

$$\therefore \quad 25 + (0.01x)^2 = 8.4334\ x^2$$

$$\therefore \quad x = \mathbf{1.7217\%}$$

This shows that the reactance can be neglected without any error.

Review Questions

1. *Which are the various types of faults which can occur in a generator ? Explain in brief.*
2. *Why the protection of generators is complex ? Explain.*
3. *Which are the various abnormal running conditions, which may exist in a generator ? What are their effects and how these effects can be minimized ?*
4. *Explain the basic differential protection scheme. What are its disadvantages ?*
5. *Explain the basic percentage differential protection scheme. Draw its operating characteristics showing positive and negative torque regions.*
6. *Draw and explain the Merz-Price protection of alternator stator windings. State its advantages.*
7. *What is the role of auxiliary relay, in Merz-Price protection ?*
8. *Explain the restricted earth fault protection of generators.*
9. *Derive the expression for the percentage of winding unprotected in the restricted earth fault protection.*
10. *Explain the operation of unrestricted earth fault protection scheme.*
11. *Draw and explain balanced earth fault protection scheme.*
12. *Is it possible that 100 % winding of generator is protected against earth faults ? How ?*
13. *Suggest the scheme for interturn fault protection for Stator of alternator.*

14. *Explain the negative phase sequence protection for the generators.*

15. *What are the methods to provide rotor earth fault protection ?*

16. *How the protection against loss of excitation is provided in generators ? Why it is important ?*

17. *A generator is provided with restricted earth-fault protection. The ratings are 11 kV, 5000 kVA. The percentage of winding protected against phase to ground fault is 80%. The relay setting such that it trips for 25% out of balance. Calculate the resistance to be added in neutral to ground connection.* **(Ans. 1.94 Ω)**

18. *The neutral point of a 10,000 V alternator is earthed through a resistance of 10 ohms, the relay is set to operate when there is an out of balance current of 1A. The C.T.s have a ratio of 1000/5. What percentage of the winding is protected against fault to earth and what must be minimum value of earthing resistance to give 90% protection to each phase winding ?* **(Ans. : 62.5%, 2.88 Ω)**

19. *A 3 phase, 2 pole, 11 kV, 10,000 kVA alternator has neutral earthed through a resistance of 7 ohms. The machine has current balance protection which operates upon out of balance current exceed 20% of full load. Determine % of winding protected against earth fault.* **(Ans. :88.4%)**

20. *The Fig. 5.34(a) shows percentage differential relay applied to the protection of an alternator winding. The relay has 10% slope of characteristics $I_1 - I_2$ vs $(I_1 + I_2)/2$.*

A high resistance ground fault occurred near the grounded neutral end of the generator winding while generator is carrying load. As a consequence, the currents in amperes flowing at each end of the winding are shown in Fig. 5.34(b). Assuming C.T. ratio of 400/5 amperes, will the relay operate to trip the breaker. **(Ans. : Relay will not operate)**

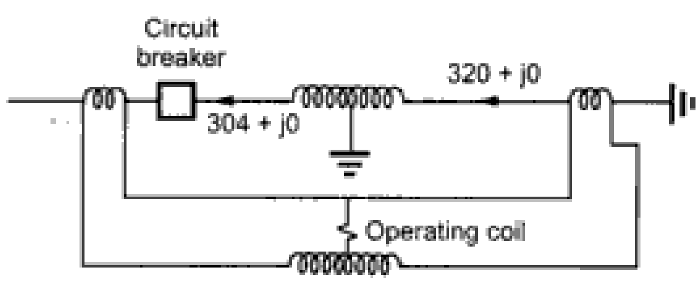


Fig. 5.34(a)

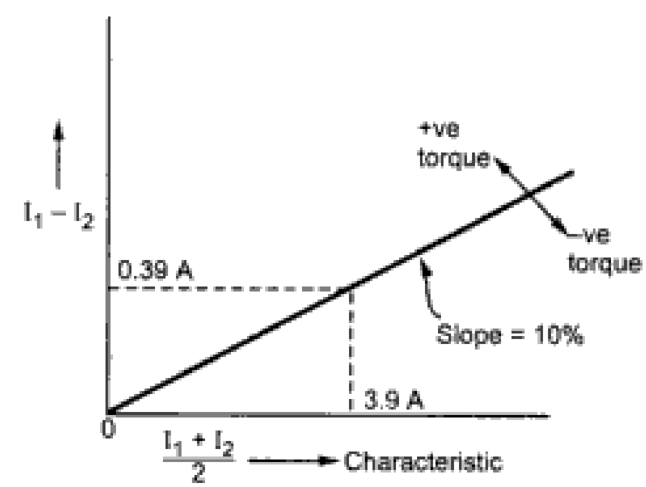


Fig. 5.34(b)

21. *A 11 kV, 3 phase alternator has full load rated current of 200 A. Reactance of armature winding is 15 percent. The differential protection system is set to operate on earth fault currents of more than 200 A. Find the neutral earthing resistance, which gives earth fault protection to 90% of stator winding.* **(Ans. : 3.145 Ω)**

22. *A star-connected 3-phase 10 MVA, 6.6 kV alternator has a per phase reactance of 10%. It is protected by Merz-Price circulating-current principle which is set to operate for fault currents not less than 175 A. Calculate the value of earthing resistance to be provided in order to ensure that only 10% of the alternator winding remains unprotected.* **(Ans. : 2.171 Ω)**

23. *A star connected, 3 phase, 10 MVA, 6.6 kV alternator is protected by Merz-Price circulating current principle using 1000/5 amperes current transformers. The star point of the alternator is earthed through a resistance of 7.5 Ω. If the minimum operating current for the relay is 0.5 A, calculate the percentage of each phase of the stator winding which is unprotected against earth faults when the machine is operating at normal voltage.* **(Ans. : 19.69 %)**

24. *A 6600 volt 3-phase turbo-alternator has a maximum continuous rating of 2,000 kW at 0.8 p.f. and its reactance is 12.5%. It is equipped with Merz-Price circulating current protection which is set to operate at fault currents not less than 200 amperes. Find what value of the neutral earthing resistance leaves 10% of the windings unprotected ?* **(Ans. : 1.89 Ω)**

25. *A 50 MVA, 3-phase, 33 kV alternator is being protected by the use of circulating current balance scheme using 2000/5 ampere current transformer. The neutral of the generator is earthed through a NGR of 7.5 ohms. If the pick up current for the relay is just above 0.5 ampere, determine what percentage of the winding of each phase unprotected against earth when the machine operates at nominal voltage.* **(Ans. : 7.88%)**

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6 Induction Motor Protection

6.1 Introduction

Based on the control action i.e. starting, stopping or reversal, various controlling elements known in electrical terms as switchgear are employed for the protection of induction motor. Generally two basic protections viz short circuit protection and overload protection are provided for each motor. The switchgear used for protection includes contactors with H.R.C fuse and thermal overload relays along with circuit breakers.

If the rating of the motor is upto 150 kW then contactors and fuses can be used while for motors having rating beyond 150 kW, circuit breakers are used. The contactor is a kind of switch through which supply can be given to the motor when its coil is energized. If the current to be interrupted is six times the rated current of the motor then contactors can be used.

6.2 Abnormal Conditions and Failure in Case of Induction Motor

The three phase induction motors are used in numerous industrial applications. Hence before studying the protection circuit we have to consider the abnormal conditions and failure that may occur in case of induction motor.

If the motor is heavily loaded beyond its capacity then it will be overload condition of motor in which case motor draws heavy current from the supply and there will be simultaneous rise in temperature of winding and deterioration of the insulation resulting in damage of winding. Hence the motor must be protected against this mechanical overloading with overload protection circuits. Normally thermal overload relays, over current relays or miniature circuit breaker with built in trip coils may be used.

It might be possible that the rotor is locked or starting lasts for longer duration or rotor does not move because of excessive load (stalling) at start. In all these cases motor draws heavy current from the supply and results in damage to the winding due to overheating as stated above. In this case thermal relays or instantaneous overcurrent relays are used.

If the supply conditions are abnormal such as loss of supply voltage, unbalanced supply voltage, phase sequence reversal of supply voltage, over voltage, under voltage or under frequency then also the performance of the motor is affected. With unbalanced supply voltage there will be excessive heating while with undervoltage the motor draws more current for the same load. For undervoltage protection, undervoltage relays are used.

With correct phase sequence, the motor runs in one direction. With change in phase sequence of supply it runs in other direction which is dangerous in some of the applications such as cranes, hoists or elevators. In such cases phase reversal relay may be provided which will disconnect the supply to the motor through the circuit breaker.

Due to excessive temperature rise, the insulation may get damaged which may lead to stator earth fault or stator phase to phase fault which are rare in nature. For low rating motors, HRC fuses provide sufficient protection against these faults while for large motors, differential protection may be used.

Due to blowing of fuse in any phase or open circuit in one of the three phases results in single phasing. In such case motor continues to run and if it is loaded to its rated value then it will draw excessive current which will damage the rotor and eventually the motor will be damaged due to excessive overheating. Normally thermal overload relays are used against single phasing. Sometimes special single phase preventer may be provided.

Summary of abnormal condition and protection circuit to be employed is given in the table.

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

Table 6.1

The motor protection circuit that is designed should be simple in operation and economically feasible. Its cost should be less than 5% of the motor cost. It should also be kept in mind that during starting and permissible overload conditions, the protection circuit should not operate. The choice of motor protecting circuit is based on various factors such as rated voltage, rated kW, size of motor, type of induction motor, type of starter, type of switchgear used, cost of motor, type of load, starting current possibility of occurrence of abnormal conditions etc.

6.3 Protection Circuit for Induction Motor

The protection circuit along with its single line diagram is shown in the Fig. 6.1.

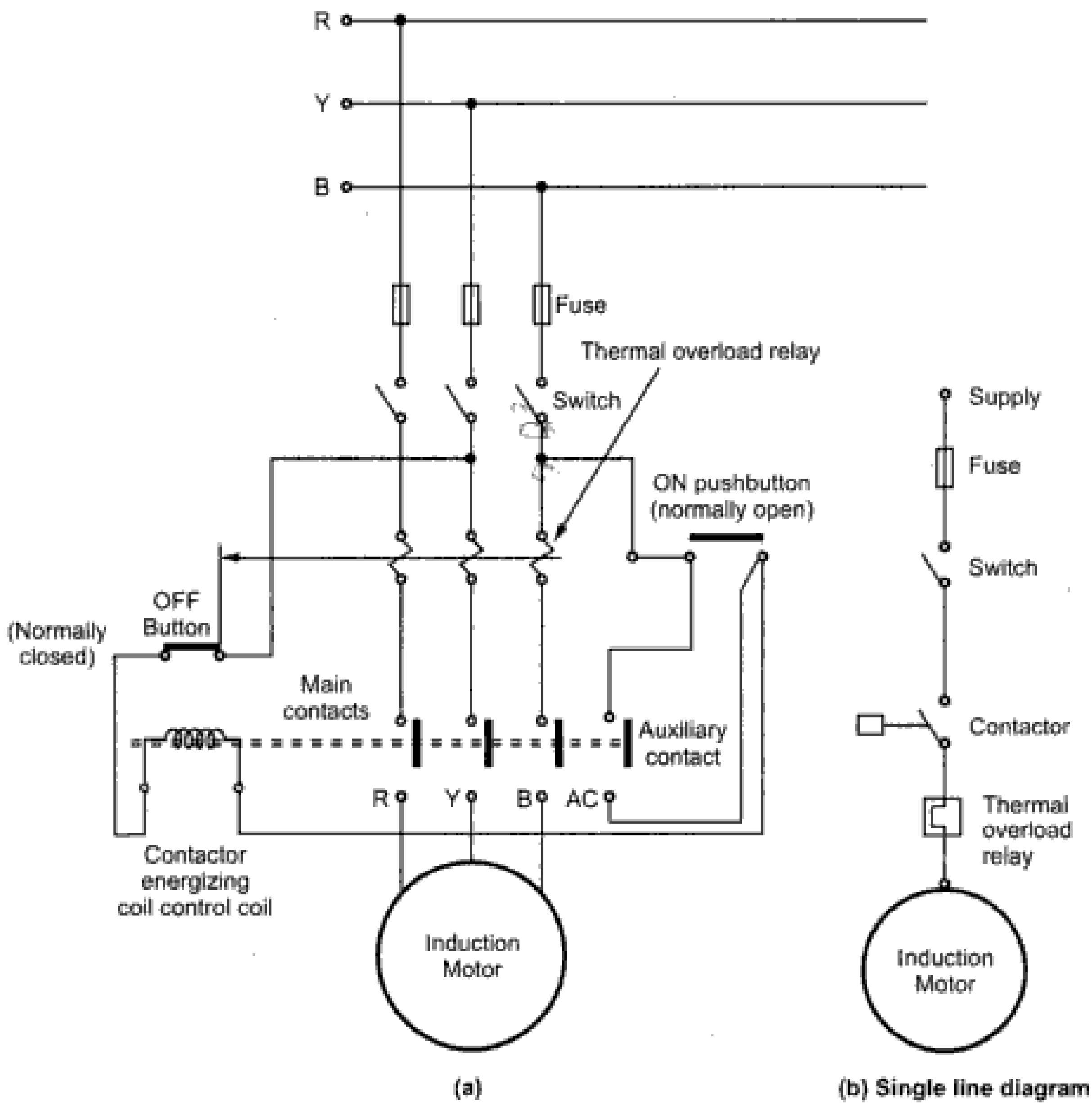

Fig. 6.1

The three phase supply is given to the motor through various elements such as fuse, switch, contactor and thermal overload relay. The control circuit of contactor consists of energizing coil, start and stop buttons. The start (ON) push button is normally open green switch while the stop (OFF) push button is normally closed red switch.

When the start button is pressed then the contactor coil is energized as it gets supply voltage. The coil attracts the plunger when excited and the main contacts are closed along with the auxiliary contact. Even if the ON push button is released, the contactor coil remains energized as it gets supply through auxiliary contacts. Thus motor starts running.

The OFF push button which is normally closed when pressed cuts the supply of the contactor coil and hence the main as well as auxiliary contacts are open so motor eventually stops. If supply voltage fails, control coil is de-energized which opens the contactor and motor stops.

During overload condition, the thermal overload relay operates. Thermal overload relay consists of bimetallic strips. Because of bending of one or more bimetallic strip results in operation of common lever which operates the trip contacts to de-energize the coil and disconnects the supply to the motor.

The bimetallic strips are either heated directly by flow of current or with the help of special heater coil through which motor current flows. For large motors, these relays are connected in secondary of current transformers. The bimetallic strips can be of self setting type or hand resetting type in which mechanical reset is required as the trip mechanism locks itself in operated condition. It should be observed that the rating of thermal relay should be such that it should not operate during normal starting conditions. A setting range is provided for adjustment for various load conditions. Protection against short circuit is provided with the help of HRC fuses.

6.4 Single Phasing Preventer

If one of the supply line is disconnected due to open circuit or improper contact in switch then still the motor continues to run. The power is then supplied to the remaining windings. The current in the other phases increases to about $\sqrt{3}$ times its normal value. This is called single phasing which results in unbalanced stator currents. The component which is present in this unbalanced current called negative sequence component causes magnetic flux rotating in opposite direction to the main flux. This results in double frequency currents to induce in the rotor to cause its heating. Thus major damage to motor may take place due to single phasing if proper precaution is not taken. As the phase overcurrent relays react slowly, they cannot give the instantaneous protection against single phasing.

For small motors separate protection against single phasing is normally not provided as thermal relays sense the increased current in remaining phases due to single phasing and provides the sufficient protection.

A separate single phasing protection circuit is required in case of large induction motors as even a small unbalance can cause damage to motor winding and rotor. The single phasing preventer is shown in the Fig. 6.2.

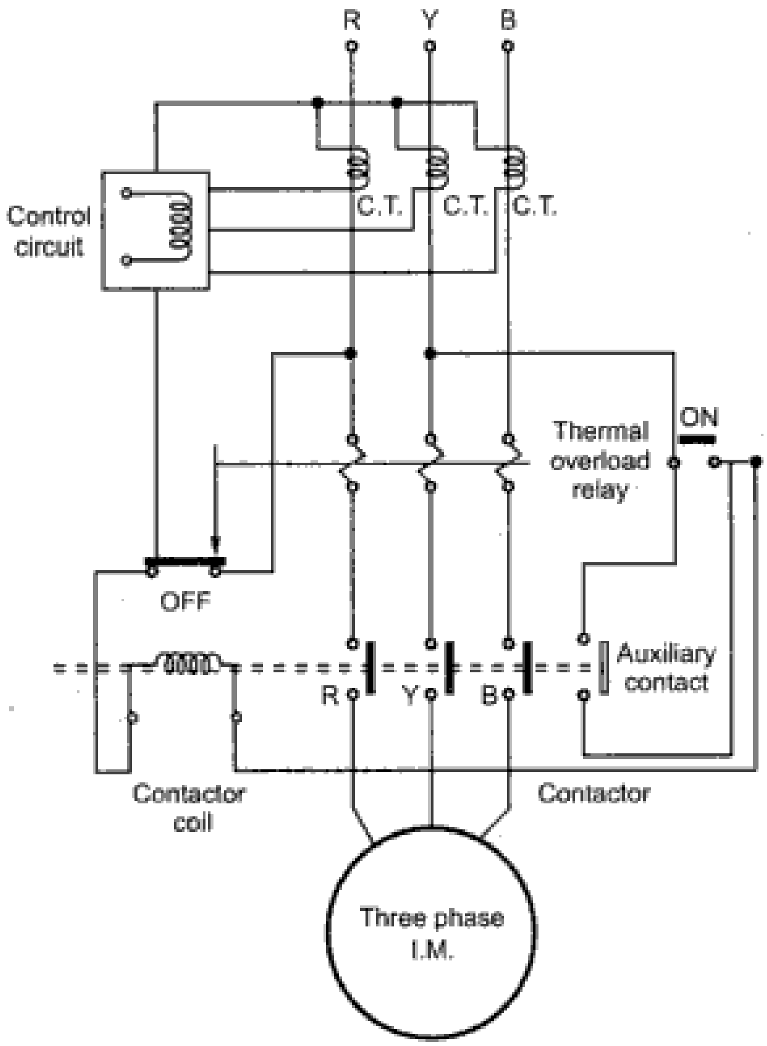

Fig. 6.2

As shown in the figure, it consists of C.Ts connected in each phase. The output of control circuit is fed to the level detector which sense the magnitude of unbalance. Depending on this output from the control circuit the tripping command to the starter or the circuit breaker is given when negative sequence current exceeds its preset limit.

6.5 Ground Fault Protection

The ground fault protection is achieved using earth leakage circuit breaker (ELCB). When the fault current or leakage current flows through earth return path then it forms the earth fault. These faults are relatively frequent and hence protection is required against these which is provided with the help of Earth leakage circuit breaker.

Consider an example of a person whose finger sticks into the socket. Even though the metal enclosure is securely earthened, the person will receive a severe shock. Under such case there must be certain device that will cut the supply. This can be done with the help of ELCB which will typically trip in around 25 ms if current exceeds its preset value.

The schematic of ELCB is shown in Fig. 6.3.

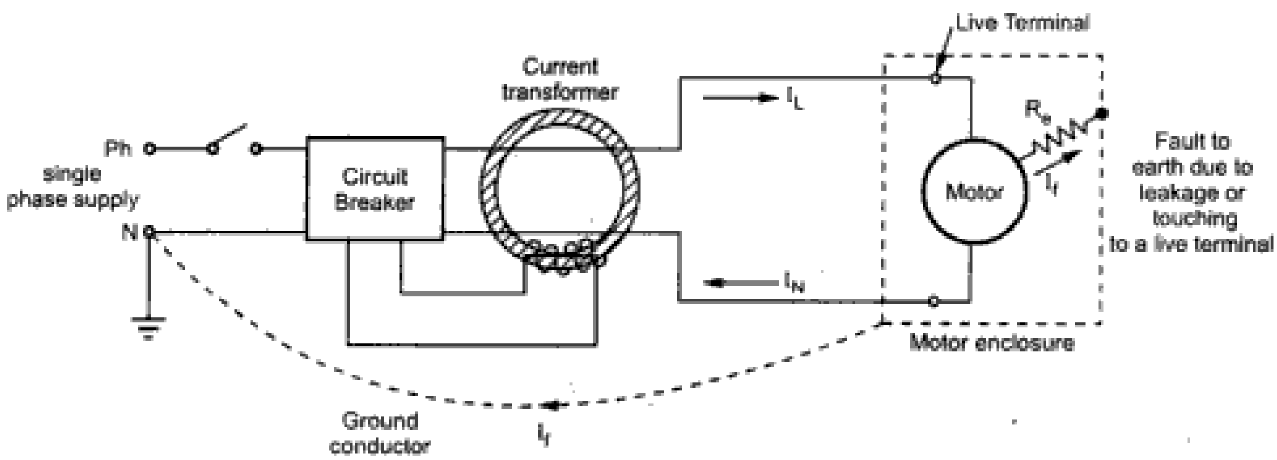

Fig. 6.3

As shown in the Fig. 6.3 ELCB consists of a small current transformer surrounding live and neutral wire. The secondary winding of current transformer is connected to relay circuit which can trip the circuit breaker which is connected in the circuit.

Under normal conditions, the current in line and neutral conductor is same so the net current $(I_L - I_N)$ flowing through the core is zero. Eventually there will not be any production of flux in the core and no induced emf. So the breaker does not trip.

If there is a fault due to leakage from live wire to earth or a person by mistake touching to the live terminal then the net current through the core will no longer remain as zero but equal to $I_L - I_N$ or I_f which will set up flux and emf in C.T. As per the preset value the unbalance in current is detected by C.T. and relay coil is energized which will give tripping singal for the circuit breaker. As C.T. operates with low value of current, the core must be very permeable at low flux densities.

In case of three phase circuits, single ring shaped core of magnetic material, encircles the conductor of all three phases as shown in the Fig. 6.4. A secondary is connected to relay circuit. Under normal condition, the component of fluxes due to fields of three conductors are balanced and secondary carries negligible current.

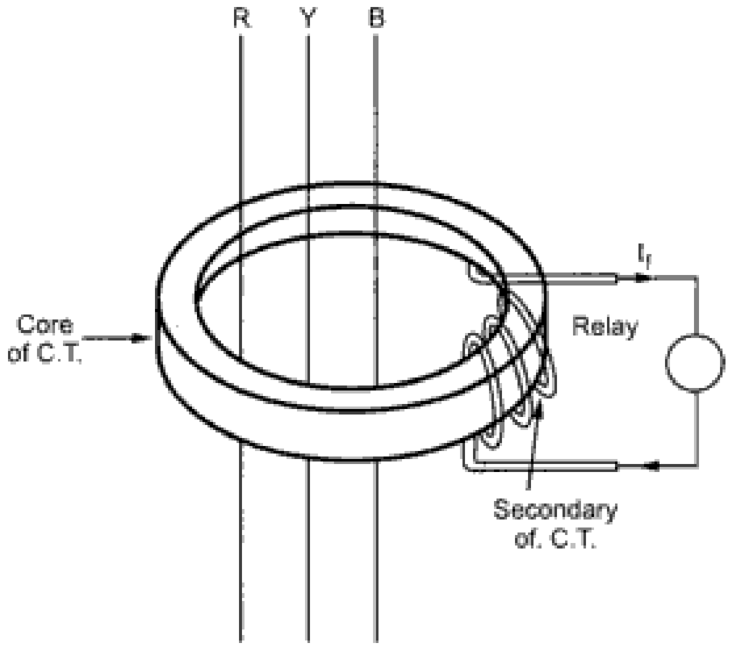

Fig. 6.4

During faulty condition, the balance is disturbed and current is induced in the secondary to trip the circuit breaker through relay.

This method to provide **earth fault protection** is called core balance type protection or **zero sequence current transformer** (ZSCT) protection. In case of earth faults, to avoid burning of coils and stampings the motor must be disconnected as quickly as possible from the supply.

The Fig. 6.5 shows ZSCT protection scheme. It is preferred for the systems with neutral earthed via resistance. (See on next page)

6.6 Phase Fault Protection

This protection is also called short circuit protection. At the time of such a fault, the current increases by 8 to 10 times the full load current of the motor. Attracted armature type relay unit is connected in each phase with a current setting of 4-5 times the full load current. This is because starting current can be 4-5 times full load current.

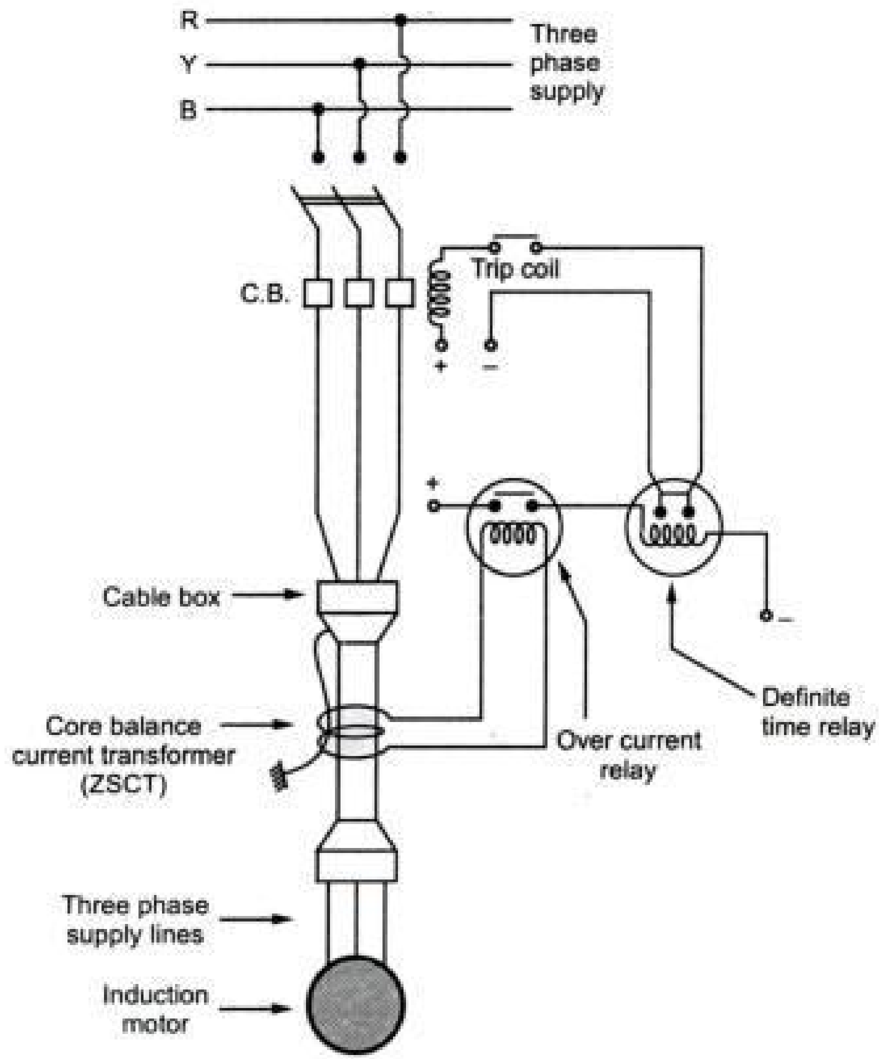

Fig. 6.5 Earth fault protection by ZSCT

Hence to operate the relay only under fault condition such a setting is necessary. Such a protection is shown in the Fig. 6.6.

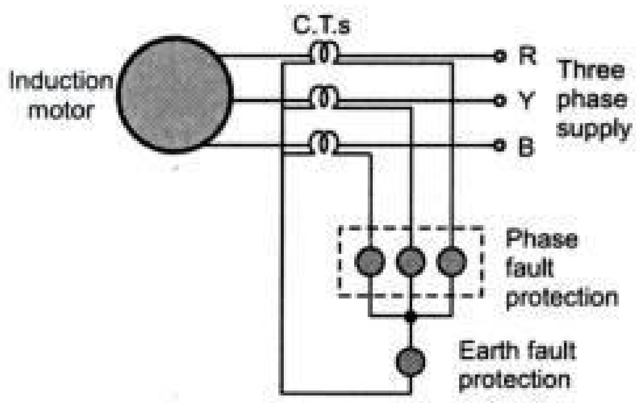

Fig. 6.6 Phase and earth fault protection

The phase faults can cause burn out of coils and stampings and hence motor should be disconnected as quickly as possible when fault occurs. Fast over current relays also are used to provide phase fault protection.

As mentioned above to avoid relay functioning during starting, the short circuit protection current setting must be just above the maximum starting current of the motor.

6.7 Phase Reversal Protection

The direction of induction motor depends on the direction of rotating magnetic field produced by the stator windings. For a particular phase sequence RYB the motor rotates in a particular direction due to corresponding direction of rotating magnetic field. But if any two lines are interchanged after repairs the phase sequence reverses such as YRB. Then the direction of rotating magnetic field also reverses and induction motor starts rotating in opposite direction. Such a change of direction is dangerous if the induction motor is used for cranes, hoists, lifts or in threading mills etc.

Thus to disconnect induction motor from supply if there is phase reversal, phase reversal protection is provided.

This protection is provided using motor driven disc working on electromagnetic principle. The secondaries of two current transformers connected in two lines drive the motor to operate the disc. The arrangement is such that for a normal direction of motor, disc rotates in a particular direction which keeps the auxiliary contacts closed. But if there is phase reversal then the torque produced reverses to rotate the disc in opposite direction. Due to this auxiliary contacts get opened. This inturn either operates the circuit breaker or de-energises starter coil to disconnect the motor from the supply. Thus phase reversal protection for the induction motor is achieved. Now a days solid state phase reversal relay sensing the phase reversal is used.

Review Questions

1. *Explain abnormal conditions and possible failure of induction motors.*
2. *Which type of protection is selected for various abnormal conditions ?*
3. *Explain the overload protection using thermal relays used for induction motor.*
4. *How earth fault protection is provided to the induction motors ?*
5. *Explain single phasing in induction motors. How motor is protected from single phasing ?*
6. *How phase faults protection is provided to the induction motors ?*
7. *What is phase reversal ? What is its effect ? How it is prevented in induction motors ?*

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7 Transformer Protection

7.1 Introduction

The transformers are static devices without having any rotating part and are totally enclosed. Hence the chances of faults occurring on transformers are much rare as compared to the faults occurring on generators. Similarly possibilities of running on abnormal conditions are also less in transformers compared to the generators.

But though the fault possibility is rare, if fault occurs, the transformer must be quickly disconnected from the system. The rare faults if not cleared quickly can get developed into the major faults which may be very serious for the transformer. Hence the protection must be provided to the transformers against possible faults.

The use of series fuses is very common in case of small distribution transformers instead of circuit breakers. Hence it is not necessary to install any automatic protective relaying equipments with the distribution transformers. But the power transformers having large ratings always need some type of automatic protective relaying equipments, to give protection against the possible faults.

7.2 Possible Transformer Faults

The generators are subjected to the number of faults and abnormal conditions but the transformers are not. The various possible transformer faults are,

1. Overheating
2. Winding faults
3. Open circuits
4. Through faults
5. Over fluxing

Let us discuss these faults.

7.2.1 Overheating

The overheating of the transformer is basically of sustained overloads and short circuits. The permissible overload and the corresponding duration is dependent on the type of transformer and class of insulation used for the transformer. Higher loads are permissible for very short duration of time. The overloading which continues for longer time is dangerous as it causes overheating of the transformer. Similarly the failure of the cooling system, though rare, is another possible cause of overheating.

Generally the thermal overload relays and temperature relays, sounding the alarm are used to provide protection against overheating. Similarly temperature indicators are also provided. On the transformers, when temperature exceeds the permissible limits, the alarm sounds and the fans are started. The thermocouples or resistance temperature indicators are also provided near the winding. These are connected in a bridge circuit. When temperature exceeds the limiting safe value, the bridge balance gets disturbed and alarm is sounded. If the corrective action is not taken within certain period of time then the circuit breaker trips.

7.2.2 Winding Faults

The winding faults are called internal faults. These faults are,

i) Phase to phase faults

ii) Earth faults

iii) Interturn faults

The overheating or mechanical shocks cause to deteriorate the winding insulation. If the winding insulation is weak, there is a possibility of short circuit between the phases or between the phase and ground. Also the possibility of short circuit between the adjacent turns of the same phase winding is also possible.

When such an internal fault occurs, the transformer must be quickly disconnected from the system. If such a fault persists for longer time, there is possibility of oil fire. The differential protection is very commonly used to provide protection against such faults. But this protection is not economical for the transformers below 5 MVA for which an over current protection is used. For the high capacity transformers in addition to main differential protection, the overcurrent protection is also provided as a backup protection. For earth fault protection, the restricted earth fault protection system, neutral current relays or leakage to frame protection system is used.

7.2.3 Open Circuits

The open circuit in one of the three phases is dangerous as it causes the undesirable heating of the transformer. A separate relay protection is not provided for the open circuits as open circuits are much harmless compared to other faults. In case of such faults, the transformer can be manually disconnected from the system.

7.2.4 Through Faults

Through faults are the external faults which occur outside the protected zone. Through faults are not detected by the differential protection. If the through faults persists for long period of time, the transformer may get subjected to the thermal and mechanical stresses which can damage the transformer. The overcurrent relays with undervoltage blocking, zero sequence protection and negative sequence protection are used to give protection against through faults. The setting of the overcurrent protection not only protects the transformer but also covers the station busbar and portion of a transmission line. Such a protection acts as a backup protection for the differential protection.

7.2.5 Overfluxing

The flux density in the transformer core is proportional to the ratio of the voltage to frequency i.e. V/f. The power transformers are designed to work with certain value of flux density in the core. In the generator transformer unit, if full excitation is applied before generator reaches its synchronous speed then due to high V/f the overfluxing of core may result. Higher core flux means more core loss and overheating of the core. The saturation of magnetic circuit is also the probable cause for the overfluxing operation. The V/f relay called volts/hertz relay is provided to give the protection against overfluxing operation. This relay does not allow exciting current to flow till the generator reaches to a synchronous speed and runs to produce voltage of proper frequency. The overfluxing relays with enough time lag also can be provided.

Apart from these faults, some other faults like tap-changer faults, high voltage surges due to lightning and switching, incipient faults i.e. slow developing faults may also occur in the transformers. The Buchholz relay is used for oil immersed transformers to give the protection against incipient faults.

7.3 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 $I_1 - I_2$ passes through the operating coil while the average current $(I_1 + I_2)/2$ 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 current flows 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 windings 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.T.s. Due to the different turns 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.T.s on low voltage side is made K times greater than that of C.T.s on high voltage side.

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

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

The Table 7.1 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

Table 7.1

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. 7.1 (a) and (b).

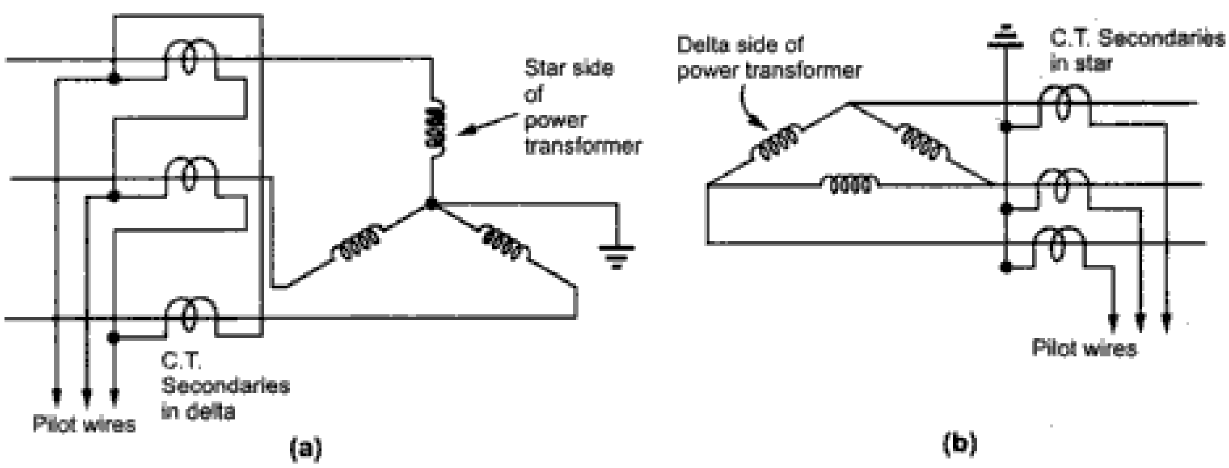


Fig. 7.1

7.3.1 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 Fig. 7.2

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.

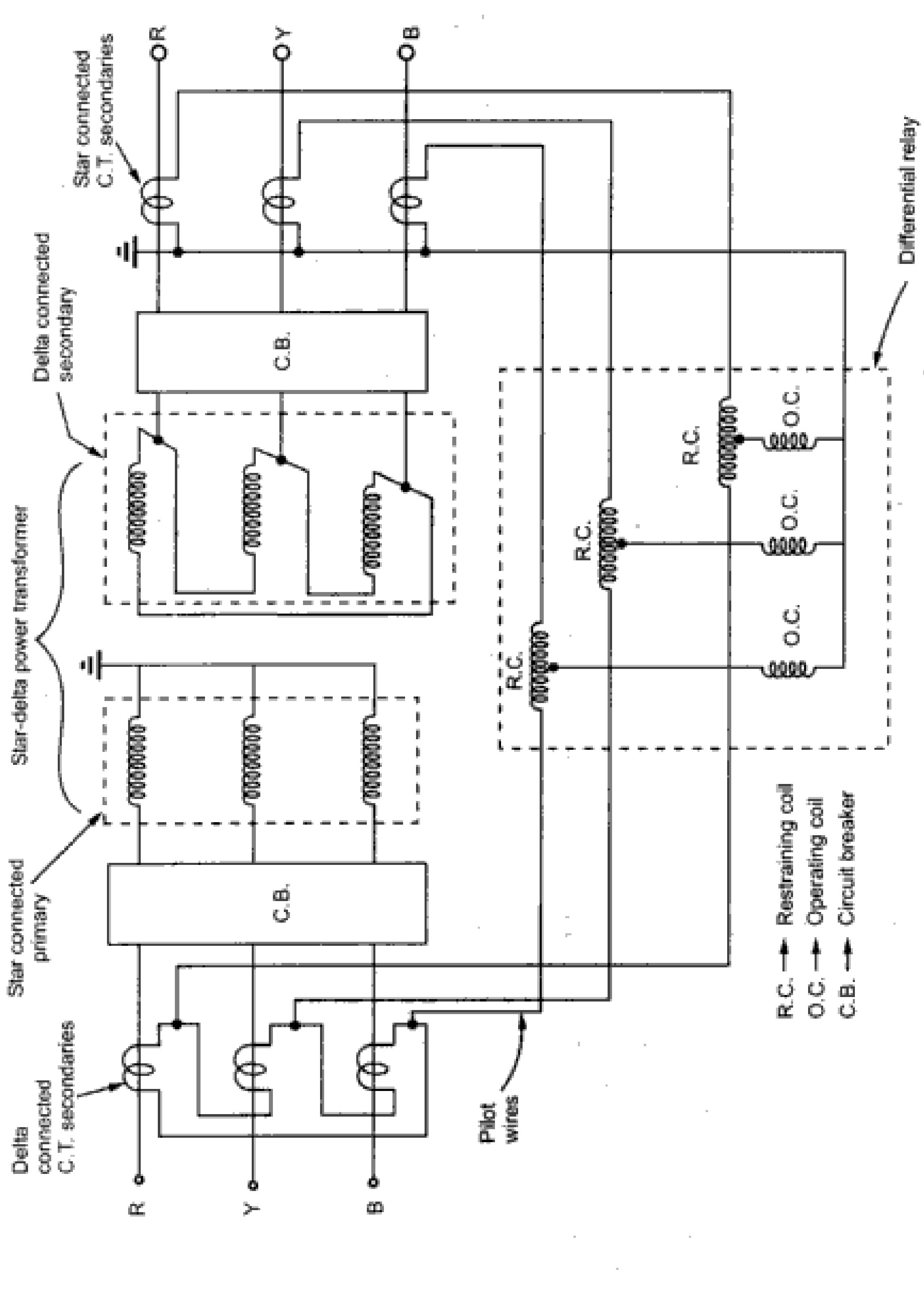


Fig. 7.2 Merz-Price protection for star-delta power transformer

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.

The basic requirements of the differential relay are,

1. The differential relay must not operate on load or external faults.

2. It must operate on severe internal faults.

The relay satisfying these requirements is used in Merz-Price protection.

It is important to note that this scheme gives protection against short circuit faults between the turns i.e. interturn faults also. This is because when there is an interturn fault, the turns ratio of power transformer gets affected. Due to this the currents on both sides of the power transformer become unbalanced. This causes an enough differential current which flows through the relay and the relay operates.

7.3.2 Merz-Price Protection for Star-Star Transformer

The Fig. 7.3 (See Fig. on next page) 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 on both the sides are connected in delta to compensate for the phase displacement.

The star points of both the windings of the power transformer are grounded. The restraining coils are connected in the C.T. secondaries. The operating coils are connected between the tappings on the restraining coil and the ground. The operation of the scheme remains same for any type of power transformer as discussed for star-delta power transformer.

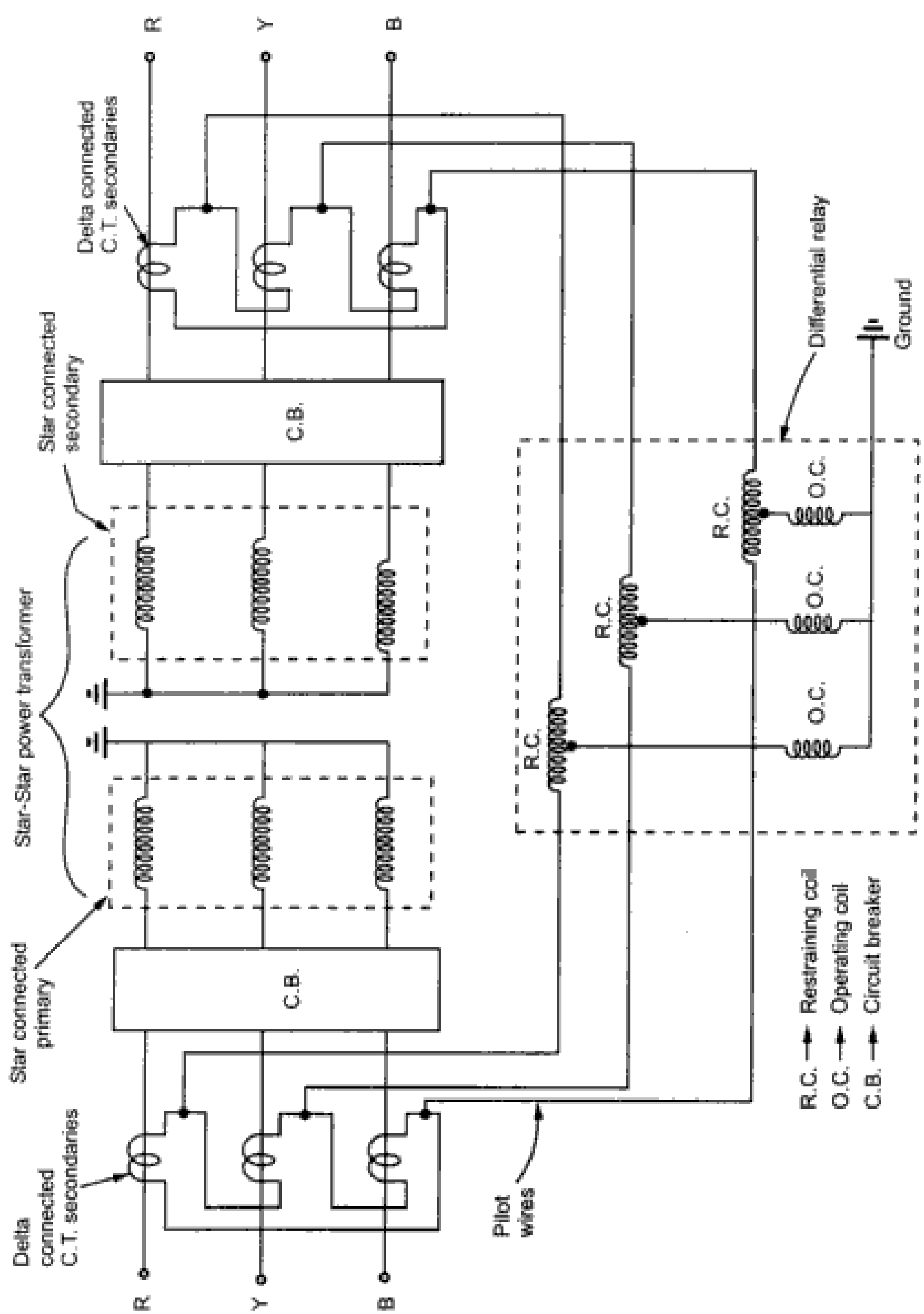


Fig. 7.3 Merz-Price protection for star-star power transformer

Example 7.1 : *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.

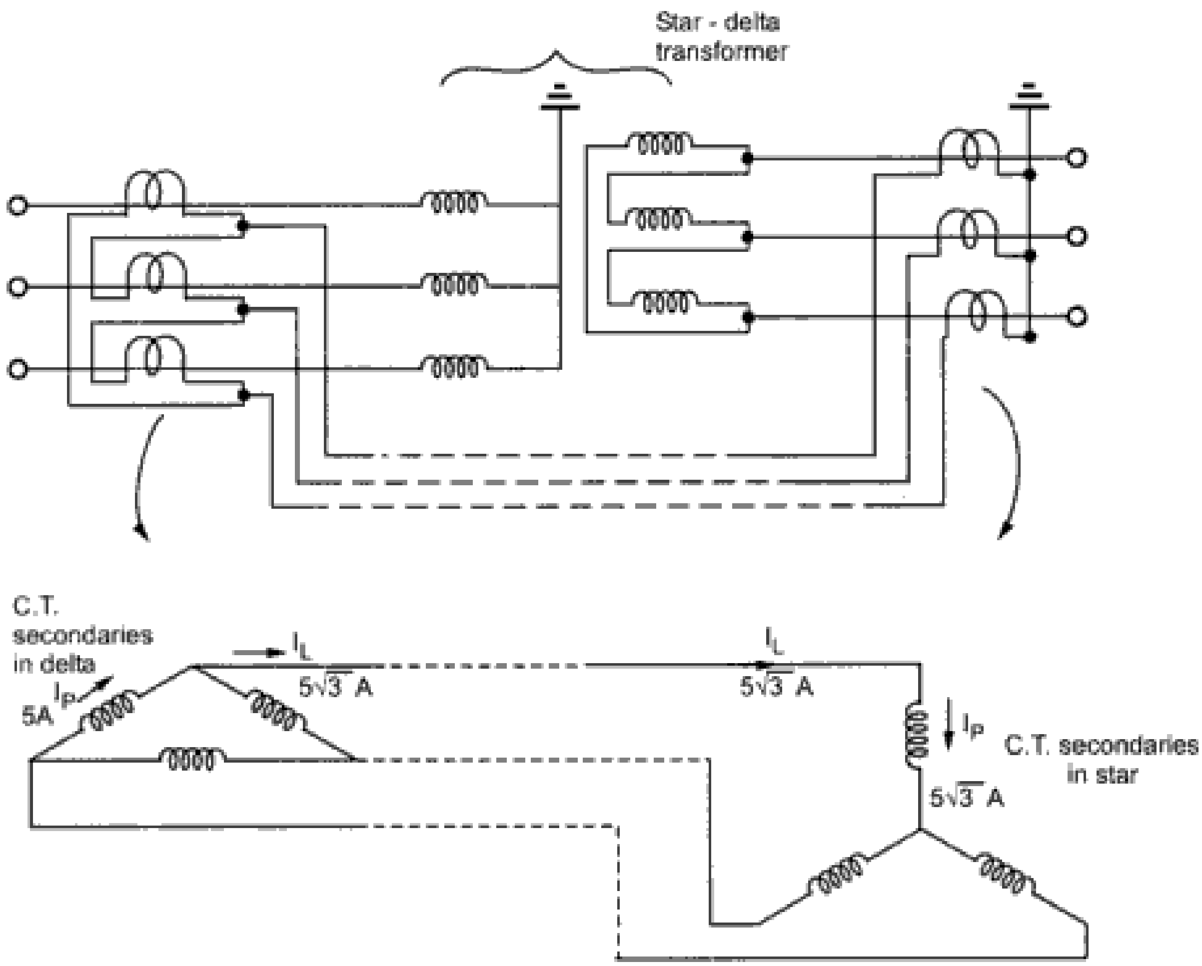


Fig. 7.4

Solution : The arrangement is shown in the Fig. 7.4.

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,

$$I_P = 1000 \times \frac{5}{1000} = 5 \text{ A}$$

This is shown in the Fig. 7.4.

$$\therefore \quad I_L = \sqrt{3}\, I_P = 5\sqrt{3} \quad \text{A}$$

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

The same current flows through the star connected C.T. secondaries. Hence each secondary 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.

$\therefore$ Primary apparent power = Secondary apparent power

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

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

$$\therefore \quad I_{L2} = \frac{400 \times 1000}{33000} = 12.12 \text{ A}$$

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

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

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

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

7.4 Problems Encountered in Differential Protection

The problems encountered in the simple differential protection are,

1. **Unmatched characteristics of C.T.s :** Though the saturation is avoided, there exists difference in the C.T. characteristics due to ratio error at high values of short circuit currents. This causes an appreciable difference in the secondary currents which can operate the relay. So the relay operates for through external faults.

   This difficulty is overcome by using percentage differential relay. In this relay, the difference in current due to ratio error exists and flows through relay coil. But at the same time the average current $(I_1 + I_2/2)$ flows through the restraining coil which produces enough restraining torque. Hence relay becomes inoperative for the through faults.

2. **Ratio change due to tap change :** To alter the voltage and current ratios between high voltage and low voltage sides of a power transformer, a tap changing equipment is used. This is an important feature of a power transformer. This equipment effectively alters the turns ratio. This causes unbalance on both sides. To compensate for this effect, the tappings can be provided on C.T.s also which are to be varied similar to the main power transformer. But this method is not practicable.

The percentage differential relays ensure the stability with respect to the amount of unbalance occurring at the extremities of the tap change range.

3. **Difference in lengths of pilot wires :** Due to the difference in lengths of the pilot wires on both sides, the unbalance condition may result. The difficulty is overcome by connecting the adjustable resistors in pilot wires on both sides.. These are called balancing resistors. With the help of these resistors equipotential points on the pilot wires can be adjusted. In percentage differential relays the taps are provided on the operating coil and restraining coil to achieve balance.

4. **Magnetizing current inrush :** When the transformer is energized, the condition initially is of zero induced e.m.f. and it is similar to the switching of an inductive circuit. Due to this the transient inrush of magnetising current flows in to the transformer. This current is called magnetizing current inrush. This current may be as great as 10 times the full load current of the transformer. This decays very slowly and is bound to operate differential protection of the transformer falsely.

The factors which affect the magnitude and direction of the magnetizing current inrush are,

a. Size of the transformer

b. Size of the power system

c. Type of magnetic material used for the core.

d. The amount of residual flux existing before energizing the transformer.

e. The method by which transformer is energized.

If the transformer is energized when the voltage wave is passing through zero, the magnetizing current inrush is maximum. At this instant, the current and flux should be maximum in highly inductive circuit. And in a half wave flux reversal must take place to attain maximum value in the other half cycles. If the residual flux exists, the required flux may be in same or opposite direction. Due to this magnetizing current inrush is less or more. If it is more, it is responsible to saturate the core which further increases its component.

This current decays rapidly for first few cycles and then decays slowly. The time constant L/R of the circuit is variable as inductance of circuit varies due to the change in permeability of the core. The losses in the circuit damp the inrush currents. Depending on the size of the transformer, the time constant of inrush current varies from 0.2 sec to 1 sec.

The waveforms of magnetizing inrush current in three phases is shown in the Fig. 7.5.

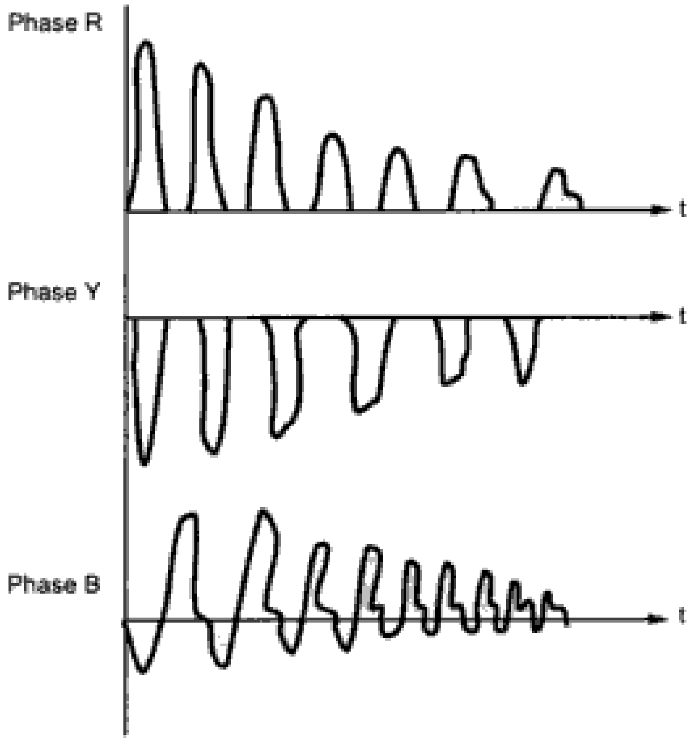


Fig. 7.5 Typical magnetizing inrush current waveforms

There are number of ways ensuring immunity from the operation by magnetizing surges. Firstly the relay may be given a setting higher than 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. But these simple remedies are inconsistent with high speed and low primary operating current.

In the latest method, the harmonic content of the magnetizing current flowing in the operating circuit is filtered out and passed through a restraining coil. This is called harmonic current restraint.

7.4.1 Harmonic Restraint and Harmonic Blocking

The high initial inrush of magnetizing currents consist of a high component of even and odd harmonics.

Table 7.2 gives the typical values of harmonic contents in a magnetizing current.

Order of harmonic content in magnetizing current	Amplitude as a % of fundamental
2^{nd}	63.0
3^{rd}	26.8
4^{th}	5.1

5^{th}	4.1
6^{th}	3.7
7^{th}	2.4

Table 7.2

The operating coil carries the fundamental component of the inrush current only. The harmonic contents and fundamental together is passed through the restraining coil.

Thus more the harmonic contents in the inrush current, more is the restraining torque and the relay does not operate. So use of percentage differential protection rather than simple differential protection is preferred. The circuit used to compensate the effect of magnetizing current using harmonic restraint method is shown in the Fig. 7.6.

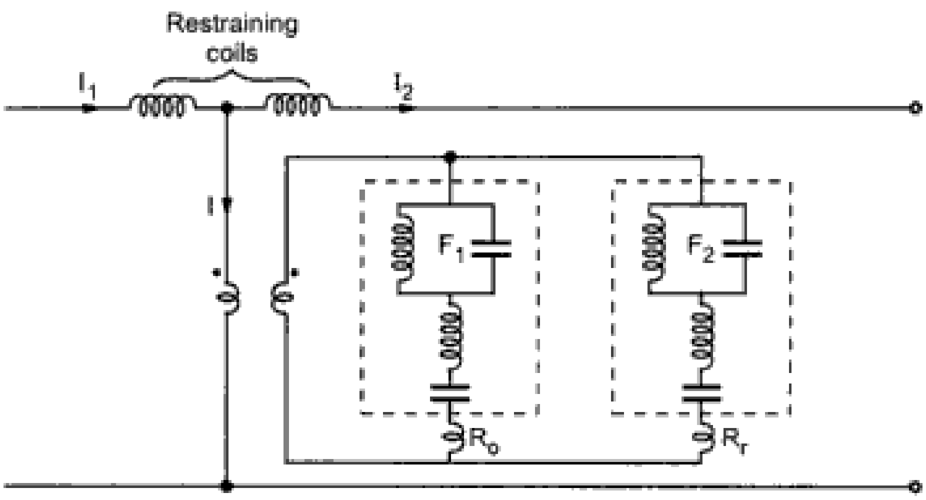


Fig. 7.6 Magnetizing current compensation

The filter F_1 is designed to pass the fundamental 50 Hz component which excites the operating coil R_o. The magnetizing current has large third harmonic component. There is an additional restraining coil R_r. The filter F_2 is designed to pass the third harmonic component which energizes the additional restraining coil R_r. The current passing through normal restraining coil and current passing through additional restraining coil R_r produce sufficient restraining torque. This compensates for the differential current resulting due to the flow of magnetizing current.

The separate blocking relay in series with the differential relay is used. The operation of this relay is based on harmonic component of inrush current. This relay consists of 100 Hz blocking filter in operating coil while 50 Hz filter in restraining coil. At the time of inrush current, second harmonic component is maximum and thus blocking relay is blocked with its contacts remain open.

In short circuit case, the harmonic component is negligible and 50 Hz component is dominant. Hence the blocking relay operates to close its contact. This principle is called **harmonic blocking**.

7.5 Frame Leakage Protection

This protection is nothing but the method of providing earth fault protection to the transformer. This protection can be provided to the metal clad switchgear.

The arrangement is shown in the Fig. 7.7.

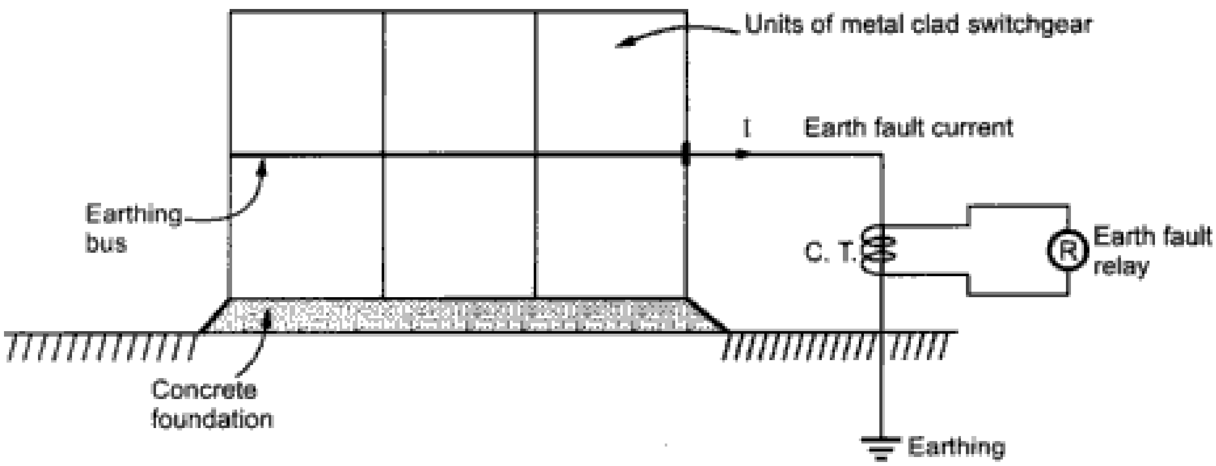


Fig. 7.7 Frame leakage protection

The metal clad switchgear is lightly insulated from the earth.

The frame of the switchgear i.e. enclosure is grounded. This is done through a primary of current transformer in between.

The concrete foundation of switchgear and the other equipments are lightly insulated from the ground. The resistance of these equipments with earth is about 12 ohms.

When there is an earth fault, then fault current leaks from the frame and passes through the earth connection provided. Thus the primary of C.T. senses the current due to which current passes through the sensitive earth fault relay. This operates the relay.

Such a protection is provided only for small transformers. For the large transformers, the differential protection is enough to sense and operate for the earth faults.

7.6 Buchholz Relay

The Buchholz relay is a gas operated relay used for the protection of oil immersed transformers against all the types of internal faults. It is named after its inventor, Buchholz. The slow developing faults called incipient faults in the transformer tank below oil level operate Buchholz relay which gives an alarm. If the faults are severe it disconnects the transformer from the supply.

It uses the principle that due to the faults, oil in the tank decomposes, generating the gases. The 70% component of such gases is hydrogen which is light and hence rises upwards towards conservator through the pipe. Buchholz relay is connected in the pipe, as shown in the Fig. 7.8. Due to the gas collected in the upper portion of the Buchholz relay, the relay operates and gives an alarm.

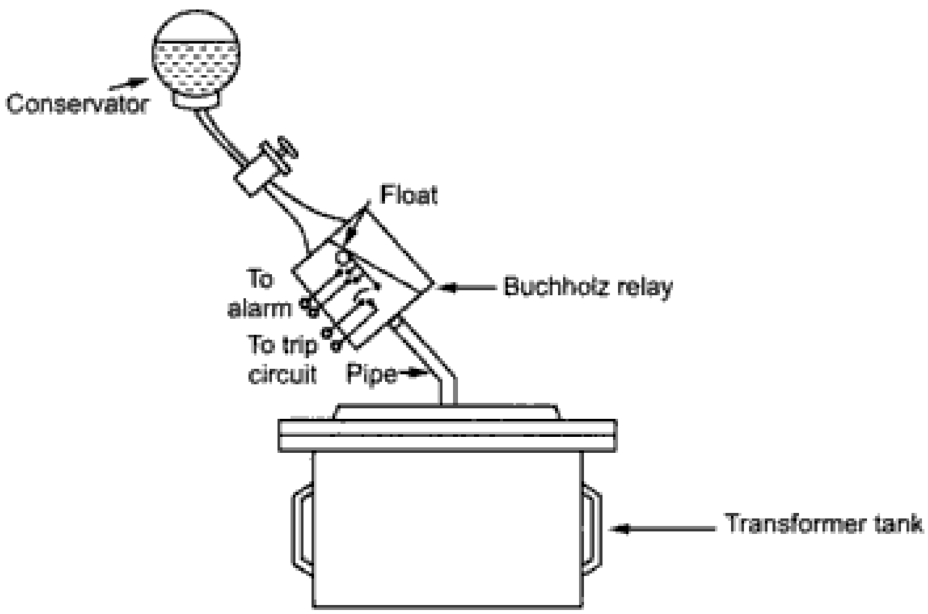


Fig. 7.8 Basic arrangement of Buchholz relay

The constructional features of Buchholz relay are shown in the Fig. 7.9.

(See Fig. 7.9 on next page.)

Under normal conditions, the Buchholz relay is full of oil. It consists of a cast housing containing a hinged hollow float. A mercury switch is attached to a float. The float being rotated in the upper part of the housing. Another hinged flap valve is located in the lower part which is directly in the path of the oil between tank and the conservator. Another mercury switch is attached to a flap valve. The float closes the alarm circuit while the lower flap valve closes the trip circuit in case of internal fault.

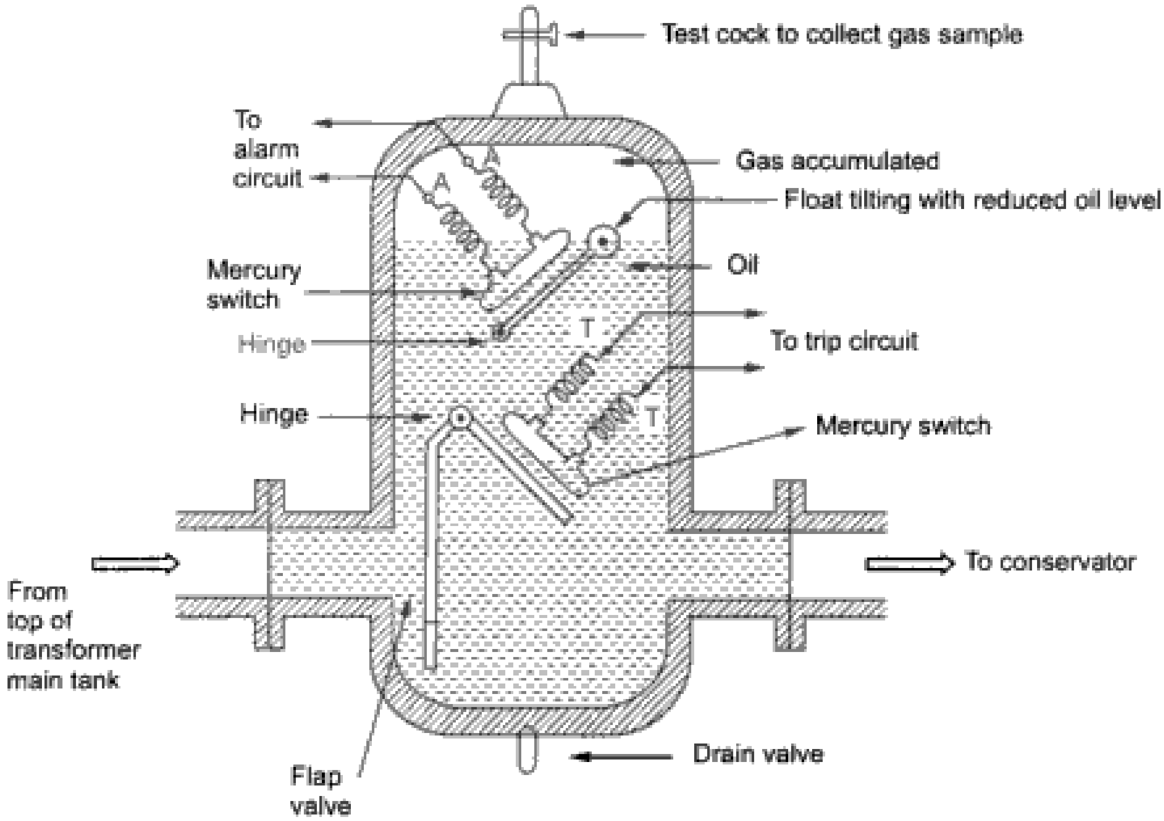


Fig. 7.9 Construction of Buchholz relay

7.6.1 Operation

There are many types of internal faults such as insulation fault, core heating, bad switch contacts, faulty joints etc. which can occur. When the fault occurs the decomposition of oil in the main tank starts due to which the gases are generated. As mentioned earlier, major component of such gases is hydrogen. The hydrogen tries to rise up towards conservator but in its path it gets accumulated in the upper part of the Buchholz relay. Through passage of the gas is prevented by the flap valve.

When gas gets accumulated in the upper part of housing, The oil level inside the housing falls. Due to which the hollow float tilts and close the contacts of the mercury switch attached to it. This completes the alarm circuit to sound an alarm. Due to this operator knows that there is some incipient fault in the transformer. The transformer is disconnected and the gas sample is tested. The testing results give the indication, what type of fault is started developing in the transformer. Hence transformer can be disconnected before fault grows into a serious one. The alarm circuit does not immediately disconnects the transformer but gives only indication to the operator. This is because some times bubbles in the oil circulating system may operate the alarm circuit through actually there is no fault.

However if a serious fault such as internal short circuit between phases, earth fault inside the tank etc. occurs then the considerable amount of gas gets generated. Thus due to fast reduce level of oil, the pressure in the tank increases. Due to this the oil rushes towards the conservator. While doing so it passes though the relay where flap valve is present. The flap valve gets deflected due to the rushing oil. Due to this the mercury switch contacts get closed. This energizes the trip circuit which opens the circuit breaker. Thus transformer is totally disconnected from the supply.

The connecting pipe between the tank and the conservator should be as straight as possible and should slope upwards conservator at a small angle from the horizontal. This angle should be between 10 to 11°.

For the economic considerations, Buchholz relays are not provided for the transformers having rating below 500 kVA.

7.6.2 Advantages

The various advantages of the Buchholz relay are,

1. Normally a protective relay does not indicate the appearance of the fault. It operates when fault occurs. But Buchholz relay gives an indication of the fault at very early stage, by anticipating the fault and operating the alarm circuit. Thus the transformer can be taken out of service before any type of serious damage occurs.
2. It is the simplest protection in case of transformers.

7.6.3 Limitations

The various limitations of the Buchholz relay are,

1. Can be used only for oil immersed transformers having conservator tanks.
2. Only faults below oil level are detected.
3. Setting of the mercury switches can not be kept too sensitive otherwise the relay can operate due to bubbles, vibration, earthquakes mechanical shocks etc.
4. The relay is slow to operate having minimum operating time of 0.1 seconds and average time of 0.2 seconds.

7.6.4 Applications

The following types of **transformer** faults can be protected by the Buchholz relay and are indicated by alarm :

1. Local overheating
2. Entrance of air bubbles in oil
3. Core bolt insulation failure

4. Short circuited laminations
5. Loss of oil and reduction in oil level due to leakage
6. Bad and loose electrical contacts
7. Short circuit between phases
8. Winding short circuit
9. Bushing puncture
10. Winding earth faults.

Examples with Solutions

Example 7.2 : *A 11 kV/132 kV power transformer is connected in delta-star. The C.T.s on the low voltage side have turns ratio of 600/5. Find the suitable turns ratio for the C.T.s on high voltage side.*

Solution : The connections are shown in the Fig. 7.10.

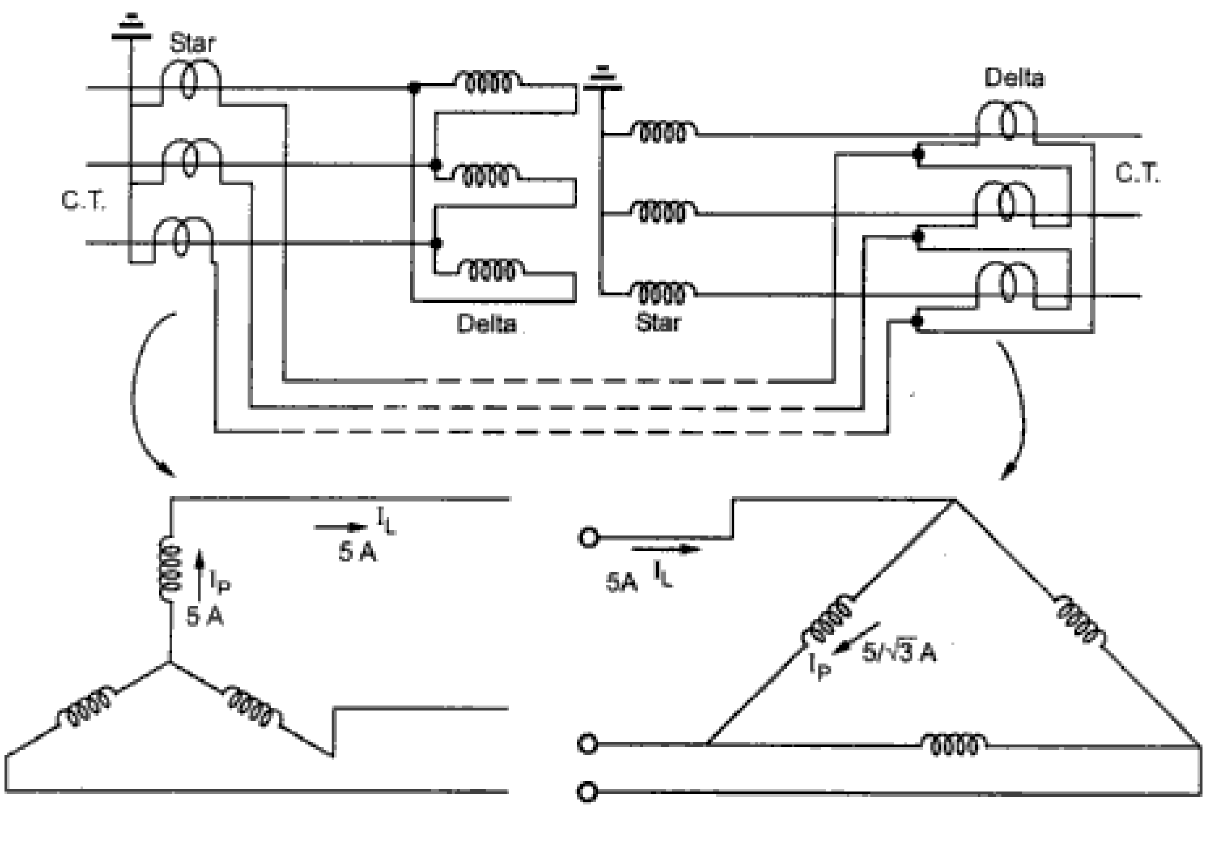


Fig. 7.10

Let the current on the primary i.e. low voltage side of power transformer be 600 A.

This current will flow through each line on primary of transformer.

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

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

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

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

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

Now apparent power on both sides is same,

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

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

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

$$= 50 \text{ A}$$

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

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

$$= 17.32 : 1$$

Example 7.3 : *A 3 phase, 200 kVA, 11 kV/400 V transformer is connected in delta-star. The C.T.s on low voltage side have turns ratio of 500/5. Determine the C.T. ratio on high voltage side. Also obtain the circulating current when the fault of 750 A of following types occur on the low voltage side :*

i) Earth fault within the protective zone

ii) Earth fault outside the protective zone

iii) Phase to phase fault within the protective zone

iv) Phase to phase fault outside the protective zone

Assume balanced voltage.

Solution : The connections are shown in the Fig. 7.11.

On primary which is delta connected, C.T.s are connected in star while

On secondary which is star connected, C.T.s are connected in delta.

Let current on low voltage side be 500 A.

$$\text{Now} \qquad I_{L2} = 500 \text{ A}$$

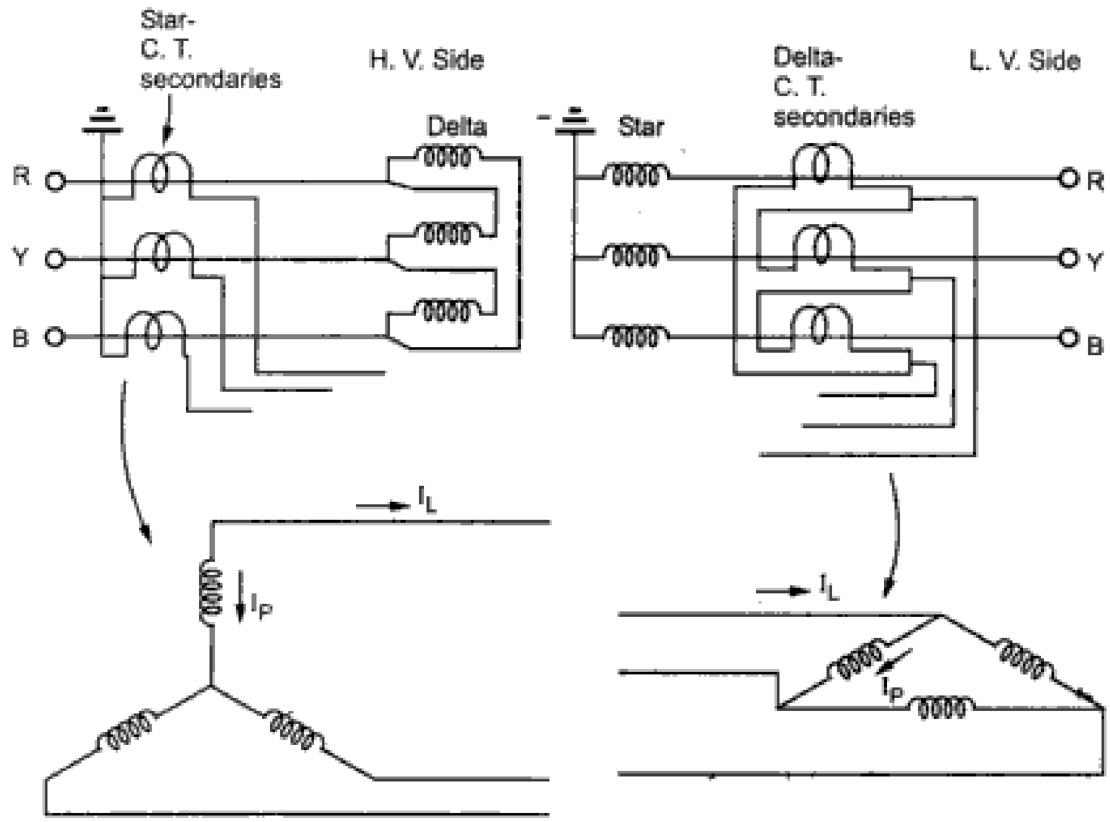


Fig. 7.11

C.T. ratio 500/5

$\therefore$ Current through primary of C.T. on low voltage side

$$= I_{L2} = 500 \text{ A}$$

$\therefore$ I_P = Current through each secondary of delta connected C.T.s

$$= 500 \times \frac{5}{500} = 5 \text{ A}$$

$\therefore$ I_L = Line current through pilot wires

$$= \sqrt{3}\, I_P$$

$$= 5\sqrt{3} \text{ A}$$

Same is the current through each secondary of star connected C.T. on high voltage side.

$\therefore$ $I_P = 5\sqrt{3}$ A on h.v. side C.T. secondaries

Apparent power on both sides of transformers is same.

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

$$\therefore \quad \sqrt{3} \times 11000 \times I_{L1} = \sqrt{3} \times 400 \times 500$$

$$\therefore \quad I_{L1} = \frac{400 \times 500}{11000}$$

$$= 18.18 \text{ A}$$

This is current through each primary of C.T.s connected in star.

$\therefore$ Current ratio of C.T.s on high voltage side

$$= \frac{18.18}{5\sqrt{3}}$$

$$= 2.099 : 1$$

(i) Consider the earth fault within the protective zone as shown in the Fig. 7.12.

(See Fig. 7.12 on next page.)

Now $I_{L2} = 750$ A

Equating apparent power,

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

$$\therefore \quad \sqrt{3} \times 11000 \times I_{L1} = \sqrt{3} \times 400 \times 750$$

$$\therefore \quad I_{L1} = 27.27 \text{ A}$$

This is the line current on h.v. side under fault condition.

The C.T. ratio is 2.099 : 1. Hence corresponding current through C.T. secondary on h.v. side is, $= 27.27 \times \frac{1}{2.099} = 12.99$ A

So 12.99 A current will flow through the relay and relay will operate.

(ii) Consider the earth fault outside the protective zone as shown in the Fig. 7.13. The line current on secondary is 750 A.

$$\therefore \quad \text{Secondary C.T. current} = 750 \times \frac{5}{500}$$

$$= 7.5 \text{ A}$$

$$\therefore \quad \text{Current in pilot wires} = 7.5 \times \sqrt{3} = 12.99 \text{ A} \quad \text{as delta connected}$$

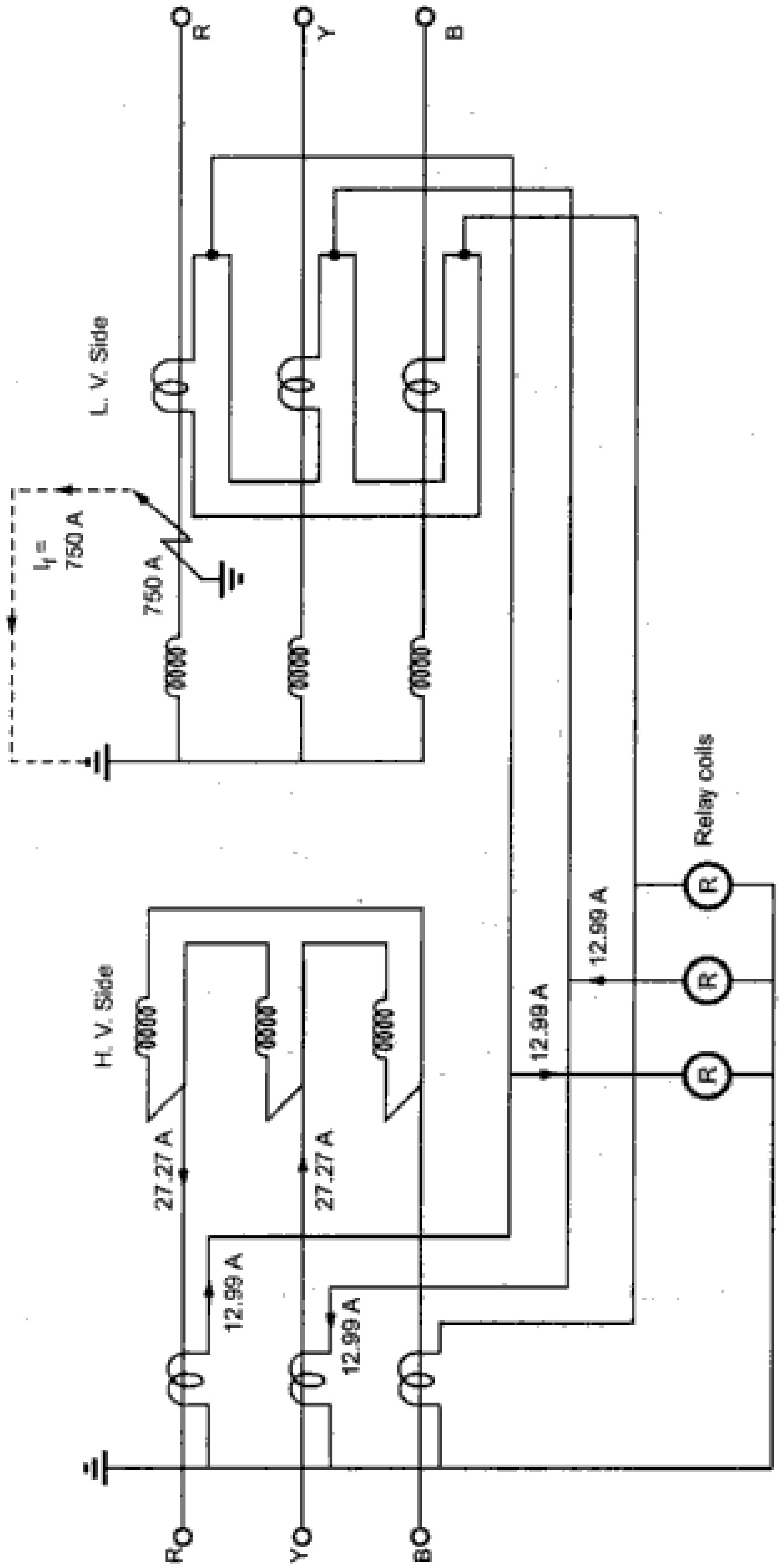

R
Y
B
L. V. Side
I_f = 750 A
750 A
H. V. Side
27.27 A
27.27 A
12.99 A
12.99 A
12.99 A
12.99 A
R
R
R
Relay coils

Fig. 7.12

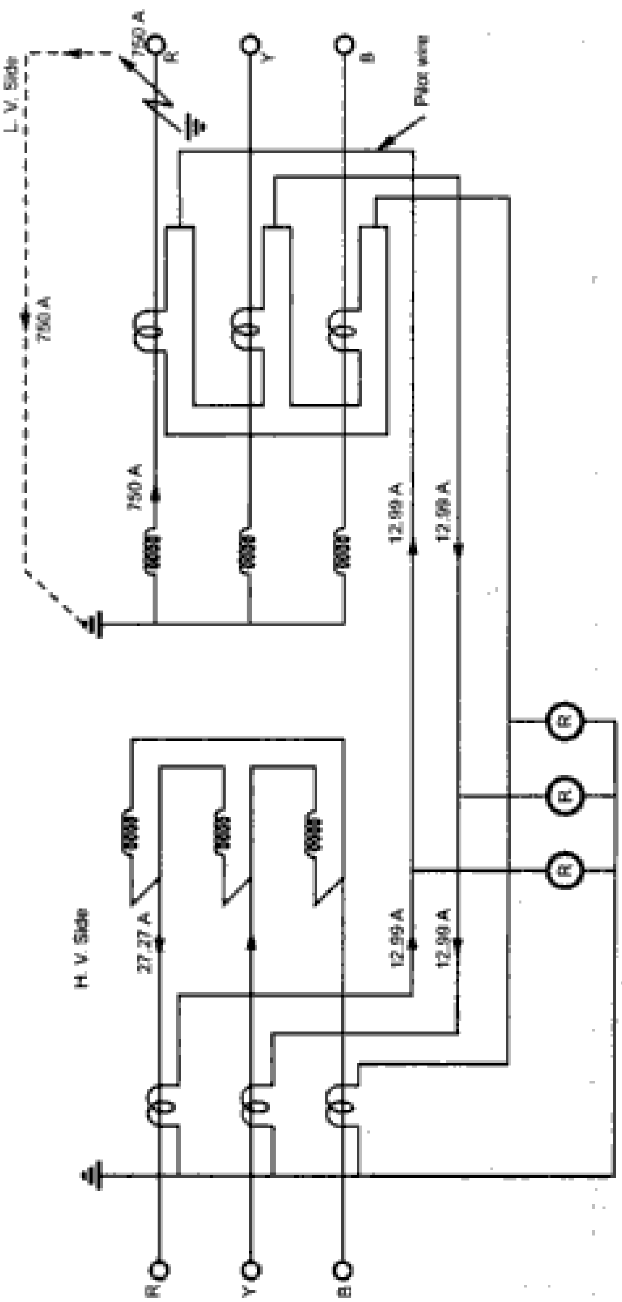


Fig. 7.13

The currents are shown in the Fig. 7.13.

So on both sides the current is balanced hence no current will flow through the relay and relay will not operate.

iii) Phase to phase fault in the protected zone on low voltage side. This is shown in the Fig. 7.14.

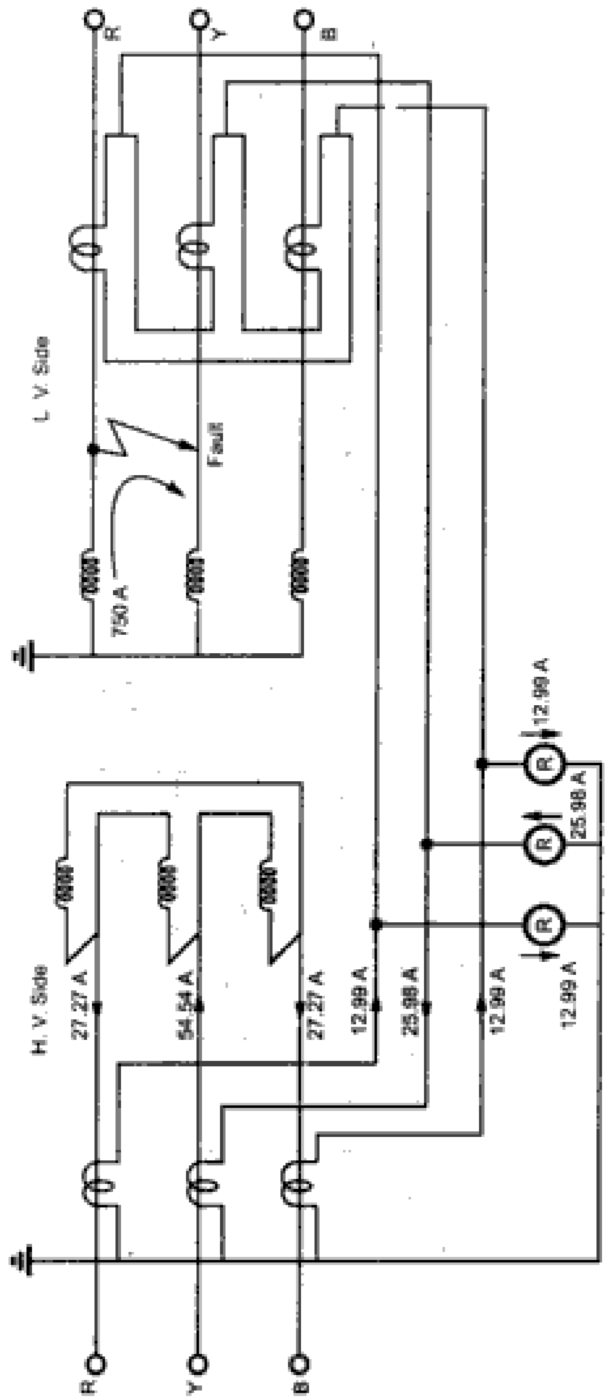


Fig. 7.14

Due to such fault current will flow in two phases of low voltage winding but in all three phases in high voltage winding as shown in the Fig. 7.14. This current on high voltage side will flow through the relay and relay will operate.

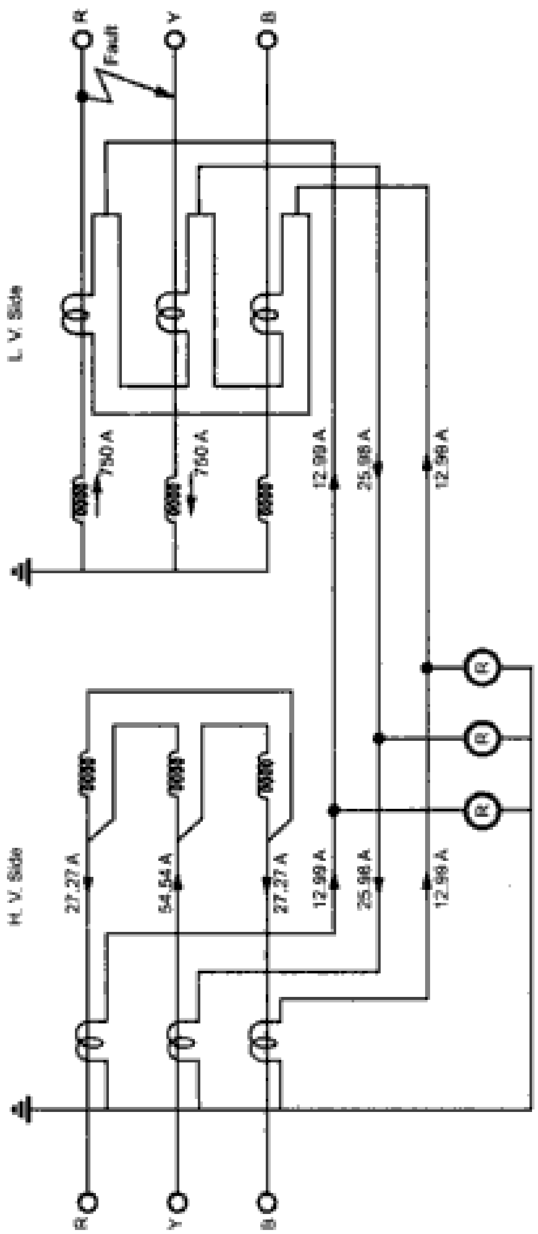


Fig. 7.15

iv) Consider phase to phase fault outside the protected zone as shown in the Fig. 7.15. The various currents and corresponding distribution is also shown in the Fig. 7.15.

As the currents on both sides are balanced, no current flows through the relay hence relay will not operate.

Example 7.4 : *A 3 phase transformer rated for 33 kV/6.6 kV is connected star/delta and the protecting current transformers on the low voltage side have a ratio of 400/5. Determine the ratio of the current transformers on H.V. side. Draw the connection diagram showing how the relay operates under fault conditions.*

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

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

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

Now primary apparent power = secondary apparent power

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

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

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

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

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

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

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

The connection diagram is shown in the Fig. 7.16.

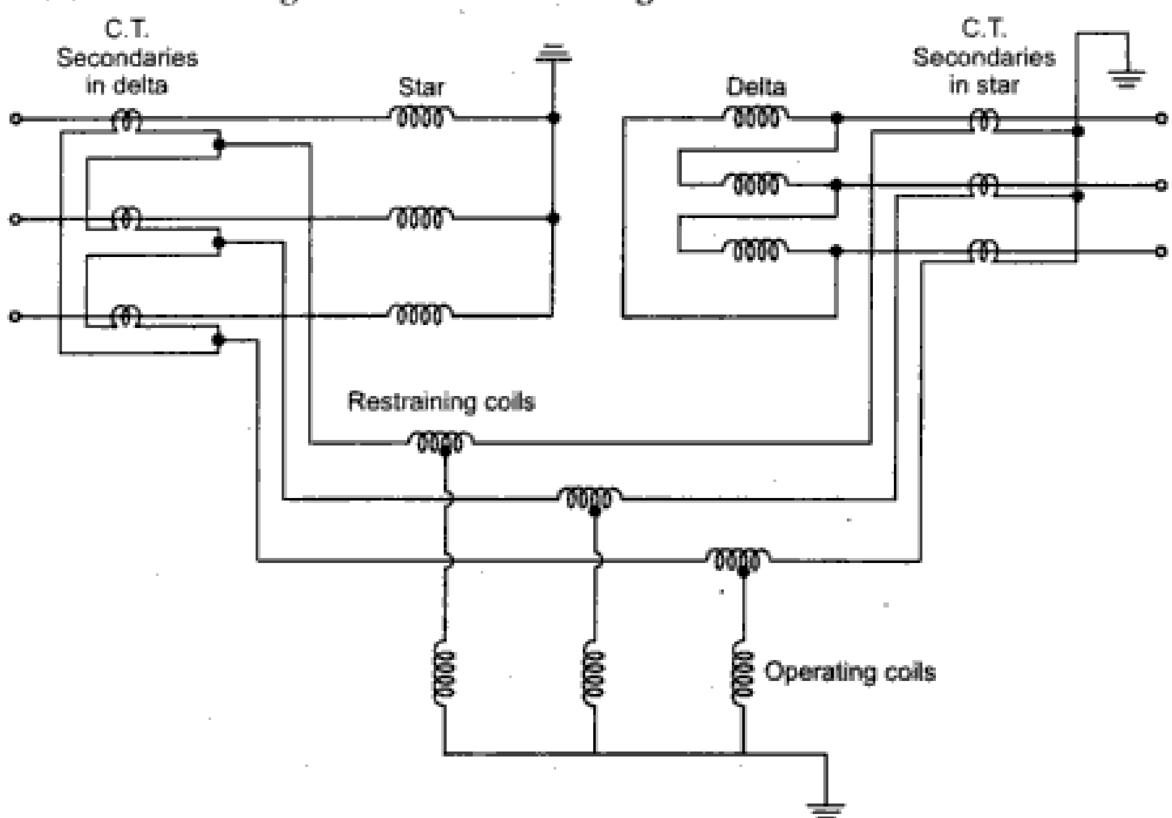


Fig. 7.16

Example 7.5 : *A 3-phase transformer having line voltage ratio of 440 V/11 kV is connected in star/Delta. The protection transformer on the LV side have a current ratio of 500/5. What must be the ratio of the protection transformer connected on HV side ?*

(AU-April-2005)

Solution : The arrangement is shown in the Fig. 7.17

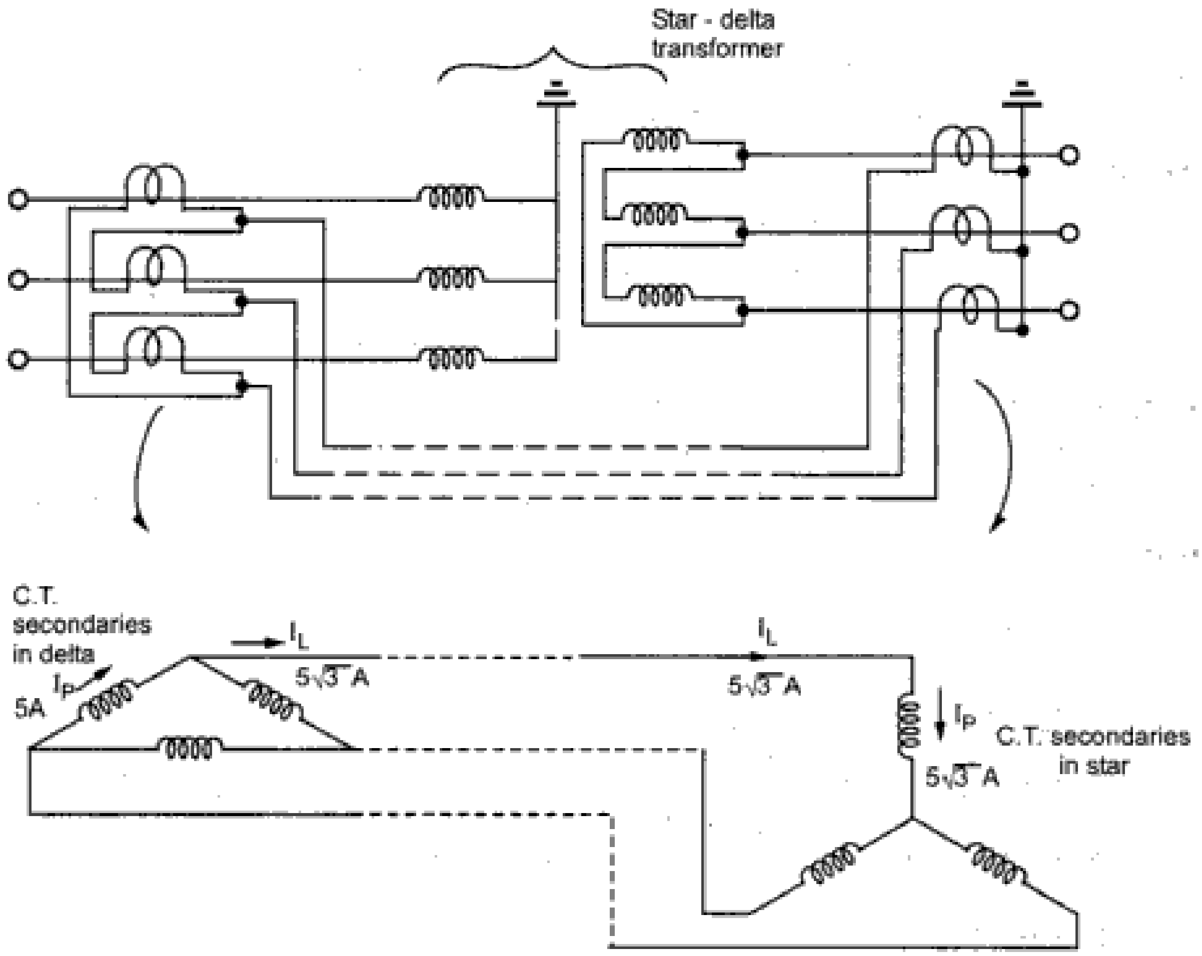


Fig. 7.17

On primary side which is 440 V side, let the current be 500 A.

Thus C.T.s will carry the current of 500 A.

The C.T. ratio is 500/5 A hence secondary phase current of C.T.s on primary side is,

$$I_p = \frac{5}{500} \times 500 = 5A$$

$\therefore$ $I_L = \sqrt{3} \quad I_p = 5\sqrt{3}$ A ... Delta connected C.T.s

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

The apparent power on both sides must be same :

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

$$\therefore \quad \sqrt{3} \times 440 \times 500 = \sqrt{3} \times 11 \times 10^3 \times I_{L2}$$

$$\therefore \quad I_{L2} = 20 \text{ A}$$

Thus each primary of C.T.s connected in star on H.V. side carries a current of 20 A while each secondary carries current of $5\sqrt{3}$ A.

Hence the C.T. ratio on 11 kV side is,

$$= \frac{\text{Primary current}}{\text{Secondary current}} = \frac{20}{5\sqrt{3}}$$

$$= 2.309 : 1 \qquad \text{... Required C.T. ratio on H.V. side}$$

➡ **Example 7.6 :** *A 3 phase 500 kVA, 11 kV/0.4 kV transformer is connected in Delta/star. The protection transformer on the LV side have turns ratio of 500/5. What will be the C.T. ratio on the HV side of the transformer ?* **(AU-Dec.-2005)**

Solution : The connections are shown in the Fig. 7.18.

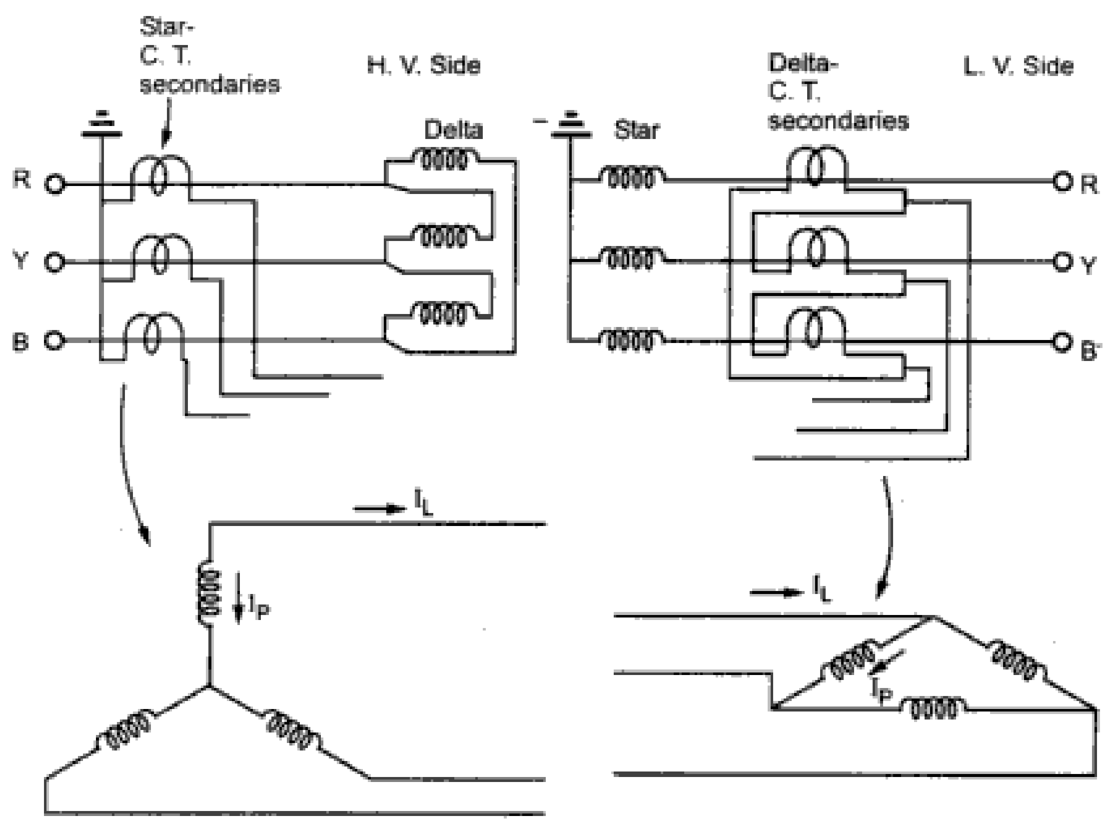


Fig. 7.18

5. *State the problems encountered in a simple differential protection of transformers.*
6. *Write a notes on,*
   i) Magnetic current in rush
   ii) Harmonic restraint and harmonic blocking
   iii) Frame leakage protection
7. *Draw and explain the construction and working of Buchholz relay. Against which faults Buchholz relay gives the protection ? State its advantages and disadvantages.*
8. *Describe with the help of a neat diagram the connections of differential protection of a transformer. A 3-phase 33/6.6 kV star/delta connected transformer is protected by differential system. The C.T.'s on LT side have ratio of 300/5. Show that the C.T.s on HT side will have a ratio 60 : $5\sqrt{3}$.*
9. *A 3 phase transformer of 220/11,000 line volts is connected in star/delta. The protective transformers on 220 V side have a current ratio of 600/5. What should be C.T. ratio on 11,000 V side ?* **(Ans. : 1.385 : 1)**
10. *A 3-phase, 220/11000 V transformer is connected in star-delta and the protective transformers on the 220 V sides have a current ratio of 600/$\frac{5}{\sqrt{3}}$. What must be the ratio of the C.T.s on the 11,000 V side and how shall they be connected ?* **(Ans. : 12 : 5)**
11. *A three phase 66 kV/11 kV power transformer is connected in star/delta. The transformer is protected by Merz-Price circulating current system. Protecting current transformers on the low voltage side have a ratio of 250/5. Find the ratio of the current transformers on high voltage side.* **(Ans. : 14.1 : 1)**
12. *A three phase power transformer has a voltage ratio of 33/6.6 kV and is star delta connected. The protective C.T.s on the 6.6 kV side have a current ratio of 100. What must be the ratio of protective C.T.s on the 33 kV side ?* **(Ans. : 35 : 1)**

❑❑❑

8 Carrier Aided Protection and Static Relays

8.1 Block Schematic of Carrier Aided Protection

Carrier aided protection is used for the protection of transmission lines. The carrier currents with high frequency range are transmitted and received with the help of transmission lines for protection. The schematic representation of carrier current protection is shown in the Fig. 8.1.

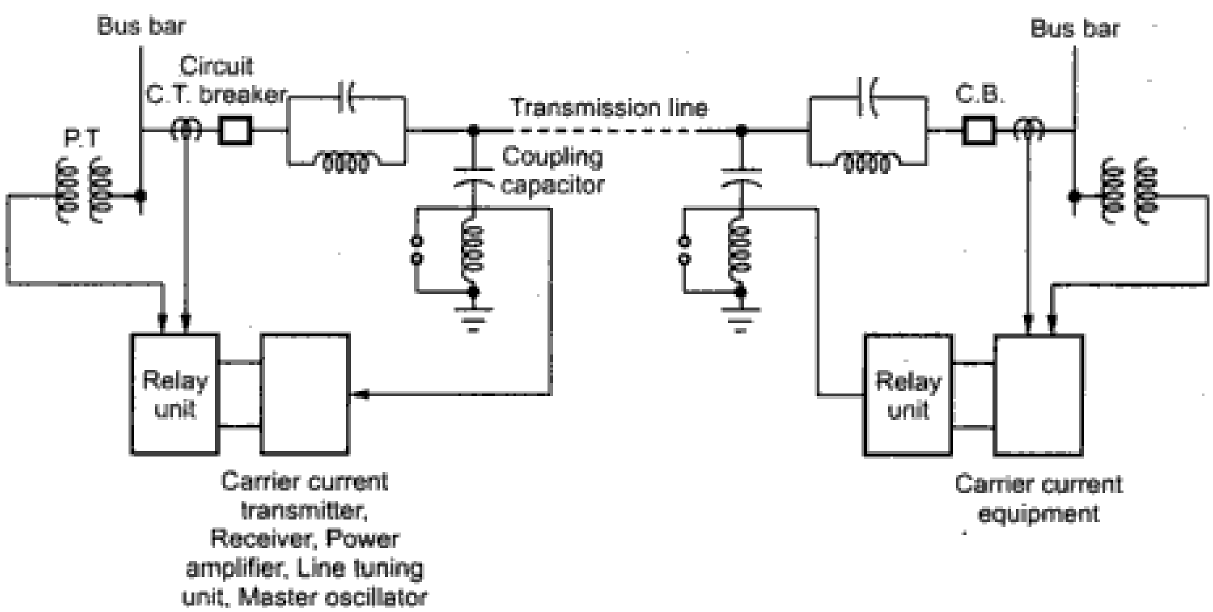


Fig. 8.1 Schematic of carrier current protection

The identical carrier equipments which include transmitter, receiver, line tuning unit, master oscillator, power amplifier etc. are provided at each end of the transmission line. The description of various blocks in the schematic representation is given below.

1. Coupling capacitor

The various carrier equipments described above are connected to the transmission line with the help of coupling capacitor. The capacitive reactance is given by $\frac{1}{\omega C}$. Hence for carrier frequency it offers less reactance while high reactance for normal power frequency. It can be seen that the carrier current signals are allowed to pass through this capacitor and enter in carrier equipment while power frequency currents are blocked. The inductance connected in series with the coupling capacitor reduces the impedance to further low value. Thus a condition of resonance is achieved at carrier frequency.

2. Line Trap Unit

This unit is between the busbar and the connection of coupling capacitor to the line. It consists of parallel combination of inductance (L) and capacitance (C) acting as tuned circuit. This circuit offers low impedance to power frequency currents while offers very high impedance to carrier frequency currents which prevents the high frequency carrier to enter in the neighbouring line and carrier currents flow only in the protected line.

3. Protection and Earthing of Coupling Equipment

Due to lightning, switching transients or faults, overvoltage surges are produced on the transmission lines. These overvoltages may produce stress on coupling equipment and line trap unit. For protection purpose, the nonlinear resistors are connected across line trap unit in series with a protective gap. These resistors with protective gap is connected across inductor in the coupling unit. The length of the gap is adjusted in such a way that, spark over takes place at a set value of overvoltage. The earth rod is used is for earthing of coupling unit so as to get low resistance earth path. The relay room consists of carrier equipment panel which is connected to station earthing system.

4. Electronic Equipments

Following electronic equipments are generally used at each end of the line,

a) Transmitter unit

b) Receiver unit

c) Relay unit

a) Transmitter Unit :

The general representation of power line carrier equipments is shown in the Fig. 8.2.

Normally the frequencies with range from 50 to 500 kHz are employed in various frequency bands with each has specific bandwidth. The oscillator is used for the generation of carrier frequency and it is tuned for a particular frequency which is chosen for particular application. Sometimes a crystal oscillator may also be used which gives particular bandwidth after selecting particular type of crystal. Voltage stabilizers are employed for maintaining the oscillator output voltage constant. The losses in the transmission path between transmitter and receiver at remote end of line

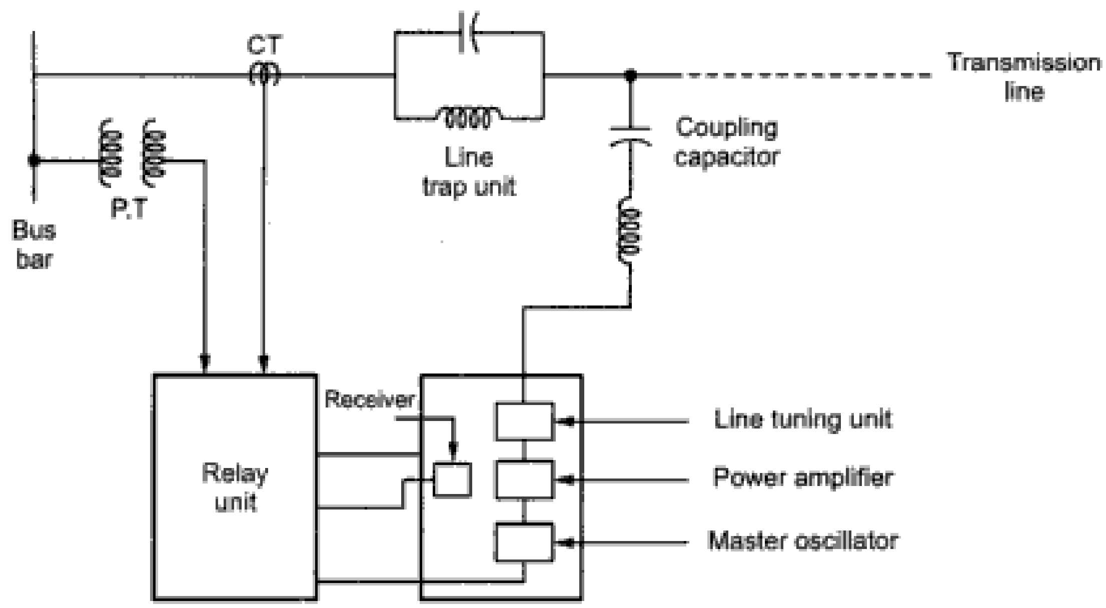


Fig. 8.2 Representation of carrier current protection unit

are overcome with the help of amplifier which increases the level of the signal to be transmitted.

The attenuation in signal is due to losses in coupling equipment which are constant for given frequency range. Depending on length of line, frequency whether conditions and the size and type of line, the line losses vary.

If weather is fairly reasonable then the attenuation is of the order of 0.1 dB/kHz at 80 kHz which increases 0.2 dB/km at 380 kHz. If we consider 250 km line then the output of power amplifier is about 20 W. For a particular bandwidth the amplifier should give maximum power. Depending on the type of protection required, various methods are adopted for the control of transmitter. The interconnection between oscillator and amplifier is done through control circuit. The block diagram representation of transmitting unit is shown in the Fig. 8.3 (a).

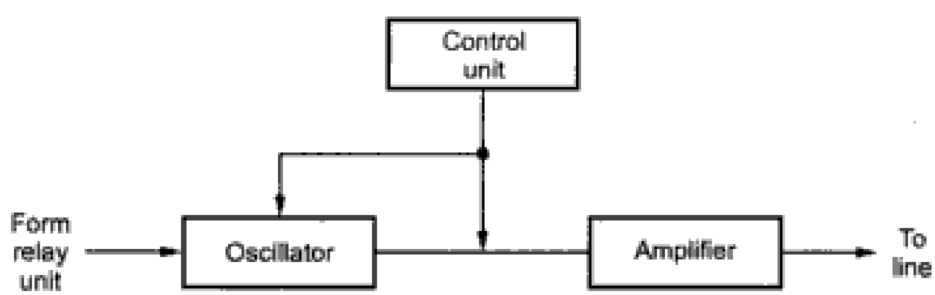


Fig. 8.3 (a) Transmitting unit

b) Receiving Unit :

The block schematic of receiving unit is shown in the Fig. 8.3 (b).

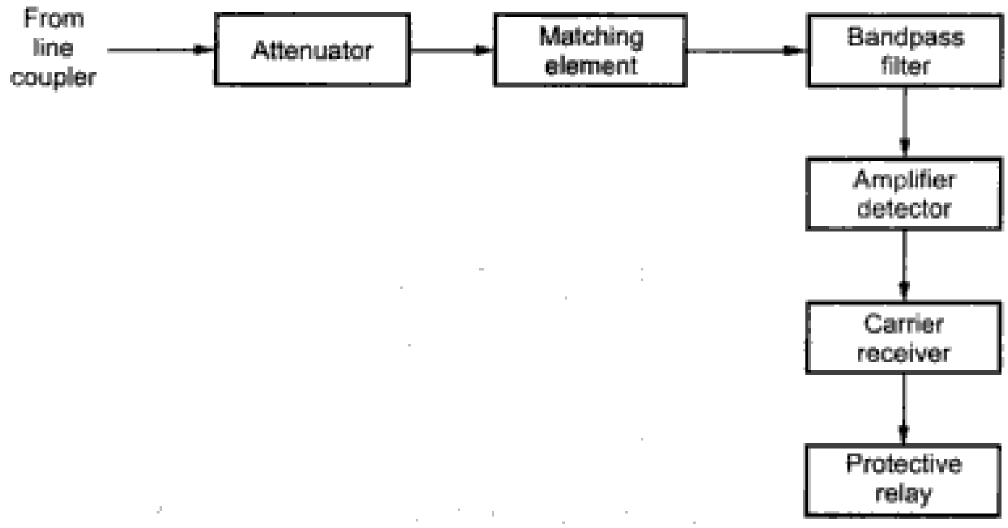


Fig. 8.3 (b) Receiving unit

The signal is reduced to a safe value with the help of attenuator. The undesired signals which are signals from subsequent sections or spurious signals are prevented by using band pass filter. The matching element matches the impedance of the transmission line and receiving section. The undesired signals are generated either by short circuits or radio interferences. The malfunctioning of this unit is avoided due to the noise signals by using the set value above 2 milliwatts which is above noise level. If the carrier signals have power level of 20 W and receiver unit is set at higher level of 5 milliwatts then the operation is unaffected by spurious signals. For avoiding the overloading, the signals should be attenuated before applying it to the amplifier detector.

c) Frequency Spacing : The subsequent line sections use various frequencies. The carrier signals are prevented from entering into next section by wave traps. The filters from receiving unit filters other frequencies. The frequency bands of various sections are properly co-ordinated.

d) High Frequency Signal Modulation

For modulation of power frequency signals, the modulator is used. The signal after modulation is passed to the amplifier and then transmitted through coupling unit. From the half cycle line currents, the required blocks of carrier signals are generated with the help of oscillator. The level of line current at which oscillator generates these carrier blocks should be theoretically constant but practically there is critical minimum current. The modulation of line current into high frequency carriers is shown in the Fig. 8.4.

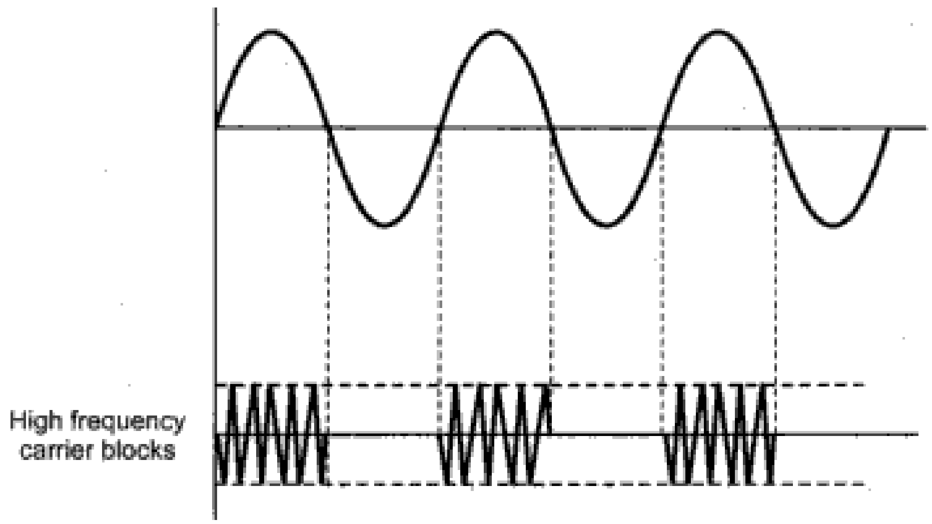


Fig. 8.4 Modulation of line current

8.2 Phase Comparison Method of Carrier Current Protection

There are various methods of carrier current protection. Some of them are as given below :

1. Directional comparison method
2. Phase comparison method

The block diagram of the phase comparison method is shown in the Fig. 8.5.

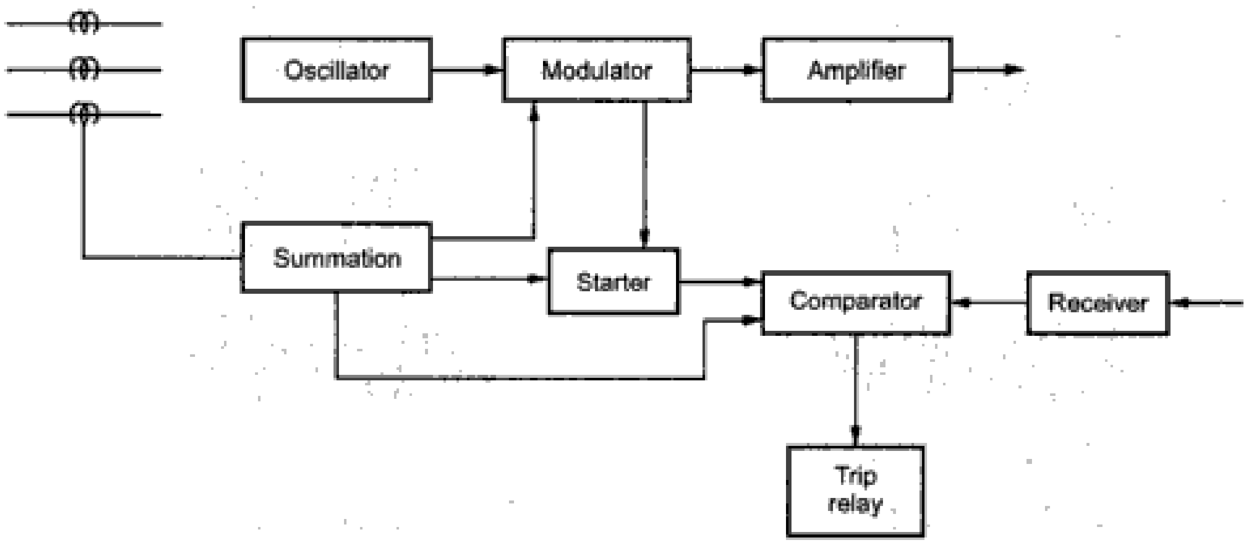


Fig. 8.5 Block diagram of phase comparison method

In this method, the phase relation between the current entering in the protected zone and current leaving the protected zone is compared without comparison of magnitudes of currents. It does not provide back up protection which is to be additionally provided but it acts as main protection.

In this method the signals are sent from each end of the line while they are received at the other end. The signals are obtained from C.T. secondaries and are related to the current flow in the main line.

In the absence of any fault on the line, the signal is sent for alternate half cycles from each end resulting in continuous signal on the line. For external fault the same condition holds good. If there is an internal fault, the current in one of the lines reverses in phase and remains below fault detector setting resulting in sending the carrier only for half the time. The relay is arranged to sense the absence of signal in the line. When the phase angle between the two signals reaches to a certain set value, the tripping occurs.

For internal fault condition, the transmitted signals and received signals are almost in phase with each other. The comparator compares these signals. For alternate half cycles, the signal is absent so the comparator gives output which operates to trip relay. Various signals in primary circuit, secondary circuit transmitter, receiver comparator during external fault are shown in the Fig. 8.6.

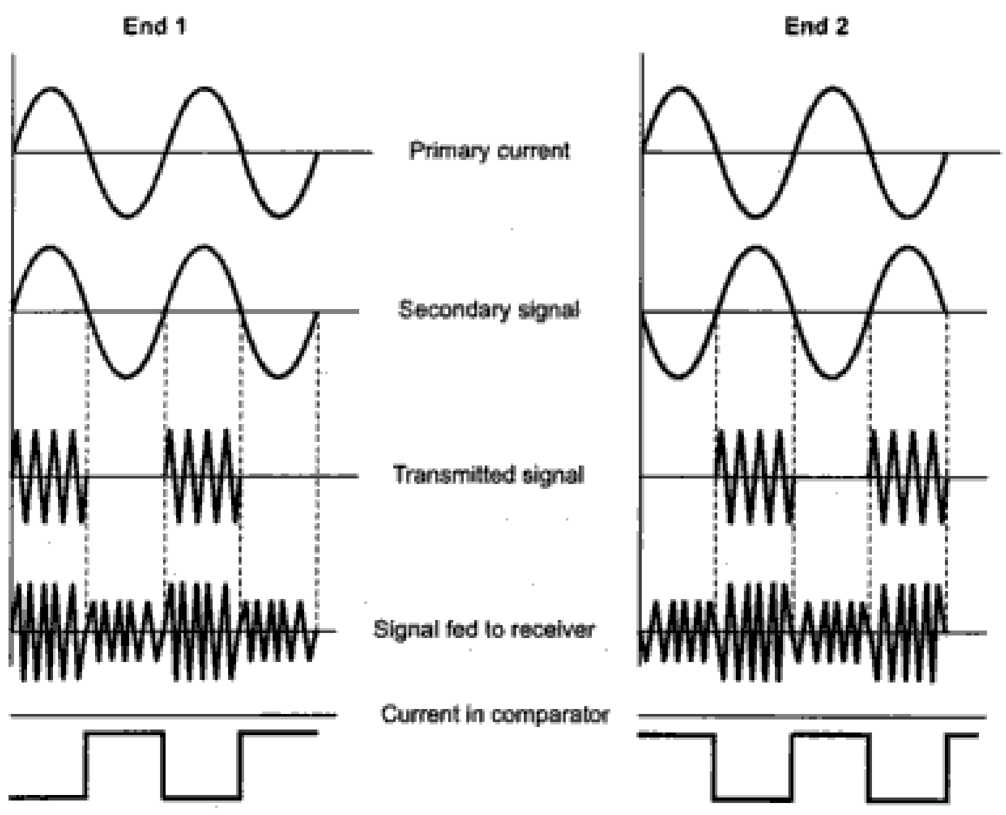


Fig. 8.6 (a) External fault

8.5 Basic Elements of a Static Relay

The Fig. 8.7 shows the block diagram of a static relay indicating its basic elements.

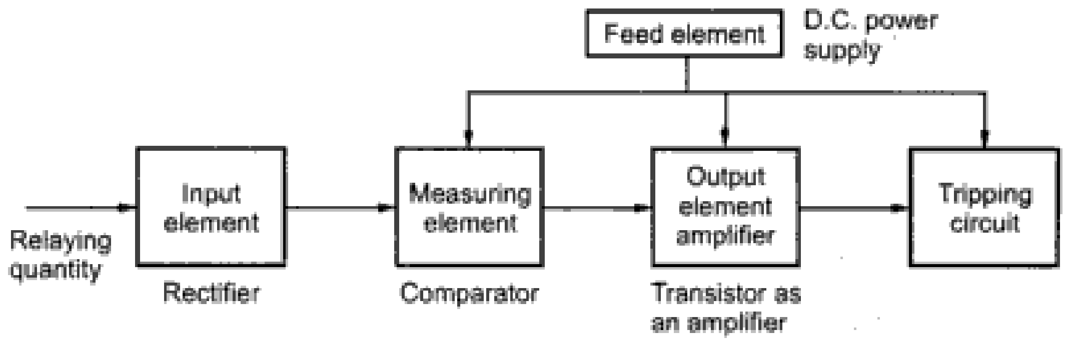


Fig. 8.7 Block diagram of a static relay

8.5.1 Input Element

The relaying quantity can be the output of C.T. or P.T. or it may be the output of a transducer or it may be combination of various signals. Thus an electronic circuit such as rectifier is required as an input element to get the input signal in a convenient form before applying it to a measuring element. Some mixing circuits such as op-amp adder may also be required as an input element.

8.5.2 Measuring Element

This is the heart of the static relay. It compares the output of an input element with a set value and decides the signal to be applied to the output element which ultimately drives the tripping circuit. Thus measuring element is a deciding signal generator.

Measuring element can be classified as,

1. Single input device
2. Two input device
3. Multi-input device

The single input devices, depending on the protection and control schemes are further classified as,

a. Noncritical Repeat Function (All or Nothing Relay) :

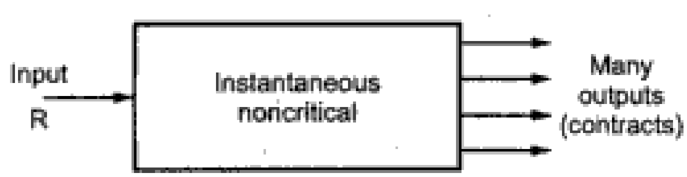


Fig. 8.8 Noncritical repeat function

As the name suggests, these devices are completely unenergized or energized much higher than the marginal condition required, to produce very fast response. It can be represented as shown in the Fig. 8.8. The input R is either zero or too higher than the marginal operating level. Such devices are instantaneous with response time less than 20 ms. The switching power gain associated with them is generally 10^3. Such devices have multiple output contacts.

The main functions of such devices in the protection are,

1. To produce final tripping signal to the circuit breaker.
2. To produce signals to perform supplementary functions such as alarming, intertripping etc.
3. To act as intermediate switching stages in a complex protection scheme.

b. Critical Measuring Function :

This device is a sort of on-off controller. It activates when the input signal reaches to some critical level decided by the protection scheme. Such a device is shown in the Fig. 8.9.

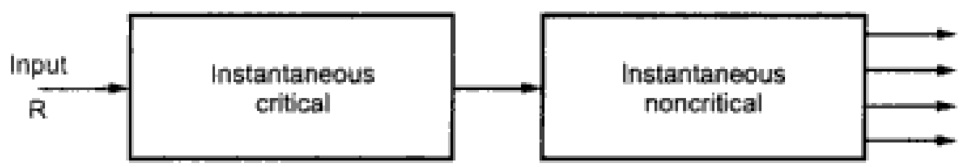


Fig. 8.9 Instantaneous critical function

Thus when input R is greater than some critical value P, it operates. While for reset, input R must be less than kP $(k \leq 1)$.

It has only one output and switching gain need not be high. The output of such device then can be connected to instantaneous noncritical to obtain multiple outputs.

The various requirements of critical function devices are,

1. High accuracy.
2. Long term consistency.
3. Fast and reliable operation.
4. High controllable reset ratio.

c. Definite or Fixed Time Function :

This is nothing but a delay function element. It produces a define time delay between its input and the output. The delay may be provided between the application of input and activation of output or between removal of input and resetting of output. It is shown in the Fig. 8.10.

Fig. 8.10 Definite time function

The input is noncritical type i.e. either zero or too high than the marginal requirement. Practically charging time of a capacitor is controlled to obtain fixed time delay.

d. Input Dependent Time Function :

This function depends on the input characteristics and decides the time accordingly.

The common form of input dependent time function characteristics is,

$$t = f(R^n) \quad \text{where } R = \text{input}$$

and $$n = \text{negative}$$

The function and its characteristics are shown in the Fig. 8.11.

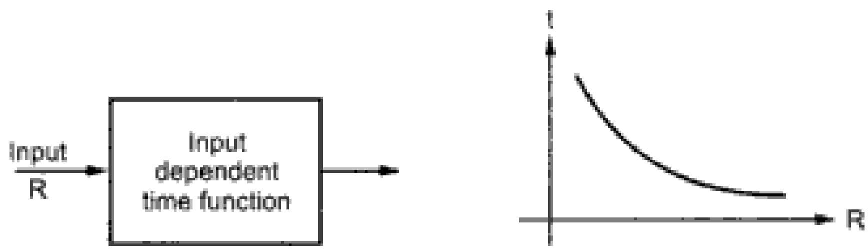


Fig. 8.11 Input dependent time function

As n is negative, as the input increases the operating time decreases. So operating time is inversely proportional to some power of the input. The examples of such relays are inverse definite minimum time lag overcurrent and earth fault relays.

The two input devices are very common such as comparators, level detectors etc. while multiple input devices are extension of two input devices to extend the range of characteristics.

8.5.3 Output Element

The signals obtained from the measuring element are required to be amplified before applying to the tripping circuit. Thus output element is an amplifier. Sometimes this element not only amplifies the signals but multiplies them or combines them with other signals to delay them.

8.5.4 Feed Element

The measuring element uses electronic circuits consisting transistors, diodes etc. The output element uses transistor as an amplifier. All these components, circuits alongwith the tripping circuit require d.c. supply for the proper functioning. The feed element provides the d.c. voltage required by the various elements.

8.6 Comparison of Static and Electromagnetic Relays

The conventional electromagnetic relays use the moving parts such as an armature, disc etc. Thus they are bulky in size. These relays are robust and highly reliable. These are subjected to differential forces under fault conditions and hence required to have delicate setting of small contact gaps, special bearing arrangements, clutch assemblies etc. Thus there are lot of manufacturing difficulties and problems related to mechanical stability associated with electromagnetic relays. The current and potential transformers are subjected to high burdens in case of electromagnetic relays.

The static relays are commonly using the transistor circuits and called transistor relays. This is because transistor can be used as an amplifying device as well as a switching device. Hence any functional characteristics as per the requirement can be obtained by the static relays. The transistor circuits can perform functions like summation, integration, comparison etc.

8.6.1 Advantages of Static Relays

The various advantages of static relays are,

1. The moving parts are absent. The moving parts are present only in the actual tripping circuit and not in the control circuit.
2. The burden on current transformers gets considerably reduced thus smaller C.T.s can be used.
3. The power consumption is very low as most of the circuits are electronic.
4. The response is very quick.
5. As moving parts are absent, the minimum maintenance is required. No bearing friction or contact troubles exist.
6. The resetting time can be reduced and overshoots can be reduced due to absence of mechanical inertia and thermal storage.
7. The sensitivity is high as signal amplification can be achieved very easily.
8. The use of printed circuits eliminates the wiring errors and mass production is possible.
9. As electronic circuits can be used to perform number of functions, the wide range of operating characteristics can be obtained, which almost approach to ideal requirements.
10. The low energy levels required in the measuring circuits make the relays smaller and compact in size.
11. The testing and servicing is simplified.

8.6.2 Limitations of Static Relays

Inspite of various advantages, the static relays suffer from the following limitations,

1. The characteristics of electronic components such as transistors, diodes etc. are temperature dependent. Hence relay characteristics vary with temperature and ageing.
2. The reliability is unpredictable as it depends on a large number of small components and their electrical connections.
3. These relays have low short time overload capacity compared to electromagnetic relays.
4. Additional d.c. supply is required for various transistor circuits.
5. Susceptable to the voltage fluctuations and transients.
6. Less robust compared to electromagnetic relays.

Now a days effect of temperature on the semiconductor devices can be compensated by careful design of the circuits.

8.7 Semiconductor Devices used in Static Relays

The various electronic components, devices and circuits which are commonly used in static relays are,

1. **Semiconductor diodes :** This includes the conventional p-n junction diode, zener diode, avalanche diode and the circuits using these diodes such as rectifiers, regulators, references etc.
2. **Transistors :** This includes bipolar junction transistors (BJT) and field effect transistors (FET). The transistors are used as amplifiers or as switches in the static relays. The direct coupled amplifiers using transistors are also used in the static relays.
3. **Unijunction transistor :** The device UJT having negative resistance characteristics is often used to obtain relaxation oscillator, the output of which is used to trigger SCR.
4. **Thyristor family :** This includes various two and three terminal and four layer electronic devices such as silicon controlled rectifier (SCR), triac, diac, silicon controlled switch (SCS). Such devices are used in static relays to obtain high speed switching characteristics.
5. **Logic circuits :** Most of the relays are bistable devices i.e. they are operated in two stable states either ON or OFF. The logic circuit also has two states high

i.e. ON and low i.e. OFF. Hence logic circuits play an important role in the static relays.

6. **Filter circuits** : The RC and LC filters are also used in static relays after rectifiers to obtain smoothing of d.c. voltage generated. To obtain fast smoothing instead of conventional capacitor filter, the phase splitting before the rectification is used in static relays.
7. **Multivibrators** : The various multivibrators using transistors are used to produce square waveforms in static relays. The diode clippers also can be used to obtain square waveforms.
8. **Time delay circuits** : The variety of time delay circuits such as delay lines, RC circuits, timer circuits, resonant circuits using transistors, thyristors and ICs are used in static relays. Depending upon the requirement of time delay, the particular circuit is chosen. The delay lines are used for shorter delays while RC charging and discharging circuits are used for longer delays. The time delays of the order of micro secs to hours can be achieved using such time delay circuits.
9. **Level detectors** : In static relays, it is necessary to detect the operating levels of various signals and used it to produce the necessary actuating signals. The level detector circuits using the diodes, rectifier and RC elements are commonly used in static relays.
10. **Analog circuits** : The op-amp available in IC form is very common in building analog circuits such as adder, subtractor, differentiator, integrator, inverting amplifier, noninverting amplifier etc. Op-amp also can be used to obtain the circuits like zero crossing detector, Schmitt trigger etc. All such circuits are used in various types of static relays.

8.8 Static Time Current Relay

This is nothing but instantaneous overcurrent relay. The Fig. 8.12 shows the block diagram of static time current relay.

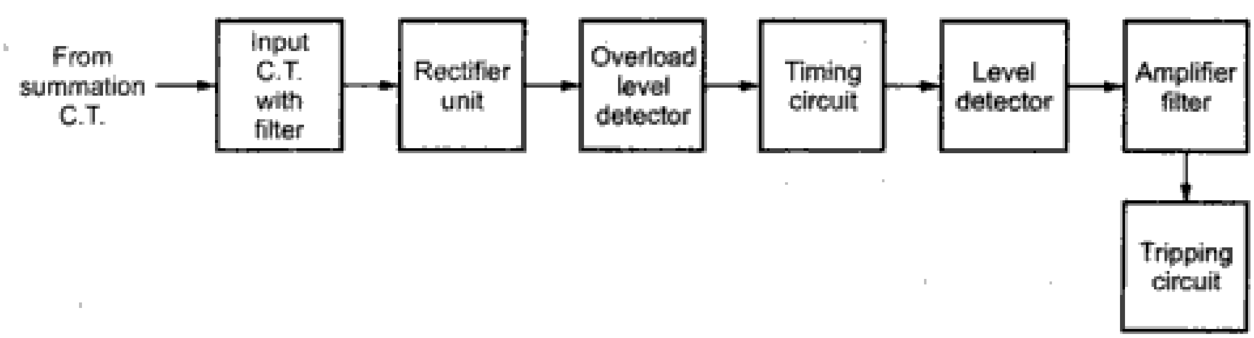


Fig. 8.12 Block diagram of time current static relay

The secondaries of line C.T.s are connected to the summation circuit. The output of summation C.T. is given to the input C.T. The input C.T. is called auxiliary C.T. which has taps on the primary for selecting the required pickup and current range. Then the output of auxiliary C.T. is rectified and smoothened. It is then applied to overload level detector and RC timing circuit. When the voltage across the timing capacitor reaches to a critical value then it triggers the level detector. The output of the level detector is amplified as per the requirement and given to the tripping circuit. This operates the output device. The charging of capacitor in a timing circuit is achieved by a voltage derived from CT current. This voltage is obtained across a nonlinear resistor by passing rectified current through it. The proper selection of nonlinear resistor and RC timing circuit allows to obtain desired shape of time current characteristics of the static relay.

The current at which the level detector trips is called **threshold current** denoted as $I_{threshold}$. Thus for an overcurrent relay,

when $I_{in} < I_{threshold}$, level detector does not trip

when $I_{in} \geq I_{threshold}$, level detector trips

8.8.1 Static Time-Current Characteristics

The time-current characteristics is inverse type of characteristics and given by the expression,

$$t = \frac{K(TMS)}{I^n - I_p^n}$$

where

t = Time of operation in seconds

K = Design constant of relay

TMS = Time multiplier setting

I = Tap current multiplier

I_p = Multiple of tap current at which pickup occurs

n = Characteristic index of relay

The shape of the characteristics and degree of inverse nature is standardized. According to British standards,

For standard inverse characteristics (IDMT),

$$K \times (TMS) = 0.14, \quad n = 0.02 \quad \text{and} \quad I_p = 1 \text{ A}$$

For standard very inverse characteristics,

$$K \times (TMS) = 13.5, \quad n = 1 \quad \text{and} \quad I_p = 1 \text{ A}$$

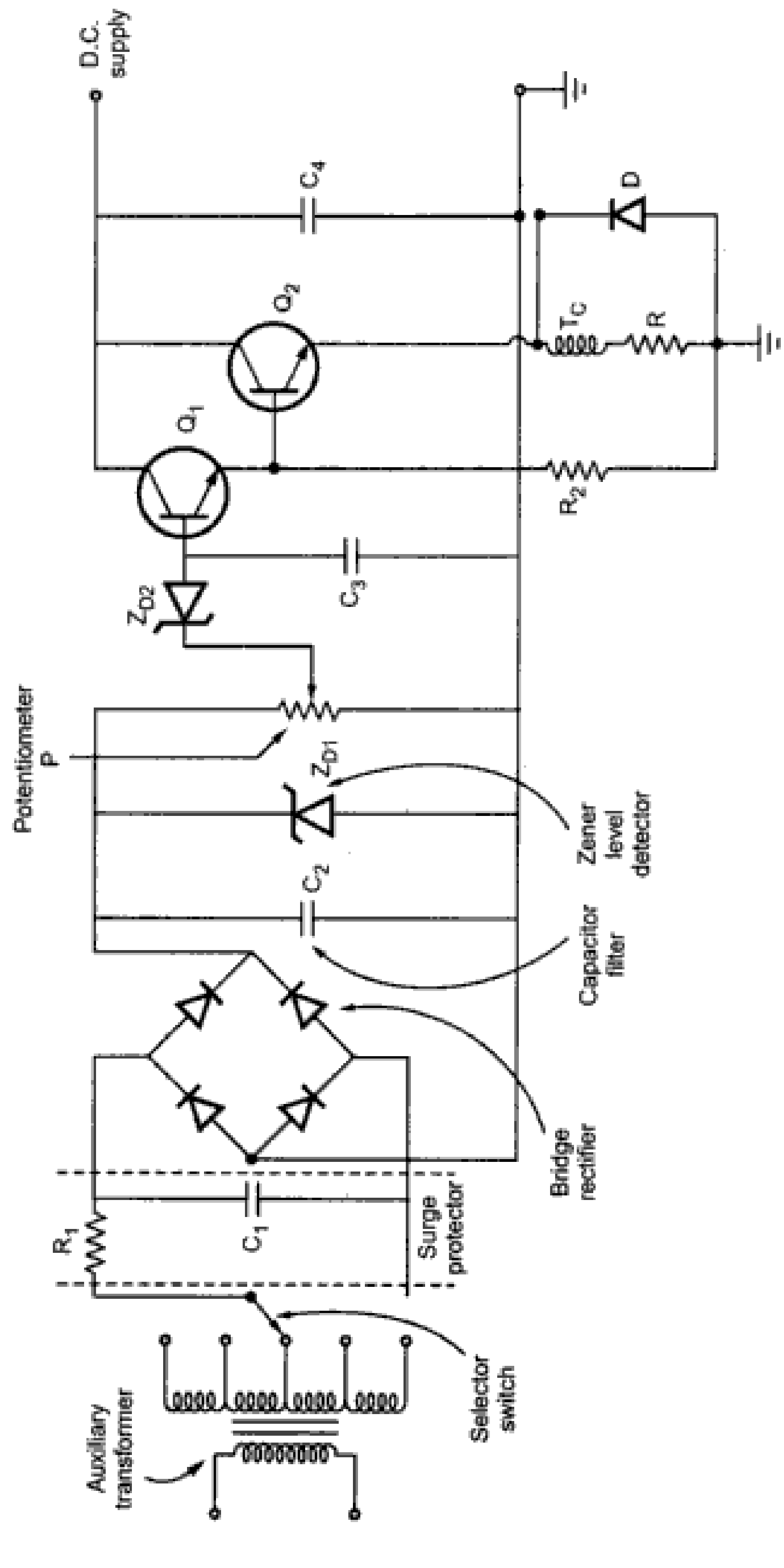


Fig. 8.14 Static overcurrent relay

8.8.3 Inverse Time-Current Relay

The Fig. 8.15 shows the circuit diagram of static inverse time-current relay.

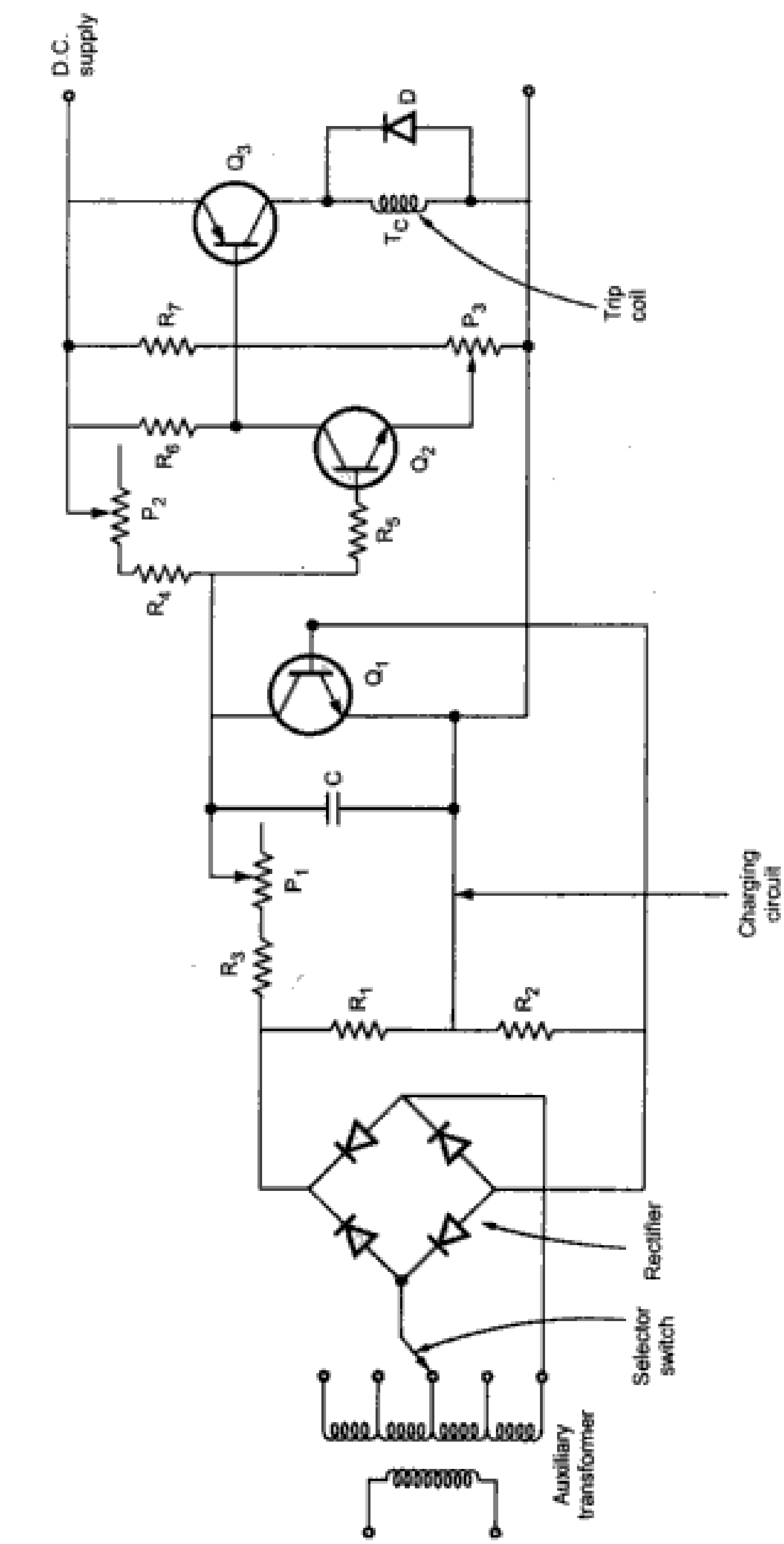


Fig. 8.15

Under normal conditions, Q_1 gets biasing from d.c. supply applied through R_4 and P_2 and conducts. Hence capacitor C is short circuited. When fault current exceeds the pick up value set by the potentiometer P_2 and selector switch then the transistor Q_1 becomes OFF. The capacitor C starts charging through R_3 and P_1 by the voltage developed across R_1. This charging time varies as per the severity of the fault. More severe is the fault, more is the voltage developed across R_1 and less is the time for charging capacitor C to a critical level. When voltage across the capacitor reaches to a predetermined level set by the potentionmenter P_3 then the transistor Q_3 conducts. This energizes the trip coil and the circuit breaker opens. The diode D protects the transistor from the high reverse voltage. Thus more is the fault current, less is the time required to operate relay hence it is inverse time-current relay.

8.9 Directional Static Overcurrent Relay

The directional relay is nothing but a directional power relay which operates when the power in the circuit flows in a particular direction. Thus it requires to sense the system voltage as well as the system current.

The Fig. 8.16 shows block diagram of the directional static overcurrent relay.

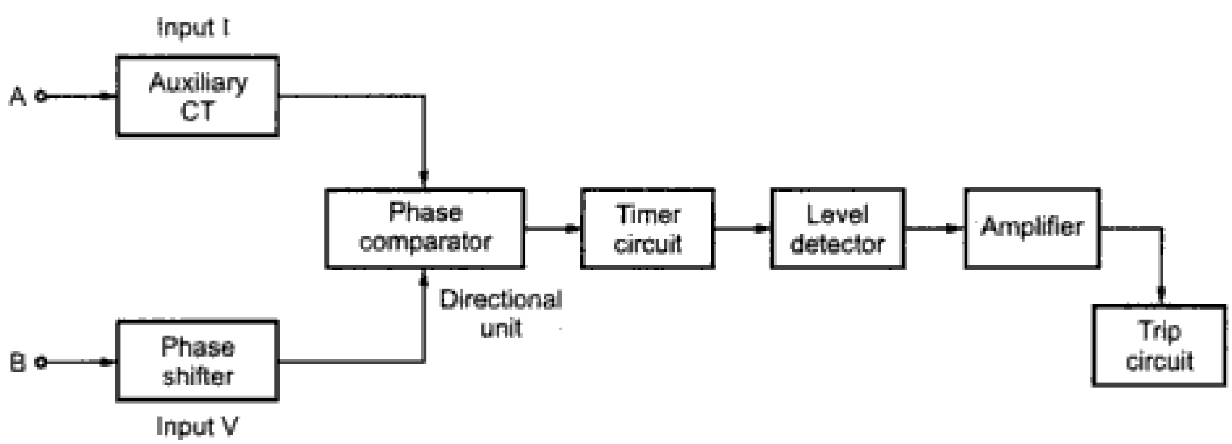


Fig. 8.16 Directional static overcurrent relay

The input A is proportional to the system current supplied to a directional unit through auxiliary transformer. The input B is proportional to the system voltage, supplied to a directional unit through phase shifter.

The phase comparator compares the phase angle between the two inputs. Let this angle is ϕ while the relay characteristics angle is θ. Let I_p be the current setting magnitude. Then the relay operates when,

$$I_p \leq I \cos(\phi - \theta)$$

The output of the phase comparator is applied to a level detector through timer if time delay is required. The output of the level detector is amplified and given to the trip circuit.

The phase comparator is generally of two types,

1. Hall effect generator which is popularly used in Russian countries.
2. Rectifier bridge type comparator which is popularly used in European countries.

The static directional overcurrent relays are very sensitive and directional unit can be made reliable down to 1% of the system voltage.

8.10 Static Differential Relay

A differential relay is the relay which operates when the phasor difference of two or more similar electrical quantities exceed a predetermined value.

In static differential relay, two similar quantities either voltages or currents are compared. The comparator measures the vector difference between the two similar input signals. The rectifier bridge type comparator is generally used in the static differential relay. The block diagram is shown in the Fig. 8.17.

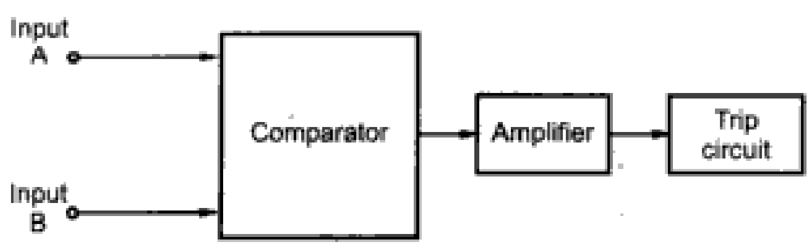


Fig. 8.17 Static differential relay

In normal conditions, the two quantities balance each other and the comparator output is zero and the relay is inoperative.

For any internal fault conditions, the comparator senses the phase difference between the two quantities and produces the output. This is amplified and given to the trip circuit which operates the relay.

This scheme is used for protection of the generators and transformers against any type of internal fault.

The various advantages of static differential relay over electromagnetic differential relay are, highly sensitive, compact, very fast in operation, low power consumption, less burden on input CTs and inrush current proof characteristics.

The basic static differential relay scheme is shown in the Fig. 8.18.

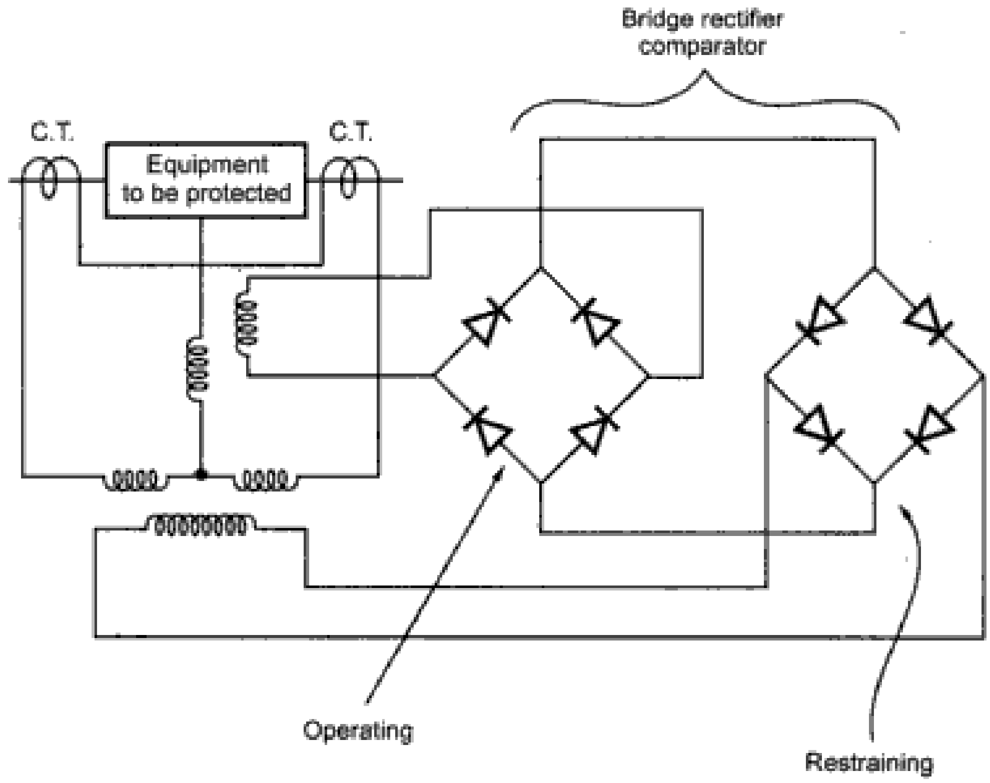


Fig. 8.18 Static differential relay scheme

Let n_o and n_r be the number of turns of operating and restraining coils respectively. Then the relay operates when,

$$K_1 n_o I_o > K_2 n_r I_r + K'$$

where k_1 and k_2 are design constants while K' is the spring control torque.

8.11 Static Distance Relay

In the distance relay, the operation is dependent on the ratio of the voltage and current, which is expressed interms of an impedance. The relay operates when the ratio V/I i.e. impedance is less than a predetermined value. The distance relays include impedance, reactance and admittance relays as discussed earlier. In static relays the comparison of voltage and current is achieved by electronic comparator circuits.

The basic block diagram of static distance relay is shown in the Fig. 8.19.

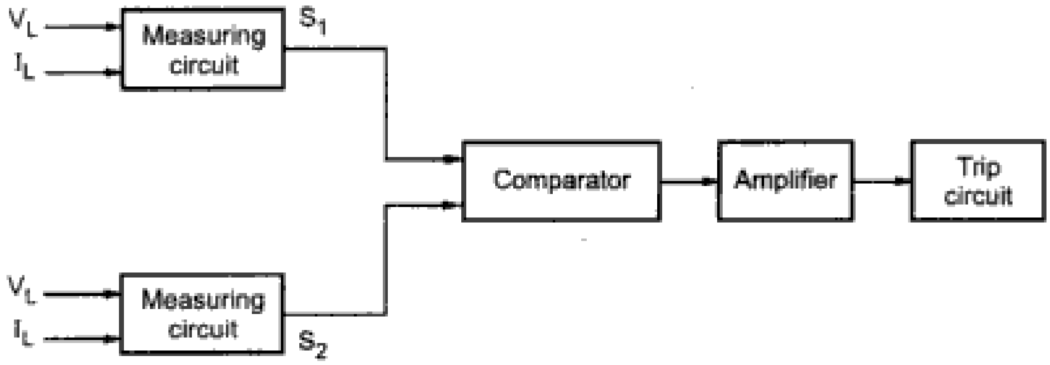


Fig. 8.19 Basic static distance relay scheme

The line voltage V_L and line current I_L are given as the inputs to the two measuring circuits. The circuits produce the outputs S_1 and S_2 depending upon their characteristics. Thus,

$$S_1 = K_1 V_L + K_2 I_L$$

$$S_2 = K_3 V_L + K_4 I_L$$

where K_1, K_2, K_3 and K_4 are to be selected according to the requirement of the characteristics.

Now depending upon whether the comparator is amplitude or phase comparator and the constants K_1 to K_4, the various characteristics of the distance relay can be obtained.

The various types of derived voltages S_1 and S_2 for amplitude and phase comparators to obtain particular characteristics are given in the Table. 8.1.

No.	Amplitude comparator		Phase comparator		Distance relay scheme
	Operating	Restraining	Operating	Restraining	
1	$\left\lvert I_L + \frac{V_L}{Z_R} \right\rvert$	$\left\lvert I_L - \frac{V_L}{Z_R} \right\rvert$	$I_L Z_R$	V_L	Directional
2	$\lvert I_L \rvert$	$\frac{\lvert V_L \rvert}{\lvert Z_R \rvert}$	$I_L Z_R - V_L$	$I_L Z_R + V_L$	Impedance
3	$\left\lvert I_L - \frac{V_L}{X_R} \right\rvert$	$\frac{\lvert V_L \rvert}{\lvert X_R \rvert}$	$I_L Z_R - V_L \sin\theta$	$I_L Z_R$	Reactance
4	$\lvert I_L \rvert$	$\left\lvert I_L - \frac{V_L}{Z_R} \right\rvert$	$I_L Z_R - V_L$	V_L	Mho

Table 8.1

The characteristics of various schemes as obtained from above Table 8.1 are shown in the Fig. 8.20.

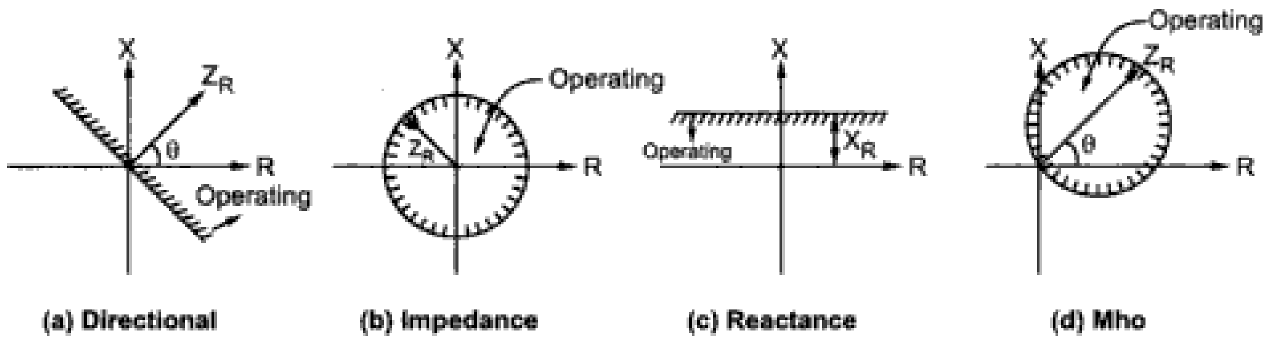


Fig. 8.20

The static distance relays are used popularly for protection of medium and long transmission lines, parallel feeders and interconnected and T connected lines.

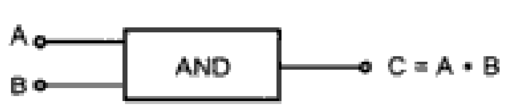
8.12 Microprocessor Based Relay

Let us see the relay logic which is very important in understanding the microprocessor based relay. The relay can be ON or OFF i.e. it has two stable states. Similarly output of a logic function is ON i.e. high or OFF i.e. low. The three basic logic functions are,

1. AND 2. OR 3. NOT

AND function :

The block schematic of AND function and the truth table is shown in the Fig. 8.21. In the truth table 1 indicates high while 0 indicates low. AND is nothing but a multiplication.



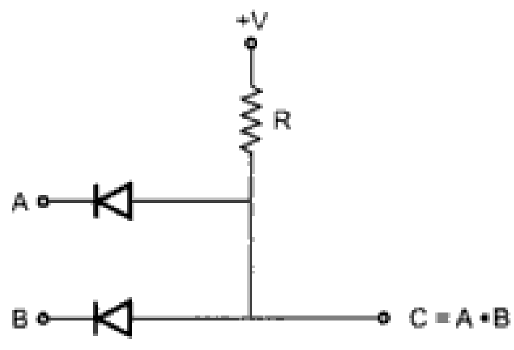
(a) Block schematic

A	B	C = A AND B
0	0	0
0	1	0
1	0	0
1	1	1

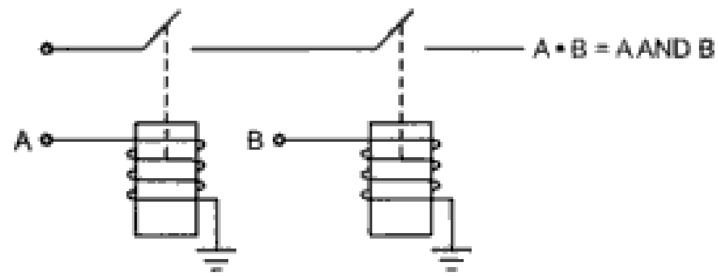
(b) Truth table

Fig. 8.21 AND function

The diode AND gate is shown in the Fig. 8.22 (a) while the AND operation using relays is shown in the Fig. 8.22 (b).



(a) Diode AND

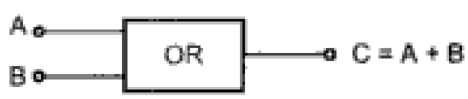


(b) AND with relays

Fig. 8.22

OR function :

The block schematic of OR function and the truth table is shown in the Fig. 8.23. The OR function is nothing but an addition.



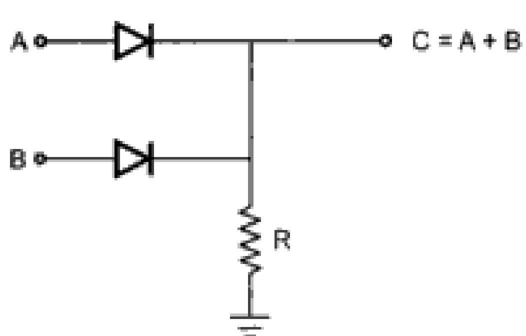
(a) Block schematic

A	B	C = A OR B
0	0	0
0	1	1
1	0	1
1	1	1

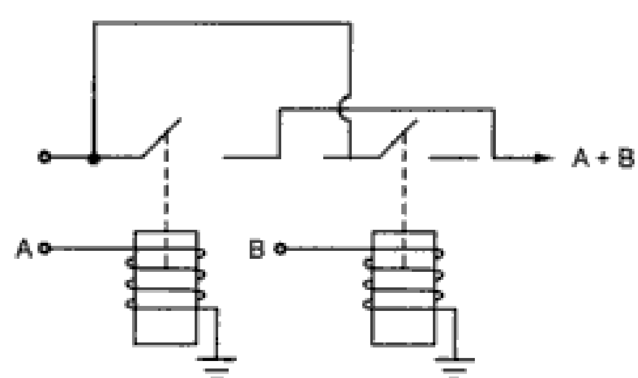
(b) Truth table

Fig. 8.23 OR function

The diode OR gate is shown in the Fig. 8.24 (a) while the OR operation using relays is shown in the Fig. 8.24 (b).



(a) Diode OR

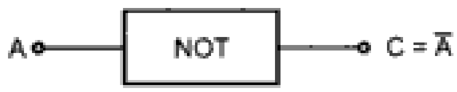


(b) OR with relays

Fig. 8.24

NOT function :

The NOT function is inverting function of the input. So if input A is 0 then output is 1 and viceversa. The output is denoted as $\overline{A}$. It is shown in the Fig. 8.25.



(a) Block schematic

A	$C = \overline{A}$
0	1
1	0

(b) Truth table

Fig. 8.25 NOT function

By using NOT function with basic AND and OR two more logical functions can be obtained which are NAND and NOR.

The truth tables for NAND and NOR are given in the Table. 8.2.

A	B	NAND	NOR
0	0	1	1
0	1	1	0
1	0	1	0
1	1	0	0

Table 8.2

All these functions can be achieved using transistors also. It is called transistor transistor logic (TTL).

The Fig. 8.26 shows the block diagram of microprocessor based relay.

The output of line CT is given to the input receiver block where signal is processed. The signal processing includes surge protector, rectifier, smoothening filters, auxiliary CT etc. depending upon the requirement. This signal is an analog signal. The A/D converter converts this to a digital signal which is accepted by the microprocessor. The microprocessor is a decision making block. The digital signal received is compared with the reference to generate the proper tripping signal. This is a digital signal which is converted to analog again to operate the tripping coil. This is achieved by the D/A converter. The data logger captures the data and feeds it to the microprocessor when there is a request from the microprocessor. The information can be displayed with a proper display device by taking signal from the microprocessor.

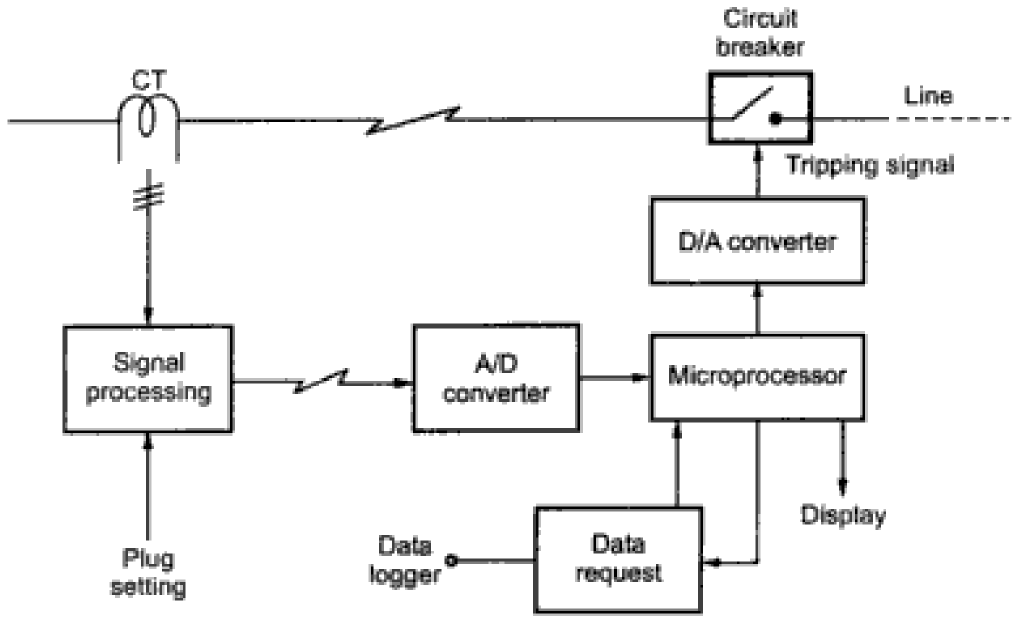


Fig. 8.26 Microprocessor based overcurrent relay

The main advantage of such relay is that it is programmable. The programme can take care of on line calculations and take the decision accordingly. Another important advantage of microprocessor based relay is that one microprocessor unit can perform the relaying operation of several systems.

Thus various advantages of microprocessor based relay are,

1. Very efficient and reliable.
2. Highly accurate.
3. Very fast in operation.
4. Programmable in nature.
5. One unit can perform relaying of several systems.
6. Economical for large systems.
7. Useful for centralley co-ordinated back up protection.

Only are must be taken that the microprocessor unit must be properly shielded as it gets affected by external interferences and environment. Proper care of earthing must also be taken.

Review Questions

1. *Draw and explain block schematic of carrier aided protection.*
2. *Which electronic equipments are used at each end of the line ?*
3. *Explain the transmitting unit used in carrier aided protection.*
4. *Explain the block diagram of phase comparision method.*

5. *State the advantages of carrier current protection.*
6. *Explain the basic elements of static relays.*
7. *Compare static and electromagnetic relays.*
8. *State the advantages of static relays.*
9. *Which are the various semiconductor devices used in static relays ?*
10. *Draw and explain the block diagram of static time-current relay.*
11. *Draw and explain the circuit diagram of static instantaneous over current relay.*
12. *Draw and explain circuit diagram of static inverse time over current relay.*
13. *Draw and explain the circuit diagram of static directional overcurrent relay.*
14. *Draw and explain the circuit diagram of static differentical relay.*
15. *Write a note on static distance relays.*
16. *Write a note on microprocessor based relay.*

❑❑❑

9 Theory of Arc Quenching

9.1 Introduction

The different circuits of a power system viz transmission lines, distributors, generating stations etc. are required to be operated under both normal and abnormal conditions. Whenever any fault occurs somewhere in the system, it must be immediately detected and disconnected from the system. This is necessary since it ensures less damage to the faulted apparatus and the fault is not spread into the system. Also quick recovery of fault results in less interruption of service to the consumers.

Previously the function of switching on and off of the power system elements was accomplished with the help of switch and fuse which is placed in series with the circuit. But it suffers some difficulties such as replacement of fuse takes a long time. So supply to the consumers will be restored after long time. The another limitation is that it will not be able to interrupt successfully the heavy fault currents. Due to these disadvantages the use of switch and fuse unit is restricted to the low voltage and small capacity circuits where frequent operations are not performed.

With the development in power system the transmission lines and various equipments operate at very high voltages carrying large currents. The switch and fuse arrangement explained earlier will fail to serve the desired function in high capacity circuits. The use of circuit breakers can facilitate the opening and closing of heavy electric circuits smoothly and efficiently. **A circuit breaker can make or break a circuit either manually or automatically under no load, full load or short circuit conditions.** Thus it forms important element in any protective scheme.

Any circuit breaker essentially consists of fixed contact and moving contact. Under abnormal conditions or whenever the circuit breaker is operated then the internal mechanism makes the moving contact to move away from the fixed contact. Whenever contacts are separated from each other the circuit is not breaked immediately as heavy arc is drawn between the contacts which will continue for some time. The resistance of this arc is high which causes large power loss in the process. Also the components of circuit breaker are under heavy mechanical and electromagnetic stresses.

9.2 Formation of an Arc

Now let's see the formation of an arc. Under faulty conditions heavy current flows through the contacts of the circuit breaker before they are opened. As soon as the contacts start separating, the area of contact decreases which will increase the current density and consequently rise in the temperature. The medium between the contacts of circuit breaker may be air or oil. The heat which is produced in the medium is sufficient enough to ionoise air or oil which will act as conductor. Thus an arc is struck between the contacts. The p.d. between the contacts is sufficient to maintain the arc. So long as the arc is remaining between the contacts the circuit is said to be uninterrupted.

The current flowing between the contacts depends on the arc resistance. With increase in arc resistance the current flowing will be smaller. The arc resistance depends on following factors,

a) **Degree of ionisation :** If there are less number of ionised particles between the contacts then the arc resistance increases.

b) **Length of arc :** The arc resistance is a function of length of arc which is nothing but separation between the contacts. More the length, more is the arc resistance.

c) **Cross-section of arc :** If the area of cross-section of the arc is less then arc resistance is large.

9.2.1 Initiation of Arc

There must be some electrons for initiation of an arc when fault occurs circuit breaker contacts start separating from each other and the electrons are emitted which are produced by following methods.

i) By high voltage gradient at the cathode, resulting in field emission

ii) By increase of temperature, resulting in thermionic emission.

9.2.1.1 By High Voltage Gradient

As the moving contacts start separating from each other, the area of contact and pressure between the separating contacts decreases. A high fault current causes potential drop (of the order of 10^6 V/cm) between the contacts which will remove the electrons from cathode surface. This process is called **field emission**.

9.2.1.2 By Increase of Temperature

With the separation of contacts there is decrease in contact area which will increase the current density and consequently the temperature of the surface as seen before, which will cause emission of electrons which is called **thermal electron emission**.

In most of the circuit breakers the contacts are made up of copper which is having less thermionic emission.

9.2.2 Maintenance of an Arc

In the previous section we have seen the initiation of the arc by field emission and thermionic emission. The electrons while travelling towards anode collide with another electrons to dislodge them and thus the arc is maintained. The ionizing is facilated by,

i) High temperature of the medium around the contacts due to high current densities. Thus the kinetic energy gained by moving electrons is increased.

ii) The increase in kinetic energy of moving electrons due to the voltage gradient which dislodge more electrons from neutral molecules.

iii) The separation of contacts of circuit breaker increases the length of path which will increase number of neutral molecules. This will decrease the density of gas which will increase free path movement of the electrons.

9.2.3 Arc Extinction

It is essential that arc should be extinguished as early as possible. There are two methods of extinguishing the arc in circuit breakers which are namely,

a) High resistance method

b) Low resistance or current zero method

9.2.3.1 High Resistance Method

In high resistance method the arc resistance is increased with time. This will reduce the current to such a value which will be insufficient to maintain the arc. Thus the current is interrupted and the arc is extinguished. This method is employed in only d.c. circuit breakers. The resistance of the arc may be increased by lengthening the arc, cooling the arc, reducing the cross-section of the arc and splitting the arc. These methods will be discussed in detail later in this chapter.

9.2.3.2 Low Resistance Method

The low resistance or current zero method is employed for arc extinction in a.c. circuits. In this method arc resistance is kept low until current zero where extinction of arc takes place naturally and is prevented from restriking. This method is employed in many of the modern a.c. circuit breakers.

9.3 D.C. Circuit Breaking

The breaking in case of d.c. circuits can be explained as follows. For this, we will consider a circuit which will consist of generator with voltage E, resistance R, inductor L and the circuit breaker as shown in the Fig. 9.1 (a).

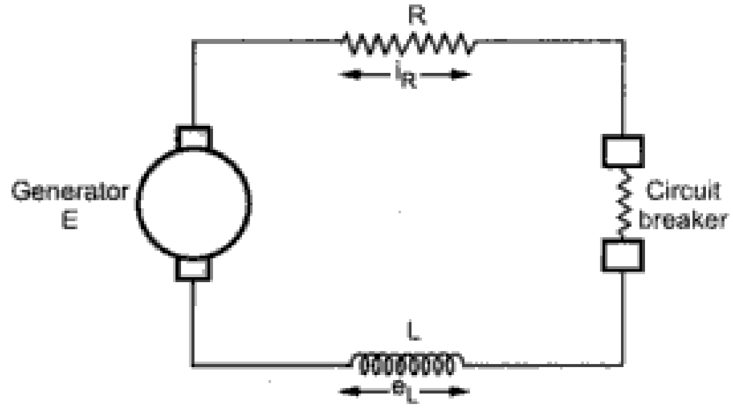


Fig. 9.1 (a)

The voltage-current relationship can be represented as shown in the Fig. 9.1 (b).

From the Fig. 9.1 (b), it could be seen that curve AB represents the voltage E – iR, i is nothing but current at any instant. The curve XY represents the voltage-current characteristics of the arc for decreasing currents.

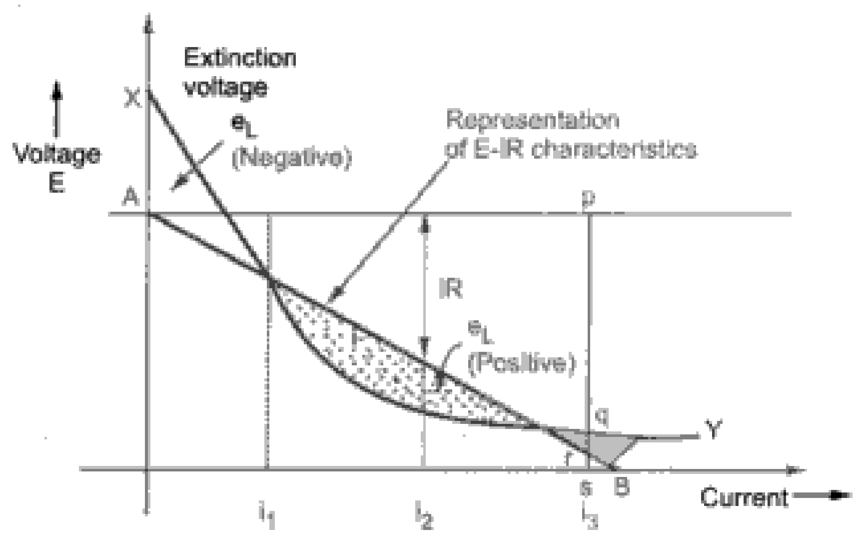


Fig. 9.1 (b) Voltage-current relationship

When the circuit breaker starts opening it carries the load current $I = \frac{E}{R}$. In the graph shown the current is shown to be reduced to i_1, i_2 and i_3 respectively. Section pr represents voltage drop i_3R whereas qs represents arc voltage which is greater than available voltage. The arc becomes unstable and the difference in voltage is supplied by inductance L across which the voltage is $e_L = L \frac{di}{dt}$. For decreasing values of currents this voltage is negative and according to Lenz's law it tries to maintain the arc.

The voltage across inductance L is seen to be positive in the region of currents i_1 and i_2 since the arc characteristics lies below the curve AB. The arc current in this region tries to increase so interruption of current is not possible in this region. Afterwards the arc is lengthened with increase in contact separation which will raise the arc voltage above the curve AB.

The operation in case of d.c. circuit breakers is said to be ideal if the characteristics of the arc voltage are above the curve AB even in the region of currents i_1 and i_2. This is shown in the Fig. 9.2.

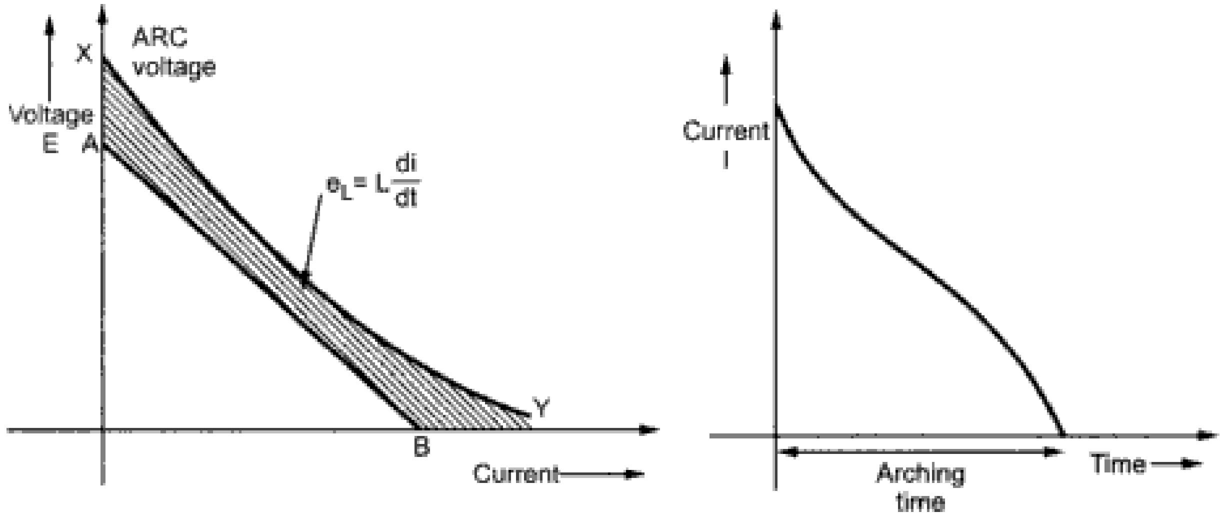


Fig. 9.2 Arc voltage characteristics

It can be seen that arc voltage is greater than E – iR and the balance between the voltages is supplied by the voltage across the inductance e_L which is proportional to rate of change of current $\frac{di}{dt}$.

Thus the function of the circuit breaker is to raise the arc characteristics without affecting its stability. This is done by reducing the arcing time which is the time from contact separation to final extinction of arc. But it will increase extinction voltage. Hence compromise between arcing time and arc extinction voltage is made.

9.4 A.C. Circuit Breaking

There is a difference between breaking in case of d.c. and a.c. circuits. In a.c. circuits the current passes through zero twice in one complete cycle. When the currents are reduced to zero the beakers are operated to cut-off the current. This will avoid the striking of the arc. But this conditions is difficult to achieve and very much expensive.

The restriking of arc when current is interrupted is dependent on the voltage between the contact gap at that instant which will inturn depend on power factor. Higher the power factor, lesser is the voltage appearing across the gap than its peak value.

Now before studying the actual current interruption in a.c. circuits we will see some theory which will help us in understanding this concept.

9.5 Short Circuit in R- L Series Circuit

Consider a series R-L circuit as shown in the Fig. 9.3 in which switch S is suddenly closed at time t = 0.

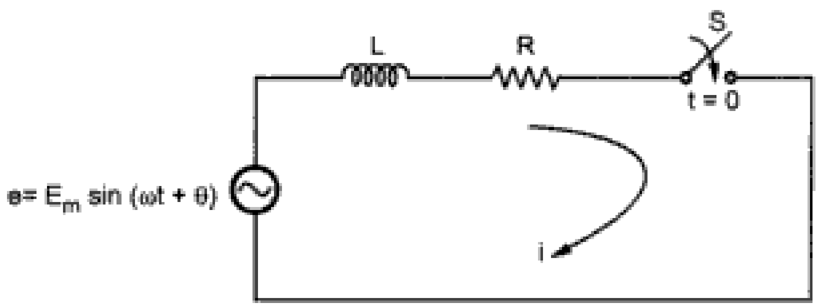


Fig. 9.3 R-L series circuit

Applying KVL to above circuit,

$$L\frac{di}{dt} + Ri = e$$

$$L\frac{di}{dt} + Ri = E_m \sin(\omega t + \theta) \quad \ldots (1)$$

This equation can be solved to get the expression for current i. This is a non-homogeneous differential equation whose solution consists of two parts viz complementary solution and particular solution i.e. $i = i_C + i_P$.

Complementary Solution : To get the complementary solution we will consider the auxiliary equation which is obtained by equating right hand side of above equation to zero.

$$L\frac{di}{dt} + Ri = 0 \quad \ldots (2)$$

Separating the variables,

$$\frac{di}{i} = -\frac{R}{L}dt$$

Integrating and solving,

$$\log i = -\frac{R}{L} t + K \qquad \text{where K is constant of integration}$$

Considering $K = \log_e A$

$$\therefore \quad \log_e i = \log_e e^{(-R/L)t} + \log_e A$$

$$\therefore \quad \log_e i = \log_e A e^{(-R/L)t}$$

Taking antilog on both sides,

$$i = A e^{(-R/L)t}$$

This is complementary solution. This component of current is seen to be exponentially decaying component and called D.C. component. The constant of integration A depends on initial conditions which may be zero, positive or negative.

$$\therefore \quad i_C = A e^{(-R/L)t} \qquad \dots (3)$$

Particular Solution : For particular solution we will take a trial solution as,

$$i = C \cos(\omega t + \theta) + D \sin(\omega t + \theta) \qquad \dots (4)$$

Taking $\frac{di}{dt}$ and $\frac{d^2 i}{dt^2}$ of above equation,

$$\frac{di}{dt} = -C\omega \sin(\omega t + \theta) + D\omega \cos(\omega t + \theta)$$

$$\frac{d^2 i}{dt^2} = -C\omega^2 \cos(\omega t + \theta) - D\omega^2 \sin(\omega t + \theta)$$

Putting this value in equation (1) and equating like coefficients,

$$C = -E_m \frac{\omega L}{R^2 + \omega^2 L^2}$$

$$D = E_m \frac{R}{R^2 + \omega^2 L^2}$$

Substituting these values of C and D in the trial solution we get,

$$i = -E_m \frac{\omega L}{R^2 + \omega^2 L^2} \cos(\omega t + \theta) + E_m \frac{R}{R^2 + \omega^2 L^2} \sin(\omega t + \theta) \qquad \dots (5)$$

If ϕ is the impedance angle then,

$$\therefore \quad \tan\phi = \frac{\omega L}{R}$$

$$\therefore \quad \sin\phi = \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}$$

$$\therefore \qquad \cos\phi = \frac{R}{\sqrt{R^2+\omega^2 L^2}}$$

$$i = \frac{-E_m}{\sqrt{R^2+\omega^2 L^2}} \sin\phi \cos(\omega t+\theta) + \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} \cos\phi \sin(\omega t+\theta)$$

$$= \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} [\sin(\omega t+\theta)\cos\phi - \cos(\omega t+\theta)\sin\phi]$$

$$= \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} \sin(\omega t+\theta-\phi)$$

$$i_P = \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} \sin(\omega t+\theta-\phi) \qquad \ldots (6)$$

The particular solution given by above equation is **sinusoidal** and is called **A.C. component.**

Complete Solution : The total current i is given by,

$$i = i_C + i_P$$

$$\therefore \qquad i = A\, e^{-(R/L)t} + \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} \sin(\omega t+\theta-\phi) \qquad \ldots (7)$$

To find the value of A let us put the initial conditions. At $t = 0$, $i = 0$. If R is assumed to be very small compared to $\omega^2 L^2$; $\sqrt{R^2+\omega^2 L^2} \approx \omega L$

and $\phi = \tan^{-1}\dfrac{\omega L}{R} \approx 90°$

Case (i) : If switch is closed at $e = 0$

$$t = 0; \quad e = 0 \qquad \therefore \quad \theta = 0$$

Also $\qquad i = 0$ at $t = 0$.

$$\therefore \qquad 0 = A + \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} \sin(-90°)$$

$$A = \frac{E_m}{\sqrt{R^2+\omega^2 L^2}} = \frac{E_m}{\omega L}$$

This is the maximum value of A. **Thus the d.c. component is maximum when switch is closed at zero voltage.**

Case (ii) : If switch is closed at $e = E_{max}$

$$t = 0; \quad e = E_{max} \qquad \therefore \quad \theta = 90° = \pi/2$$

$$\therefore \quad 0 = A + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(90° - 90°)$$

$$A = 0$$

If switch is closed when e = E_{max} then A = 0 i.e. d.c. component is zero.

Thus when the circuit consisting of R and L supplied with alternating voltage, is closed at t = 0, the resulting current consists of two components viz a.c. and d.c. components which are superimposed on each other. The d.c. component magnitude is decided by the voltage at the instant of switching. When switch is closed at voltage zero, the d.c. component is maximum whereas the d.c. component is zero when switch is closed at voltage maximum.

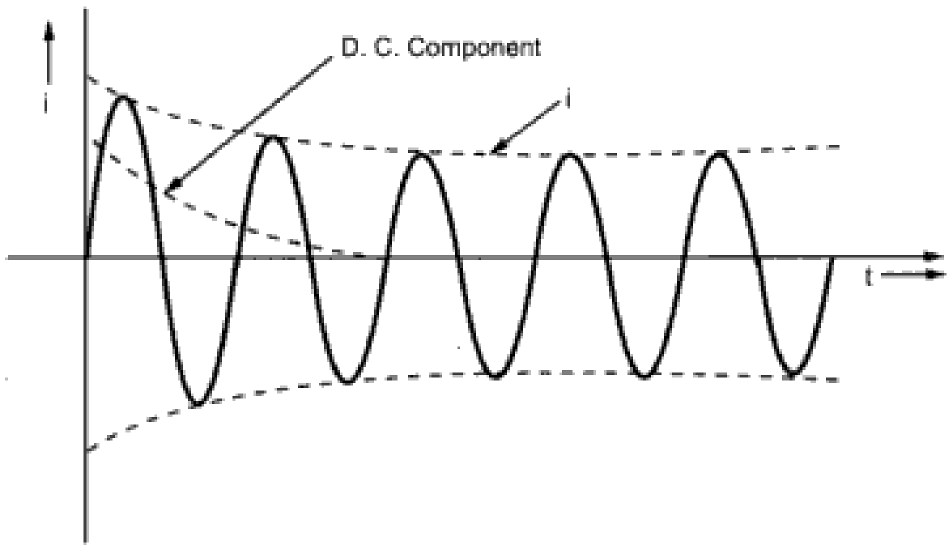


Fig. 9.4 Maximum D.C. component

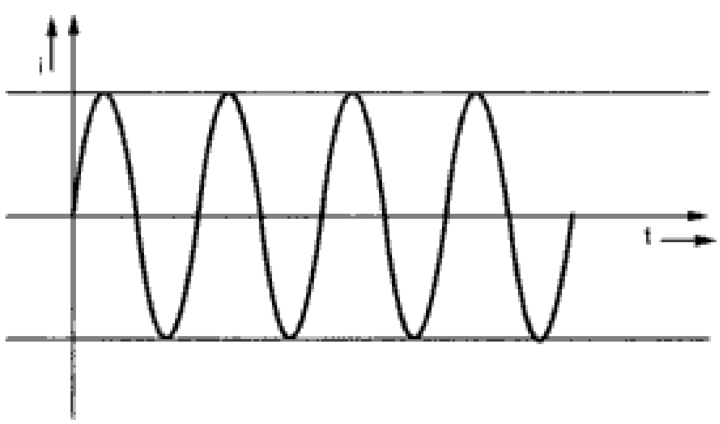


Fig. 9.5 No D.C. component

The analysis of three phase short circuit of an alternator is done by similar way as we have done the analysis of short circuit of series R-L circuit. The current flowing through the phases of alternator during short circuit has similar waveform to that of

R-L circuit as shown previously if we neglect armature reaction and variation in the field current.

During the short circuit, the current flowing through alternator rises rapidly to a high value during first quarter cycle. The flux which is crossing the air gap is large during first couple of cycles.

The subtransient reactance denoted by X_d'' is defined as that reactance during first two or three cycles. This is very less and correspondingly short circuit current is large.

After first few cycles which are coming under subtransient state the r.m.s. value of short circuit current goes on reducing but the decrease in current is not fast as in subtransient state. This state is called transient state and the corresponding reactance is called transient reactance denoted by X_d'. The circuit breaker contacts separate in this state.

Finally the transients vanish and current will reach to steady sinusoidal state called steady state. The reactance in this state is called steady state reactance denoted by X_d.

The currents in the different phases are having different d.c. components. So their waveforms will be different. In the Fig. 9.6 the oscillogram of the current in the phase having zero d.c. component is shown.

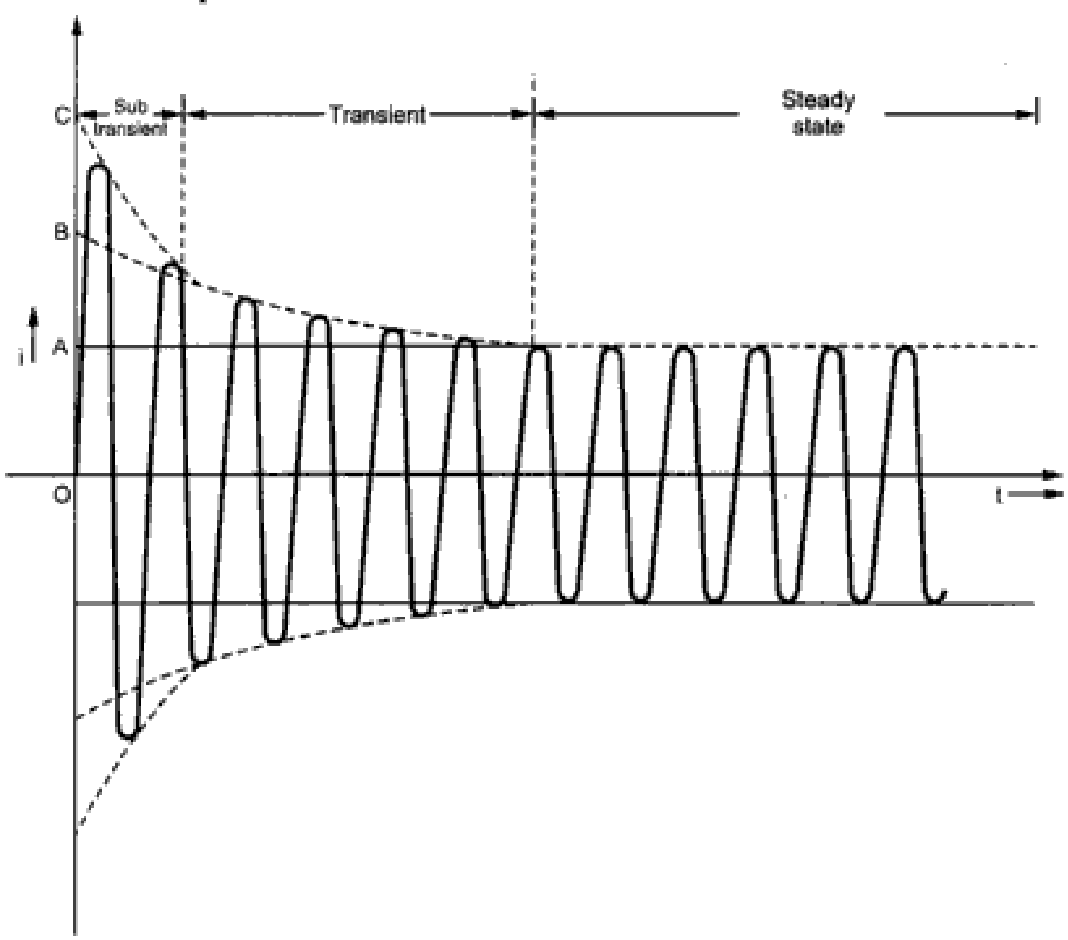


Fig. 9.6 Oscillogram of current in the phase having zero d.c. component

9.6 Current Interruption in A.C. Circuit Breakers

Now we will see how the current interruption takes place in a.c. circuit breakers. Generally the a.c. circuit beakers employ zero point interruption technique.

Let us consider an alternator on no load to which a circuit breaker is connected which is shown in the Fig. 9.7. The circuit breaker is in open position with its other side short circuited.

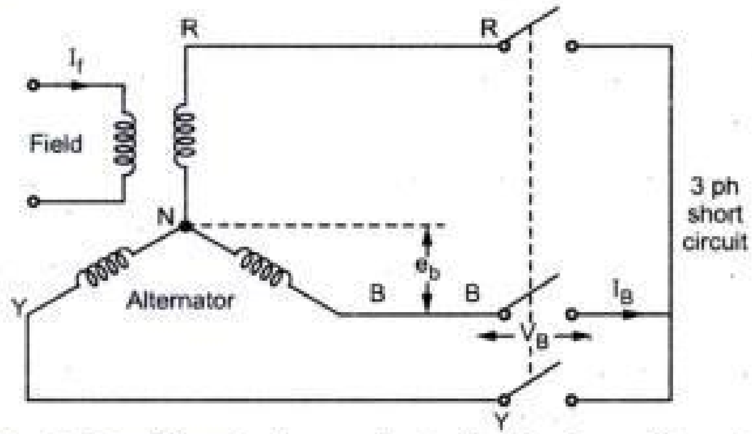


Fig. 9.7 Sudden 3 phase short circuit of an alternator

When the voltage of phase B w.r.t neutral is zero, the circuit breaker is closed. Under this condition the B phase current will have maximum d.c. component and its current waveform will be unsymmetrical about normal zero axis. This is shown in the Fig. 9.8.

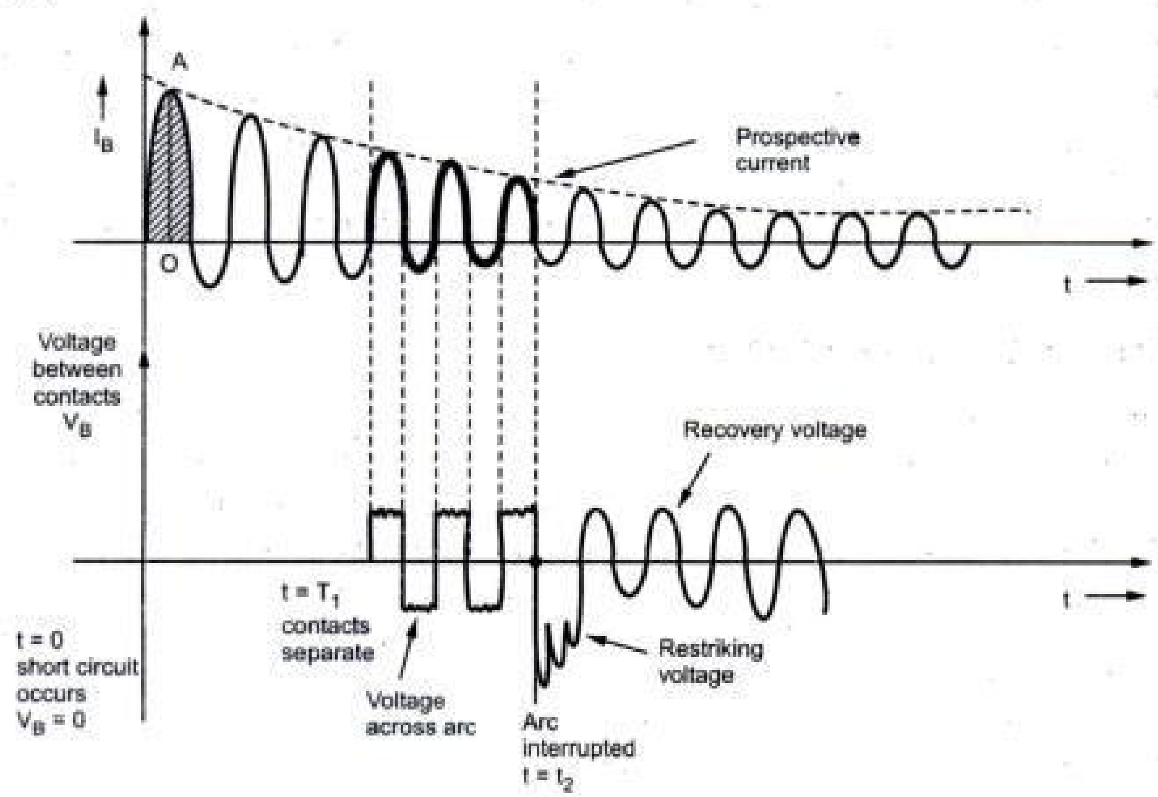


Fig. 9.8 Current and voltage during fault clearing

The current is zero before $t = 0$ as the alternator is on no load. The short circuit is applied at $t = 0$ and current increases to very high value (nearly 10 to 25 times full load current) during first quarter cycle. The peak of first current loop is shown by OA which is maximum instantaneous value of current during short circuit. This instantaneous peak value of first current loop is called making current which is expressed as kA peak.

Now the circuit breaker contacts will separate after few cycles which are taken by relay and other operating mechanism. At time say $t = T_1$ the contacts of circuit breaker separate. The r.m.s. value of short circuit current at that instant of contact separation is called breaking current.

As seen earlier an arc is struck between the contact when they start separating. The arc current varies sinusoidally for few cycles. At $t = T_2$ the arc is interrupted as the dielectric strength of arc space builds sufficiently. This will avoid the continuation of arc. Thus the arc will be extinguished.

The voltage waveform is shown in the Fig. 9.8. Before the instant $t = 0$, the contacts are closed so the voltage between them is zero. At the instant $t = T_1$, the contacts begin to separate and voltage across them starts increasing. This voltage is nothing but the drop across the arc. The current and the voltage across arc are in phase as the arc is resistive. Due to increased arc resistance the voltage across contacts increases in the next cycles. Finally at $t = T_2$ the arc is extinguished. A high frequency transient voltage appears across the contacts which is superimposed on power frequency voltage. This high frequency voltage tries to restrike the arc. Hence it is called Restriking Voltage or Transient Recovery Voltage. This is the voltage which appears across circuit breaker contact which is responsible for restriking of arc. The power frequency system voltage between the circuit breaker contacts after arc extinction is called Recovery Voltage. The prospective current shown in the waveform may be defined as the current that would flow in the circuit if circuit breakers were replaced by solid conductor.

9.7 Transient Recovery Voltage

The transient recovery voltage has effect on the behaviour of circuit breaker. This voltage appears between the contacts immediately after final arc interruption. This causes high dielectric stress between the contacts. If this dielectric strength of the medium between the contacts does not build up faster than the rate of rise of the transient recovery voltage then the breakdown takes place which will cause restriking of arc. Thus it is very important that the dielectric strength of the contact space must build very rapidly that rate of rise of transient recovery voltage so that the interruption of current by the circuit breaker takes place successfully. The rate of rise of this transient voltage depends on the circuit parameters and the type of the switching duty involved. The rate of building up of the dielectric strength depends on the effective design of the interrupter and the circuit breaker.

If it is desired to break the capacitive currents while opening the capacitor banks, there may appear a high voltage across the contacts which can cause reigintion of the arc after initial arc extinction. Thus if contact space breaks down within a period of one fourth of a cycle from initial arc extinction the phenomenon is called Reigintion. If moving contacts of circuit breakers move a very small distance from the fixed contacts then reigintion may occur without overvoltage. But the arc gets extinguished in the next current zero by which time moving contacts should be moved by sufficient distance from fixed contacts. Thus the reignition is in a way not harmful as it will not lead to any overvoltage beyond permissible limits.

If the breakdown occurs after one fourth of a cycle, the phenomenon is called Restrike. In restriking, high voltage appear across the circuit breaker contacts during capacitive current breaking. In successive restrikes, voltage will go on increasing which may lead to damage of circuit breaker. Thus the circuit breakers used for capacitors should be free from Restrike i.e. they should have adequate rating.

9.8 Effect of Different Parameters on Transient Recovery Voltage (TRV)

As seen from the previous section, after the final current, zero high frequency transient voltage appears across the circuit breaker poles which is superimposed on power frequency system voltage and tries to restrike the arc. This voltage may last for a few tens or hundreds of microseconds. If the shape of this TRV is seen on the oscilloscope then it can be seen that it may be oscillatory, non-oscillatory or a combination of two depending upon the characteristics of the circuit and the circuit breaker. The waveform is as shown in the Fig. 9.9.

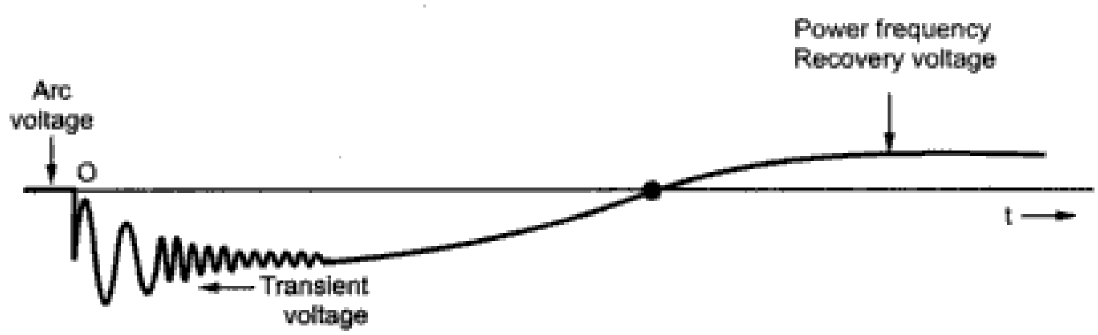


Fig. 9.9 Shape of transient recovery voltage

This voltage has a power frequency component and an oscillatory transient component. The oscillatory component is due to inductance and capacitance in the circuit. The power frequency component is due to the system voltage. This is shown in the Fig. 9.10.

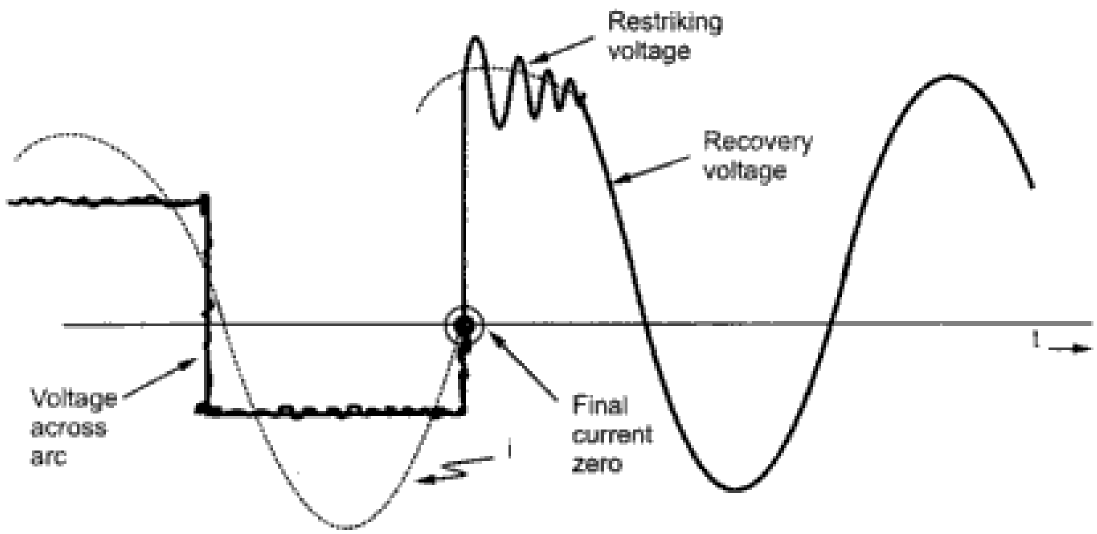


Fig. 9.10 Voltages after final current zero

The transient oscillatory component lasts for few microseconds after which power frequency voltage remains. The transient component has frequency given by,

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

where f_n = Frequency of transient recovery voltage

L = Equivalent inductance

C = Equivalent capacitance

9.8.1 Effect of Natural Frequency on TRV

With increase in the natural frequency the rate of rise of TRV at current zero increases. This is shown in the Fig. 9.11. The rate of rise of transient recovery voltage is represented by slopes of tangents to the three waveforms drawn at different frequencies.

Rate of rise of TRV causes voltage stress on the contact gap which will continue the arc. If the frequency is increased then relatively small time is available for building of dielectric strength of contact gap. Hence increase in frequency causes greater stresses. The rate of rise of TRV is related with the breaking capacity of a circuit breaker. Thus it also means rate of rise of TRV is dependent on natural frequency of TRV. As frequency increases the breaking capacity reduces.

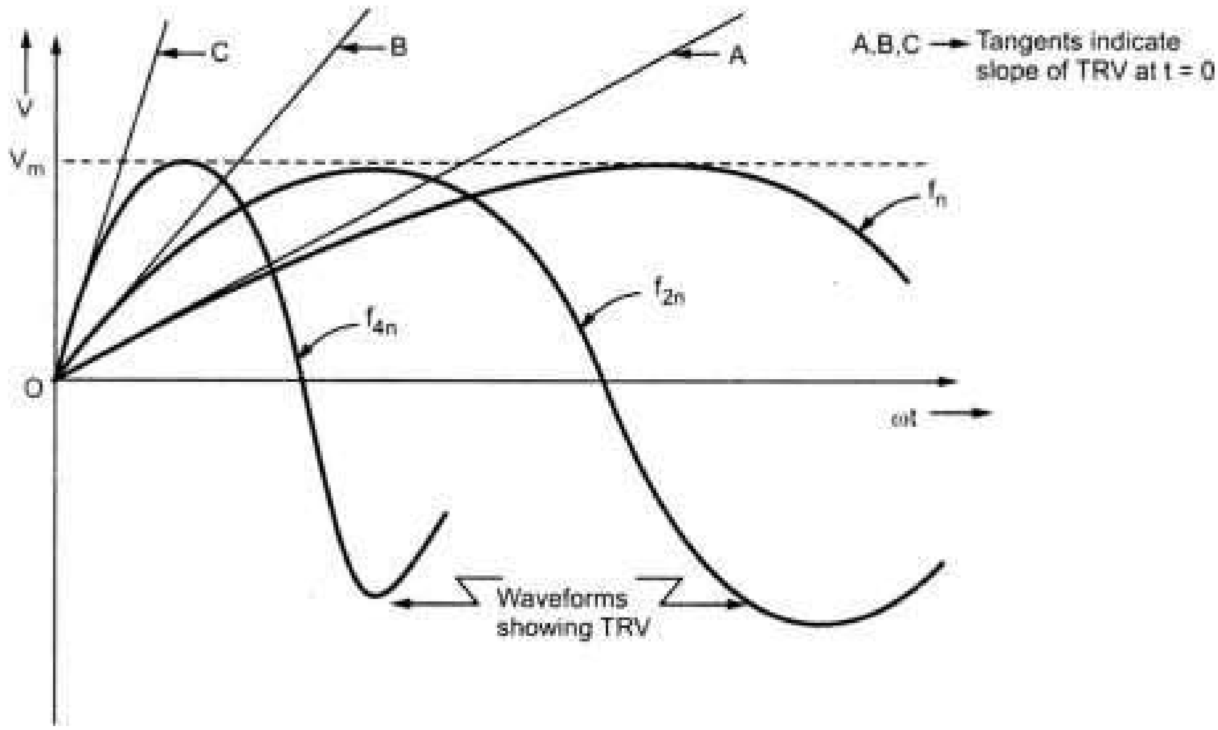


Fig. 9.11 Effect of frequency of TRV

9.8.2 Effect of Power Factor on TRV

At the instant of final current zero the voltage appearing across the C.B. contacts is affected by the p.f. of the current. At current zero the arc is extinguished. After this power frequency voltage appears across the circuit breaker. The instantaneous value of the voltage at current zero depends on phase angle between the current and voltage.

For unity p.f. load as shown in the Fig. 9.12 both voltage and current are in phase and are zero at the same instant.

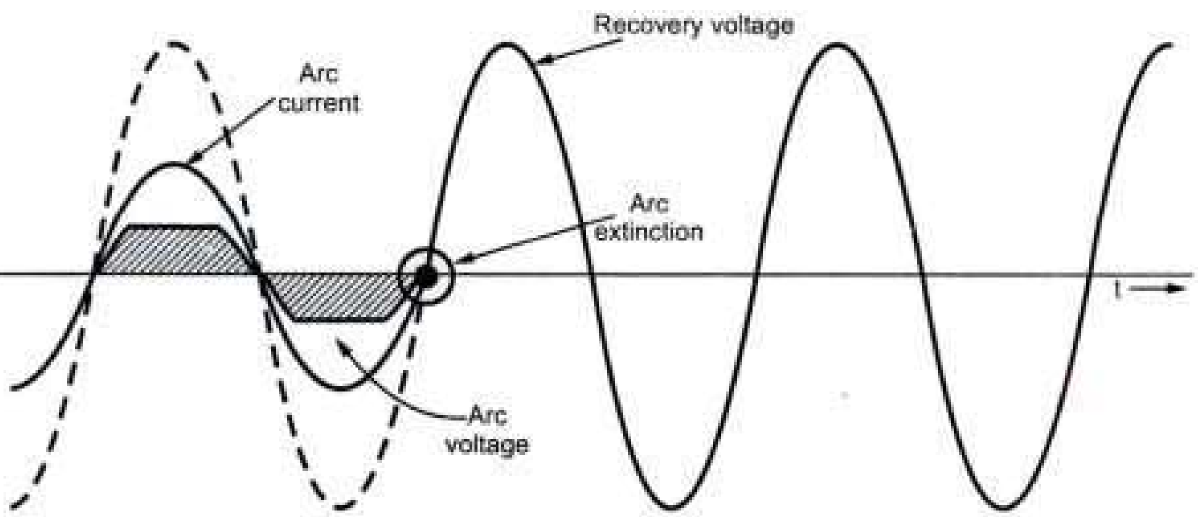


Fig. 9.12 Unity power factor

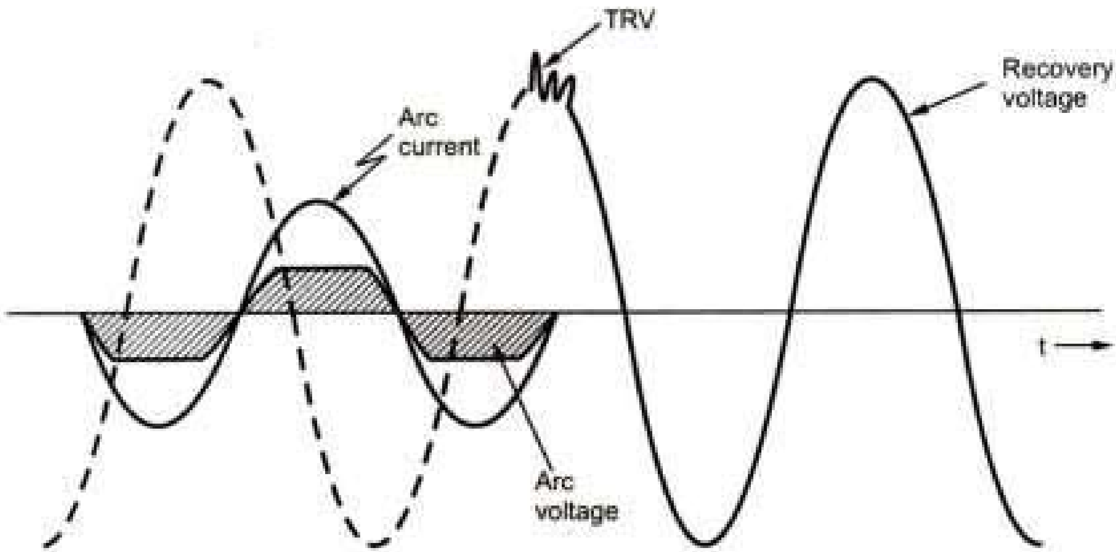


Fig. 9.13 Zero power factor

If we consider zero power factor currents, the peak voltage E_{max} is impressed on the circuit breaker contacts at the current zero instant. This instantaneous voltage gives more transient and provides high rate of rise of TRV. Hence if the p.f. is low then interrupting of such current is difficult.

9.9 Recovery Voltage

As seen previously it is the voltage having normal power frequency which appears after the transient voltage.

9.9.1 Effect of Reactance Drop on Recovery Voltage

Before fault is taking place let us consider that the voltage appearing across circuit breaker is V_1. As the fault current increases, the voltage drop in reactance also increases. After fault clearing the voltage appearing say V_2 is slightly less than V_1. The system takes some time to regain the original value.

9.9.2 Effect of Armature Reaction on Recovery Voltage

The short circuit currents are at lagging power factor. These lagging p.f. currents have a demagnetizing armature reaction in alternators. Thus the induced e.m.f. of alternators decreases. To regain the original value this e.m.f. takes some time. Thus the power frequency component of recovery voltage is less than the normal value of system voltage.

9.10 Single Frequency Transient

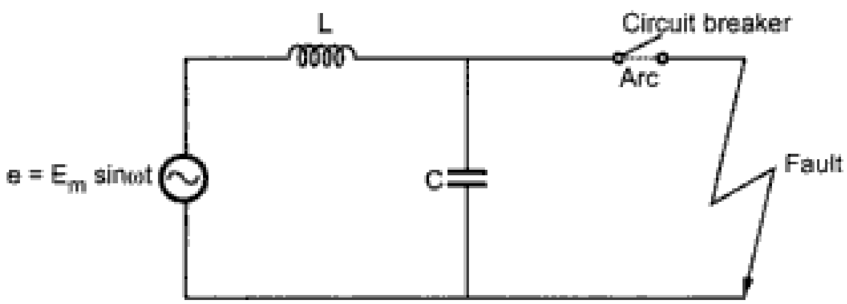


Fig. 9.14

Consider the circuit shown in the Fig. 9.14. This circuit produces the single frequency restriking voltage transient.

The natural frequency of oscillation is given by,

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

where L = Inductance in henry

C = Capacitance in farads

Depending upon the values of L and C, the frequency ranges from 10 Hz to 10 kHz. The circuit configuration in actual power system is complicated and it has distributed capacitance and inductances. In such circuits the TRV has several components of frequencies which is shown in the Fig. 9.15.

The transient shown in the Fig. 9.15 is obtained by operating the terminal fault where reactance between the fault and circuit breaker is negligible.

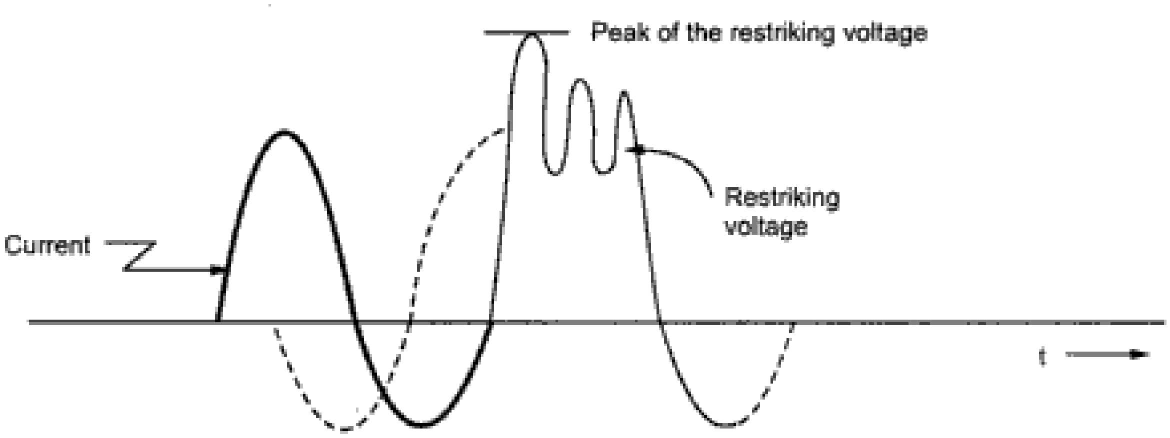


Fig. 9.15

9.11 Double Frequency Transient

In last section we have considered inductance L and capacitance C on only one side of circuit breaker. But it may be on both sides of circuit breaker. This is shown in the Fig. 9.16.

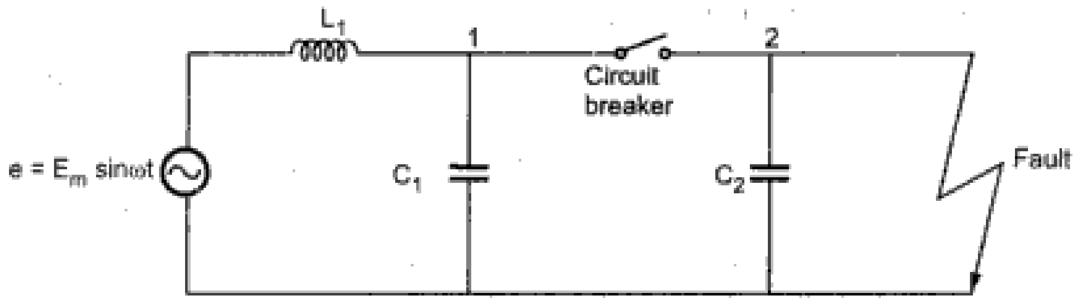


Fig. 9.16

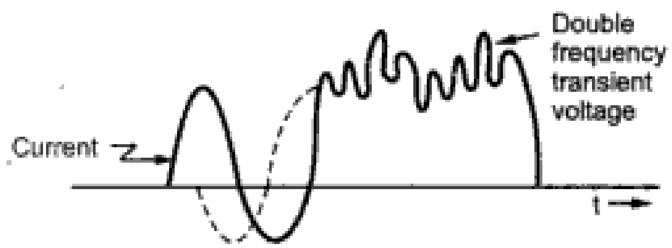


Fig. 9.17

The points 1 and 2 are equipotential points before clearing the fault. But after the arc extinction there will be two circuits which may oscillate at their own natural frequencies and thus a composite double frequency transient appears across circuit breaker. This is shown in the Fig. 9.17.

The circuit configuration, the type of fault and the type of neutral earthing are the important factors which will decide the frequency, rate of rise and peak value of the TRV.

The TRV wave is defined by specifying the peak value and time required to reach the same or it can be specified by defining the segment of lines which enclose the TRV waveform.

9.12 Derivation of Rate of Rise of TRV

As seen previously the transient voltage that appears across the circuit breaker contacts at the instant of arc extinction is called Restriking Voltage. The rate of rise of restriking voltage RRRV is nothing but rate which is expressed in volts per micro-second. This will represent the rate at which Transient Recovery Voltage is increasing. The rate of rise of TRV is dependent on system parameters.

With e as the restriking voltage in volts then

$$\text{RRRV} = \frac{de}{dt} \quad \text{volts / } \mu\text{sec}$$

The maximum instantaneous value attained by the restriking voltage is called the peak restriking voltage.

With the given specifications of TRV the circuit breaker must be able to interrupt the short circuit breaking current. The peak value of TRV, time to reach the peak

where,

e = voltage across breaker terminals nothing but restriking voltage

Differentiating (1),

$$\frac{di}{dt} = \frac{e}{L} + C\frac{d^2e}{dt^2} \qquad \dots (2)$$

The solution of 'e' will thus depend on the current and if interruption takes place at current zero i.e. when t = 0 then,

$$i = \frac{E_m}{\omega L} \sin \omega t$$

and after opening of circuit breaker,

$$\frac{di}{dt} = \frac{E_m}{\omega L} \cdot \omega \cos \omega t$$

$$= \frac{E_m}{L} \cos \omega t \qquad \text{at } t = 0$$

Substituting this in (2),

$$\frac{E_m}{L} \cos \omega t = \frac{e}{L} + C\frac{d^2e}{dt^2}$$

This is standard equation and solution of this equation is,

$$\boxed{e = E_m\left[1 - \cos\left(\frac{t}{\sqrt{LC}}\right)\right]} \qquad \dots (A)$$

This is an **expression for restriking voltage** in which,

E_m = Peak value of recovery voltage phase to neutral in volts.

t = time in sec.

L = inductance in henries

C = capacitance in farads

e = restriking voltage

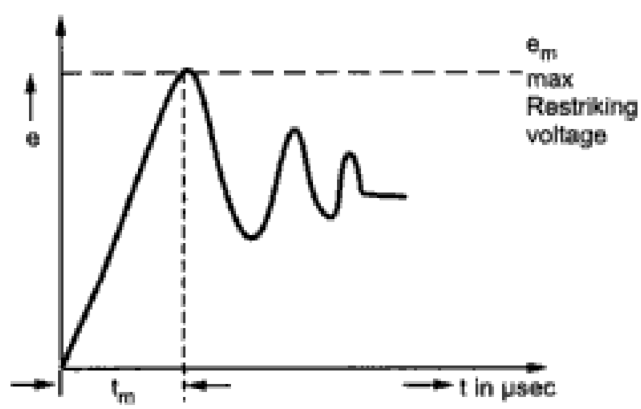


Fig. 9.19

9.12.1 Expression for Maximum Value of Restriking Voltage E_m and Corresponding Time t_m

Now

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

if 'e' is to be maximum

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

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

∴ Time at which maximum restriking voltage occurs is,

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

And peak value of restriking voltage,

$$\boxed{e_m = 2\,E_m}$$

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

9.12.2 Expression for RRRV and Maximum RRRV

Now $$\text{RRRV} = \frac{de}{dt} = \frac{d}{dt}\left[E_m\left(\cos\left[\frac{t}{\sqrt{LC}}\right]\right)\right]$$

$$\therefore \qquad \boxed{\text{RRRV} = \frac{E_m}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}}}$$

and $$\boxed{\text{maximum RRRV} = \frac{E_m}{\sqrt{LC}}}$$

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

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

$$\therefore \quad \boxed{t = \frac{\pi\sqrt{LC}}{2}} \qquad \text{for maximum RRRV}$$

9.12.3 Frequency of Oscillation of Restriking Voltage (Transient)

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

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

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

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

9.12.4 Restriking Voltage Under Various Conditions

The restriking voltage 'e' under various conditions will be,

$$e = V_{ar}\left(1 - \cos\left[\frac{t}{\sqrt{LC}}\right]\right)$$

where V_{ar} active recovery voltage i.e. the instantaneous value of recovery voltage at current zero and V_{ar} can be written as

$$V_{ar} = K_1 K_2 K_3 E_m$$

Here E_m is the peak value of system voltage where,

K_1 is factor which takes into accounts effect of circuit p.f. and $K_1 = \sin\phi$

So if $\phi = 90°, \quad K_1 = 1$

K_2 is factor which accounts effect of armature reaction on recovery voltage.

K_3 is phase factor or first pole to clear factor.

9.12.5 First Pole to Clear Factor

The first pole to clear factor is given by,

$$\text{Factor pole to clear factor} = \frac{\text{RMS voltage between healthy phase and faulty phase}}{\text{Phase to neutral voltage with fault removed}}$$

In three phase systems if fault does not involve the earth, the voltage across the circuit breaker pole first to clear is 1.5 times the phase voltage. The arc extinction in the three poles of three phase circuit breakers is not simultaneous as currents are 120° out of phase. In practical systems the recovery voltage of the pole first to extinguish the arc is of the order of 1.2 to 1.5 times of the phase voltage.

If fault involves earth and the neutral is grounded through reactor, the recovery voltage is influenced by the equivalent system reactances.

Thus in 3 phase circuits $K_3 = 1$ if neutral is earthed and fault is also earthed. While $K_3 = 1.5$ if neutral is earthed and fault is insulated or neutral is insulated and fault is earthed.

➠ **Example 9.1 :** *In short circuit test on a 3 pole, 132 kV circuit breaker, the following observations are made p.f. of fault 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillations of restriking voltage 16 kHz. Assume neutral is grounded and fault is not grounded. Determine average RRRV.*

Solution :

$$e = V_{ar}\left[1 - \cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

where

$$V_{ar} = K_1 K_2 K_3 E_m$$

$$K_1 \text{(takes into account p.f. effect)} = \sin\phi$$

$$K_2 \text{ (takes into account armature reaction effect)} \approx 0.9$$

K_3 (Phase factor or 1st pole to clear factor)

$$= 1 \quad \text{for both neutral and fault grounded}$$

$$= 1.5 \quad \text{for any one of the two not grounded.}$$

In the problem,

$$K_1 = \sin\phi = \sin[\cos^{-1} 0.4] = 0.9165$$

$$K_2 = 0.9 \qquad K_3 = 1.5$$

Peak value of voltage i.e. line to ground

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

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

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

$$= 2\pi \times 16 \times 10^3$$

$$= 1 \times 10^5$$

Time to reach maximum restriking voltage

$$\text{Maximum } t_m = \pi\sqrt{LC} = \frac{\pi}{1 \times 10^5}$$

Maximum restriking voltage,

$$= 2\, V_{ar}$$

$$= 2\, K_1\, K_2\, K_3\, E_m = 2 \times 0.9165 \times 0.9 \times 1.5 \times 107.77 \times 10^3$$

$$= 2.66682 \times 10^5 \text{ V}$$

Average RRRV,

$$\frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}} = \frac{2.66682 \times 10^5}{\pi / 1 \times 10^5}$$

$$= 8.48 \times 10^9 \text{ V/sec} = 8.48 \times 10^6 \text{ kV/sec} = 8.48 \text{ kV}/\mu\text{sec}$$

Example 9.2 : *In a short circuit test on a 130 kV, 3 phase system, the breaker gave the following results : p.f. of fault 0.45, recovery voltage 0.95 times full line voltage, breaker current symmetrical, and restriking transient had a natural frequency 16 kHz. Determine average RRRV. Assume fault is grounded.*

Solution :

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

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

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

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

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

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

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

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

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

Example 9.3 : *Calculate the RRRV of 132 kV circuit breaker with neutral earthed. S.C. data as follows: Broken current is symmetrical, restriking voltage has frequency 20 kHz, p.f. 0.15. Assume fault is also earthed.*

Solution :

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

$$K_2 = 1$$

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

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

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

$$= 106.54889 \text{ kV}$$

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

$$= 213.09778 \text{ kV}$$

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

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

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

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

$$= 8.52 \text{ kV}/\mu\text{sec}$$

Example 9.4 : *A 50 Hz generator has e.m.f. to neutral 7.5 kV (r.m.s.). The reactance of generator and the connected system is 4 Ω and distributed capacitance to neutral is 0.01 μF with resistance negligible . Find,*

i) maximum voltage across the circuit breaker contacts

ii) frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Solution :

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

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

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

1) Maximum voltage $= 2 \times E_m$

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

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

$$= 14.1227 \text{ kHz}$$

3) Maximum time to reach maximum voltage is,

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

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

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

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

Example 9.5 : *In a system having 220 kV, the line to ground capacitance 0.015 μF, inductance 3.5 H. Determine voltage appearing across pole of circuit breaker if a magnetising current of 6.5 A instantaneous, is interrupted. Determine also the value of resistance to be used across the contacts to eliminate the restriking voltage.*

Solution :

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

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

Energy stored in 'L' = energy given to capacitor

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

$$= 6.5\sqrt{\frac{3.5}{(0.015 \times 10^{-6})}}$$

$$= 99.3 \text{ kV}$$

To eliminate restriking voltage and critical damping condition,

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

$$= 0.5\sqrt{\frac{3.5}{(0.015 \times 10^{-6})}} = 7.635 \text{ k}\Omega$$

Example 9.6 : *A 50 Hz, 3 ph alternator, has rated voltage 13.5 kV, connected to circuit breaker, inductive reactance 4 Ω/ph, C = 2 μF.*
Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

Solution :

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

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

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

$$\text{Maximum restriking voltage} = 2E_m = 22.0454 \text{ kV}$$

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

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

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

$$\therefore \text{Maximum RRRV} = 2\pi f_n E_m = \pi \times 0.997\times 10^3 \times 22.0454 \text{ kV/sec} = 0.06907 \text{ kV/}\mu\text{sec}$$

9.13 Interruption of Capacitive Currents

In power systems capacitor banks are used in the network which supplies reactive power at leading power factor. There are various conditions such as opening a long transmission line on no load or disconnecting a capacitor bank etc., in which it is required to interrupt the capacitive currents which is a difficult task for the circuit breakers. To understand this difficulty let us consider a simple circuit shown in the Fig. 9.20.

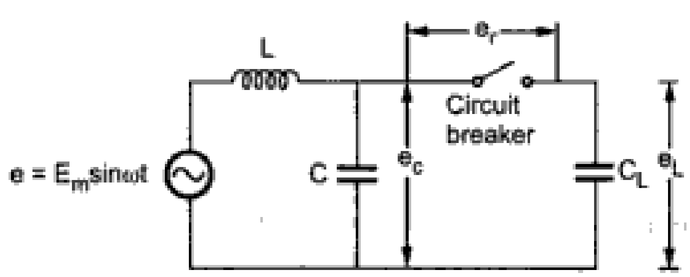


Fig. 9.20 Interruption of capacitive currents

The value of load capacitance C_L is greater than C. The voltage across a capacitor cannot change instantaneously. The currents supplied to the capacitor are generally small and interruption of such currents take place at first current zero. Also at the beginning, the rate of rise of recovery voltage is low and increases slowly. Whenever such circuit is opened a charge is trapped in the capacitance C_L. The voltage e_L across the load capacitance will hold the same value when circuit was opened. This voltage is nothing but peak of supply voltage as power factor angle is nearly 90° leading.

After opening the circuit the voltage V_C across the capacitance C oscillates and approaches a new steady value. But due to small value of capacitance C, the value attained is close to the supply voltage. The recovery voltage e_r is nothing but difference between e_C and e_L. Its initial value is zero as the circuit breaker will be closed and increases slowly in the beginning. When V_C reverses after half cycle, the recovery voltage is about twice the normal peak value. Therefore it is possible that at this instant arc may restrike as the electrical strength between the circuit breaker contacts is not sufficient. The circuit will be reclosed and e_L oscillates at a high frequency.

The supply voltage at this instant will be at its negative peak; therefore a high frequency oscillation takes place.

At the instant of restrucking the arc, the recovery voltage V_r is zero. The voltage across the load capacitance reaches – 3 times the peak value of normal supply voltage. The recovery voltage then starts increasing. If again restriking of arc takes place, a high frequency of oscillation of e_L takes place. Such several repetitions of the restriking cycle will increase the voltage across load capacitance to a dangerously high value. In practice this voltage is limited to 4 times the normal peak of the voltage. This is represented in the Fig. 9.21.

Thus in the successive restrikes, the energy $\frac{1}{2} CV^2$ is to be dissipated which is quite large and the circuit breaker may get damaged in the process of restriking. Hence the circuit breakers those are to be used for capacitors must be free from restriking and should have adequate rating for capacitive current switching so that severe voltage transients can be avoided.

If circuit breakers are closed while switching capacitor banks in parallel, the pre-arcing that is arc is struck before contacts touch together, takes place. This may damage the contacts as the energy in the arc is converted into heat. Thus while switching with capacitor banks suitable reactor L must used in series to limit high frequency inrush current.

Consider the circuit shown in the Fig. 9.22.(a).

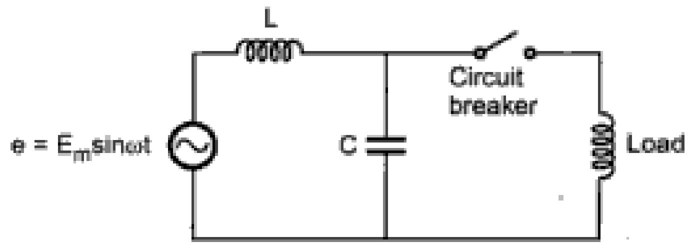


Fig. 9.22 (a) Circuit diagram showing interruption of inductive currents

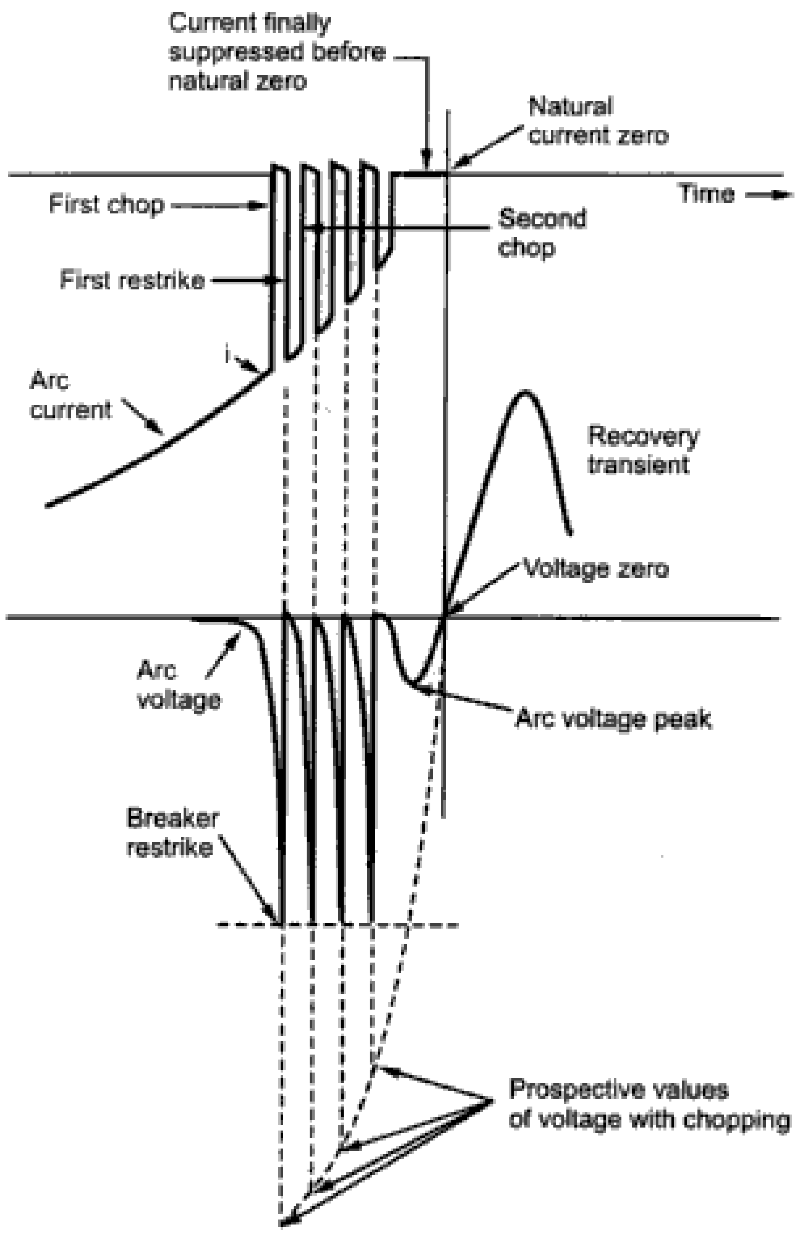


Fig. 9.22 (b)

While interrupting low inductive currents the rapid deionization of contact space and blast effect may cause the current to reduce abruptly to zero well before the natural current zero. This current chopping causes very serious voltage oscillations.

Let the arc current be i when it is chopped down to zero value. The stored energy in the inductor which $\frac{1}{2}$ L i^2 will be discharged in to the capacitance so that the capacitor is charged to a prospective voltage V such that,

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

$$\therefore \quad V = i\sqrt{L/C} \quad \text{volts}$$

This prospective voltage is extremely high as compared to the normal system voltage. The frequency of natural oscillations is given by,

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

To understand this point let us consider a small example of 220 kV circuit breaker interrupting a magnetizing current of 10 A r.m.s. of transformer. Let the current be chopped at the instantaneous value of 7A. Let the value of inductance and capacitance be 35 H and 0.0020 μF

Assuming that all the inductive energy is transferred to capacitance and using the above formula,

$$e = 7\left[\sqrt{\frac{35}{0.0020 \times 10^{-6}}}\right]$$

$$\therefore \quad e = 926 \text{ kV}$$

This voltage will appear across the circuit breaker contacts. Such a transient voltage having high RRRV appears across the contacts. There will be restriking of arc at some point. If the arc restrikes further, chop may occur. Thus before final interruption of current there will be many chops and the circuit breaker will fail to clear the fault. Alternately if the restrike does not occur, the severe voltage stress will appear across circuit breaker contacts.

The rise of voltage before restriking is an important factor. The lower is the rate of rise, more is the time required for deionization and high voltage will be reached.

After first chopping the deionising force which is still in action acts and second chop of current takes place. But the arc current is now smaller than the previous one and arc current collapses and restriking voltage is again build. Thus a sequence of chops will occur and arc will continuously decrease until a final chop brings arc current to zero. There will not be any further restriking as the gap is almost deionise. This is represented in the Fig. 9.22 (b).

9.15 Resistance Switching

It can be seen from previous sections that the interruption of low inductive currents, interruption of capacitive currents give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance R across the circuit breaker contacts. This process is known as Resistance Switching.

When the resistance is connected across the arc, a part of the arc current flows through the resistance. This will lead to decrease in arc current and increase in rate of deionization of the arc path and resistance of arc. This will increase current through shunt resistance . This process continues until the current through the arc is diverted through the resistance either completely or in major part. If the small value of the current remains in the arc then the path becomes so unstable that it is easily extinguished.

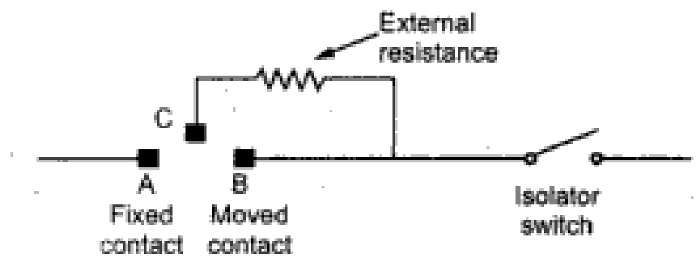


Fig. 9.23 Typical resistor connection

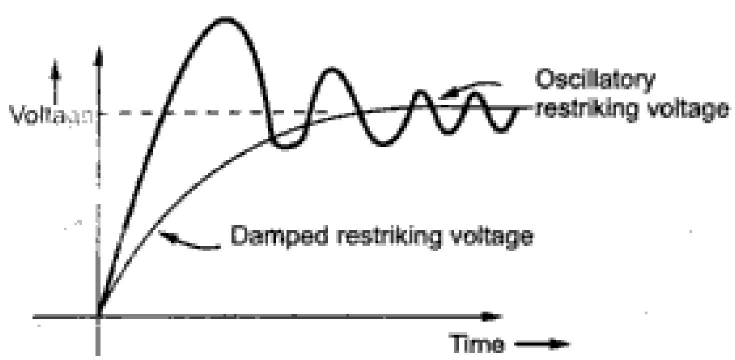
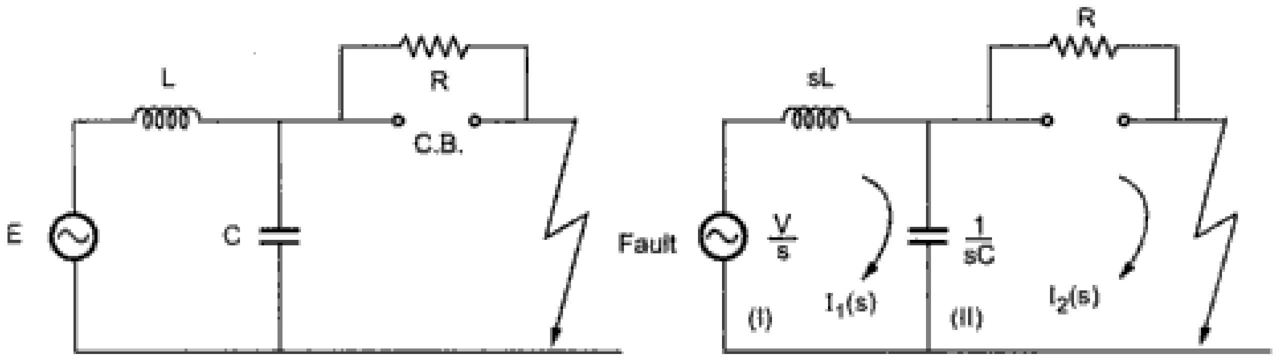


Fig. 9.24

The resistance may be automatically switched in and arc current can be transferred. The time required for this action is very small. As shown in the Fig. 9.23 the arc first appears across points A and B which is then transferred across A and C.

The shunt resistance also ensures the effective damping of the high frequency re-striking voltage transients. This is shown in the Fig. 9.24.

We will now derive a relation which will show how damping is achieved. Consider the circuit and Laplace transform equivalent as shown in the Fig. 9.25.



(a) Circuit

(b) Equivalent circuit

Fig. 9.25

Applying KVL to loop (I)

$$\frac{V}{s} = \left(sL + \frac{1}{sC}\right) I_1(s) - \frac{1}{sC} I_2(s) \quad \text{... (i)}$$

Applying KVL to loop (II),

$$0 = -\frac{1}{sC} I_1(s) + \left(R + \frac{1}{sC}\right) I_2(s) \quad \text{... (ii)}$$

From equation (ii),

$$I_1(s) = (1 + sCR)\, I_2(s)$$

Substituting this value in equation (i)

$$\frac{V}{s} = \left(sL + \frac{1}{sC}\right)(1 + sCR)\, I_2(s) - \frac{1}{sC} I_2(s)$$

$$\therefore \quad \frac{V}{s} = \left[sL + s^2 RLC + \frac{1}{sC} + R - \frac{1}{sC}\right] I_2(s)$$

$$\therefore \quad \frac{V}{s} = (RLCs^2 + Ls + R)\, I_2(s)$$

$$\therefore \quad I_2(s) = \frac{V}{s(RLCs^2 + Ls + R)} = \frac{V/RLC}{s\left(s^2 + \frac{1}{RC} + \frac{1}{LC}\right)}$$

Using partial fractions,

$$I_2(s) = \frac{V}{R}\left\{\frac{1}{s} - \frac{s+\frac{1}{2RC}}{\left(s+\frac{1}{2RC}\right)^2 + \frac{1}{LC} - \left(\frac{1}{2RC}\right)^2} - \frac{\frac{1}{2RC}}{\left(s+\frac{1}{2RC}\right)^2 + \frac{1}{LC} - \left(\frac{1}{2RC}\right)^2}\right\}$$

Put $$x = \frac{1}{2RC}, \quad y = \frac{1}{LC} - \left(\frac{1}{2RC}\right)^2$$

$$I_2(S) = \frac{V}{R}\left\{\frac{1}{s} - \frac{s+x}{(s+x)^2 + \left(\sqrt{y}\right)^2} - \frac{x}{(s+x)^2 + \left(\sqrt{y}\right)^2}\right\}$$

Taking inverse Laplace transform,

$$i_2(t) = \frac{V}{R}\left[1 - e^{-xt}\left(\cos\sqrt{y}\,t + \frac{x}{y}\sin\sqrt{y}\,t\right)\right]$$

The natural frequency of oscillation is given by,

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

It can be seen that with the value of the resistance R equal to or less than $\frac{1}{2}\sqrt{L/C}$, the oscillatory nature of the transient will not be there and RRRV will be within the permissible limits of circuit breaker.

For critical damping

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

Considering different values of R, the oscillations observed are shown in the Fig. 9.26.

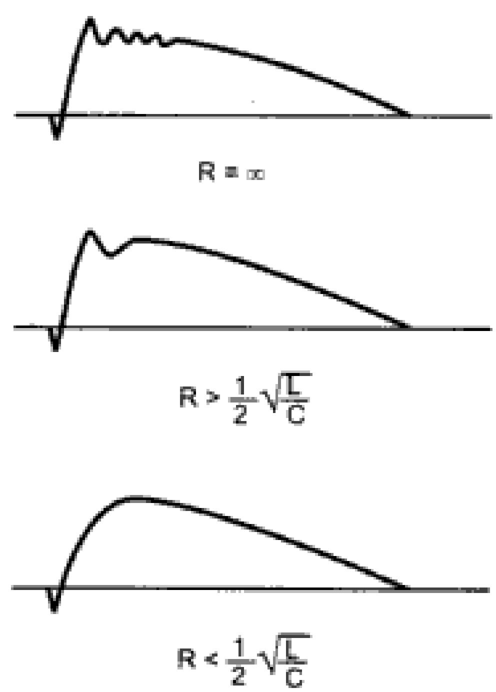


Fig. 9.26

In air blast circuit breakers it is observed that the rate at which dielectric strength of gap increases is lower than in oil breakers. Since air has a much lower dielectric strength than the gases at same temperature and pressure in oil circuit breaker. The dielectric strength of a gas increases with pressure. Thus the air blast circuit breaker is more sensetive to restriking voltage transient. In low or medium voltage air blast circuit breaker the rate or rise of restriking voltage is higher. Thus shunt resistors are used for low and medium voltage air blast circuit breakers. Also in case of oil circuit breakers the resistance switching is not employed as it is not sensitive to RRRV.

➠ **Example 9.7 :** *In 132 kV transmission system, the phase to ground capacitance is 0.01 μF. The inductance being 6 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetizing current of 10 A is interrupted. Find the value of resistance to be used across contact space to eliminate the striking voltage transient.*

Solution :

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

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

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

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

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

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

$$= 10\,(24494.89)$$

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

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

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

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

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

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

9.16 Arc Extinction

The electric discharge which is taking place between the electrodes is nothing but the electric arc. We have seen that when contacts of circuit breakers are separated, an arc is established between the contacts which will last for some period. The circuit breaker should be capable of extinguishing this arc without damaging. The behaviour of circuit breaker is greatly influenced by the arc.

Interruption of arc in case of d.c. circuits is much more difficult than that in case of a.c. circuits. In a.c. currents the natural current zero point is available where the arc vanishes and prevented from restriking.

The arc extinction in case of circuit breakers is not taking place frequently but still it produces lot of stress on the breaker. The different methods adopted for the arc extinction can be grouped into following three categories,

9.16.1 High Resistance Interruption

In this technique the resistance of current path is increased rapidly so that voltage drop is increased. The arc gets extinguished when the system voltage is insufficient to maintain the arc due to high voltage drop. This is normally used in d.c. circuit breakers and air break type a.c. circuit breakers having low capacity. The system inductance stores the energy which is dissipated in the arc.

9.16.2 Low Resistance or Current Zero Interruption

This method is used only in case of a.c. circuit breakers. At the natural current zero point of a.c. wave, the arc is interrupted and is prevented from restriking though there is high restrking voltage by increasing the dielectric strength of the contact gap. This method is used in high power a.c. circuit breakers.

9.16.3 Artificial Current Zero Interruption

In HVDC systems this method is employed for breaking d.c. currents where current is made zero artificially.

9.17 Ionization of Gases

The non-ionized gas is generally a good dielectric medium. But the ionized gas is a conductor as it contains free electrons. In circuit breakers the contact space is ionized by following ways,

9.17.1 Thermal Ionization

At normal temperatures, molecules of gas are moving at various velocities in various directions and possess K.E. as $\frac{1}{2}$ mv^2. With increase in temperature the molecules break up in simpler form and then to atoms. At high temperature more and more collision takes place which will produce free electrons thus produces the ionization by heat and called thermal ionization.

9.17.2 Ionization by Collision

Any particle may be atom, molecule or electron at higher velocity may strike another particle so that the energy of moving particle is imparted to other one. This energy is sufficient to remove electrons from atoms. This is called ionization by collision.

9.17.3 Thermal Emission from Surface of Contacts

Whenever contacts of a breaker are closed, they are pressed against each other at high pressure. With the contact separation, the pressure between them reduces so true area of contact is decreased to a few spots on the surface. Due to this, high current density areas are produced which will cause high local temperature. Due to this, thermal emission takes place at contact surface.

9.17.4 Secondary Emission at Contact Surface

Under the influence of strong electric field between the contacts the electrons move from one contact to other producing emission from contact surface.

9.17.5 Field Emission

The voltage gradiant at the contact surface is high which is sufficient to remove electrons from surface of electrodes since as contacts separate initially voltage gradiant is very high which causes breakdown of gas. This is called field emission.

9.17.6 Photoemission

The electron emission from contact surface due to incident of light energy is called photoemission.

9.18 Deionization

In circuit breakers the deionization is an important process as it supports arc extinction. This can be discussed in short as follows,

9.18.1 Recombination

If a gas contains positive ions and electrons then there is tendency between them to combine and form a neutral atom. This is called recombination. This will assist arc extinction as combination of positive ions and negative charges takes place inside.

9.18.2 Diffusion

The electrons from highly ionized space diffuse to the surrounding weakly ionized space which is an important process in building up dielectric strength.

9.18.3 Conduction of Heat

This will make the temperature to reduce and will help recombination. Particles at high temperature travel to the space at lower temperature. Thus kinetic energy is removed from the space which is ionized between the contacts.

9.19 Arc Formation

As seen earlier the separation of contacts of circuit breaker results in high local temperature on the contact surface. The contact surface get ionized due to thermal emission and the electrons are emitted. The space between the contacts is ionized and becomes conducting. Thus the arc is initiated between the contacts.

The Fig. 9.27 shows general form of arc voltage and arc current. It can be seen that voltage is nearly constant when current is nearly at its maximum.

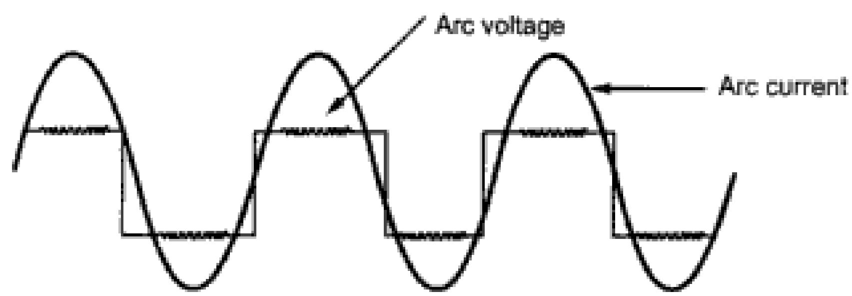


Fig. 9.27

The arc path is purely resistive and the arc voltage is in phase with an arc current. When the contacts are separated the arc voltage increases due to increase in arc length. The arc voltage is increased till it becomes more than system voltage across the contacts where arc gets extinguished.

9.20 High Resistance Arc Interruption Methods

The various methods of high resistance and interruption are,

1. Lengthening the arc
2. Splitting of arc
3. Cooling of arc

9.20.1 Lengthening the Arc

In this method the arc length is increased by using arc runners which are horn like blades of conducting material. The arc runners are connected to arcing contacts and it is in the shape of letter 'V'. The arc is initiated at the bottom and blows upwards due to electromagnetic force. Due to this arc length increases and consequently arc is extinguished.

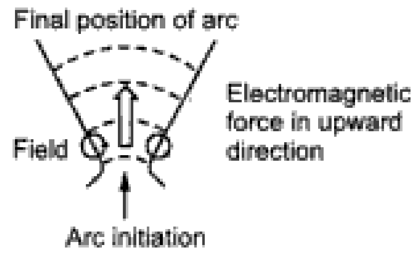


Fig. 9.28 Arc lengthening

9.20.2 Splitting of Arc

In this method elongation of arc is done and the arc is split using arc splitters which are specially made plates of resin bonded fibre glass. These plates are placed in perpendicular path to arc so that it will be pulled towards it by electromagnetic force. When the arc is pulled upwards it gets elongated then split and cooled due to which it gets extinguished. This is shown in the Fig. 9.29.

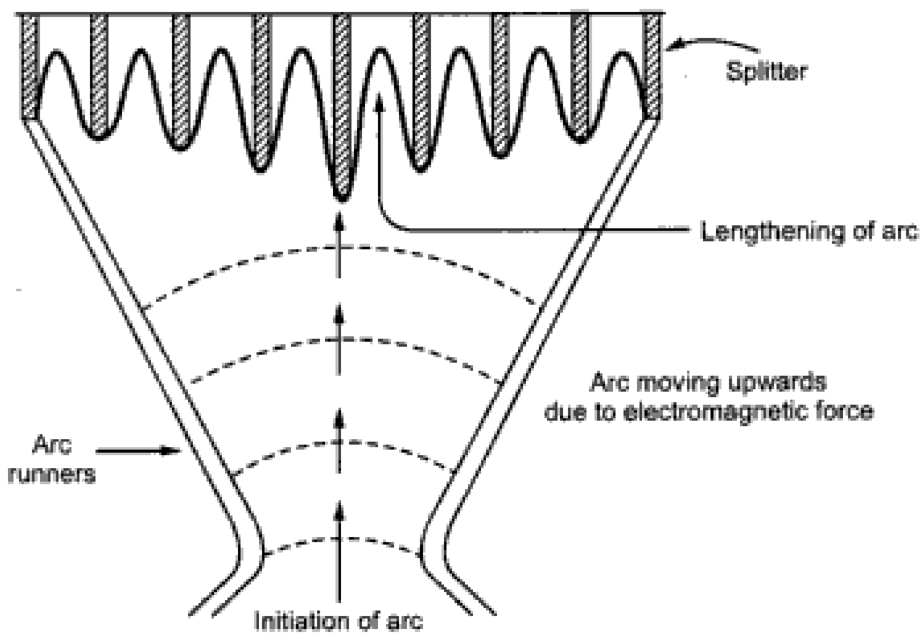


Fig. 9.29 Arc splitting

9.20.3 Cooling of Arc

As already seen, the recombination of ionized particles can be done by cooling the arc which removes heat from the arc. This is done by bringing the arc in contact with cooled air. Due to cooling the arc diameter reduces which will increase its resistance. This will help in arc extinction.

9.21 Low Resistance or Zero Point Extinction

This method is used in a.c. arc interruption. The current becomes zero two times in a cycle. So at each current zero point the arc vanishes for small instant and again it appears.

But in a.c. circuit breakers the arc is interrupted at a current zero point. The space between the contacts is deionized quickly if there is fresh unionized medium such as oil or fresh air or SF_6 gas between the contacts at current zero point. This will make dielectric strength of the contact space to increase such that arc will be interrupted and discontinued after current zero. This action produces high voltage across the contacts which is sufficient to reestablish the arc. Thus the dielectric strength must be build more than the restriking voltage for faithful interruption of arc. Then the arc is extinguished at next current zero.

While designing the circuit breakers the care is taken so as to remove the hot gases from the contact space immediately after the arc. So that it can be filled by fresh dielectric medium having high dielectric strength.

In summary we can say that the arc extinction process is divided in thee parts,

a) Arcing phase

b) Current zero phase

c) Post arc phase

In arcing phase, the temperature of the contact space is increased due to the arc. The heat produced must be removed quickly by providing radial and axial flow to gases. The arc can not be broken abruptly but its diameter can be reduced by the passage of gas over the arc. When a.c. current wave is near its zero, the diameter of the arc is very less and consequently arc is extinguished. This is nothing but current zero phase. Now in order to avoid the reestablishment of arc, the contact space must be filled with dielectric medium having high dielectric strength. This is post arc phase in which hot gases are removed and fresh dielectric medium is introduced.

9.22 Arc Interruption Theories

There are two main theories explaining current zero interruption of arc

1) Recovery Rate Theory or Slepian's Theory

2) Energy balance theory or Cassie's Theory

9.22.1 Slepian's Theory

Slepian described the process as a race between the dielectric strength and restriking voltage. After every current zero, there is a column of residual ionised gas. This may cause arc to strike again by developing necessary restriking voltage and this voltage stress is sufficient to detach electrons out of their atomic orbits which releases great heat.

So in this theory rate at which positive ions and electrons recombine to form neutral molecules is compared with rate of rise of restriking voltage. Due to recombination dielectric strength of gap gets recovered. So rate of recovery of dielectric strength is compared with rate of rise of restriking voltage.

If the restriking voltage rises more rapidly than the dielectric strength, gap space breaks down and arc strikes again and persists.

In the Fig. 9.30,

a) Rate of dielectric strength is more than restriking voltage.

b) Rate of dielectric strength is less than rate of rise of restriking voltage.

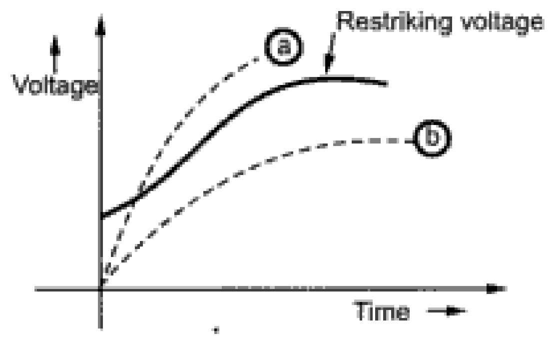


Fig. 9.30

The assumption made while developing this theory is that the restriking voltage and rise of dielectric strength are comparable quantities which is not quite correct. The second drawback is that the theory does not consider the energy relations in the arc extinction. The arcing phase is not covered by this theory so it is incomplete.

9.22.2 Cassie's Theory

Alternative explanation of above process is afforded by Cassie's theory or also called Energy balance theory.

Cassie suggested that the reestablishment of arc or interruption of an arc both are energy balance process. If the energy input to an arc continues to increase, the arc restrikes and if not, arc gets interrupted.

The theory makes the following assumptions :

a) Arc consists of a cylindrical column having uniform temperature at its cross section. The energy distributed in the column is uniform

b) The temperature remains constant.

c) The cross section of the arc adjusts itself to accomodate the arc current.

d) Power dissipation is proportional to cross sectional area of arc column

The energy equation as expressed by Cassie is given by,

$$\frac{dQ}{dt} = EI - N$$

where Q = Energy content / length of arc in cm

E = volts / cm

I = Total current

N = Total power loss / cm

Breakdown occurs if power fed to the arc is more than power loss. The theory is true for high currents.

Immediately after current zero, contact space contains ionised gas and therefore has a finite post zero resistance.

Now there is rising restriking voltage. This rising restriking voltage causes a current to flow between the contacts. Due to this current flow, power gets dissipated as heat in the contact space of circuit breaker.

Initially when restriking voltage is zero, automatically current and hence power is zero. It is again zero when the space has become fully deionise and resistance between the contacts is infinitely high. In between these two extreme limits, power dissipated rises to a maximum. If the heat so generated exceeds the rate at which heat can be removed from contact space, ionisation will persist and breakdown will occur, giving an arc for another half cycle.

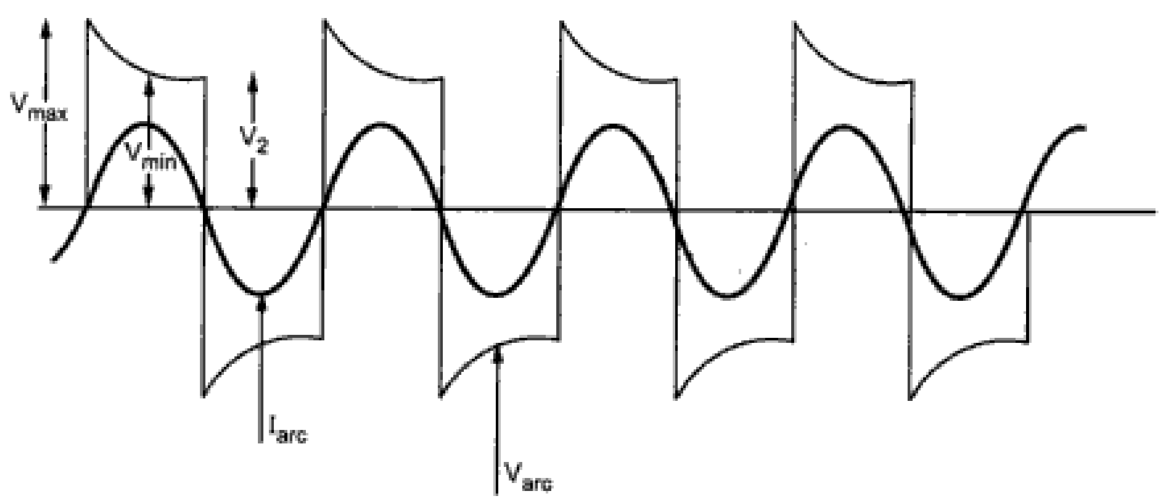


Fig. 9.31 Waveform of a.c. arc

Examples with Solutions

Example 9.8 : *A 50 cycles, 3 phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit breaker. The capacitance to earth between the alternator and circuit breaker is 0.003 μF per phase. The circuit breaker opens when rms value of current is 7500 A. Determine the following:*

i) Maximum rate of rise of restriking voltage.

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

iii) Frequency of oscillations

Neglect first pole to clear factor.

Solution :

i = 7500 A, L = 1.6 mH, C = 0.003 μF

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

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

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

$$= 5331.4083 \text{ V}$$

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

$$= \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}$$

$$= 72643.96 \text{ Hz}$$

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

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

$$= 2433.4438 \text{ V/μsec}$$

Time for maximum RRRV

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

$$= 3.4414 \text{ μsec}$$

Example 9.9 : *In a short circuit test on a 132 kV, 3-phase system the breaker gave the following results p.f. of the fault 0.4, recovery voltage 0.95 of full line value, breaking current is symmetrical and the restriking transient had a natural frequency of 16 kHz. Determine RRRV assuming that the fault is grounded.* **[AU-May-2004]**

Solution :

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

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

Here $\phi = \cos^{-1} 0.4 = 66.42°$

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

$K_2 = 0.95$

$K_3 = 1$

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

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

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

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

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

Example 9.10 : *What is the prospective voltage e across the stray capacitance of 0.0023 μF, when the instantaneous current chopped by circuit breaker is 7 A. The value of the inductance in the circuit is 35.2 H ?* **[AU, Dec.-2004]**

Solution : Prospective voltage appearing across C.B. is given by,

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

$L = 35.2 \text{ H}$

$C = 0.0023 \ \mu\text{F} = 0.0023 \times 10^{-6} \text{ F}$

$i = 7 \text{ A}$

$\therefore$ $$e = 7\sqrt{\frac{35.2}{0.0023 \times 10^{-6}}}$$

$$= 7(123710.74)$$

$\therefore$ $e = \mathbf{865.97 \text{ kV}}$

Example 9.11 : *A circuit breaker is rated at 1200 A, 1500 MVA, 33 kV, 3 sec, 3-phase. What are its rated breaking current and making current ?* **[AU, Dec.-2004]**

Solution :

$$\text{Rated symmetrical breaking current (rms)} = \frac{\text{MVA}}{\sqrt{3} \times \text{kV}}$$

$$= \frac{1500 \times 10^6}{\sqrt{3} \times 33 \times 10^3}$$

$$= \mathbf{26.24\ kA}$$

$$\text{Rated making current} = 2.55 \times 26.24$$

$$= 66.92 \text{ kA}$$

$$\text{Short time rating} = \mathbf{26.24\ kA\ for\ 3\ sec.}$$

Example 9.12 : *A 3-phase alternator has the line voltage of 11 kV. The generator is connected to a circuit breaker. The inductive reactance upto the circuit breaker is 5 Ω / phase. The distributed capacitance upto circuit breaker between phase and neutral is 0.001 μF. Determine peak restriking voltage across the CB, frequency of restriking voltage transients, average rate of restriking voltage upto peak restriking voltage, maximum RRRV.* **[AU, Dec.-2004]**

Solution :

$$E_m = \frac{\sqrt{2} \times 11}{\sqrt{3}} = 8.98 \text{ kV}$$

$$X = 2\pi f L$$

$$L = \frac{X}{2\pi f} = \frac{5}{2\pi(50)} = 0.01591 \text{ H}$$

$$C = 0.001 \ \mu\text{F}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(0.01591)(0.001 \times 10^{-6})}} = \mathbf{39901.11\ Hz.}$$

$$\text{Maximum restriking voltage} = 2E_m = 2(8.98) = 17.96 \text{ kV}$$

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

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin\frac{t}{LC}$$

This is the expression of RRRV

$$\therefore \quad \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} = \frac{8.98}{\sqrt{(0.01591)(0.001 \times 10^{-6})}}$$

$$= \mathbf{2.251\ kV/\mu sec}$$

$$\text{Average RRRV} = \frac{\text{Maximum e}}{\text{Maximum t}} = \frac{2 \times 8.98}{(1/2\ f_n)} = \frac{17.96}{(1/2 \times 39901.11)}$$

$$= \mathbf{1.43\ kV/\mu sec}$$

Example 9.13 : *In a system of 132 kV, the circuit phase to ground capacitance is 0.02 microfarad, the inductance is 5H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetic circuit of 8 A is interrupted instantaneously. Calculate the value of the pre-insertion resistor to be used across the contact space.* **[AU, May-2005]**

Solution : $L = 5$ H, $C = 0.02\ \mu F = 0.02 \times 10^{-6}$ F

$i = 8$ A

Voltage appearing across poles of circuit breaker is given by,

$$V = i\sqrt{\frac{L}{C}} = 8\sqrt{\frac{5}{0.02 \times 10^{-6}}} = 8\sqrt{250 \times 10^6}$$

$$\therefore \quad \mathbf{V = 126.491\ kV}$$

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

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

$$= \frac{1}{2}\sqrt{\frac{5}{0.02 \times 10^{-6}}}$$

$$= \frac{1}{2}(\sqrt{250 \times 10^6})$$

$$\therefore \quad \mathbf{R = 7.9056\ k\Omega}$$

Example 9.14 : *In a short circuit test on a circuit breaker the following readings were observed on a single frequency transient time to reach the peak recovery voltage 40 μsec and the peak restriking voltage 100 kV. Determine the average RRRV and the frequency of oscillations.* **[AU, May-2005]**

Solution : Average RRRV is given as,

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

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

$$\therefore \quad \textbf{Average RRRV} = \mathbf{2500\ V/\mu sec}$$

Natural frequency f_n is given by,

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

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

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

Review Questions

1. *Define a circuit breaker ? Describe its operation in brief.*
2. *Discuss the arc phenomenon in a circuit breaker.*
3. *What are different arc interruption methods ? Explain any one in detail*
4. *Explain the following terms related to circuit breaker.*

   i) Arc voltage ii) Restriking voltage iii) Recovery voltage
5. *Explain the fault clearing process by giving oscillographs of short circuit current.*
6. *Discuss the effect of various parameters on TRV.*
7. *Obtain an expression for rate of rise of restriking voltage.*
8. *Explain resistance switching as applied to circuit breakers.*
9. *Explain in detail the theories which explain the arc extinction phenomenon.*
10. *Write a note on interruption of capacitive currents.*
11. *Write a note on current chopping phenomenon.*
12. *Explain in detail d.c. current breaking.*
13. *A 3 phase alternator has line voltage of 11 kV. The generator is connected to a circuit breaker. The inductive reactance upto circuit breaker is 5 Ω per phase. The distributed capacitance upto circuit breaker between phase and neutral is 0.01 μF. Determine*

    a) Peak restriking voltage across circuit breaker

    b) Frequency of restriking voltage transient

    c) Average rate of restriking voltage upto peak restriking voltage

    d) Maximum RRRV **(Ans. : 18 kV; 12637 c/s ; 0.456 kV/μsec; 714 V/μsec)**
14. *In a short circuit test on a 3 pole circuit breaker of fault was 0.4, the recovery voltage was 0.95 times full line voltage. The breaking current was symmetrical. The frequency of oscillations of restriking voltage was 15000 c/s. Estimate the average rate of rise of restriking voltage. The neutral is grounded and fault involves earth. Neglect first pole to clear factor.* **(Ans. : 4.8 kV/μsec)**
15. *In a system of 132 kV the circuit phase to ground capacitance is 0.01 mF, the series inductance is 6 H. Calculate the voltage appearing across the pole of a circuit breakers if a current of 10 A (instantaneous) is interrupted. Calculate value of the resistance to be used across contact space to eliminate the restriking voltage transient.* **(Ans. : 245 kV ; 12.25 kΩ)**

□□□

10 Circuit Breakers

10.1 Introduction

As already seen in the last chapter, whenever any fault occurs in the power system then that part of the system must be isolated from the remaining healthy part of the system. This function is accomplished by circuit breakers. Thus a circuit breaker will make or break a circuit either manually or automatically under different conditions such as no load, full load or short circuit. Thus it proves to be an effective device for switching and protection of different parts of a power system.

In earlier days fuse was included in the protective system. But due to some limitations they are not used in practice now a days. The main difference between a fuse and circuit breaker is that under fault condition the fuse melts and it is to be replaced whereas the circuit breaker can close or break the circuit without replacement.

10.2 Requirements of Circuit Breaker

The power associated with the circuit breakers is large and it forms the link between the consumers and suppliers. The necessary requirements of circuit breakers are as follows,

1. The normal working current and the short circuit current must be safely interrupted by the circuit breaker.
2. The faulty section of the system must be isolated by circuit breaker as quickly as possible keeping minimum delay.
3. It should not operate with flow of overcurrent during healthy conditions.
4. The faulty circuit only must be isolated without affecting the healthy one.

10.3 Basic Action of a Circuit Breaker

The Fig. 10.1 shows the elementary diagram of a circuit breaker. It consists of two contacts a fixed contact and a moving contact. A handle is attached at the end of the moving contact. It can be operated manually or automatically. The automatic operation needs a separate mechanism which consists of a trip coil. The trip coil is energized by secondary of the current transformer. The terminals of circuit breaker are brought to power supply.

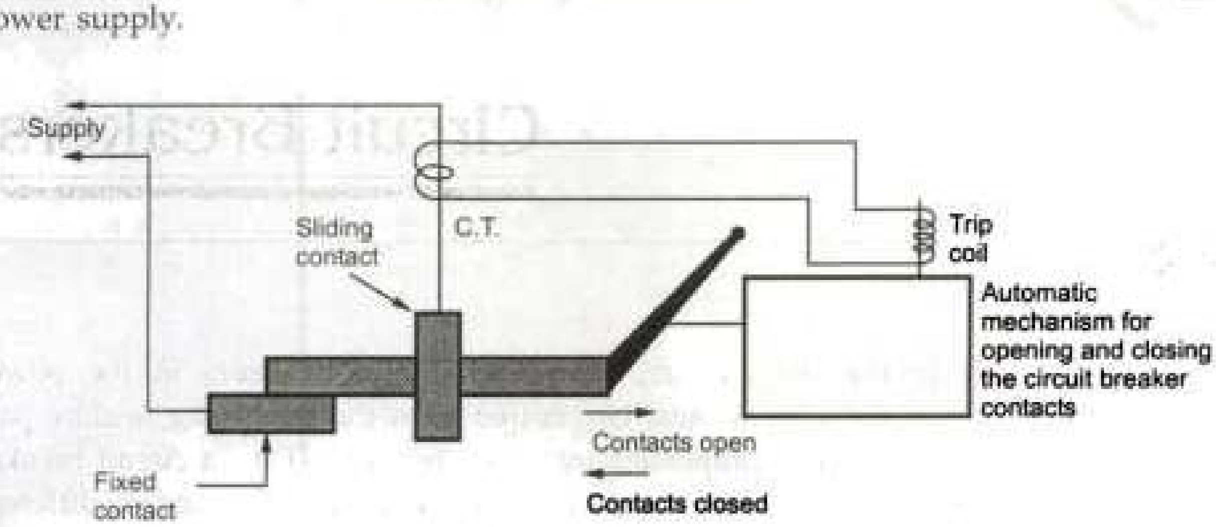


Fig. 10.1 Basic action of circuit breaker

Under normal working conditions the e.m.f. produced in the secondary winding of the transformer is insufficient to energize the trip coil completely for its operation. Thus the contacts remain in closed position carrying the normal working current. The contacts can be opened manually also by the handle.

Under abnormal or faulty conditions high current in the primary winding of the current transformer induces sufficiently high e.m.f. in the secondary winding so that the trip coil is energized. This will start opening motion of the contacts. This action will not be instantaneous as there is always a time lag between the energization of the trip circuit and the actual opening of the contacts. The contacts are moved towards right away from fixed contact.

As we have seen already the separation of contacts will not lead to breaking or interruption of circuit as an arc is struck between the contacts. The production of arc delays the current interruption and in addition to this it produces large amount of heat which may damage the system or the breaker. Thus it becomes necessary to extinguish the arc as early as possible in minimum time, so that heat produced will lie within the allowable limit. This will also ensure that the mechanical stresses produced on the parts of circuit breaker are less.

The time interval which is passed in between the energization of the trip coil to the instant of contact separation is called the **opening time**. It is dependent on fault current level.

The time interval from the contact separation to the extinction of arc is called arcing time. It depends not only on fault current but also on availability of voltage for maintenance of arc and mechanism used for extinction of arc.

10.4 Classification of Circuit Breakers

The circuit breakers are classified by various ways. The different criteria for classification of circuit breakers are as follows,

i) Interrupting medium
ii) According to service
iii) Way of operation
iv) Action
v) Method of control
vi) Way of mounting
vii) Tank construction
viii) Contacts

According to the interrupting medium the circuit breakers are classified as air circuit breaker, air blast circuit breaker, oil circuit breaker and magnetic blast circuit breaker.

According to service there are two types of circuit breakers viz indoor circuit breaker and outdoor circuit breaker.

Depending on the operation, the types of circuit breakers are gravity opened, gravity closed and horizontal break circuit breaker.

On the basis of action, the circuit breakers are classified as automatic and non-automatic circuit breaker.

According to method of control, the circuit breaker may be controlled directly or it may be operated remotely. The remote control may be manual, pneumatic or electrical.

The way of mounting classifies the circuit breakers into panel mounted, rear of panel or remote from panel type.

Depending on the tank construction, the circuit breakers are classified as separate tank for each pole type or one tank for all poles type.

On the basis of contacts, the different types of circuit breakers are Butt, Wedge, Laminated flat contact, Explosion chamber etc.

Out of the various ways of classification of circuit breakers the general way of classification is on the basis of medium used for arc extinction which is normally oil, air, Sulphur Hexa Flouride (SF_6) or vacuum.

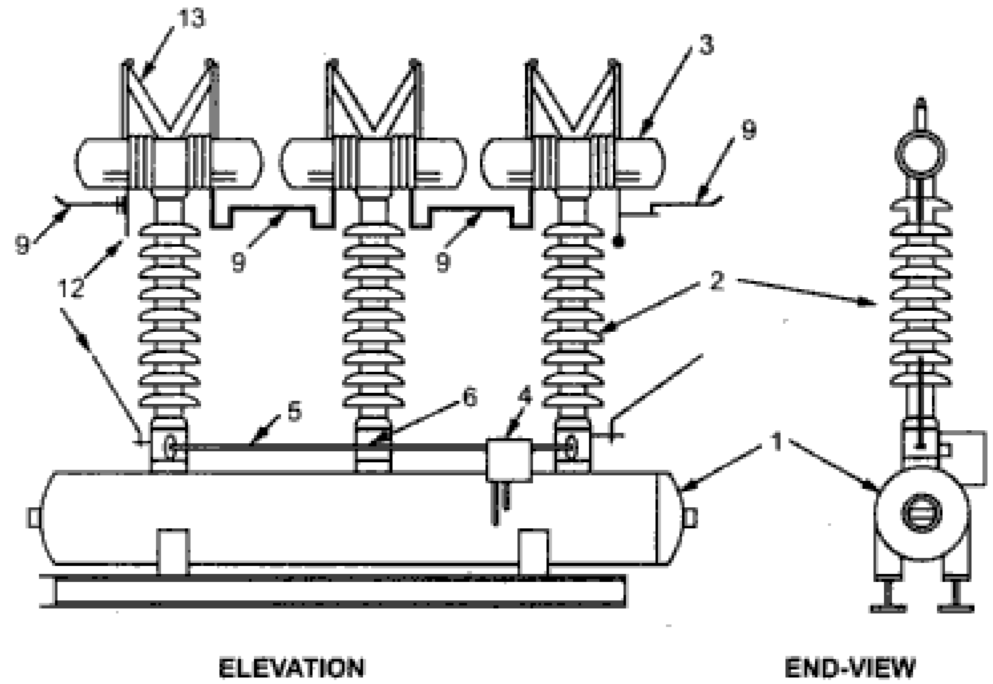
Each type of circuit breaker is associated with its own advnatages and disadvantages. We will now consider some types of circuit breakers in detail.

10.5 Air Blast Circuit Breakers

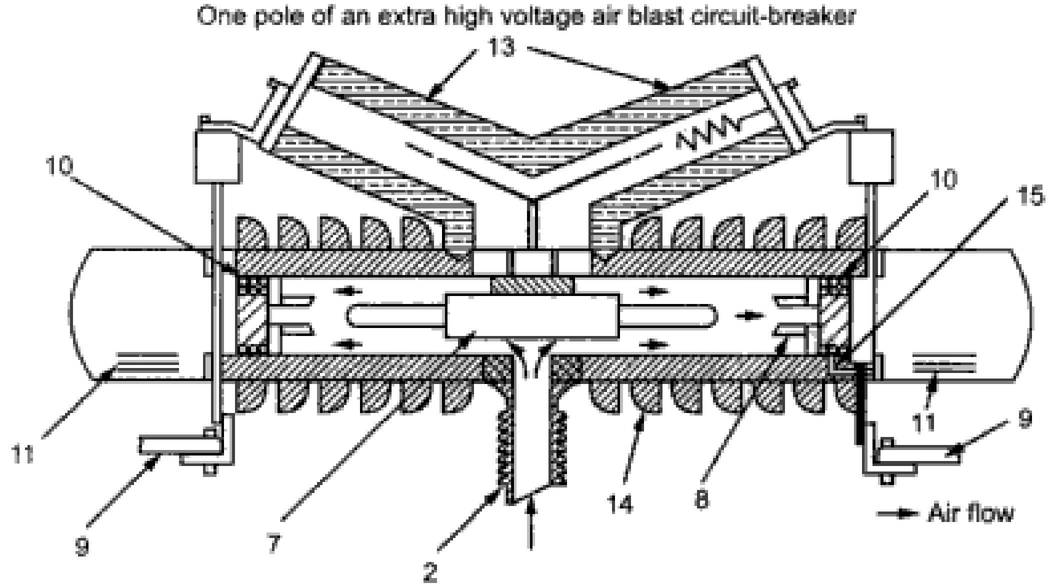
These type of circuit breakers were employed in earlier days for voltages ranging from 11 to 1100 kV. At high voltages this type of circuit breakers are most suitable. In this type of circuit breakers the compressed air is used for the arc extinction. Hence it is called compressed air circuit breaker.

10.5.1 Construction of an Air Blast Circuit Breaker

The Fig. 10.2 shows the constructional details of air blast circuit breaker.



One pole of an extra high voltage air blast circuit-breaker



Details of double arc extinction chamber

1. Tank air reservior (receiver)
2. Hollow insulator assembly
3. Double arc extinction chamber
4. Pneumatic operating mechanism
5. Operating rod
6. Pneumatic value
7. Fixed contact (in 3)
8. Moving contact (in 3)
9. Connection for current
10. Compression springs
11. Openings for air outler
12. Arcing horns Optional
13. Resistance switching unit
14. Enclosure
15. Port

Fig. 10.2 Construction of air blast circuit breaker

At the bottom there is a tank which is called air reservoir with the valves. On this reservoir there are three hollow insulator columns. On the top of each insulator column there is double arc extinguishing chamber. The current carrying parts are connected to the arc extinction chambers in series. The assembly of entire arc extinction chamber is mounted on insulators as there exists large voltage between the conductors and air reservoir.

The double arc extinction chamber is shown separately in the Fig. 10.2 (b). It can be seen that for each circuit breaker pole there are six breaks as there are three double arc extinction poles in series. Each arc extinction chamber consists of two fixed and two moving contacts. These contacts can move axially so as to open or close. The position depends on air pressure and spring pressure. The opening rod is operated by the opening mechanism when it gets control signal (may be electrical or pneumatic). This will lead to flow of high pressure air by opening the valve. The high pressure air enters the double arc extinction chamber rapidly. Due to the flow of air the pressure on moving contacts increases than spring pressure and contacts open. The contacts travel through a small distance against the spring pressure. Due to the motion of moving contacts the port for outgoing air is closed and the whole arc extinction chamber is filled with high pressure air. But during the arcing period the air passes through the openings shown and takes away ionized air of arc. In case of making operation the valve is turned which connects hollow column of insulator and the reservoir. The air is passed to the atmosphere due to which pressure of air in the chamber is dropped to atmospheric pressure and closing of moving contacts is achieved against spring pressure.

10.5.2 Working

An auxiliary compressed air system is required by this type of circuit breaker. This will supply air to the air reservior of the breaker. During the opening operation, the air is allowed to enter in the extinction chamber which pushes away moving contacts. The contacts are separated and the blast of air will take ionized gases with it and helps in extinguishing the arc. This will require only one or two cycles. There are two major types - cross blast and axial blast.

In cross blast type, the blast of air cuts across the arc. It is less frequently used in the practice. In axial blast type, the blast of air is along the arc. This type of design is common in use.

10.5.2.1 Cross Blast Type

The Fig. 10.3 shows the schematic arrangement of a cross blast type.

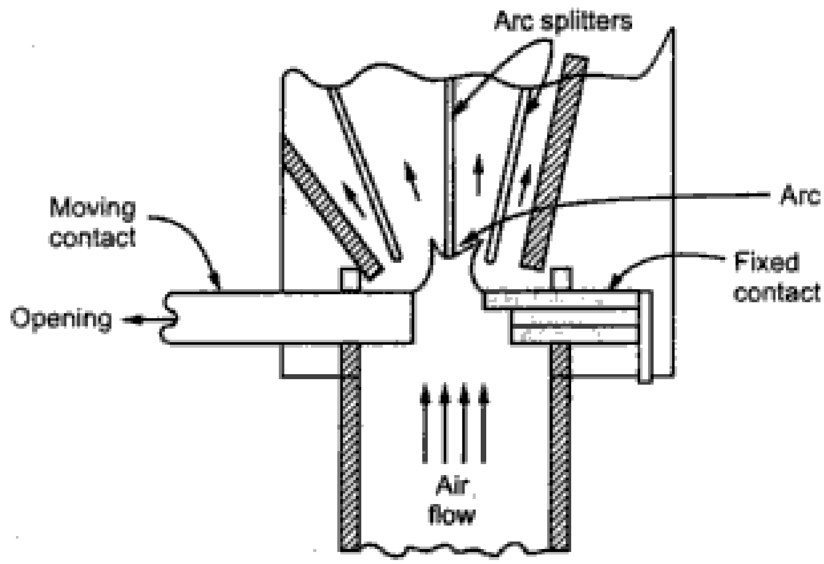


Fig. 10.3 Cross blast type circuit breaker

The flow of air is across the arc. The moving contact is near to the arc splitter assembly. The air blast forces the arc on to the arc splitter plates. These plates will lengthen the arc. Depending upon the breaking capacity of the breaker, the size and number of plates are decided. The fixed contact is mounted at the base between the two insulating blocks. It consists of a number of silver surfaced spring loaded copper fingers. The arcing portion is surfaced with a silver tungsten alloy. The moving contact consists of flat copper silver faced blade. Resistance switching is not required as sufficient resistance is automatically introduced in the arc to control the restriking transient. The cross blast breakers are commonly used in indoor circuit breakers of medium high voltage class.

10.5.2.2 Axial Blast Type

In this type the flow of blast of air is along the line of arc. This is shown in the Fig. 10.4.

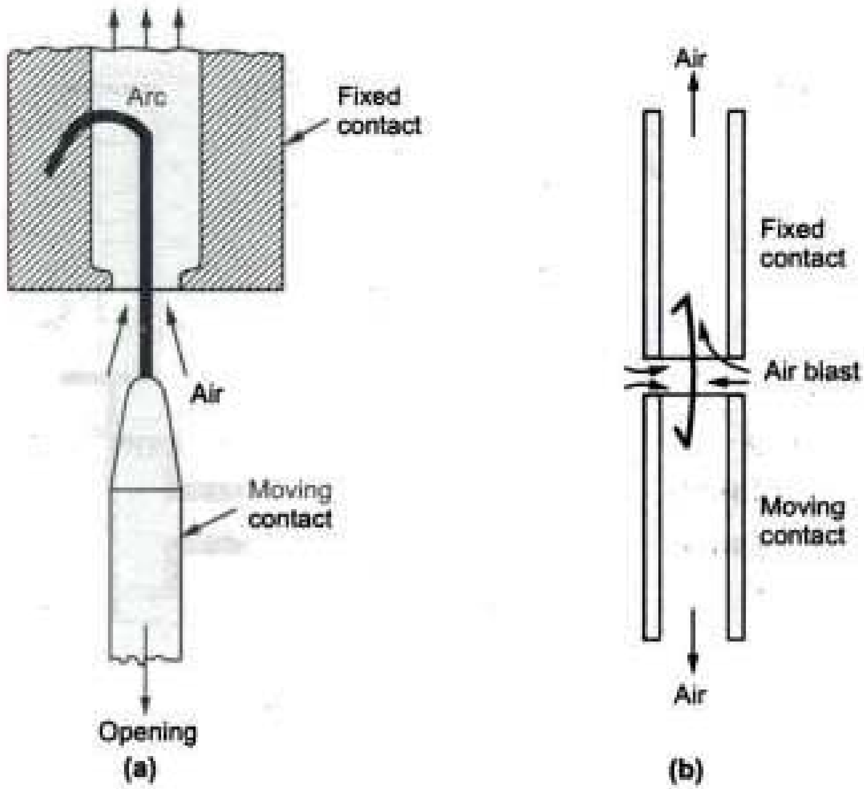


Fig. 10.4 Axial blast type circuit breaker

There are two subtypes which are shown in the Fig. 10.4 (a) and (b) viz single blast type and double blast type. The double blast arrangement is also called radial blast type due to the fact that the blast flows radially into the space between the contacts.

In this type air flows from high pressure reservior to the atmosphere through a nozzle, whose design makes air to expand in the low pressure zone. It will attain high velocity. The high speed air flowing axially along the arc will cause removal of heat from the periphery of the arc. The diameter of arc reduces to a low value at current zero. At this instant of the arc interruption the contact space is filled with the fresh air. This will make possible to remove the hot gases and fast building up of the dielectric strength of the medium.

As already seen during the contact closing, the air from the extinction chamber is allowed to pass to the atmosphere. This will reduce the pressure on the moving contacts and will assist the closing operation. The total operation is represented in the Fig. 10.5.

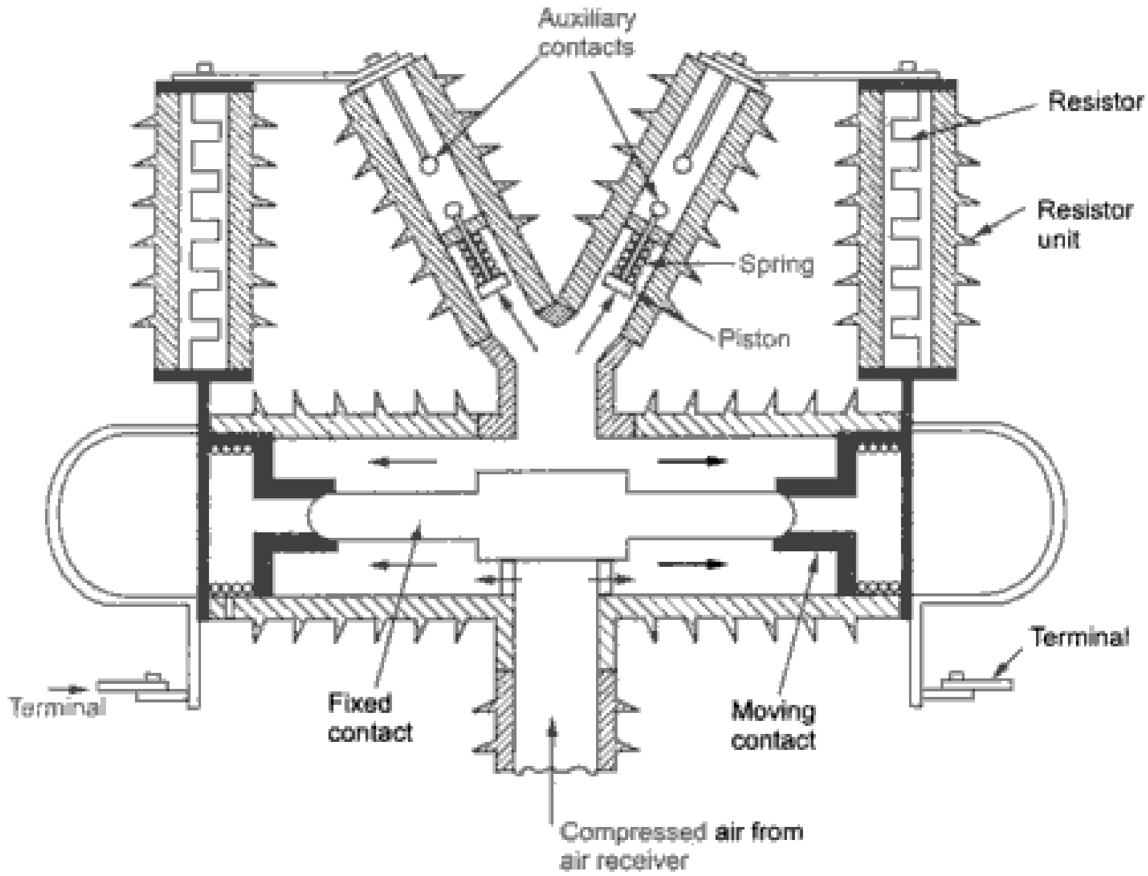


Fig. 10.5 Modification in air blast circuit breaker

In air blast circuit breaker, the pressure generated in the extinction chamber is independent of arc current the circuit breaker is said to be of external energy source. The air pressure in this type of breaker is constant which is sufficient enough to break the rated breaking current. In this type of circuit breakers the breaking capacity is found by pressure of extinguishing medium.

For low values of currents, the arcing time does not change appreaciably since air pressure is independent of arc current. For breaking low current, high pressure air will be required. Due to this the current gets chopped before reaching natural zero. This will give rise to high restriking voltage and the contact space is not likely to break down. Therefore these high voltages must be allowed to discharge to avoid breakdown of insulation of circuit breaker. Thus resistance switching is commonly employed in these breakers.

The Fig. 10.5 shows the modified arrangement for a double arc extinguishing chamber. When the contacts are opened the air flows in the arc extinguishing chamber. The separating of main contacts lead to closing of auxiliary contacts which will connect resistance across the arc for a short time. The auxiliary contacts are mounted in inclined V shaped insulators.

After the arc extinction the pressure on either side of auxiliary contacts is adjusted in such away that auxiliary contacts open and resistor circuit is interrupted. Ceramic resistances of non-linear characteristics are used for resistance switching.

10.5.3 Compressed Air System for Air Blast Circuit Breaker

The schematic arrangement shown in the Fig. 10.6 represents compressed air system.

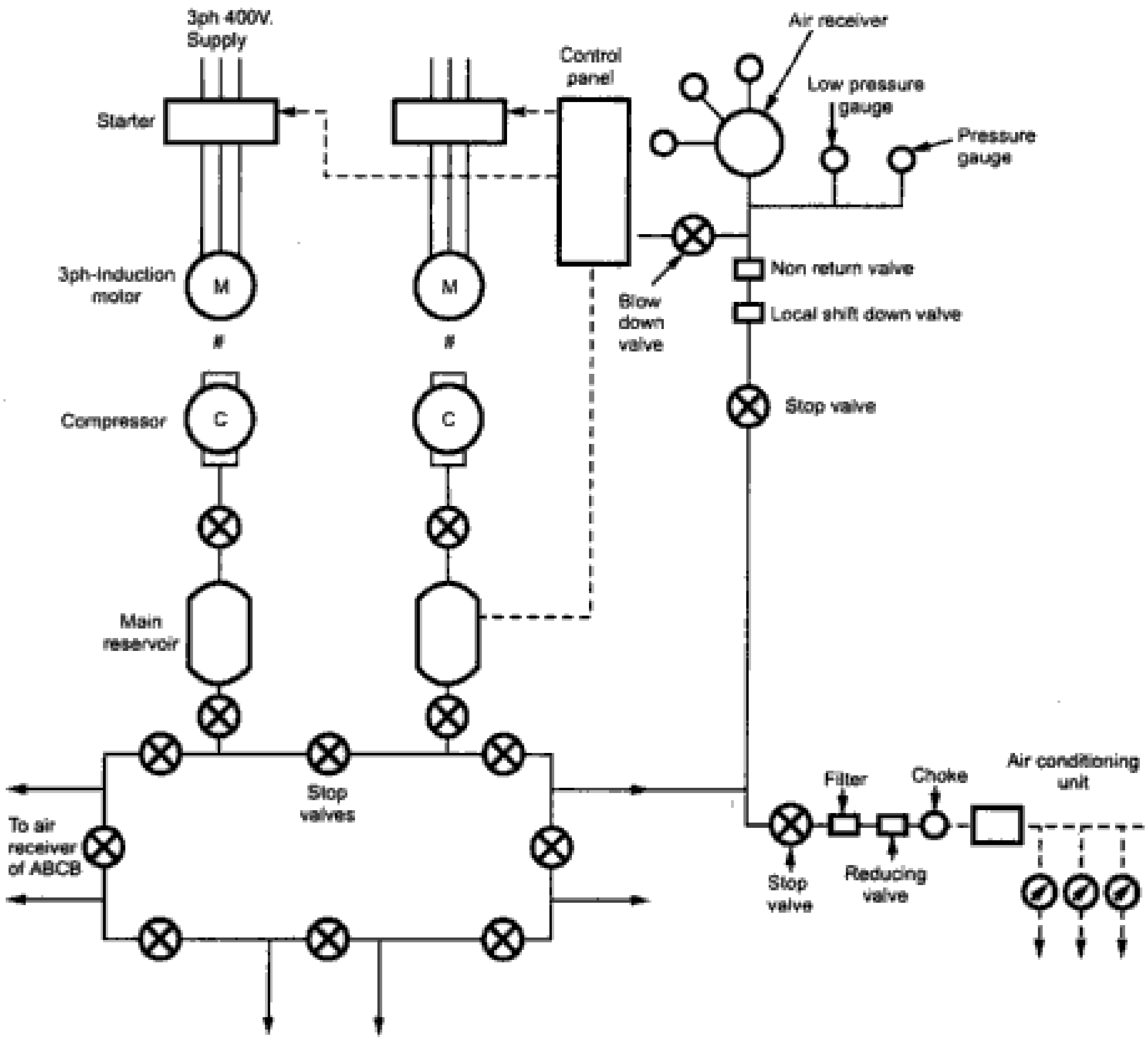


Fig. 10.6 Diagram of compressed air system

The air reservoir in the air blast circuit breaker contains air of pressure of the order of 20-30 kg force/cm^2. This air pressure is maintained by these reservoirs for 4 to 12 repeated operations.

When the pressure in the air reservoir of the circuit breaker reduces below a certain value say 20 kgf/cm^2, the pneumatic valve opens automatically and air is allowed to enter in the air reservoir from compressed air system at high pressure. The pressure in the air reservoir is then maintained at a desired value.

The size of compressor depends upon the number of circuit breakers, the number of makes and breaks expected and amount of air to be used in each make and break. The compressor feeds the air at high pressure into the main receiver through oil filters and water filters.

10.5.4 Advantages

The various advantages of air blast circuit breakers are,

i) No fire hazards are possible with this type of circuit breaker.

ii) The high speed operation is achieved.

iii) The time for which arc persists is short. Thus the arc gets extinguished early.

iv) As arc duration is short and consistent, the amount of heat released is less and the contact points are burnt to a less extent. So life of circuit breaker is increased.

v) The extinguishing medium in this type of circuit breaker is compressed air which is supplied fresh at each operation. The arc energy at each operation is less than that compared with oil circuit breaker. So air blast circuit breaker is most suitable where frequent operation is required.

vi) This type of circuit breaker is almost maintenance free.

vii) It provides facility of high speed reclosure.

viii) The stability of the system can be well maintained.

10.5.5 Disadvantages

The various disadvantages of air blast circuit breakers are,

i) If air blast circuit breaker is to be used for frequent operation it is necessary to have a compressor with sufficient capacity of high pressure air.

ii) The maintenance of compressor and other related equipments is required.

iii) There is possibility of air leakages at the pipe fittings.

iv) It is very sensitive to restriking voltage. Thus current chopping may occur which may be avoided by employing resistance switching.

10.5.6 Applications

The air blast circuit breakers are preferred for arc furnace duty and traction system because they are suitable for repeated duty. These type of circuit breakers are finding their best application in systems operating in range of 132 kV to 400 kV with breaking capacities upto 7000 MVA.

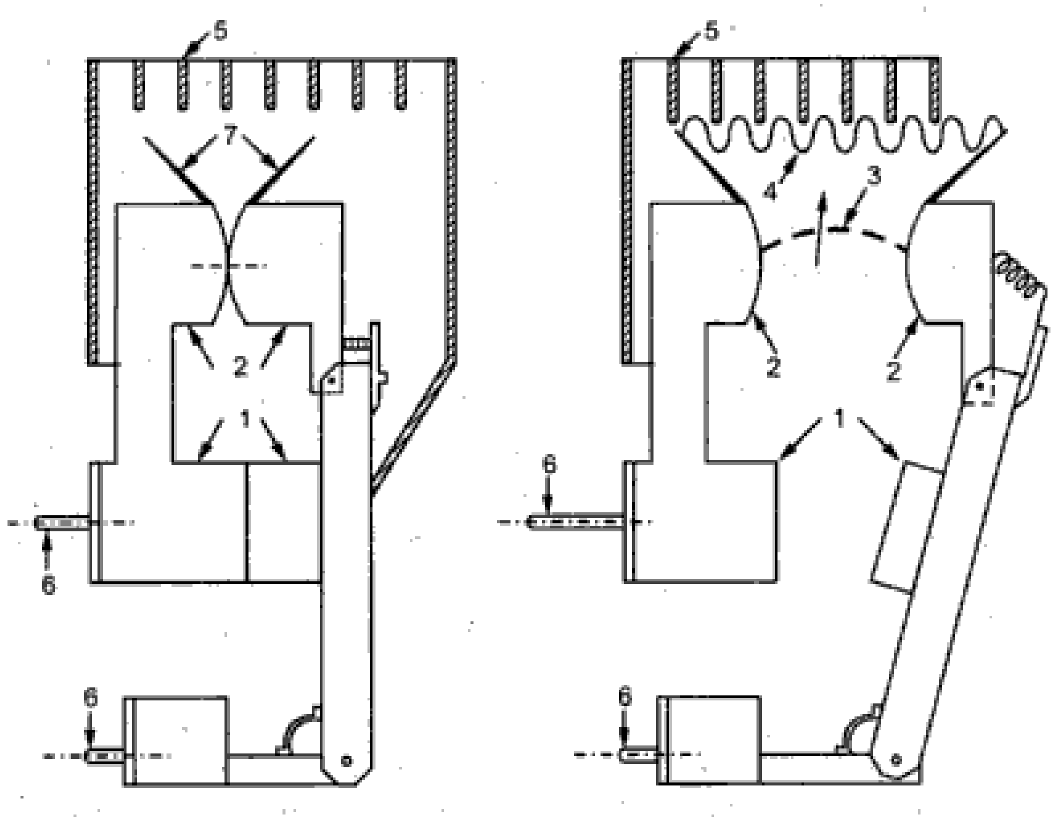
10.6 Air Break Circuit Breaker

In air circuit breakers the atmospheric pressure air is used as an arc extinguishing medium. The principle of high resistance interruption is employed for such type of breakers. The length of the arc is increased using arc runners which will increase its resistance in such a way that the voltage drop across the arc becomes more than the supply voltage and the arc will be extinguished.

This type of circuit breaker is employed in both a.c. and d.c. type of circuits upto 12 kV. These are normally indoor type and installed on vertical panels. The lengthening of arc is done with the help of mangetic fields. Some typical ratings of this type of circuit breaker are 460V – 3.3 kV with current range 400 - 3500 A or 6.6 kV with current range 400-2400 A etc.

10.6.1 Construction

The Fig. 10.7 shows the constructional details of air break circuit breaker.



Principle of air-break circuit-breaker

1. Main contacts
2. Arcing contacts
3. Arc rising in the direction of the arrow
4. Arc getting split
5. Arc splitter plates
6. Current carrying terminals
7. Arc runners

Fig. 10.7 Construction of air break circuit breaker

It consists of two sets of contacts.

1) Main contacts

2) Arcing contacts

During the normal operation the main contacts are closed. They are having low resistance with silver plating. The arcing contacts are very hard, heat resistant. They are made up of copper alloy. Arc runners are provided at the one end of arcing contact. On the upper side arc splitter plates are provided.

10.6.2 Working

As seen from the Fig. 10.8 the contacts remain in closed position during normal condition. Whenever fault occurs, the tripping signal makes the circuit breaker contacts to open. The arc is drawn in between the contacts

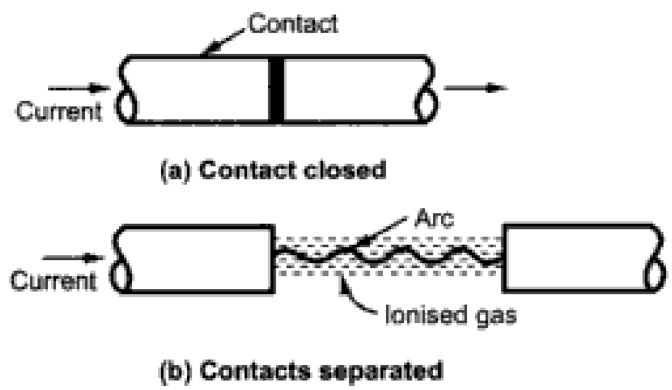


Fig. 10.8 Working of air break circuit breaker

Whenever the arc is struck between the contacts, the surrounding air gets ionised. The arc is then cooled to reduce the diameter of arc core. While separating, the main contacts are separated first. The current is then shifted to arcing contains. Later on the arcing contacts also start separating and arc between them is forced upwards by the electromagnetic forces and thermal action. The arc travels through the arc runners. Further it moves upwards and split by arc splitter plates. Due to all this finally the arc gets extinguished as the resistance of the arc is increased.

Due to lengthening and cooling, arc resistance increases which will reduce the fault current and will not allow to reach at high value. The current zero points in the a.c. wave will help the arc extinction. With increase in arc resistance the drop across it will go on increasing.

Whenever arc leaves the contacts it is passed through arc runners with the help of blow out coils which provide a magnetic field due to which it will experience a force as given by electromagnetic theory ($F = BIl$). This force will assist in moving the arc upwards. The magnetic field produced is insufficient to extinguish the arc. For systems having low inductances arc gets extinguished before reaching extremity of runners because lengthening of arc will increase the voltage drop which is insufficient to maintain the arc.

For high inductance circuits if it is not extinguished while travelling through arc runners then it is passed through arc splitters where it is cooled. This will make the effective deionization by removing the heat from arc.

10.6.3 Applications

This type of circuit breakers are commonly employed for industrial switchgear, auxiliary swithgear in generating stations.

10.7 Sulphur Hexafluoride (SF_6) Circuit Breaker

Pure sulphur hexafluoride gas is inert and thermally stable. It is having good dielectric and arc extinguishing properties. It is also an electronegative gas and has strong tendency to absorb free electrons. SF_6 gas remains in gaseous state upto a temperature of 9° C. Its density is about five times that of air and the free heat convection is 1.6 times as much as that of air. Also being inert it is non-inflamable, non-poisonous and odourless.

The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them The conducting electrons from the arc are captured by the gas to form relatively immobile negative ions. The loss of this conducting electrons developes enough strength of insulation which will extinguish the arc. Thus SF_6 circuit breakers are found to be very effective for high power and high voltage service and widely used in electrical equipments. Only the care to be taken is that some by-products are produced due to breakdown of gas which are hazard to the health of the personnel and it should be properly disposed.

Several types of SF_6 circuit breakers are designed by various manufacturers in the world during the recent years which are rated for voltages from 3.6 to 760 kV.

The property of this gas is that the gas liquifies at certain low temperatures. The liquification temperature can be increased with pressure This gas is commercially manufactured in many countries and now used extensively in electrical industry.

The gas is prepared by burning coarsely crushed roll sulphur in fluorine gas in a steel box. The box must be provided with staggered horizontal shelves each containing about 4 kg of sulphur. The steel box is gas tight. After the chemical reaction taking place in the box, the SF_6 gas obtained contains impurities in the form of fluorides such as S_2F_{10}, SF_4 etc. Thus it must be purified before it is supplied. The manufacturing of this gas at large scale reduces its cost.

The dielectric strength of SF_6 gas at any pressure is more than that of air. When the gas comes in contact with the electric arc for long period, the decomposition effects are small and dielectric strength is not considerably reduced and the metallic fluorides that are formed are good insulators and are not harmful to the breaker.

10.7.1 Properties of SF_6 Gas

The properties of SF_6 gas are divided as,

1. Physical properties
2. Chemical properties
3. Dielectric properties

10.7.1.1 Physical Properties

i) The gas is colourless, odourless, non-toxic and nonharmful to health.

ii) The gas is non-inflammable.

iii) It is heavy gas having high density.

iv) Liquification starts at low temperatures which depends on pressure.

v) The heat transferability is high as compared to air at same pressure .

vi) The heat content property is much more which will assist cooling of arc after current zero.

vii) The gas is electronegative.

10.7.1.2 Chemical Properties

i) The gas is chemically inert and stable upto 500° C. The life of metallic part, contacts is longer in SF_6 gas. The components do not get deteriorated. Hence the maintenance requirements are reduced.

ii) During arc extinction, SF_6 is decomposed to SF_4, SF_2. The products of decomposition are toxic and hence proper care must be taken for their disposal.

iii) The metallic fluorides are good dielectric materials. Hence are safe for electrical equipment.

10.7.1.3 Dielectric Properties

i) The dielectric strenght of SF_6 gas at atmospheric pressure is 2.9 times that of air and 30% less than that of dielectric oil.

ii) At higher pressure, the dielectric strength of a gas increases. This is very much advantageous as smaller clearances and small size of components are required for same kV. The variation is shown in the Fig. 10.9.

iii) The breakdown voltage in SF_6 gas is a function of pressure.The gas follows the Paschen's law which is given as " In uniformly distributed electric field the breakdown voltage in a gas isdirectly proportional to the product of gas pressure and electrode gap". The parameters affecting breakdown voltage are

vii) The breakdown is initiated at sharp edges of conducting parts having maximum stress concentration.Good dielectric stress distribution is important.

viii) The breakdown value depends on the wave shape characterised by peak value, wave front, polarity in case of impulse wave etc. The breakdown voltages reduces with increase in steepness and increase in duration of wave.

ix) Even with dilution of SF_6 with air, its dielectric strength is not much affected. As already seen the gas is electronegative so arc time constant is lower which is nothing but the time required to regain dielectric strength by medium after final current zero. This time is of the order of few microseconds in this type of circuit breaker.

10.7.2 Construction of Non-Puffer Type SF_6 Breaker

The Fig. 10.11 shows the constructional details of SF_6 circuit breaker. It consists of arc interruption chamber wherein fixed and moving contacts are enclosed. The chamber is filled with SF_6 gas. The chamber is connected to a reservoir containing SF_6 gas.

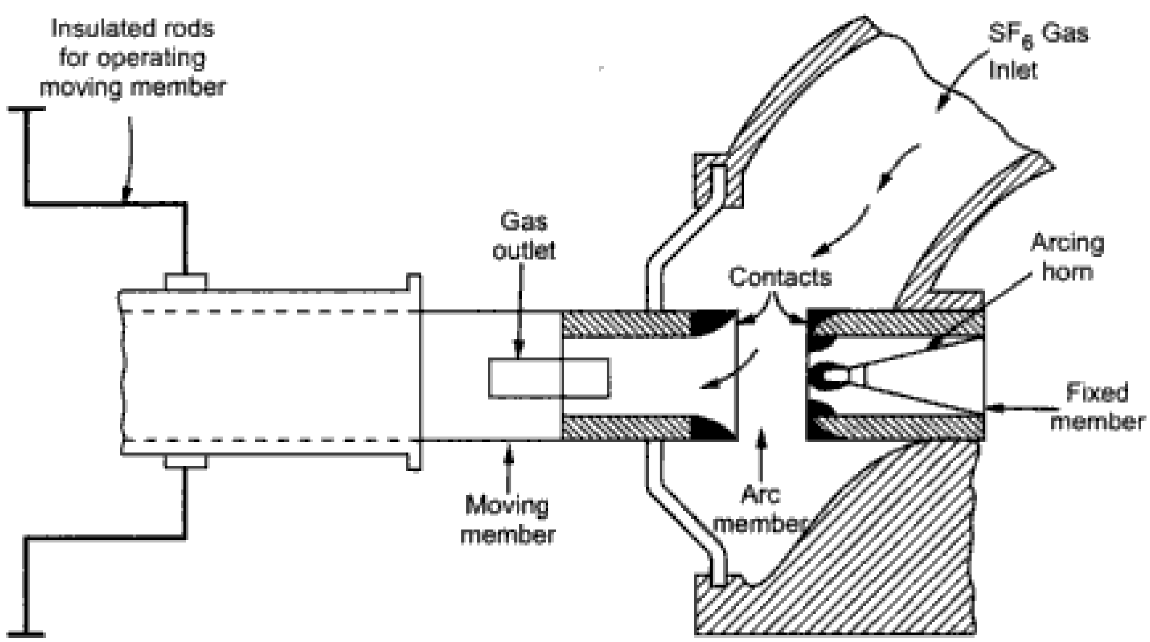


Fig. 10.11 Construction of SF_6 breaker

When the contacts of circuits breakers are opened, the valve mechanism allows high pressure SF_6 gas from the reservior to flow towards the arc interruption chamber.The fixed contact is a hollow, cylindrical current carrying contact fitted with arc horn. The moving contact is also hollow cylinder containing holes in the sides to permit SF_6 gas to pass through these holes after flowing across the arc. The tips of fixed and moving contacts are coated with copper tungsten arc resistant material. The

The single flow pattern has limited quenching ability and is used for breaking currents. The four stages of puffer action explains arc quenching process in single flow puffer type circuit breaker.

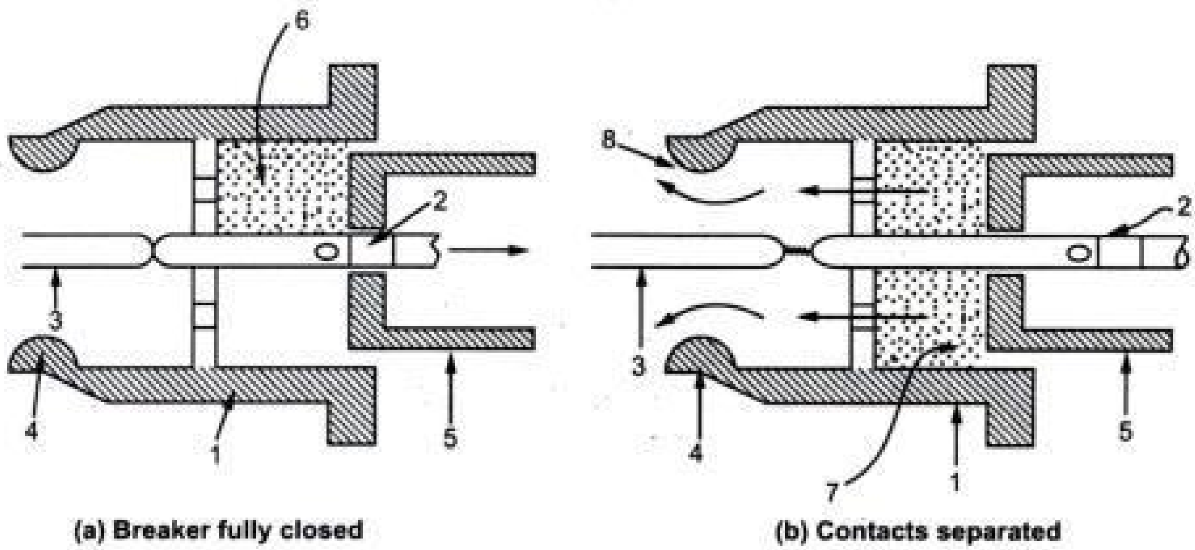
When breaker is fully closed, the pressure in puffer cylinder P_1 is equal to that of outside the cylinder. But during opening operation, puffer cylinder and moving contact tube start moving. Gas gets compressed withing puffer cylinder ($P_1 > P_2$). When contacts move further, arc is drawn. The compressed gas flows from higher pressure P_1 to lower pressure P_2 through the nozzle.

After further advancement the flow pattern was improved. The gas from puffer cylinder was allowed to flow in forward direction through nozzle and also in reverse direction through hollow contact tube.

Double flow removes the heat from the arc efficiently and causes lengthening of arc. It gives the breaking capacity one and half times more than that of single flow type. So now a days double flow pattern is used in SF_6 circuit breakers.

10.7.3 Single Pressure Puffer Type SF_6 Circuit Breaker

It employs puffer principle explained earlier. The Fig. 10.13 shows principle of operation of single pressure puffer type SF_6 circuit beraker. The operating mechanism (1) is installed at base of the insulator and is linked with movable contact in the interrupter by means of insulating operating rod (4) and a link mechanism (5).The circuit breaker is filled with SF_6 gas at a pressure of about 5 kgf/cm^2. The breaking time obtained with puffer type breaker is nearly 3 cycles.



1. Moveable Cylinder (Puffer Cylinder)
2. Moving Contact
3. Fixed Contact
4. Insulating Nozzle
5. Fixed Piston
6. Gas trapped in before compression
7. Compressed gas between 1 and 5
8. The arc being extinguished by puffer action

Fig. 10.13 Single pressure puffer type SF_6 breaker

In this case, gas is compressed by the moving cylinder system and is released through a nozzle while extinction of an arc.

The Fig. 10.13 (a) illustrates fully closed position of interrupter. Moving cylinder 1 is coupled with moving contact 2 against the fixed piston 5. As a result there is a relative motion between 1 and 5 and the gas is compressed in the cavity 6. This trapped gas is released through a nozzle hole, during arc extinction process. During the travel of moving contact 2 and movable cylinder 1 gas puffs over the arc and reduces arc diameter by axial convertion and radial dissipation. At current zero arc diameter becomes too small and arc gets extinguished.

The puffing action continues for sometime even after the arc extinction until the contact space is filled with cool and fresh gas.

10.7.4 Double Pressure Type SF_6 Circuit Breaker

In this type, gas from high pressure system is released into low pressure system through a nozzle during arc extinction process.

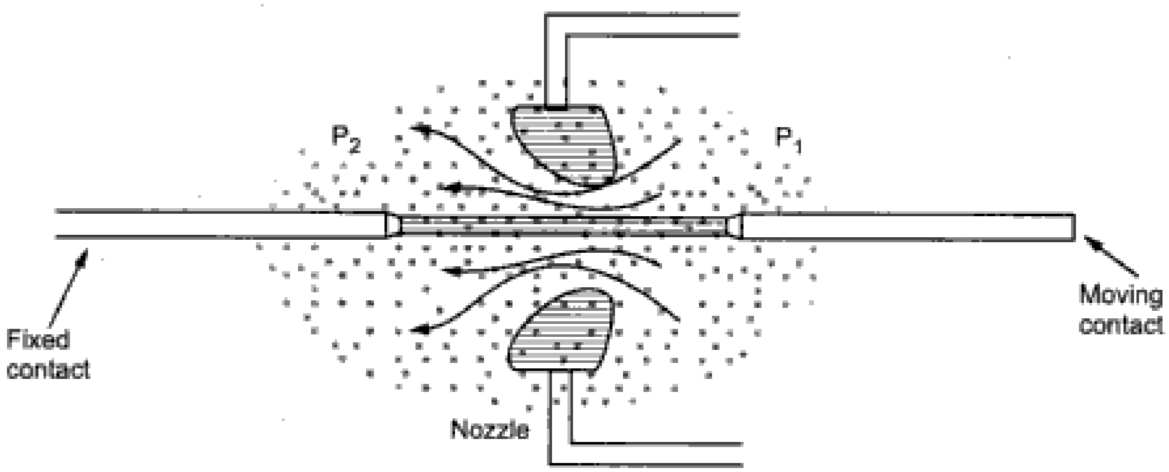


Fig. 10.14 Double pressure type SF_6 circuit breaker

In this circuit breaker, gas is made to flow from zone P_1 to P_2 through a convergent divergent nozzle. The nozzle is located such that flow of gas covers the arc. Gas flow attains almost supersonic speed in divergent portion of nozzle, thereby gas takes away the heat from periphery of arc causing reduction in diameter of the arc. Finally arc diameter becomes almost zero at current zero and arc gets extinguished. Arc space is filled with fresh SF_6 gas which increases dielectric strength of contact space.

10.7.5 Advantages of SF_6 Circuit Breaker

The advantages of SF_6 circuit breaker are,

1. The size of SF_6 breaker is smaller than conventional circuit breaker of same rating.
2. SF_6 gas is noninflammable and chemically stable, decomposition products are not explosive hence no danger of fire.
3. Same gas is recirculated in the circuit hence requirement of gas is small.
4. Ample overload margin : For the same size of conductors, current carrying ability of SF_6 circuit breaker is about 1.5 times than that of air blast circuit breaker because of more heat transferability.
5. The breaker is silent in operation and does not make sound like air blast circuit breaker due to its closed gas circuit.
6. Sealed construction avoids contamination by moisture, dust etc.There are no carbon deposites.
7. Minimum maintenance required for this breaker. It requires light foundation and minimum auxiliary equipment.
8. Ability to interrupt low and high fault currents, magnetising currents, capacitive currents without excessive overvoltages with small arcing time.
9. Problems connected with current chopping are minimum.
10. No contact replacement required. Contact corrosion is very small hence contacts do not suffer oxidation.

10.7.6 Disadvantages

The disadvantages of this type of circuit breaker are,

1. Sealing problem arises due to the type of construction
2. Imperfect joint lead to leakage of gas
3. The presence of moisture in the system is very dangerous.
4. Double pressure SF_6 circuit breaker are relatively costly due to type of construction and complex gas system.
5. Internal parts should be cleaned thoroughly during periodic maintenance under clean and dry environment.
6. Special facilities are needed for transporting the gas, which is very costly.
7. SF_6 breakers are costly as there is high cost of SF_6 gas.
8. Since the gas is to be reconditioned after every operation, additional equipment is required for the same.
9. Arced SF_6 gas is poisonous and should not be inhaled.

10.7.7 Applications

A typical SF_6 circuit breaker consists of interrupter units. Each unit is capable of interrupting currents upto 60 kA and voltages in the range 50-80 kV. A number of units are connected in series according to system voltage. SF_6 breakers are developed for voltage ranges from 115 to 500 kV and power of 10 MVA to 20 MVA ratings and with interrupting time of 3 cycles and less.

10.8 Vacuum Circuit Breakers

In vacuum type of circuit breakers, vacuum is used as the arc quenching medium. It is superior medium than any other arc quenching medium as vacuum offers highest insulting strength.

If we consider that the contacts of circuit breakers are opened in vacuum, the interruption occurs at first current zero. The dielectric strength of the contact space builds up very rapidly at a rate which is very much higher than that with other circuit breakers.

When the contacts of the breaker are opened in vacuum, an arc is produced between the contacts due to ionisation of metal vapours of contacts, which can be explained by field emission theory. An intensely hot spot is created at the instant of contact separation because of high current density.But the arc is quickly extinguished as metallic vapours, electrons and ions produced during the arc are condensed on the surface of the breaker.This will lead to fast recovery of dielectric strength. This is an important feature of vacuum as an arc quenching medium which will assist arc extinction and restriking of arc is prevented. The vacuum circuit breaker consists of one or more vacuum interrupter units per pole.

The vacuum switching devices have several merits such as high rate of rise of dielectric strength, silent operation, suitability for repeated operations, simple operating mechanism, free from explosion and long life.

The unique quality of vacuum interrupters is that the contacts are required to be travelled by small distance and less weight of moving contacts. Many repeated operations can be performed with this type of breaker

10.8.1 Electrical Breakdown in High Vacuum

The pressure below about 10^{-5} mm of mercury are considered to be high vacuum. The charged particles from one electrode moving towards other at such a pressure will not cause collision with the molecules of residual gas. Hence ionization by collision of particles is less in vacuum as compared to in the gas.

If a small gap (say 0.5 mm) is kept between the electrodes in the vacuum and voltage is gradually increased, at a certain voltage the gap breaks down and current increases rapidly. The phenomenon is called vacuum breakdown. With pressure remaining constant the breakdown chracteristics are influenced by surface, condition and material of electodes.

Due to high arc energy, electrons emission takes place from surface of the electrodes. High heat is produced and core will be at very high temperature. Few spots having high current densities are produced. Thus thermal emission takes place from surface of electrodes which is a cause for arc formation in case of these breakers

10.8.2 Construction

The Fig. 10.15 shows the schematic representation showing the constructional details of vacuum circuit breaker.

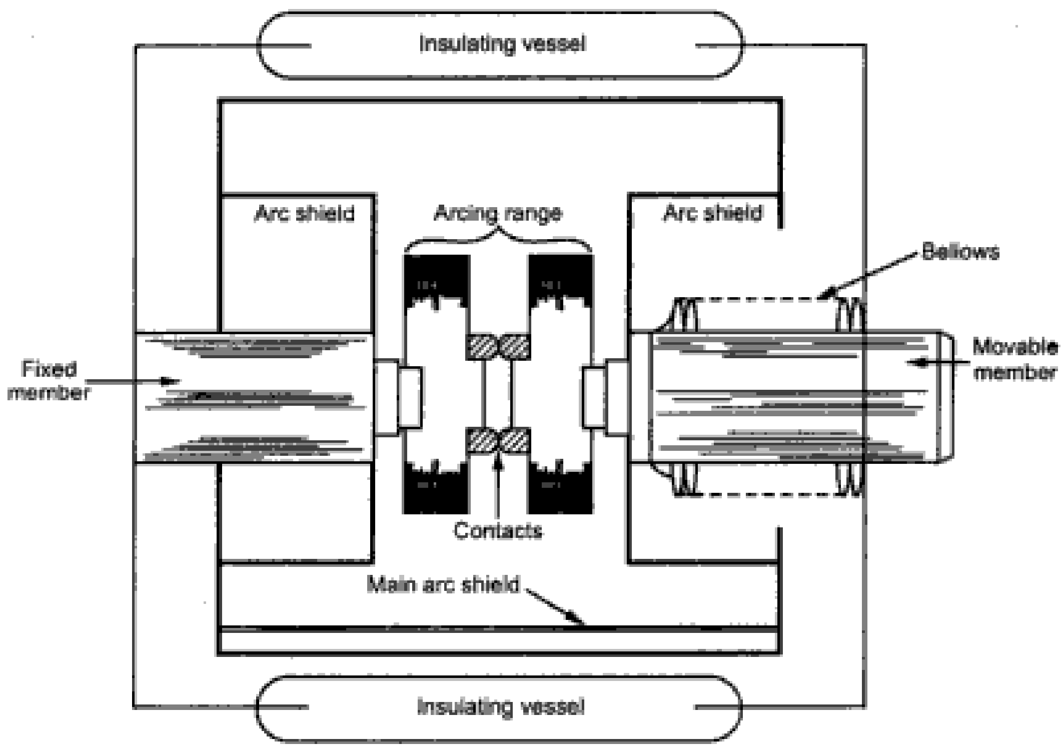


Fig. 10.15 Construction of vacuum circuit breaker

It consists of vacuum chamber in which fixed contact, moving contact and arc shield are mounted. The movable member is connected to the control mechanism by stainless steel bellows. The bellows permit the sealed construction of the interrupter. They are covered by protective shield . The contacts are made of large stem with large disc shaped faces.The disc is provided with symmetrical grooves such that segments of two contacts are not along same line. This geometry facilitates the rapid movement of arc instead of ramaining stable at one point and arc remains in diffused state. The enclosure is made up of impermeable insulating material like glass. The material should not be porous and should have capability to retain high vacuum.The supporting end flanges are made up of non-magnetic metal.

The arc shields or vapour shields are supported on insulating housing such that they cover the contact region. The metal vapour released from the contact surface during arcing is condensed on these shields and is prevented from condensing on the insulating enclosure.

The possibility of leak is eliminated due to permanent sealing of vacuum chamber. The outer insulator is made up of glass or ceramics

10.8.3 Working

When the contacts are separated due to some abnormal conditions, an arc is struck between the contacts. The arc is produced due to ionisation of metal ions and depends very much on material of contacts.

The arc interruption process in vacuum interrupters is different from other types of circuit breakers. The separation of contacts causes release of vapour which is filled in the contact space. It contains positive ions liberated from contact material. The vapour density depends on the current in the arc. When current decreases, the rate of vapour release decreases and after current zero, the medium regains its dielectric strength if vapour density is reduced.

When current to be interrupted is very small (of the order of few hundred amps) in vacuum, the arc has several parallel paths. The total current is divided into many parallel arcs which repel each other and spreads over contact surface. This is called diffused arc which can be interrupted easily.

At high values of currents, the arc gets concentrated on a small region. It causes rapid vapourisation of the contact surface. The interruption of arc is possible if arc remains in diffused state. If it is quickly removed from the contact surface, the arc will be restriked.

Arc extinction in vacuum breakers is greatly influenced by material and shape of contacts and technique of condensing metal vapour.The path of the arc is kept moving so that temperature at any one point will not be high.

After final arc interruption there is rapid building up of dielectric strength which is pecularity of vacuum breaker. They are suitable for capacitor switching as it will give restrike free performance. The small currents are interrupted before natural current zero which may cause chopping whose level depends on material of contact.

The chopping levels are affected by,

a) The vapour pressure of cathode material with increase in vapour pressure, the chopping level is lowered.

b) The thermal conductivity, if thermal conductivity is low and the chopping level is also low. Current chopping level for some materials is given in the Table 10.1

grown from molten metal which releases small quantity of gas. But the process is very slow, costly and commercially not feasible. The another possible solution to this problem is to use zone-refined copper which is gas free.

The metals like aluminium, copper, silver, tin etc were tested for electrode erosion. At high currents the cathode spots formed shows a high vapour pressure that is supplied by vapourisation. The loss from cathode, causes gain in weight for anode due to the condensation of cathode vapour on the anode when it is cold.

Another important thing that must be considered is that the electrodes should not weld with each other and dielectric strength of the gap must be recovered very rapidly.

Thus the requirements to be satisfied by a vacuum circuit breakers are complicated. Hence no single metal is suitable for the electrodes. Thus the compromise is made and it shows that use of dicopper magnesium (Cu_2Mg), dicesium copper ($CuCe_2$), copper bismuth (CuBi) gives the satisfactory performance.

10.8.6 Recovery Strength Characteristics

The satisfactory working of vacuum circuit breaker is possible if the electrical strength after arcing is properly recovered. In this type of the breaker, the conducting medium of the arc is supplied by contact erosion and recovery of electric strength mostly depends on condensation of electrode vapour.

A reduction in number of vapour ions lead to improvement in recovery strength.

When pressure is reduced to such a value that the breakdown voltage is independent of pressure then under this case, the factors affecting breakdown voltage are the type of contacts, contact surface etc. Highly polished electrodes has good breakdown strength.

10.8.7 Applications

In countries like India, the installation of such breakers proves to be effective as it requires little maintenance. They are employed for outdoor installations ranging from 22 kV to 66 kV. With limited rating ranging from 60 to 100 MVA they are suitable in many applications.

Recently installed capacities of such breakers are 11 kV, 25 kV and 33 kV.

Thus for voltages upto 36 kV, vacuum circuit breakers with single interrupter is becoming extremely popular for metal enclosed switchgear, arc furnace installations, auxiliary switchgear in generating stations and other industrial applications.

10.9 Oil Circuit Breakers

These are one of the oldest type of circuit breakers which employs oil as arc quenching medium. The contacts of the circuit breakers are separated in the oil. The bubbles of gas are formed which prevent restriking of the arc after the current reaches zero point of the cycle. There are two types of oil circuit breakers,

1) Circuit breakers using large quantity of oil or the bulk oil circuit breakers.
2) Circuit breakers using minimum quantity of oil called minimum oil circuit breakers.

After the current zero, the oil moves in the arc space which is an important part of the action of an oil circuit breaker which may be effected by,

1) the pressure developed due to natural head of oil above contacts.
2) the pressure generated by the action of arc current itself.
3) the pressure developed by external parameters.

Thus the oil circuit breakers are further grouped into following categories,

1) Plain break oil circuit breakers.
2) Self generated pressure oil circuit breakers (also called self blast oil circuit breakers.)
3) Externally generated pressure oil circuit breakers (also called force blast oil circuit breakers.)

10.9.1 Plain Break Oil Circuit Breaker

It consists of a strong, weather tight earthed tank containing oil upto certain level and air above the oil level. Both the fixed and moving contacts are immersed in oil.

When the contacts are separated, an arc is struck between the contacts with production of large amount of heat. This will increase the temperature to near about 5000°K which will vapourize the oil into gases such as hydrogen with small percentage of methane, ethylene and acetylene. With the withdrawl of moving contact, arc length increases and gas formation rate decreases as temperature lowers.

When distance between fixed contact and moving contact reaches at critical value, the arc gets extinguished at some current zero.

There are two types of plain-break oil circuit breakers,

a) Single break oil circuit breaker

b) Double break oil circuit breaker.

10.9.1.1 Single Break Oil Circuit Breaker

The single break oil circuit breaker principle is represented in the Fig. 10.16. The in and out of the current is through the terminal bushings. There is only one arc which is struck between the fixed and moving contact. The current breaks at one bushing and the moving contact is supported by the other bushing through sliding contact.

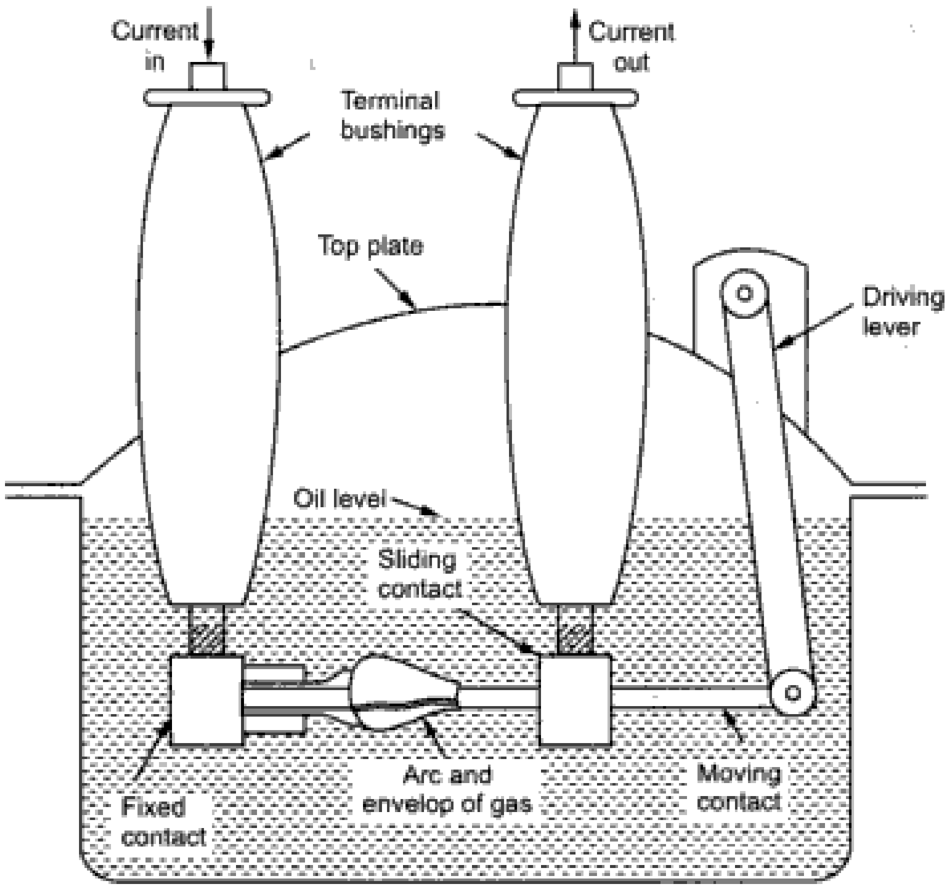


Fig. 10.16 Single break oil circuit breaker

10.9.1.2 Double Break Oil Circuit Breaker

The principle of this type of circuit breaker is shown in the Fig. 10.17. There are two fixed contacts associated with terminal bushing which makes contacts with the

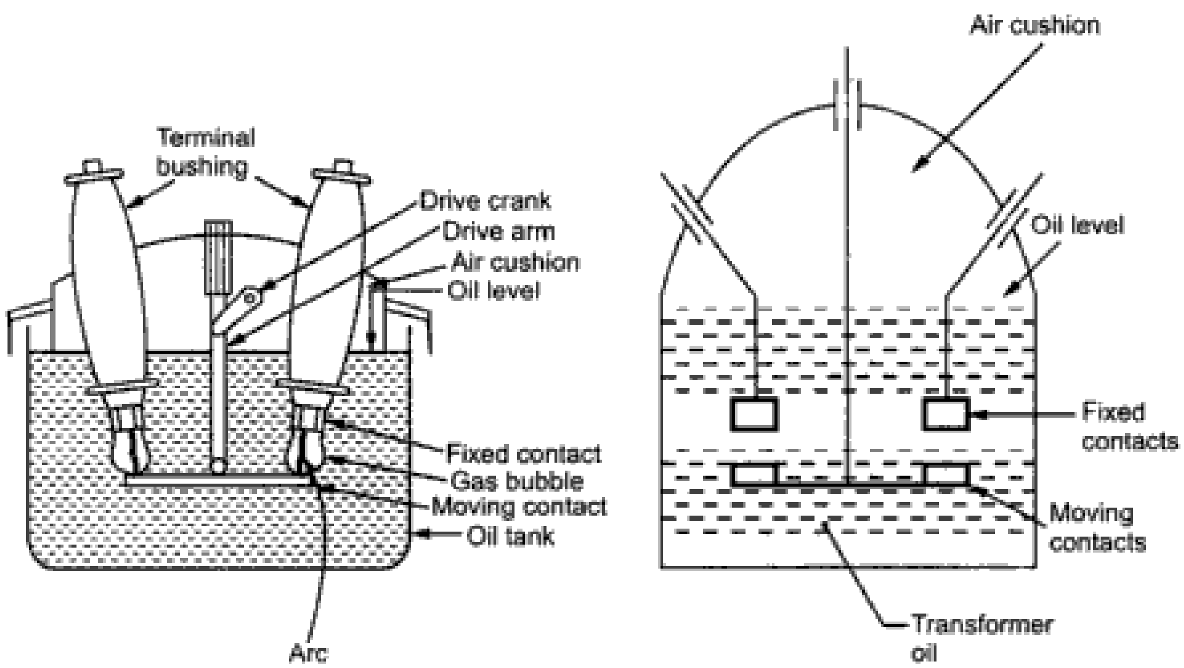
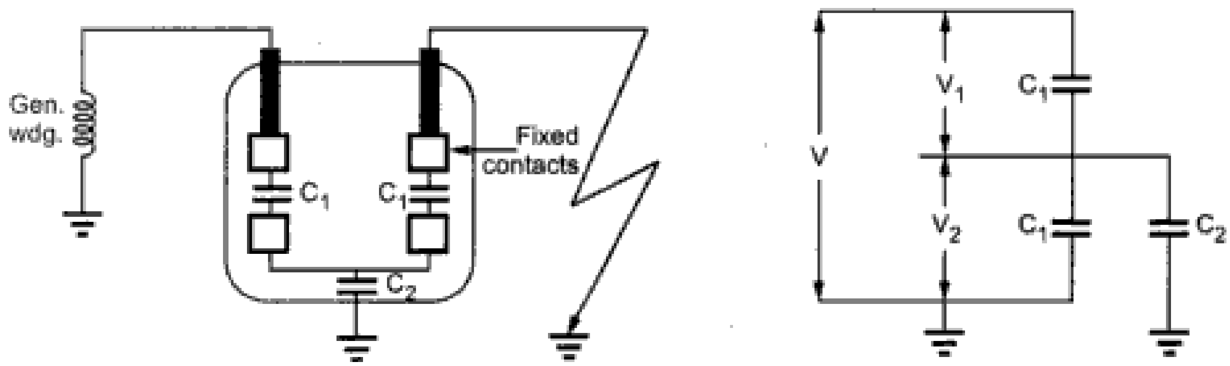


Fig. 10.17 Double break circuit breaker

moving contacts during normal operating condition. The lever containing the moving contacts can be operated with the help of crank.

When the contacts are separated, two arcs are drawn. Thus there are two breaks in series. This can achieve rapid arc lengthening which eliminates the need for a specially fast moving contact speed. But this introduces unequal voltage distribution across the breaks with uneven sharing of total interrupting duty. One break may take 70 to 80 percent of the interrupting duty.

When such a breaker interrupts an earth fault, the recovery voltage is not equally divided between the two breaks. This statement can be very well understood by considering the equivalent electrical circuit shown in the Fig. 10.18, where C_1 represents capacitance between fixed and moving contacts whereas C_2 represents capacitance between moving contact and earth.



(a) (b) Equivalent circuit

Fig. 10.18

Let I be the fault current

From the Fig. 10.18 (b),

$$V_1 = \frac{I}{\omega C_1} \text{ volts}$$

$$V_2 = \frac{I}{\omega (C_1 + C_2)} \text{ volts}$$

Let C_1 = 10 pF and C_2 = 40 pF being typical values in practice.

Now ,
$$\frac{V_1}{V_2} = \frac{\omega (C_1 + C_2)}{\omega C_1} = \frac{C_1 + C_2}{C_1}$$

$$\therefore \quad \frac{V_1}{V_2} = \frac{10 + 40}{10} = \frac{50}{10}$$

$$= 5$$

$\therefore \quad V_1 = 5 V_2$

It can be seen from the above expression that about 83% of the system voltage appears across gap and only 17% appears across moving contact and earth. In order to equalize the voltage across the gaps, high resistances or capacitors are connected across them.

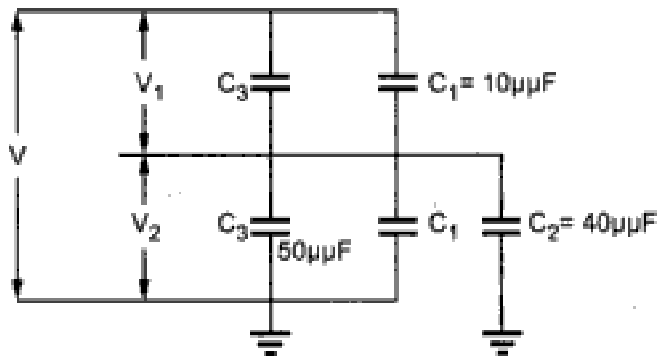


Fig. 10.19 Capacitive voltage grading

Let a capacitor of 50 pF be connected as shown in the Fig. 10.19.

Now,
$$\frac{V_1}{V_2} = \frac{C_1 + C_2 + C_3}{C_1 + C_3} = \frac{10+40+50}{10+50}$$
$$= \frac{100}{60}$$
$$= 1.66$$
$$\therefore \quad V_1 = 1.66\ V_2$$

Thus V_1 becomes equal to 1.66 times that of V_2. If value of C_3 is chosen to be high then the difference between V_1 and V_2 can be further reduced. If instead of capacitors, high values of resistors are used it will also cause damping. The resistance values are generally of the order of 10,000 to 100,000 ohms. The resistor selected may be non-linear one.

10.9.1.3 Factors Affecting Performance of Plane Break Oil Circuit Breaker

The factors which influence the performance of plain break oil circuit breakers are as follows,

i) The critical length of the break

ii) The speed of the contact movement. In order to extinguish the arc earlier, the speed should be high therefore double break circuit breakers are preferred.

iii) The head of oil above the contacts.

iv) The clearance between the live contacts and the earthed pressurized tank.

The factors which influence on increased breaking capacity are considerable head of oil and large clearances. Thus for large breaking capacity, the circuit breaker will be large.

10.9.1.4 Advantages of Plain Break Oil Circuit Breaker

The various advantages of plain oil circuit breaker are,

i) The arc energy is easily absorbed by the oil due to its decomposition.

ii) The gases formed due to oil decomposition has good cooling properties.

iii) The cooling surfaces formed by surrounding oil is close to the arc.

iv) After current zero a flow of cool oil flows in the contact space which is having dielectric strength.

v) The oil used acts as an insulator.

10.9.1.5 Disadvantages of Plain Break Oil Circuit Breaker

The various disadvantages of plain break oil circuit breaker are,

i) There is no special control over the arc other than the increase in length by separating the moving contacts. Hence large arc length is required for faithful interruption.

ii) These breakers have long and inconsistent arcing times.

iii) These breakers do not permit high speed interruption.

10.9.1.6 Applications

Such types of circuit breakers are suitable upto 150 MVA capacity and hence installed in low capacity applications having voltages not more than 11 kV.

10.9.2 Self Generated Pressure Oil Circuit Breaker

This type of circuit breakers are also called self blast oil circuit breakers where arc control is provided by internal means. The pressure developed by the arc is used in speeding up the movement of oil in the contact space at the instant after the current zero. This is achieved by surrounding the contact by a pressure chamber. This will make it possible to increase the breaking capacity of such circuit breaker while the arcing time is reduced.

The action of arc will itself set up pressure which is dependent on magnitude of currents. Thus proper design of pressure chamber must be done in order to ensure that pressure developed is sufficient to extinguish the arc at low currents, while it should not be excessive which may break the chamber at heavy currents. Thus a wide variety of designs are possible. Some of them are discussed below.

10.9.2.1 Plain Explosion Pot

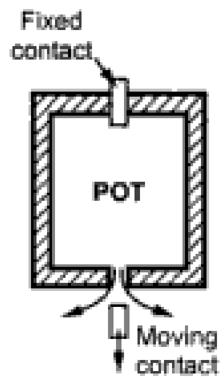


Fig. 10.20 Plain explosion pot

This is shown in the Fig. 10.20. It consists of a rigid cylinder made up of a insulating material. The cylinder contains the fixed and moving contacts. The moving contact is a cylindrical rod which can pass through a small opening called throat. The motion of moving contact is vertical.

Whenever fault occurs in the system the contacts will start separating with the formation of arc in between them. The heat contained in the arc causes the decomposition of the oil into a gas at very high pressure in the pot. This high pressure forces the oil and gas around the arc to extinguish it.

It can be seen that if the final arc interruption does not take place while the moving contact is inside the pressure chamber then it occurs immediately after the moving contact leaves the pot as emergence of moving contact from the pot allows a high velocity axial blast of gas to release through the throat producing rapid arc extinction. As the arc extinction takes place axially of the arc, it is also called axial explosion type.

The major drawback with this type is that it cannot be used for very high or very low fault currents. At low fault current values, the pressure developed is small thus arcing time is increased. On the other hand at high fault currents due to very high pressure developed there is possibility of bursting the explosion pot or chamber. Therefore it is suitable for moderate short circuit currents only.

10.9.2.2 Cross Jet Explosion Pot

It is the modification of plain explosion pot which is shown in the Fig. 10.21. The Fig. 10.21 shows the four stages of operation. It consists of cylinder made up of insulating material. There are channels on one side which act as arc splitters. The use of arc splitters is to increase the arc length which will assist arc extinction by lengthening the arc.

In stage 1 shown in Fig. 10.21, the moving contact has separated from the fixed contact and an arc is formed while in stage 4 final arc extinction is shown where the moving contact is out of the throat.

When an fault occurs, the moving contacts begin to separate. An arc is struck initially at the top of pot. The gas formed exerts pressure on the oil when the moving contact moves away from the arc splitter ducts, fresh oil is forced across the path of

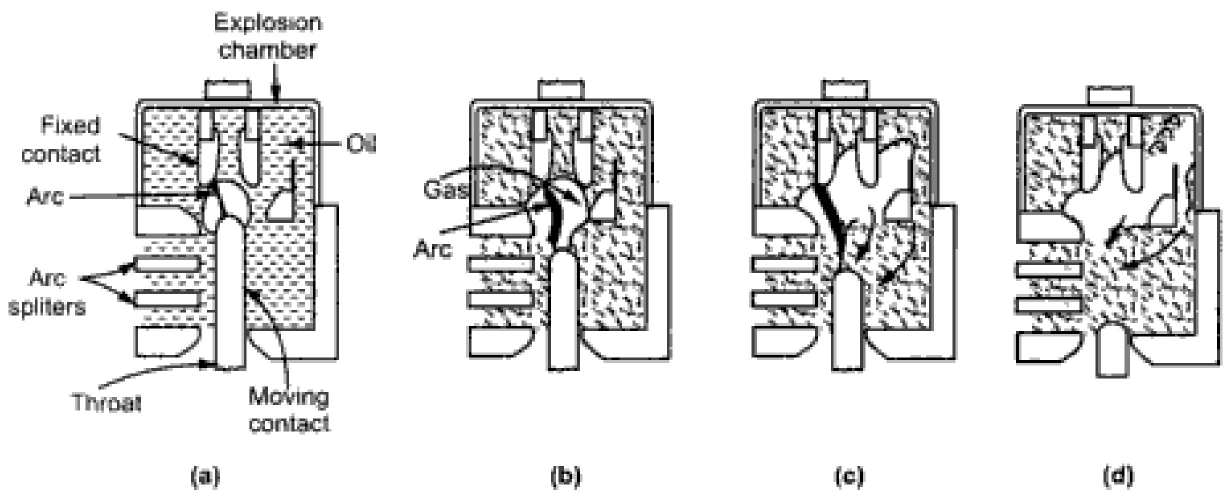


Fig. 10.21 Cross jet explosion pot

arc. The arc is then passed through the arc splitters due to which its length increases which causes the arc extinction.

This type of circuit breaker gives satisfactory performance at heavy fault currents. However for small fault current, pressure developed by gas which is function of fault current is less and the performance is not satisfactory.

10.9.2.3 Self Compensated Explosion Pot

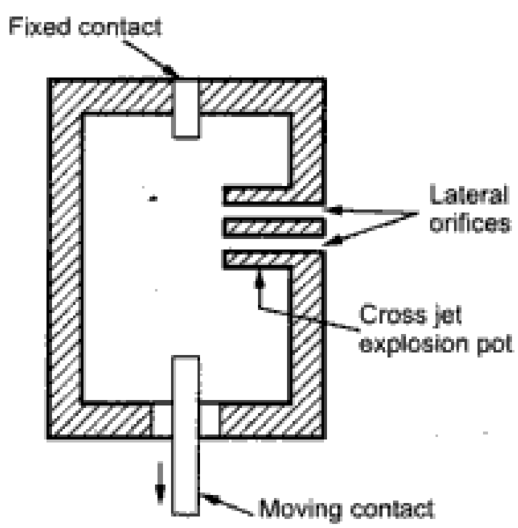


Fig. 10.22 Self compensated explosion pot

This type is essentially a combination of plain explosion and cross jet explosion type. Hence it can interrupt low as well as heavy short circuit currents effectively. It is represented in the Fig. 10.22.

It consists of two chambers, the upper chamber is the cross jet explosion pot with arc splitter ducts, while the lower chamber is the plain explosion pot.

When fault current is heavy, the rate of generation of gas is very high and it will act similar to cross jet explosion pot. When the moving contact moves away from the arc splitter duct, the arc extinction takes place.

When fault current is low the rate of gas generation is low and the tip of moving contact takes some time to reach lower chamber. By this time the gas builds up sufficient pressure as there is no much leakage. When the moving contact comes out of throat the arc is extinguished by plain pot action.

With increase in fault current level, the operation will tend more and more similar to cross jet explosion pot. Thus interruption of fault current is possible in the wide range.

10.9.2.4 Oil Blast Explosion Pot

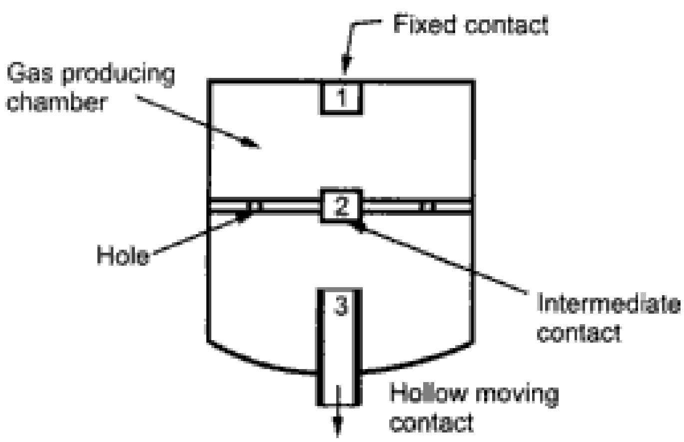


Fig. 10.23 Oil blast explosion pot

It is shown schematically in the Fig. 10.23. It consists of an intermediate contact along with moving contact. Initially the intermediate contact and lower moving contact move downwards together. An arc is struck between 1 and 2. The arc causes oil in upper chamber to be subjected to high pressure. When the intermediate contact has reached its maximum travel, the lower contacts start moving away from it and arc is struck between 2 and 3. Since the lower contact is hollow rod it is shut down by pressure which was developed by first arc. But this type has a disadvantage of long arcing time.

10.9.3 Forced Blast Oil Circuit Breakers

In the self blast oil circuit breakers, the pressure was developed due to the arc to force the oil across the arc path. The major disadvantage with this type is long arcing times and inconsistancy at lower currents as pressure developed is insufficient to force the oil in arc path. This difficulty is overcome in force blast oil circuit breakers which will not relay on the arc to generate the pressure but it is supplied from some external source.

This can be achieved by piston cylinder arrangement. The movement of piston is coupled mechanically to moving contacts or spring released by tripping mechanism. This arrangement enables high speed interruption.

When a fault occurs, the contacts get separated and an arc is struck. The piston forces a jet of oil towards the contact gap which will extinguish the arc. The typical scheme is shown in the Fig. 10.24.

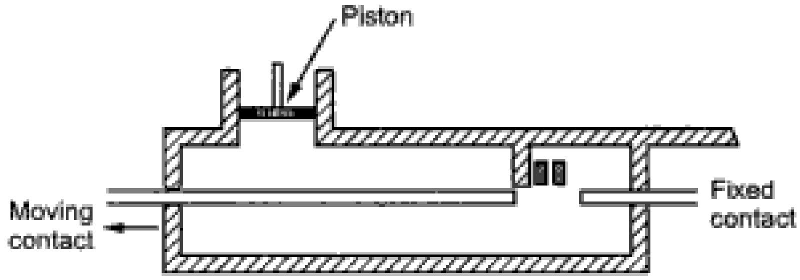


Fig. 10.24 Externally generated pressure breaker

The performance of the breaker is constant even at low currents as pressure developed is independent of fault current to be interrupted. This can be seen from following graph represented in the Fig. 10.25.

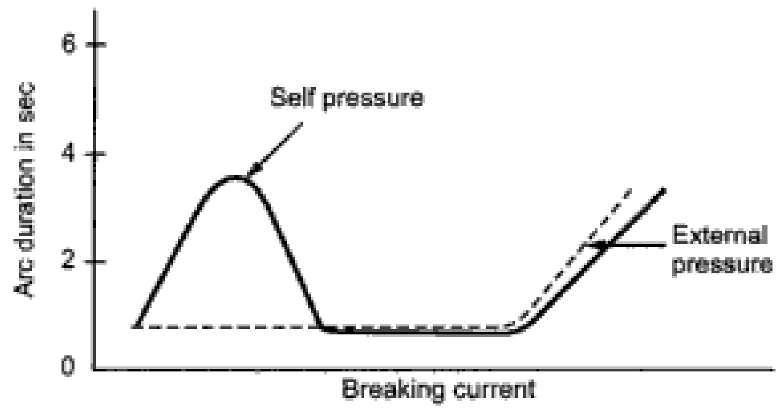


Fig. 10.25 Operating time-breaking current characteristics

Another advantage is that quantity of oil required is reduced considerably. If current chopping is there while interrupting small inductive currents then damping by resistance switching is required.

10.10 Low Oil or Minimum Oil Circuit Breaker

With the increase in system voltage the quantity of oil in bulk oil circuit breakers also increases. It gives additional expenses, increases the risk of fire and causes maintenance problem. This will make necessary the design of a type of circuit breakers which requires a low volume of oil. It is observed that oil serves two purposes. Firstly it acts as arc quenching medium and secondly it insulates live parts from earth. It is found that only a small percentage (about 10%) of oil is used for arc extinction process and major part is used for insulation purposes.

A low or minimum oil circuit breaker uses a small container having oil which is just enough for arc extinction. The container of oil is supported on porcelain insulators, so that required insulation can be obtained for live parts from earth. Thus low oil circuit breaker has added advantage that it requires less space than the bulk oil type. This is an important consideration in large installations.

With respect to quenching of arc, the oil behaves identically in bulk as well as low oil circuit breaker. By using suitable arc control devices the arc extinction can be further facilitated in low oil circuit breaker.

10.10.1 Construction

The Fig. 10.26 shows the constructional details of a single phase minimum oil circuit breaker.

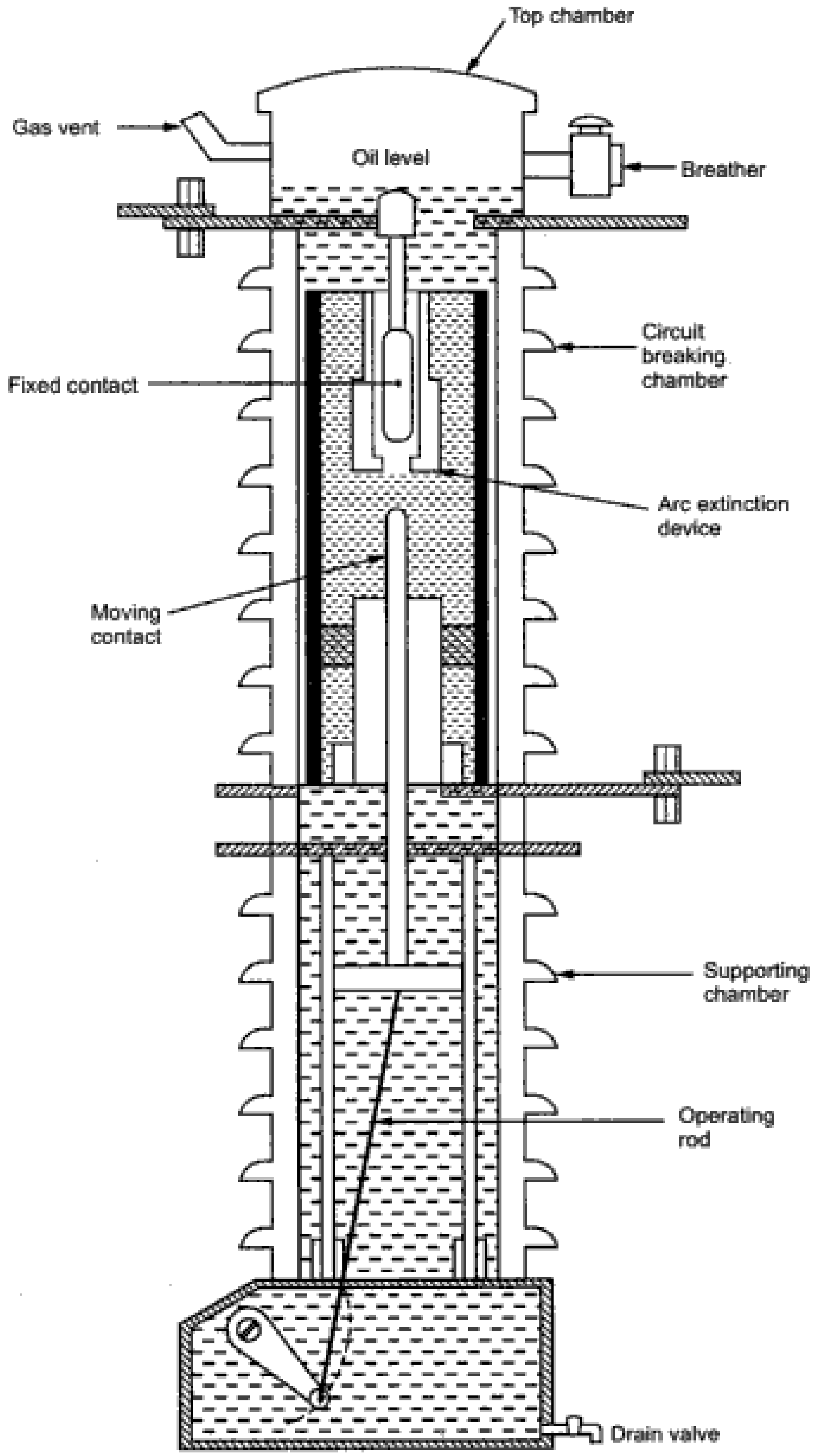


Fig. 10.26 Construction of minimum oil circuit breaker

It consists of two separate compartments which are separated from each other. Both these compartments are filled with the oil. The upper chamber is called the circuit breaking chamber while the lower chamber is called the supporting chamber. The two chambers are separated by a partition and oil from both the chambers are prevented from mixing with each other. This type of arrangement has two advantages. Firstly the circuit breaking chamber requires a small volume of oil which is just sufficient for arc extinction. Secondly small amount of oil is to be replaced as the oil in the supporting chamber does not get contaminated by the arc.

1) **Supporting Chamber :** This is a bottom chamber which is made up of procelain and mounted on metal chamber. It is filled with oil which is physically separated from the oil in circuit breaking chamber. The oil inside the supporting chamber and the annular space formed between the porcelain insulation and backelised paper is employed for insulation.

2) **Circuit Breaking Chamber :** It is a porcelain enclosure which is mounted on the top of the supporting compartment. It is also filled with oil and consists of following parts

    i) Upper and lower fixed contacts

    ii) Moving contact

    iii) Turbulator

The moving contact is hollow. It consists of a cylinder which moves down over a fixed pistion. The turbulator forms an arc control device and it has both axial and radial vents. The axial venting ensures the interruption of low currents whereas radial venting ensures interruption of heavy currents.

3) **Top Chamber :** It is a metal chamber mounted on the top of circuit breaking chamber. It provides expansion space for the oil present in circuit breaking chamber. It also contains a separator which avoids loss of oil by centrifugal action caused by circuit breaker operation during fault conditions.

10.10.2 Operation

Under normal operating conditions, the moving contact and fixed contacts are in engaged position. During abnormal conditions the moving contact is pulled down by the tripping springs. With the separation of contacts, an arc is struck between them. The energy in the arc causes vapourisation of oil. This will produce gases at high pressure. This action prevents the oil to pass through central hole in the moving contact and results in forcing series of oil through the passages of the turbulator. The process of turbulation is one in which sections of the arc successively quenched, by the effect of separate streams of oil moving across each section.

10.10.3 Maintenance of Oil Circuit Breakers

The maintenance of oil circuit breakers consists of checking of contacts and dielectric strength of the oil. After fault has been interrupted by circuit breaker, fault current flows for short time or load currents for several times, its contacts may be burnt due to arcing. Also there may be some loss of dielectric strength of oil due to carbonisation. This will reduce rupturing capacity of the breaker. Thus periodic checking of circuit breakers is essential after regular interval of 3 or 6 months. Following points should be kept in mind while checking,

i) Check the current carrying parts. It they are burnt replace them.

ii) Check the dielectric strength of oil. If its colour is changed then it should be changed or reconditioned. The oil in good condition withstands 30 kV for one minute with 4mm gap between electrodes.

iii) Check the insulation for any damage. Clean the surface with removal of carbon deposites with strong and dry fibric.

iv) The oil level should be checked.

v) The closing and tripping mechanism should be checked.

10.10.4 Advantages

The advantages of minimum oil circuit breaker are,

i) The quantity of oil required is small.

ii) The space requirement is reduced.

iii) The risk of fire is reduced.

10.10.5 Disadvantages

The disadvantages of minimum oil circuit breaker are,

i) Due to smaller quantity of oil, the degree of carbonisation is increased.

ii) The gases are difficult to remove from the contact space in time.

iii) The dielectric strength of the oil deterorates rapidly as degree of carbonisation is high.

10.10.6 Applications

Minimum oil circuit breakers are now available for all voltages and for the highest breaking capacity hence preferred in most of the protection schemes.

10.11 HVDC Circuit Breaker

In a.c. circuit breakers, arc extinction is achieved at the natural current zero of the a.c. waveform used. But in d.c. circuit breakers, natural zero of voltage and current is not available as both are continuously available. Thus for extinction of an arc, artificial current zero is required to be introduced. Such an artificial current zero is possible by connecting LC circuit in parallel with the circuit breaker. The LC circuit is responsible to produce oscillatory arc currents having many artificial current zeros. At one of the artificial current zero arc gets extinguished.

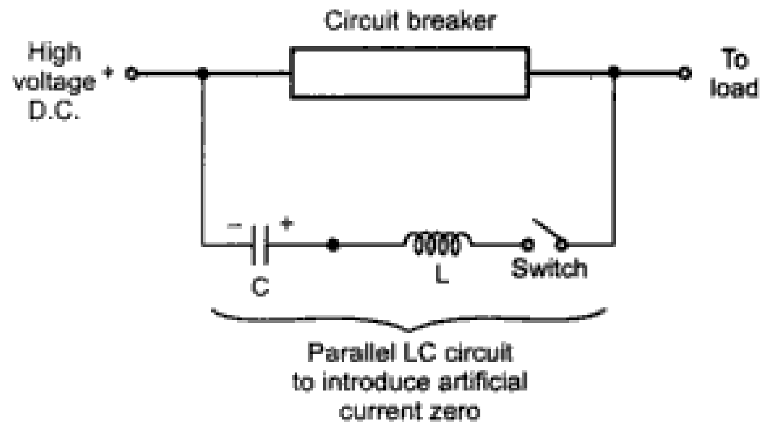


Fig. 10.27 HVDC circuit breaker

The Fig. 10.27 shows the principle of HVDC circuit breaker. The HVDC circuit breaker is nothing but a vacuum circuit breaker. The LC circuit along with a switch is connected in parallel with this circuit breaker.

The capacitor C used is precharged capacitor with the polarities as shown in the Fig. 10.27. When the circuit breaker starts opening, the switch in the LC circuit gets closed. Due to the charged capacitor, the discharging current starts flowing in opposite direction to that of load current carried by the circuit breaker. Due to this, arcing current starts oscillating producing many natural zeros. Thus artificial commutation results and arc extinction is achieved.

The large transient recovery voltage is the main constraint in HVDC circuit breaker and circuit breaker must able to withstand it. For successful operation of such a circuit breaker, the switch in LC circuit must be a high speed switch with a very fast response. Such systems are complex and very costly as they require costly protection and control systems.

10.12 Selection of Circuit Breaker

The following parameters are required to be known for selecting proper rating circuit breaker at a given location on a power system :

i) The maximum fault current which is to be interrupted by the breaker.

ii) The maximum current to be carried momentarily

As it is discussed previously the fault current consists of both a.c. and d.c. components and its correct calculation is very complex. A simplified method is recommended by IEEE committee is given below :

1. To determine firstly the required interrupting capacity of circuit breaker the highest value of initial rms alternating current for any type and location of fault. It can be considered as three phase fault as it carries maximum fault current except in some cases. This current can be obtained by using sub-transient reactance for generators and transient reactance for synchronous motors while induction motors are to be neglected. Following multiplying factors can be applied to take into account the d.c. components of currents and decrements of both a.c. and d.c. components.

8 cycle or slow breaker	1.0
5 cycle breaker	1.1
3 cycle breaker	1.2
2 cycle breaker	1.4

   Before applying multiplying factor, all the given factors are increased by 0.1 for the breakers on the generator bus where 3 phase short circuit kVA exceed 500,000.

2. To determine the required rated momentary current with time 1 sec or less of a breaker. The calculation of highest value of initial rms a.c. current can be done as given in the step (1) except using sub-transient reactances of all the machines including induction motors. Multiply the value of current obtained by 1.6.

$$\therefore \text{ Momentary rated rms current of a circuit breaker } = 1.5 \times \frac{V}{X_d''}$$

Example 10.1 : *A generator connected through 5 cycle CB to a transformer is rated 8000 kVA with the reactances of* $X_d'' = 10\ \%$, $X_d' = 16\ \%$ *and* $X_d = 100\ \%$. *It is operating at no load and rated voltage when 3 phase short circuit occurs between breaker and transformer. Find :*

i) sustained short circuit in breaker

ii) the initial symmetrical rms current in breaker

iii) maximum possible d.c. component of short circuit in breaker

iv) the momentary current rating of the breaker

v) current to be interrupted by breaker *vi) the interrupting kVA*

Solution : Let the base be 8000 kVA.

$$\therefore \quad \text{Sustained short circuit kVA} = \frac{8000}{100} \times 100 = 8000 \text{ kVA.} \quad \text{as } X_d = 100\ \%$$

$$\text{Sustained short circuit current} = \frac{\text{kVA}}{\sqrt{3} \times V_L}$$

Let $V_L = 13.8$ kV

$$\therefore \quad \text{Sustained short circuit current} = \frac{8000}{\sqrt{3} \times 13.8} = 334.70 \text{ A}$$

$$\text{Sub-transient short circuit kVA} = \frac{8000}{10} \times 100 = 80000$$

$$\text{Sub-transient or initial symmetrical current} = \frac{8000 \times 100}{10 \times \sqrt{3} \times 13.8} = 3347.05 \text{ A}$$

$$\text{Maximum possible d.c. component} = \sqrt{2} \times 3347.05 = 4732.73 \text{ A}$$

$$\text{Momentary current rating} = 1.6 \times 3347.05 = 5355.28 \text{ A}$$

$$\text{Current to be interrupted} = 1.1 \times 3347.05 = 3681.75 \text{ A}$$

$$\text{Interrupting kVA} = \sqrt{3} \times 3681.75 \times 13.8 = 87999.836 \text{ kVA}$$

10.13 Circuit Breaker Ratings

A circuit breaker is a mechanical switching device capable of making, carrying and breaking current under normal circuit conditions and also making, carrying for specified time and breaking current under specified abnormal conditions.

The circuit breaker is also required to perform some additional functions as the application demands such as,

i) to provide selectivity with breakers

ii) to provide facility for remote closing and tripping

iii) to provide facility for interlocking

iv) to provide facility for indication

Some of the important characteristics or ratings that must be possessed by every high voltage a.c. circuit breaker arc as follows,

1. Rated voltage
2. Rated insulation level
3. Rated normal current
4. Rated frequency
5. Rated duration of short circuit
6. Rated short circuit breaking current
7. Rated short circuit making current
8. Rated peak withstand current

9. Rated TRV for terminal fault
10. Rated operating sequence
11. Rated supply voltage for opening and closing devices and auxiliary circuits
12. Rated pressure of compressed gas for interruption

10.13.1 Rated Voltage

It is a voltage of a circuit breaker which refers to higher system voltage for which it is designed. It is expressed in kV and the value is r.m.s. value. In case of three phase circuits it is nothing but phase to phase voltage. A circuit breaker must be assigned two voltage ratings one corresponding to maximum nominal system voltage and other maximum design voltage which indicated the maximum operating voltage which should not be exceeded.

10.13.2 Rated Insulation Level

The different circuit breakers connected in power system are subjected to power frequency over voltages due to various effects such as regulation, Ferranti effect etc. The circuit breaker must withstand this overvoltage. This can be tested by carrying out different tests. During some single phase to ground faults voltage of healthy line to earth increases. So higher values of insulation are suggested. The insulation is provided for each pole external and internal between live parts and earth. It is also provided between poles and between terminals of same pole internal and external.

10.13.3 Rated Current

It is defined as r.m.s. value of the current that can be carried by the circuit breaker continuously with temperature rise within the specified limits. Some of the preferred values of rated currents are 400, 630, 800, 1250, 1600, 2000 A r.m.s. etc. The rated current of a circuit breaker can be checked by carrying out temperature rise tests. The current carrying parts along with the contacts are designed based on temperature rise. For given cross section of a conductor and certain value of current, the temperature rise is dependent on conductivity of material. Hence while designing high conductivity material must be used. If material is having low conductivity then cross-section of the conductor is increased.

10.13.4 Rated Frequency

The performance of circuit breaker is greatly influenced by frequency. The different characteristics like breaking capacity are based on rated frequency. With increase in frequency, eddy currents in the metallic parts will increase which will cause more heating and rise the temperature of current carrying parts. Hence if a circuit breaker designed for one particular frequency is used at some another frequency then temperature will not remain in specified limits. So the rating is to be changed accordingly.

The breaking time is also affected by the frequency as it is associated with time for half cycles during arc extinction. The breaking time decreases with increase in frequency.

The frequency has a pronounced effect on TRV and rate of rise if TRV. So a circuit breaker designed for one particular frequency can not used for other frequency unless the results are faithful for that frequency.

10.13.5 Rated Duration of Short Circuit

The short time current of a circuit breaker is r.m.s. current that it can carry in a closed position during specified time under given conditions. It is expressed in kA for a period of one second. The rated duration of short circuit is commonly 1 second. The circuit breaker must carry the current equal to its breaking capacity for this duration. This can be tested by carrying out short time current test and checked that the poles are not getting damaged or welded. The insulation should not be damaged. The poles must be able to withstand the mechanical force developed. The design for normal current rating is sufficient to carry short circuit current for 1 sec.

10.13.6 Rated Short Circuit Breaking Current

It is r.m.s. value of highest short circuit current which the circuit breaker is capable of breaking under specified conditions of TRV and power frequency voltage and expressed in kA r.m.s. at contact separation.

The voltage appearing across circuit breaker after arc interruption is nothing but Transient Recovery voltage. The limit on breaking current is governed by specified conditions of TRV and power frequency recovery voltage. This limit is determined by carrying short circuit test. The current waveform is shown in the Fig. 10.28.

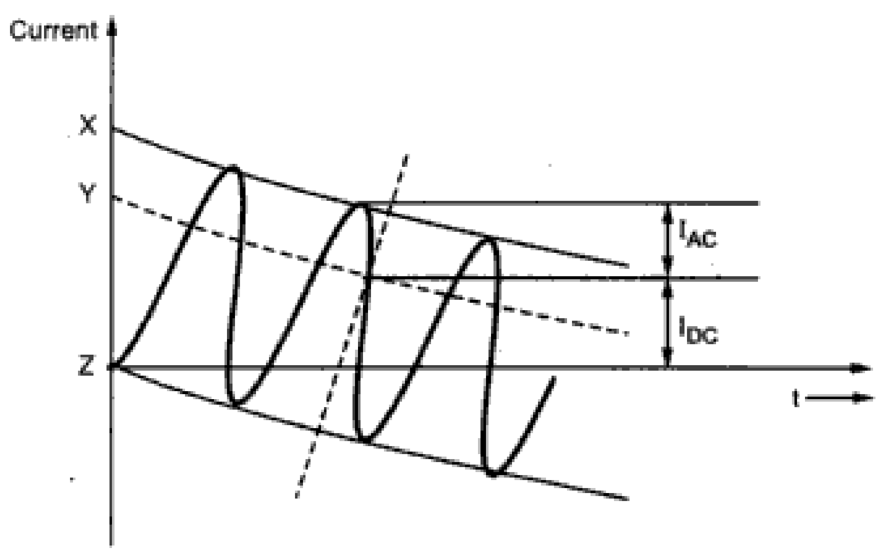


Fig. 10.28

The breaking current is expressed by two values

i) The r.m.s. value of a.c. component at the instant of contact separation given by $\frac{I_{AC}}{\sqrt{2}}$

ii) The percentage d.c. component at the instant of contact separation given by $\frac{I_{DC} \times 100}{I_{AC}}$

The standard values of r.m.s. currents are 8, 10, 123, 16, 20, 25, 31, 5, 40 kA etc.

In earlier days the breaking capacity is expressed in MVA so that fault levels can also be determined. But now it is expressed in kA for specified conditions of TRV.

10.13.7 Rated Short Circuit Making Current

This is defined as the peak value of first current loop of short circuit current which the circuit breaker is capable of making at its rated voltage. There are certain cases under which the circuit breaker may close when fault is existing. Under such cases current reaches to maximum value at peak of first current loop. The circuit breaker should be able to close without difficulty and withstand the mechanical forces developed during a closure. This is checked by carrying out making current test.

$$\text{Rated making current} = 1.8 \times \sqrt{2} \times \text{Rated short circuit breaking}$$

$$= 2.5 \times \text{Rated short circuit breaking current}$$

$\sqrt{2}$ in above expression converts r.ms. value to peak value while factor 1.8 is considered for doubling effect of short circuit current

10.13.8 Rated Peak Withstand Current

It is defined as the instantaneous value of short circuit current which circuit breaker can withstand safely in closed position. It is expressed in terms of kA instantaneous. The value suggested for this current is equal to rated short circuit making current. To test this peak withstand current short circuit with maximum asymmetry is applied to circuit breaker in one phase. The peak withstand current test is combined with short time current test. The stresses produced due to high current must be sustained by the circuit breaker.

10.13.9 Rated TRV for Terminal Faults

The TRV waveform can be specified by various methods such as specifying the peak value and time to reach it or specifying parameters which will decide the line segment which will represent TRV wave. The methods are respectively called two parameter and four parameter method. The two parameter method is represented in the Fig. 10.29.

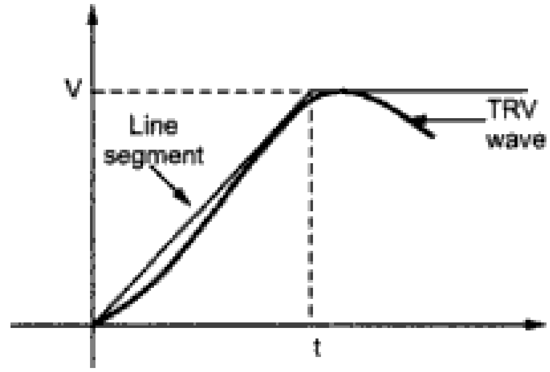


Fig. 10.29

The circuit breakers must be provided with Rated TRV. The breaking current test is carried out on circuit breaker with specified TRV.

The standards provide different parameters such as voltage, and time to plot the line segments. The TRV wave can be drawn within the segment. The circuit breaker must be tested for S.C. breaking current test with TRV waveform above standard waveform.

10.13.10 Rated Operating Sequence

It represents the sequence of opening and closing operations which circuit breaker can perform under specified conditions. As per specifications the circuit breaker should be able to perform the operating sequence as per one of the ways

i) O – t – CO – T – CO ii) CO – t′ – CO

where O = Operation of opening

t = 3 minutes for circuit breaker not to be used for rapid auto-reclosure

CO = Closing followed by opening

T = 3 minutes

t′ = 15 sec for circuit breaker not to be used for rapid auto-reclosure

10.13.11 Rated Supply Voltage for Closing and Opening Devices

The performance of auxiliary supply circuits and operating mechanisms is important in addition to ratings of or main circuit and poles. The supply voltage is provided by auxiliary circuits to the trip coil and closing coil which are having certain minimum voltage below which it will not operate. For correct operation the frequency must be properly chosen. The rated supply voltage and supply frequency of closing and opening devices and auxiliary circuits is important.

10.13.12 Rated Pressure of Compressed Gas

The air blast circuit breaker and some of the SF_6 breakers use pneumatic while some other SF_6 breakers use hydraulic operating mechanisms where minimum and maximum values of pressures are specified certain tests like no load test are carried out with conditions of the pressures. The pressure switches are also fitted in the auxiliary systems of the operating mechanism.

Some additional rated characteristics are to be specified in certain cases like rated characteristics for short-line faults for circuit breakers controlling overhead lines rated 52 kV and above, Rated line charging current for circuit breakers controlling overhead lines rated 72.5 kV and above.

There are certain special switching duties like capacitor switching, reactor switching, DC switching, inductive current switching. The stress produced is usual and severe. Different circuit breakers behaves differently. The interruption of low inductive currents is achieved by SF_6 while capacitor current switching is done excellently by VCB. Depending upon the type of application the following characteristics are specified,

i) Rated out of phase breaking current

ii) Rated cable charging breaking current

iii) Rated single capacitor bank breaking current

iv) Permissible switching overvoltages

v) Rated capacitor bank in rush overvoltages

vi) Rated small inductive breaking current

vii) Rated time quantities

viii) Repeated operating duty.

In actual design of circuit breakers following parameters are considered :

1. Current rating
2. Breaking capacity
3. Making capacity
4. Type of protective mechanism
5. Short time rating
6. Type of mechanism
7. Accessories
8. Indications
9. Locks and interlocks
10. Operational life
11. Ease of maintenance
12. Volume / weight
13. Control voltage

14. Availability of spares
15. Cost

Depending upon the above parameters the different circuit breakers are designed for their efficient operation.

10.14 Type Tests

As mentioned earlier these tests are carried out on first few circuit breakers to prove the rated characteristics of the breakers. The necessary information which includes assigned ratings, drawings, reference standards, rated operating pressure and voltage, support structure etc must be supplied to the testing authorities before conducting these tests. These details are included in the type tests report. After certifying the breaker by carrying out these tests, there should not be any change in design.

Type tests are classified as follows,

a) Mechanical tests

b) Tests of temperature rise, millivolt drop test

c) High voltage test

d) Basic short circuit test

i) Making test

ii) Breaking test

iii) Operating sequence tests at 10%, 30%, 60%, 100% of rated breaking current with specified TRV conditions.

e) Critical current tests

f) Single phase short circuit test

g) Short time current test

In addition to above tests some more tests are recommended on circuit breakers to be used in specific applications, which are,

a) Short line fault tests

b) Out of phase switching tests

c) Cable charging current switching test

d) Capacitive current switching tests

e) Small inductive current breaking tests

f) Reactor current switching tests

10.15 Routine Tests

Before dispatch of circuit breakers, these tests are performed. Routine test is defined as a test of every circuit breaker made to the same specifications. They include the following tests.

a) Mechanical operation tests

b) Millivolt drop test, Measurement of resistance

c) Power frequency voltage tests

d) Voltage tests on auxiliary circuits, control circuits

The quality of the circuit breaker can be very well checked by these tests. Also any defects in the materials and construction is detected.

10.16 Development Tests

These tests, are very much essential to observe the effect of different parameters on the circuit breakers performance. Variety of tests are performed on individual items as well as on complete assemblies.

If a circuit breaker is tested frequently with change in its contact speed, then we can see the effect of contact speed on breaking capacity. The different parameters and their effects are theoretically predicted. Full scale prototypes are manufactured after testing and measurement. The data available in the company is used by the designers for example for the design of contacts, the configuration can be derived from available designs of contact assemblies.

Each subassembly has certain functional requirement e.g. the contacts should give low resistance in closed position. Therefore to verify the capability of contact configurations, development tests are conducted, depending on functional requirements. The modifications are done on the basis of these test results.

10.17 Reliability Tests

The newly manufactured circuit breakers are tested by type tests and routine tests. But the conditions during these tests are not the conditions that exist at the field. At site the circuit breaker is subjected to various stresses due to,

a) Variation in ambient temperatures

b) Extremely low and high temperatures

c) Rain moisture

d) Vibrations on account of earthquakes

e) Dust and chemical fumes

f) Overloads and over voltages

Also the maintenance of the breaker may not be done by skilled persons. Thus the performance of the breaker is tested under these adverse conditions by reliability tests. The circuit breaker is subjected to extremely high temperature created in test chambers. The various parts are critically examined after testing.

10.18 Commissioning Tests

These test are performed after the proper installation of the breaker at the site. The operational readiness and proper assembly is verified. High accuracy is not generally expected in such tests. The test facilities available at site is also important factor.

These include following tests,

a) Mechanical operation tests

b) Measurement of travel, simultaneous touching of contacts

c) Measurement of insulation resistance and DC resistance

d) Checking the operation by energising of relays

e) Checking the operation by energising the manual operating signal

10.19 Short Circuit Test Layout

The short circuit testing is an experimental method for proving the ratings of the breaker and checking its performance for further developments. Many of these tests come under type tests. By carrying out experimentation and problems related to circuit breaking, the modern EHV (Extra High Voltage) breakers are developed.

Due to short circuits, severe stresses are produced on circuit breakers. The circuit breaker must be capable of withstanding the stresses. The short circuit current duration is about 1 sec or 3 sec. The short time current test verify the capability of breaker.

Due to short circuit, thermal stresses are produced on contacts and current carrying parts. The stress is also produced on insulation. The poles and terminals experience electro-dynamic forces.

The making capacity checks the ability of breaker to close on short circuit. The breaker should be capable of closing effectively without contact welding. The breaking capacity verify the ability to clear short circuits. The operating mechanism and the interrupter should able to perform these functions efficiently.

The stresses developed during short circuit depend on magnitude of fault current and design of breaker. After current zero, the contact space is subjected to TRV. Therefore for reliable operation and performance of circuit breaker on short circuit, short circuit testing plants are specially built.

10.19.1 Short Circuit Testing Plants

There are three types of testing stations which are as follows,

a) Field type testing station where power required for testing is taken directly from large power system and the breaker under tests is connected.

b) Laboratory type testing station where the short circuit generators provide the power for testing. The breaker may be tested directly or indirectly.

c) Composite testing station which is a combination of field type testing station and laboratory type testing station.

10.19.2 Layout of a Short Circuit Testing Station

It is represented in the Fig. 10.30. The short circuit generators provide the power required. There may be two or more generators though in the figure shown it is only one. Three phase induction motor drives the generator and impulse excitation is provided.

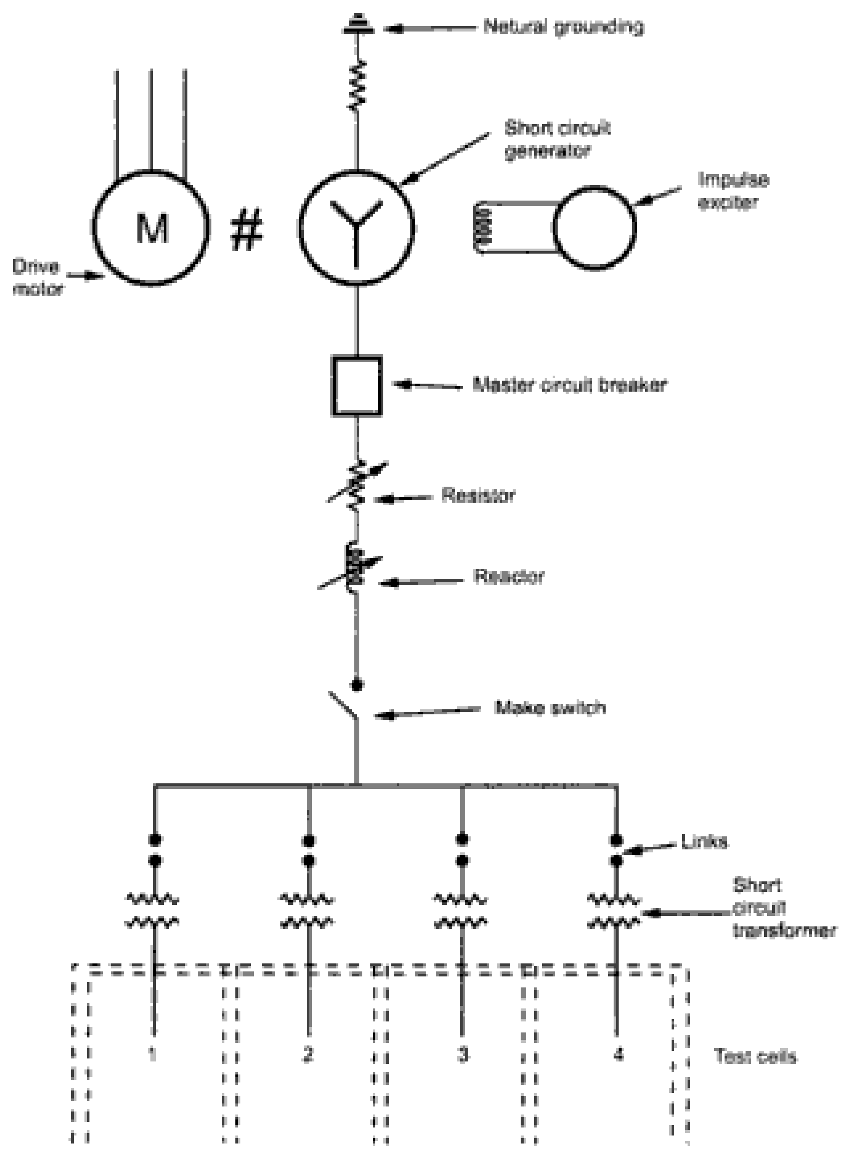


Fig. 10.30 Layout of short circuit test

For adjusting magnitude of short circuit current, variable series resistors and reactors are provided. The master circuit breaker has higher capacity than the breaker under test. If breaker under test fails to operate, then master breaker operates to protect the circuit. Making switch is a closing device specially designed which can close at desired moment and carries the making currents.

The test voltages are obtained by transformers. These single phase units are connected in various ways to get different test voltages. This also includes some equipments necessary for measurement, record and control, and auxiliary equipments with a sequence switch to obtain sequential operation.

10.19.3 Short Circuit Generator and Drive Motor

The circuit breakers under test are supplied power with this generator. The generator must withstand high reactive power surges for short duration. Their design is therefore somewhat different from conventional alternators.

The generator is driven by a three phase induction motor mounted on same shaft. The impulse excitation is provided by separate d.c. converter. The short circuit current at lagging power factor have a demagnetizing effect which reduces e.m.f. So the voltage before the short circuit will be less. Thus the generator field current is boosted by impulse excitation. The field current is increased to about 10 times its normal value at the time of short circuit. The arrangement of circuit is shown in the Fig. 10.31.

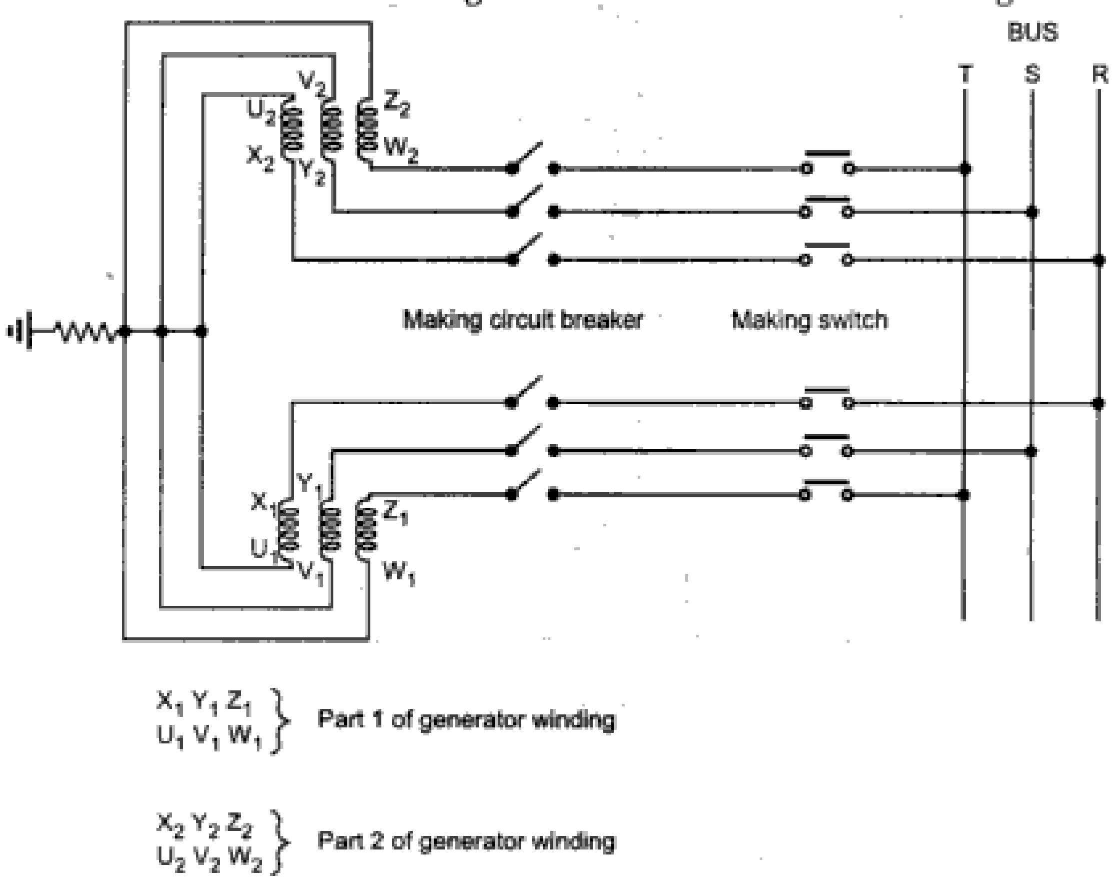


Fig. 10.31 Circuit arrangement in short circuit test layout

10.19.11 Sequence Switch

During short circuit testing, many operations are performed in a sequence and total time is very less to perform manual operation. A sequence switch performs the sequential operations as it is a drum switch with several contacts which is rotated by a motor. Due to rotation of drum, control circuits are opened or closed as per specific sequence. The sequences for breaking capacity test in one test are as follows which takes nearly 0.2 seconds,

i) Drive motor of short circuit generator made off

ii) Impulse excitation switched on

iii) Master circuit breaker closed

iv) Oscillogram circuit connected

v) Make switch closed

vi) Circuit breaker under test opened

vii) Master circuit breaker opened

viii) Excitor switched off and its field supressed

10.19.12 Different Measurements

Since the test events takes very short time, all measurements must be recorded by oscillographs. Light beam oscillograph which are easily operated are used for slow varying quantities like current, voltage, contact travel or trip signal etc. TRV phenomenon requires only 1 msec. For recording such fast quantities, CRO is used.

The following quantities are recorded during the test,

i) Short circuit current in each phase

ii) Voltage across each pole before, after and during short circuit

iii) Fluid pressure

iv) Contact travel speed

v) Generator voltage

vi) TRV

vii) Current in trip circuit

10.20 Indirect Testing

It is possible that the short circuit power that can be obtained from the testing station may be insufficient to test a breaker of high capacity. Even a single pole of a EHV breaker can not be tested by direct means.

The EHV circuit breaker consists of many arc interrupter units which are separately tested called unit testing. If one unit is tested, the capacity of complete pole and breaker is determined. This method of Unit Testing is adopted internationally.

Synthetic testing is another popular method which permits testing of breaker.

10.20.1 Unit Testing

The modern EHV circuit breakers contains two or more similar interrupters per pole. These interrupters operate simultaneously and share the voltage across the pole equally. The breaking capacity is also equally shared. The results obtained on one unit can be extended further for total capacity of breaker. This is known as unit testing or element testing. It is internationally accepted method.

During the application of unit test, the voltage must be reduced by a factor b so the corresponding impedances are also reduced by b to get test voltage across the unit by following expression.

$a = \frac{1}{m}$ where m = number of units per pole and one unit is tested

$a = \frac{n}{m}$ where n units are tested

Let us consider the examples of a 3 pole, 220 kV breaker with 3 units per pole

$$\text{Voltage across one pole} = \frac{220}{\sqrt{3}} = 127 \text{ kV}$$

$$a = \frac{1}{m}; \quad m = 3 \quad \therefore \quad a = \frac{1}{3}$$

$\therefore$ Voltage required for testing one unit = a × voltage per pole = $127 \times \frac{1}{3} = 42.33$ kV

L and C of the test circuit is also reduced to get same natural frequency as that of direct testing.

In direct test,

$$\text{Natural frequency,} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\text{In unit testing,} \quad f_n = \frac{1}{2\pi\sqrt{aL \times \frac{C}{a}}} = \frac{1}{2\pi\sqrt{LC}}$$

The natural frequency of TRV remains unchanged. Time scale also remains unchanged.

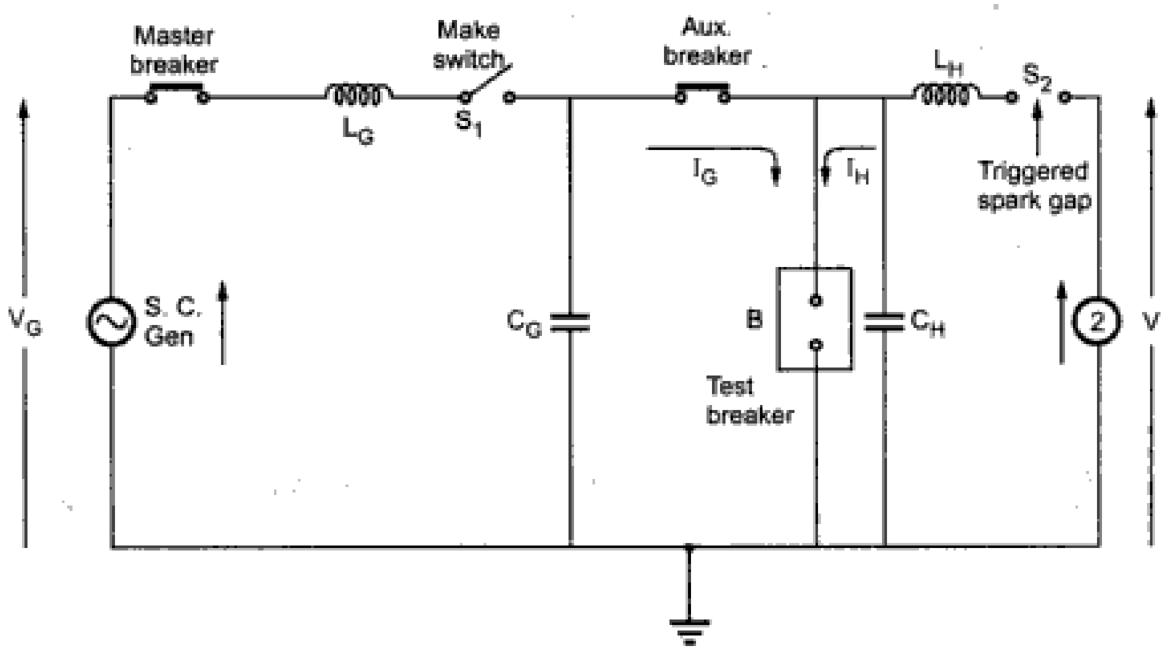


Fig. 10.33 (a) Parallel current injection method

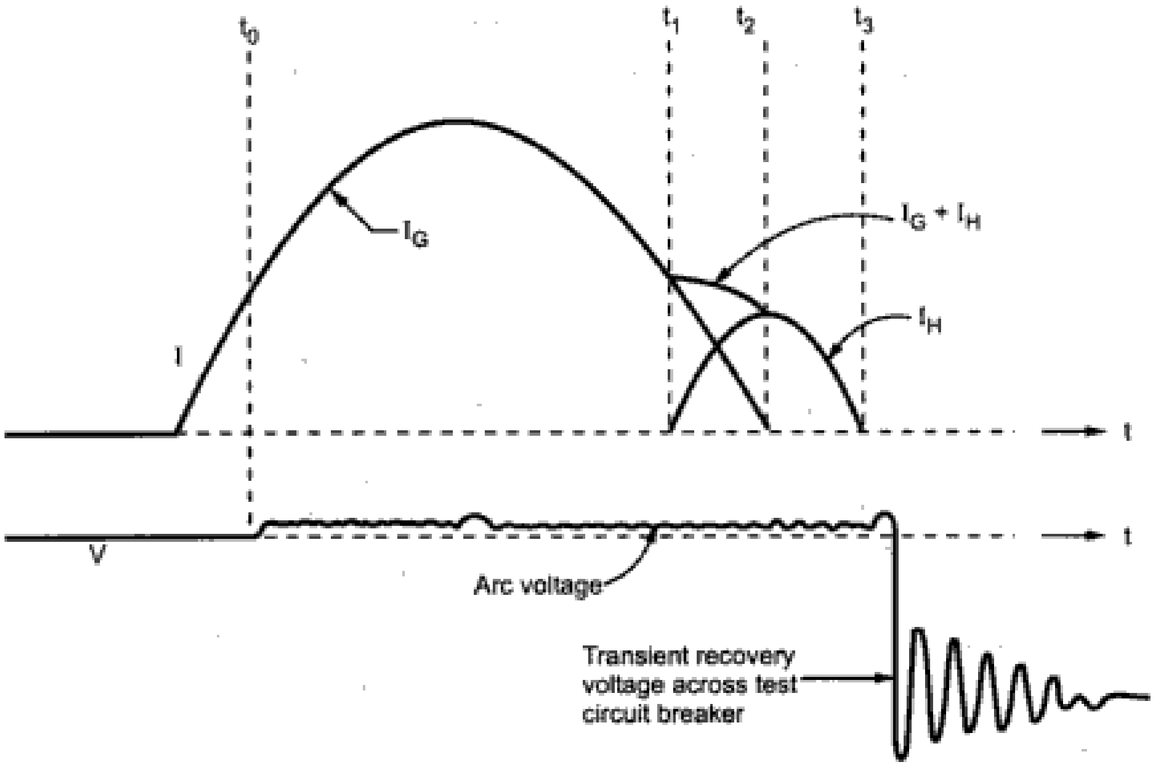


Fig. 10.33 (b) Parallel current injection method waveforms

In this method the voltage circuit (2) is effectively connected in parallel with current circuit (1) and test breaker before main current I_G in test breaker current is properly simulated.

are in opposition. The stresses produced in the synthetic test and those in actual network must be same but it is not the actual case because of several factors like high current, high voltage, instant of applying voltage etc.

10.21.3 Brown Boveri's Synthetic Testing Circuit

This circuit is shown in the Fig. 10.35. The short circuit current is supplied from low voltage circuit. The restriking and recovery voltage is supplied by different high voltage circuit.

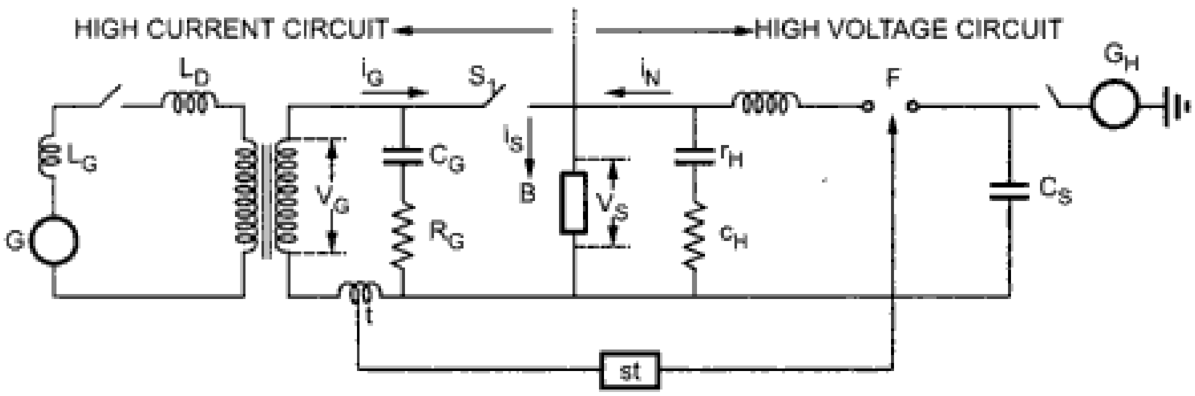


Fig. 10.35 Brown-Boveri's synthetic testing circuit

The high current circuit on left side consists of short circuit generator G, short circuit transformer with resistor R_G and capacitor C_G which controls natural frequency of current. The short circuit power is supplied at voltages V_S which corresponds to about 30 kV which is smaller than recovery voltage required for testing. The recovery voltage is supplied by high voltage circuit on right side.

The test breaker and auxiliary breaker S_1 are opened together. Before the current interruption takes place in breaker B, the spark gap is triggered by control S_t and voltage V is applied to breaker B. During final current zero only current i_H flows through breaker B. Previously $i_S = i_G + i_H$ which is interrupted by S_1 and breaker B. But now breaker B has to interrupt only i_H. Hence restriking voltage across breaker B is given by HV circuit.

Review Questions

1. *State the requirements of a circuit breaker and explain the basic action of circuit breaker.*
2. *State the classification of circuit breaker based on different factors.*
3. *Explain the construction and working of air break circuit breaker.*
4. *Write a note on air blast circuit breaker.*
5. *Explain plain break oil circuit breaker.*
6. *Explain with the help of neat sketch the construction and working of minimum oil circuit breaker.*

What are its advantages and disadvantages, compared to bulk oil circuit breaker ?

7. *Explain in brief cross jet and plain jet explosion pot.*
8. *Why SF_6 gas is preferred in circuit breakers ?*
9. *Write a note on dielectric properties of SF_6 gas.*
10. *Explain the construction and working of SF_6 circuit breaker.*
11. *What are advantages and disadvantages of SF_6 breaker ?*
12. *Explain the construction, working, advantages and the disadvantages of vacuum circuit breakers.*
13. *Explain the arc interruption taking place in vacuum.*
14. *What are the possible applications of vacuum circuit breakers ?*
15. *Explain the process of arc extinction in vacuum.*
16. *Write a note on*

    i) Unit testing ii) Synthetic testing
17. *Describe short circuit test layout for a circuit breaker.*
18. *What are the different ratings of circuit breakers ? Explain any one in detail ?*
19. *Wrie a note on HVDC circuit breaker.*

❑❑❑

11

Power System Earthing

11.1 Introduction

The earthing or grounding is nothing but the connection of neutral point of the supply system to the general mass of earth in such a way that immediate discharge of electricity can take place without danger.

When grounding is provided then it ensures the safety of personnel against electrical shocks and avoids accidents. The equipment is also protected against lightning and voltage surges. The voltage stress on lines is reduced along with that on the equipments with respect to earth under abnormal conditions. With earthing, the earth fault currents are controlled for protective relays.

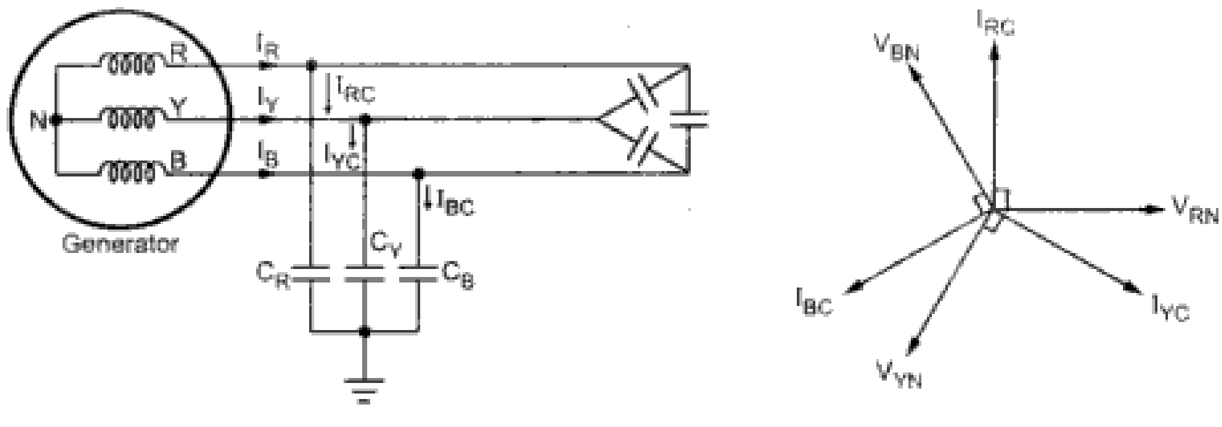
There are two ways in which the three phase systems can be operated. These are viz. with isolated neutral and with earthed neutral.

But presently isolated neutral system is not used as with such system during fault, large transient voltages with magnitude several times that of normal value is produced which may cause breakdown of insulation. This results in damage of the concerned equipment and interruption of the supply system. Inspite of this the advantage of this system is under earth fault on one of the phases, the remaining two healthy phases will continue supplying load for a shorter period.

11.2 Ungrounded or Isolated Neutral System

As the name indicates, the system neutral is not connected to the earth in this system. Thus the neutral is isolated from the earth. A simple isolated neutral system is shown in the Fig. 11.1.(a)

There is always capacitive coupling between conductors and earth which causes capacitive currents to flow in the system. The line conductors have capacitance between one another and to earth. The capacitance between conductors is represented in delta while capacitance between conductor and earth is in star for 3 phases. As the grounding characteristics of the system are little affected by line capacitances, they can be neglected.



(a) Ungrounded system (b) Phasor diagram

Fig. 11.1

The capacitance to earth of each phase is uniformly distributed along its entire length and for all the calculations this capacitance is grouped to form a single capacitor connected between each phase and earth. These currents lead their respective voltages by 90° as shown in the phasor diagram. Fig. 11.1 (b)

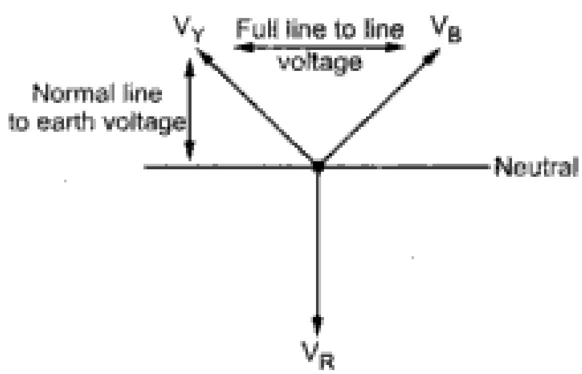


Fig. 11.2 Potential of each phase to earth before fault

For a perfectly transposed line (symmetrically spaced) the capacitive currents I_{RC}, I_{YC} and I_{BC} are equal in magnitude and displaced from each other by an angle of 120°. In balanced load condition with symmetrical spacing between conductors, the potential of neutral will be equal to that of earth as shown in the Fig. 11.2.

The charging currents I_{RC}, I_{YC} and I_{BC} are balanced and their resultant is zero and no current flows to the earth. Now let us consider the earth fault on Y phase say at point P. The corresponding phase will be at earth potential while the remaining healthy phases acquire line value from phase value as shown in the Fig. 11.3.

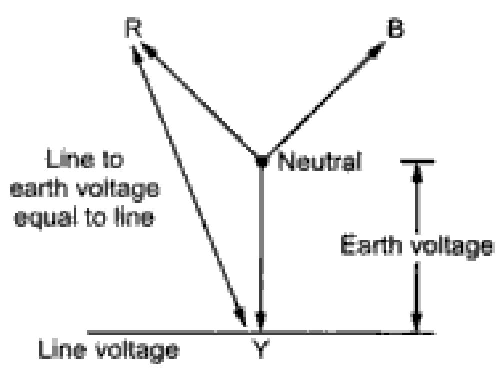


Fig. 11.3

The capacitive current will not flow in this phase. The potential of neutral is not zero but it is shifted from earth potential position to position shown in the Fig. 11.3.

The circuit diagram and the corresponding phasor diagram during the fault is as shown in the Fig. 11.4.

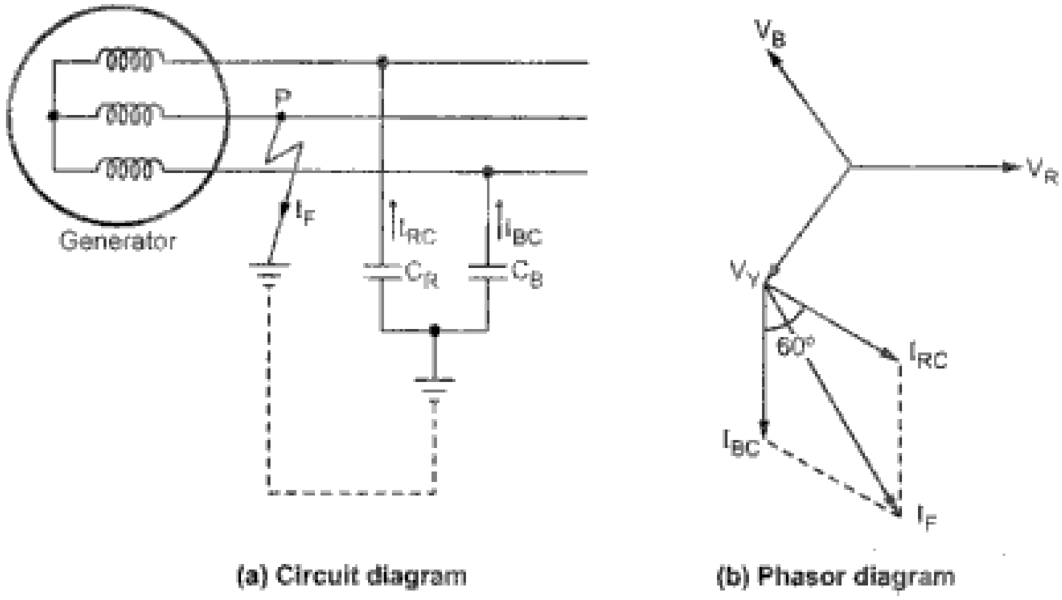


Fig. 11.4

Under fault condition, the capacitive currents are unbalanced and the fault current flows through the faulty line, into the fault and returns to the system via earth and through the earth capacitances C_R and C_B. The current in Y line has two components one I_{RC} and other I_{BC} and the respective voltages driving these currents are V_{RY} and V_{YB} and the phase difference between currents and voltages is 90° due to capacitive nature of the impedance of the circuit. The vector sum of I_{RC} and I_{BC} gives fault current I_F.

$$\text{Voltage to earth of R phase} = \sqrt{3} \cdot V_R$$

$$\text{Voltage to earth of B phase} = \sqrt{3} \cdot V_B$$

We have,

$$I_{RC} = \frac{V_{RY}}{X_{RC}} = \frac{\sqrt{3}\, V_{phase}}{X_C}$$

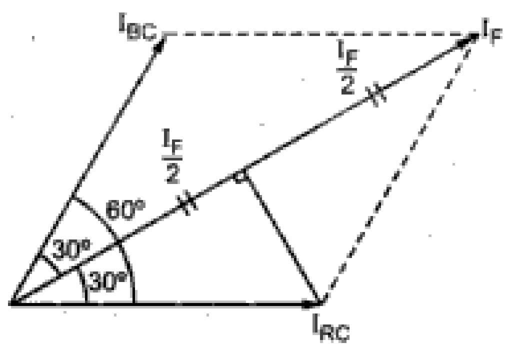


Fig. 11.5

Similarly we have,

$$I_{BC} = \frac{V_{YB}}{X_{BC}} = \frac{\sqrt{3}\, V_{phase}}{X_C}$$

Both V_{phase} and X_C are equal and the fault current is given by vector sum of I_{RC} and I_{BC} as shown in the Fig. 11.5.

From the diagram,

$$\cos 30^\circ = \frac{(I_F / 2)}{I_{RC}}$$

$$\therefore \quad \frac{I_F}{2} = I_{RC} \cdot \cos 30^\circ$$

$$\therefore \quad \frac{I_F}{2} = I_{RC} \cdot \frac{\sqrt{3}}{2}$$

$$\therefore \quad I_F = \sqrt{3} \cdot I_{RC}$$

$$\therefore \quad I_F = \sqrt{3} \cdot \frac{\sqrt{3}\, V_{phase}}{X_C}$$

$$\therefore \quad I_F = \frac{3\, V_{phase}}{X_C}$$

From the above equation, it can be seen that the current flowing through faulty phase is three times the normal line to neutral capacitive current flowing in each phase of the healthy system.

The following observations can be seen from the above analysis

1. With an ungrounded neutral system, if there is phase to earth fault then the voltages of the healthy phases with respect to earth rise from normal phase to neutral value towards full line value which may result in insulation breakdown.
2. The capacitive current in the remaining healthy phases increases to $\sqrt{3}$ times its normal value.
3. The capacitive current in the faulty phase is 3 times its normal value.
4. A capacitive current flows into the earth. If its magnitude is in excess of 4 to 5 amperes then it is sufficient to maintain an arc in the ionized path of the fault. This current can remain even after clearance of fault. This phenomenon of persistant arc is called arcing ground. The system capacity will be charged and discharged in cyclic order due to which high frequency transients may occur which will cause high voltages of the order of 5 to 6 times the normal value may be present which results in insulation breakdown. This may cause another line to line fault because of insulation breakdown either on same circuit or on another circuit. Thus a minor fault also results in insulation breakdown and interruption of supply.

Due to unbalance in capacitive currents during fault, discriminative type of fault indicator can not be installed. But the neutral shift indicator may be inserted in the system which only indicates the occurrence of earth fault but does not give its location.

The advantages of isolated neutral includes the operation of the system with single line to ground fault. Also the radio interference is minimized due to absence of zero sequence currents.

In summary, the ungrounded system does not provide protection against earth fault to adequate level with chances of insulation breakdown because of which a phase to phase fault may occur. Due to all these reasons this system is not commonly used in practice now a days. The earthed neutral system has many advantages due to which it is preferred in modern power system installations.

11.3 Earthed Neutral System

In this system, the neutral is earthed either directly or through resistance or reactance depending on the requirement. Thus the system neutral can be grounded effectively or non-effectively. In effectively grounded system, the neutral is grounded directly and hence it is called solid grounding. Following methods are adopted for non-effectively grounded systems.

i) Resistance earthing

ii) Reactance earthing

iii) Arc supression coil or resonant earthing

iv) Voltage transformer earthing

v) Earthing transformer

The advantages of neutral earthing are as follows,

i) The arcing grounds are prevented from occuring by employing suitable switchgears.

ii) As the neutral point is not shifted in this system, thus the voltages of healthy phases remains nearly constant.

iii) The static charges which are induced are grounded immediately and are thus prevented from causing any disturbance.

iv) The faulty part of the system can be isolated from the remaining system with the help of earth fault relays.

v) The magnitude of transient voltage is small in this system.

vi) The discriminative type fault indicator can be installed on such systems.

vii) This system is more reliable, provides safety to personnel and equipment with reduced operational and maintenance cost than ungrounded system.

11.4 Solid Grounding

In this method of earthing, neutral is directly connected to earth by a metallic connection or a wire of negligible resistance and reactance. The charging currents flow through the system under normal condition similar to ungrounded system.

Because of the connection of system neutral point to earth, it always remains at earth potential at all operating conditions and under faulty conditions voltage of healthy phase will not exceed.

The solid grounding is represented in the Fig. 11.6.

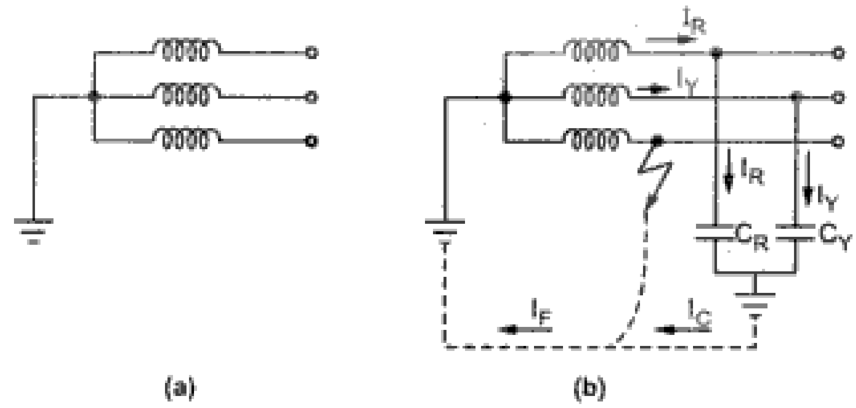


Fig. 11.6 Solid earthing

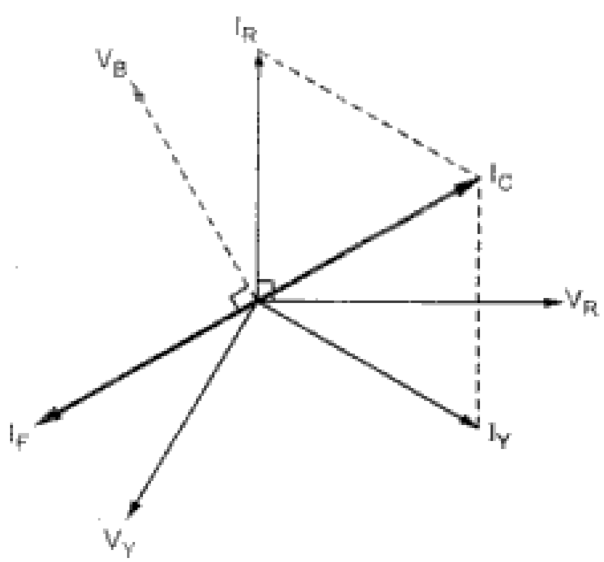


Fig. 11.7 Phasor diagram

Whenever there is earth fault on any one phase (phase B in this case), the phase to earth voltage of faulty phase is zero while voltage to earth of the remaining two healthy phases will be normal phase voltages as neutral in this case is not shifted. The phasor diagram corresponding to this condition is shown in the Fig. 11.7.

Let the capacitive currents flowing in the healthy phases be I_R and I_Y. the resultant capacitive current is vector sum of I_R and I_Y. The alternator in addition to capacitive current also provides the fault current I_F. This current flows from fault point through faulty phase and then return to the alternator through earth and neutral connection. The resistance of earth fault is negligible. The magnitude of fault current after the analysis is given by,

$$I_F = \frac{3V_{ph}}{Z_1 + Z_2 + Z_0}$$

This current is mainly dependent on zero sequence impedance of the source of power and that of phase conductor upto fault point. As the resistive component of zero sequence impedance is normally negligible, the fault current which is large can be assumed as lagging the faulty phase voltage by 90°. From the phasor diagram, it can be seen that I_F and I_C are exactly opposite due to which capacitive current is neutralised by high fault current which eliminates the possibility of arcing grounds and overvoltages. The discriminative types of switchgears may be used in this method.

Following are disadvantages of this method,

i) Due to high value of fault currents, the system may become unstable and there will be greater interference to neighbouring circuits. Thus this method is employed where system impedance is sufficiently large to limit fault current.

ii) With high values of fault currents, circuit breakers are difficult to handle and heavy contacts are to be provided in the circuit breakers.

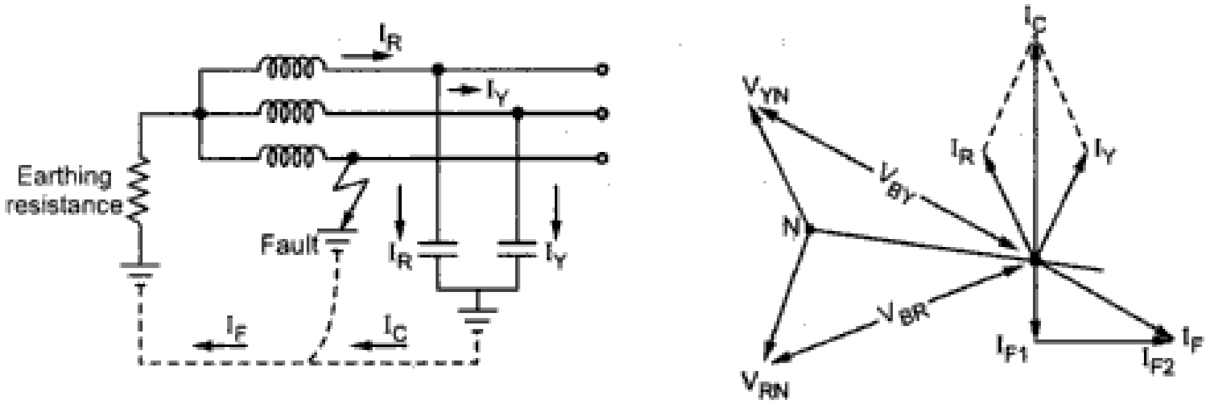
The above disadvantages can be overcome by employing high rupturing capacity and high speed circuit breakers along with fast operating relays.

This method is used in high voltage systems with voltages below 33 kV with total capacity not exceeding 5000 kVA for the economic reasons.

11.5 Resistance Earthing

In the cases where it is necessary to limit the fault current then the current limiting element must be inserted in the neutral and earth. One of the ways of achieving this is the use of resistance earthing where one or more resistances are connected between neutral and earth. The resistor may be either of wire or water column resistances for voltages of 6.6 kV and above. Metallic resistors do not change with time and requires little maintenance. But owing to its inductive nature they have disadvantage with overhead lines exposed to lightning as impulses or the travelling waves are subjected to positive reflection and cause stress on insulation resulting in its breakdown. Liquid resistors are free from these disadvantages and have simple and robust construction.

As shown in the Fig. 11.8(a) let the earth fault occurs on phase B. The corresponding phasor diagram is shown in the Fig. 11.8(b). The capacitive currents I_R and I_Y flow through the healthy lines. The fault current not only depends on the zero sequence impedance of the source but also on the resistance in the earth circuit. This fault current can be resolved into two components one inphase with the faulty phase voltage and other lagging the faulty phase voltage by 90°. This lagging component of current is in phase opposition to capacitive current and it changes with change in value of earthing resistance. Thus the value of this resistance is designed in such a way that during fault on any phase, a current equal to full load current of largest alternator or transformer flows in earth resistance which will keep the overvoltages within limits. With fault current lagging component equal to capacitive current the system operation is similar to solidly earth system and no transients occur due to arcing ground.



(a) Circuit representation **(b) Phasor diagram**

Fig. 11.8

With high value of earthing resistance and low value of reactive current than the capacitive current then system conditions approach to that of ungrounded system with chances of transient over voltages to occur. The line to earth voltage of the healthy phases at the time of fault is little more than line to earth voltage of the solidly grounded system operating under similar conditions. The duration of this voltage can be reduced by using suitable protective switchgears to avoid any harmful effect that may be caused.

The value of resistance to be inserted in earth circuit is given by,

$$R = \frac{V_L}{\sqrt{3} \cdot I}$$

where V_L = Line to Line voltage

I = Full load current of largest alternator or transformer

The advantages of this system are as follows,

1) The discriminative type of switchgears may be used for protection.

2) The hazards due to arcing grounds are minimized.

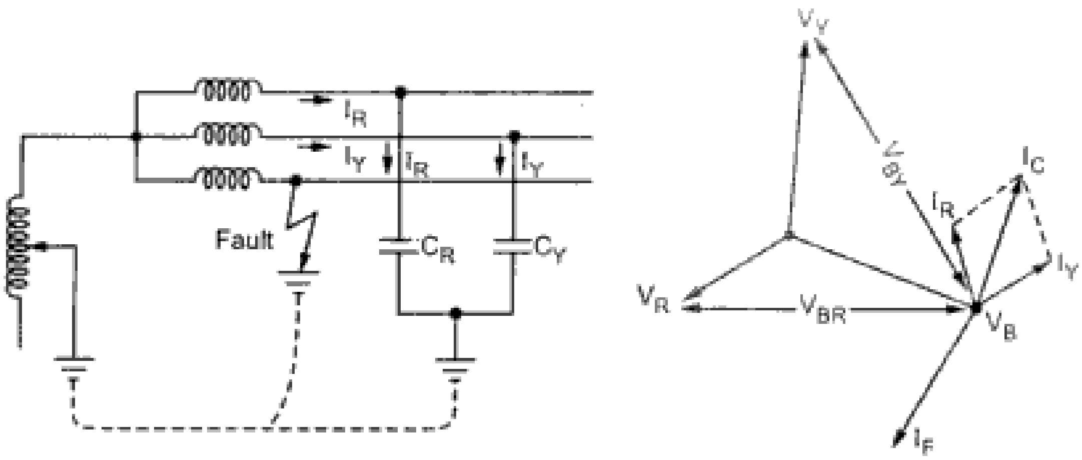
3) The influence on neighbouring communication circuits is minimized due to lower value of fault current flowing through earth as compared to that in case of solidly grounded system.

isolated neutral system along with reduced possibility of arcing grounds and numerous other advantages.

It consists of a coil called Peterson coil or Ground fault neutralizer or arc supression coil whose function is to make arcing earth faults self extinguishing and in the case of sustained faults to reduce the earth current to low value so that system can supply power with one line earthed.

This system works on the principle that when inductance and capacitance are connected in parallel, resonance takes place between them and because of the characteristics of resonance, the fault current is reduced or can be neutralized.

The system with fault on phase B is shown in the Fig. 11.10(a). The corresponding phasor diagram is shown in the Fig. 11.10 (b)



(a) Circuit Representation (b) Phasor diagram

Fig. 11.10 Resonant grounding

An arc supression coil is an iron-cored reactor similar to oil immersed transformer connected between neutral of system and earth. This coil is provided with number of tappings so that it can be tuned with the capacitance which may vary due to varying operational conditions.

As the system operation is similar to isolated neutral system, the phase to earth voltage of healthy phase is $\sqrt{3}$ times the normal phase voltage and the resultant capacitive current is 3 times the normal charging current of one phase. The resultant capacitive current will lead by 90° with faulty phase voltage while the fault current lags by 90° with faulty phase voltage.

Now we have, $I_F = I_C$ at resonance

$$I_F = \frac{V_{ph}}{X_L} \quad ; \quad I_C = \frac{3\, V_{ph}}{X_C}$$

$$\therefore \quad \frac{V_{ph}}{X_L} = \frac{3\,V_{ph}}{X_C}$$

$$\therefore \quad X_L = \frac{X_C}{3}$$

$$\therefore \quad \omega L = \frac{1}{3\omega C}$$

$$\therefore \quad L = \frac{1}{3\omega^2 C}$$

There is one problem with the above method. As the operating conditions vary, the capacitance of the network also vary. This can be overcome by using a tapped coil. The appropriate tapping is required to be used for each of the change in the network conditions. The current rating of the coil is given by,

$$I_F = \frac{3\,V_{ph}}{X_C}$$

The time rating of coils used in systems where earth faults are located and removed is around ten minutes. In other systems continuous time rated coils are used.

The arc supression coil is shown in the Fig. 11.11.

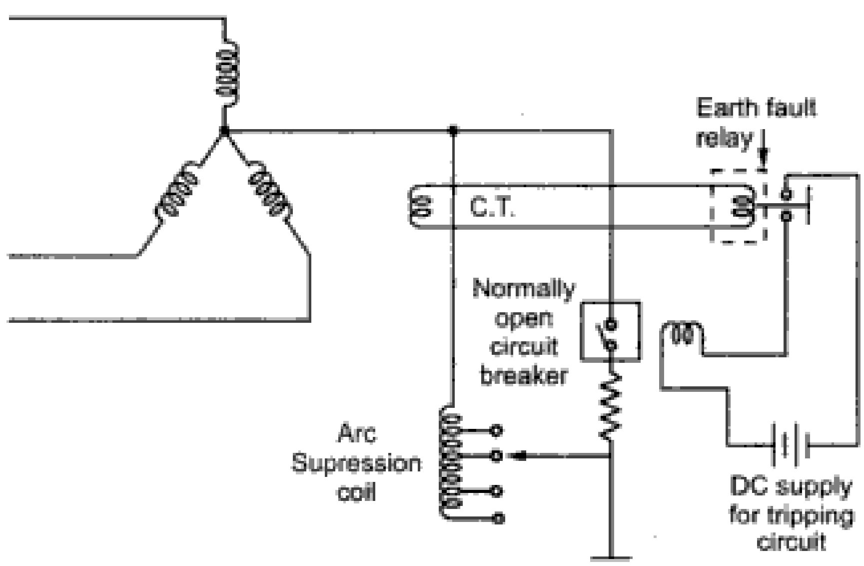


Fig. 11.11

The coil is tapped in order to select the reactance depending upon the length of transmission line and the capacitance to be neutralized. The arc supression coil is connected between neutral and ground.

The reactance of the coil can be evaluated by using the expression $L = \frac{1}{3\omega^2 C}$

The rating of the coil is continuous and equal to the maximum earth fault current. If a double phase to ground fault or another ground fault occurs, the current flowing through the coil is more. This can be prohibited with closing of a circuit breaker after certain time lag. The earth fault current flows through the parallel circuit by passing the arc supression coil. Here the circuit breaker is normally open and closes after the closure of relay tripping circuit by passing arc supression coil.

This method of neutral grounding is used in medium voltage overhead transmission line which are connected to system generators through intermediate power transformers. This is because the higher insulation requirement on the apparatus associated with arc supression coil grounding system is easily incorporated in power transformers than in generators. Also the overhead lines are usually subjected to earth faults due to lightning. Hence protection is required.

11.8 Voltage Transformer Earthing

In this system of earthing, the neutral point is earthed through a single phase voltage transformer. The system thus acts as an insulated neutral system. A very high reactance earthing is provided due to the voltage transformer.

The connection diagram is shown in the Fig. 11.12.

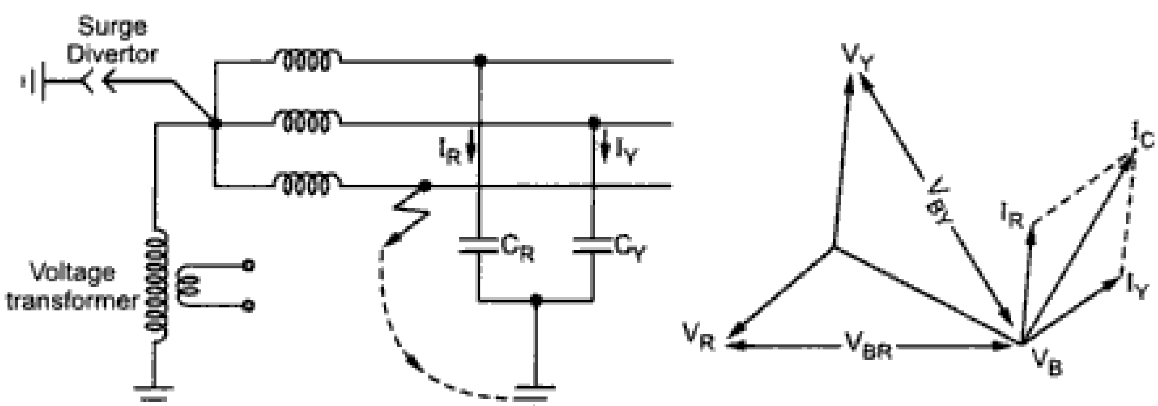


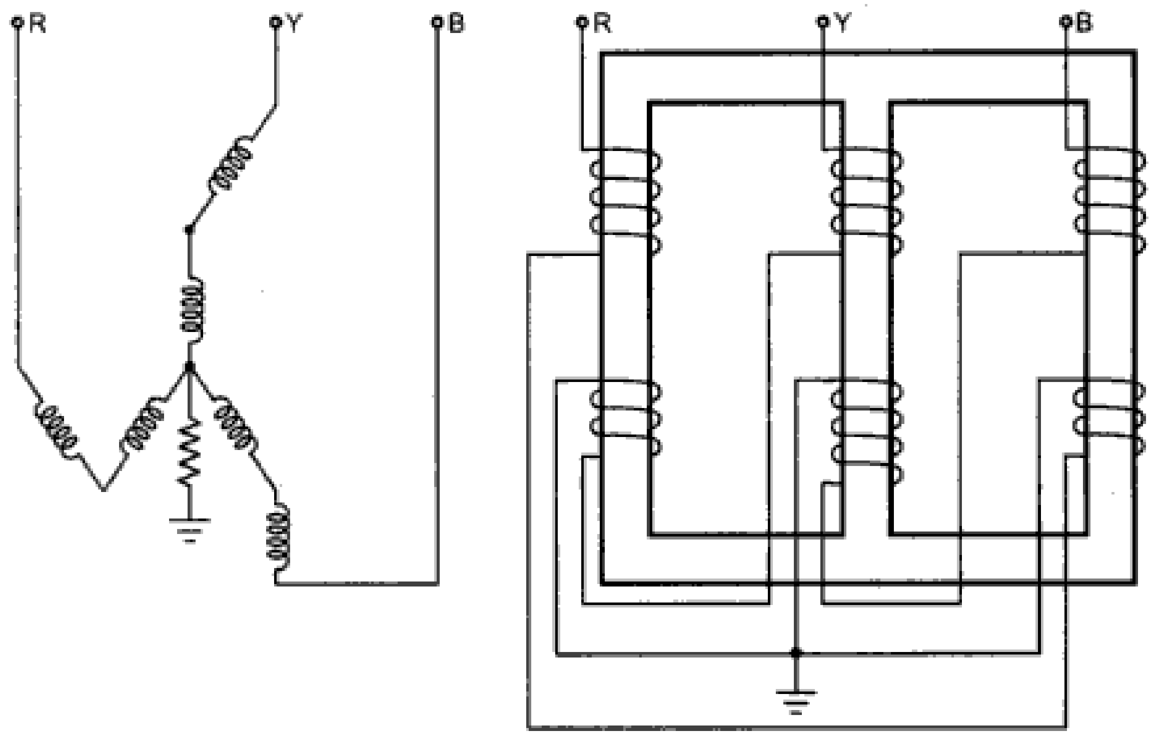
Fig. 11.12

The voltage transformer shown in the above figure measures the voltage so that earth fault on the system is indicated. The travelling waves passing through the machine winding are reflected through voltage transformer. A surge divertor is used between neutral and earth to avoid the rise of voltage.

The voltage transformer is used normally in generator circuits which are directly connected to step up transformers. The generator circuits are physically isolated from the main distribution system. The electrostatic capacity of the circuit is negligible as the interconnecting cables between the generator and transformer windings are normally short. The risk of overvoltage conditions arising due to arcing ground is eliminated.

11.9 Earthing Transformer

When the transformers or generators are delta connected or if the neutral points are not accessible then artificially the neutral earthing point can be created with the use of star connected earthing transformer. Such transformer has no secondary. Each phase of primary has two equal parts. There are three limbs and each limb has two windings providing opposite flux during normal condition. Such a transformer is shown in the Fig. 11.13.



(a) Winding of an earthing transformer

(b) Schematic arrangement of winding of an interconnected star connected earthing transformer

Fig. 11.13

One set of windings are connected in star providing the neutral point. The other ends of this set of windings are connected to the second set of windings as shown in the Fig. 11.13. The directions of the currents in the two windings on each limb are opposite to each other. The small exciting current is circulated in the windings during normal operation. Under faulty condition, the transformer offers a low impedance path to the flow of zero phase sequence currents. The value of fault current is limited in some cases by the use of a resistor in series with the neutral earthing connection. This is necessary in systems with operating voltage between 2.2 kV and 3.3 kV.

These transformers are of short time ratings in the range of 10 seconds to 1 minute Hence the size of these transformers is small as compared to power transformers of same rating. If the earthing transformer is not available then a star-delta transformer is used.

11.10 Resistance of Grounding Systems

The ground resistance of an electrode system is nothing but the resistance between the system of electrodes and other infinitely large electrode in the ground at infinite spacing. The ground resistance is also decided by soil resistivity which is electro-physical property. The soil resistivity depends on various factors such as type of soil, moisture content, dissolved salt etc. It is also affected by grain size and its distribution. The temperature and pressure are the other factors which have influence on soil resistivity.

In practice it is not possible to have homogeneous soil. The apparent resistivity is hence defined for an equivalent homogeneous soil.

The moisture content in the soil is also a variable factor which changes with seasons. With increase in moisture content, resistivity of soil reduces. To overcome this difficulty, the grounding systems may be installed near to the permanent water level so that the change in resistivity due to change in seasons is minimized.

With decrease in temperature, the soil resistivity increases and the discontinuity is observed at freezing point. The quantity of salt dissolved in the moisture reduces the resistivity appreciably. Various salts have different effects on the soil resistivity. With finer graining, the resistivity of soil reduces while the large value of pressure decreases soil resistivity.

The variation of soil resistivity with moisture and salt content is shown in the Fig. 7.14 (a) and (b).

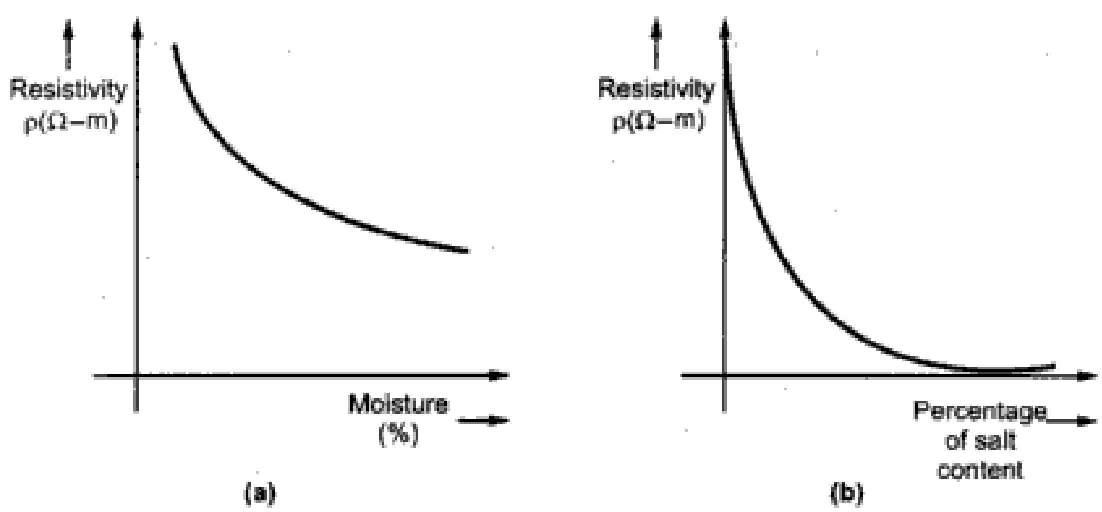
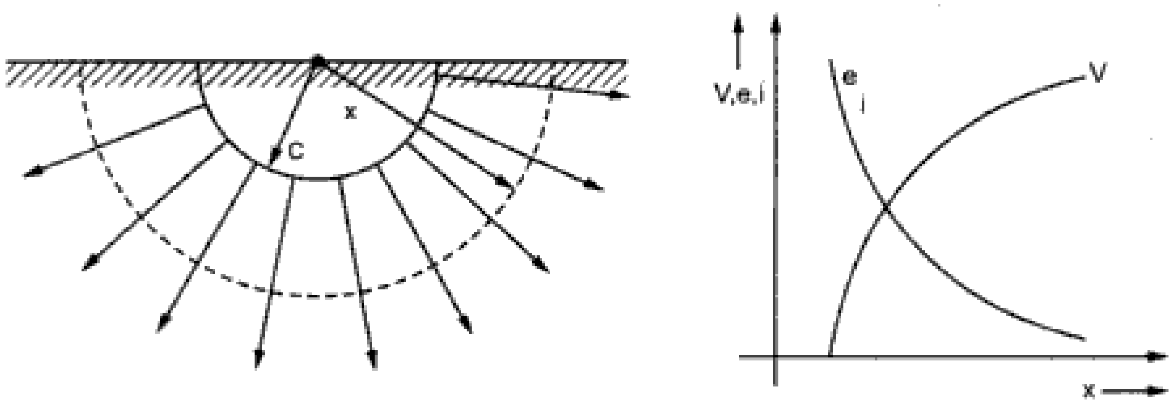


Fig. 11.14 Variation of soil resistivity with moisture and salt content

Resistance of Grounding Point Electrode

Consider a hemispherical electrode buried in the soil as shown in the Fig. 11.15 (a) which is simplest possible form of electrode.



(a)

(b)

Fig. 11.15

The total resistance in this case can be divided into three parts which are viz. i) resistance of conductor ii) contact resistance between the surface of electrode and main body of earth which is negligible iii) resistance of body of earth surrounding the electrode which is the main part.

Let I be the current dissipated by the electrode. This current spreads out radically in the earth. At a distance x from the centre of hemisphere the current density is given by,

$$i = \frac{I}{2\pi x^2}$$

The electric field strength e due to current density i is given by,

$$e = \rho\, i = \frac{\rho I}{2\pi x^2}$$

The line integral of the field strength e from the surface of sphere of radius R to the distance x gives the voltage V.

$$\therefore \quad V = \int_c^x e.dx = \int_c^x \frac{\rho I}{2\pi x^2} = \frac{\rho I}{2\pi}\left[\frac{1}{C} - \frac{1}{x}\right]$$

The variation of e, V and i with respect to distance x is shown in the Fig. 11.15 (b).

The voltage between the hemispherical electrode and a point at infinity i.e. $x = \infty$ is given by,

$$V = \frac{\rho I}{2\pi C}$$

The earth resistance is therefore given by,

$$R = \frac{V}{I} = \frac{\rho}{2\pi C}$$

11.10.1 Generalised Equation

Consider a system with two electrodes having their potentials as V_1 and V_2. Let V be the potential at any point in the medium having resistivity as ρ. Let ψ be electrostatic potential.

The current flow normal to surface at any point of the electrode is $\frac{1}{\rho}\frac{\delta V}{\delta n}$

Total flow of current from the electrode in the outward direction is,

$$-\frac{1}{\rho}\iint \frac{\partial V}{\partial n} \cdot ds = \frac{1}{\rho}\iint \frac{\partial \psi}{\partial n} \cdot ds$$

Here ds is an element of the electrode surface.

If Q is the charge on this electrode then by Gauss theorem.

$$-\iint \frac{\partial \psi}{\partial n} \cdot ds = 4\pi Q$$

The total flow of current is given by,

$$I = \frac{4\pi Q}{\rho}$$

If C is the capacitance between the electrodes in air then

$$\psi_1 - \psi_2 = V_1 - V_2 = \frac{Q}{C}$$

R is the resistance between the electrodes which is given by,

$$R = \frac{V_1 - V_2}{I} = \frac{Q}{C}\left(\frac{\rho}{4\pi Q}\right) = \frac{\rho}{4\pi C}$$

Suppose C is the capacitance of the single electrode with the return electrode at infinity then R is the resistance of earth for single electrode.

If we consider a sphere of radius S then the capacitance of sphere in air is equal to radius S.

$$R = \frac{\rho}{4\pi S}$$

If this elecrode is hemispherical and buried with its lower half in the earth then the resistance is given by,

$$R = \frac{\rho}{2\pi S}$$

In general the equation for any electrode is given by,

$$R = \frac{\rho}{2\pi C}$$

where C is the electrostatic capacity of the electrode along with its image above the surface of the earth. The combined electrode is considered as in air.

11.11 Resistance of Driven Rods

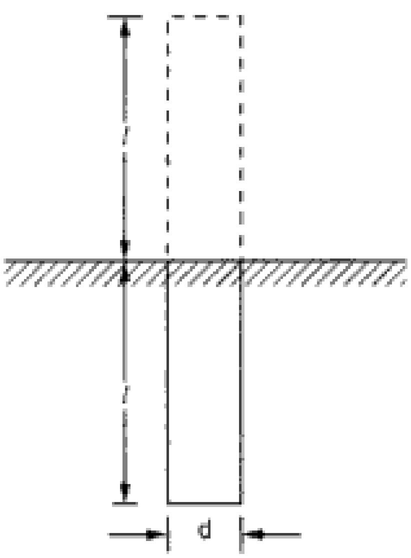


Fig. 11.16

The most simple and cheap form of electrodes is nothing but driven rod. It is shown in the Fig. 11.16 with its length as l and diameter d with its image. It can be considered equivalent to an ellipsoid of revolution with a major axis very much large as compared to minor axis.

The capacity of rod and its image is

$$C = \frac{2l}{2ln\frac{4l}{d}} = \frac{l}{ln\frac{4l}{d}}$$

The earthing resistance of driven rod is given by

$$R = \frac{\rho}{2\pi l} ln\frac{4l}{d}$$

For the cylindrical rod with hemisphere end the above expression becomes,

$$R = \frac{\rho}{2\pi l} ln\frac{2l}{d}$$

An alternative expression for the resistance of driven rod is obtained by using uniform current dissipation method and is given by,

$$R = \frac{\rho}{2\pi l}\left(ln\frac{8l}{d} - 1 \right)$$

From the expression for resistance of driven rods, it can be seen that, the earthing resistance is inversely proportional to length l.

Generally resistance of single rod is not sufficient. Hence number of rods are connected in parallel. It is necessary to minimize the overlap among the areas of influence of the rods. This is possible by keeping large distance between the rods. It is difficult to achieve this in practice and approximate method is used.

In this method, a rod is replaced by hemispheric electrode having same resistance. If n rods are connected in parallel then their resistance is greater than $\left(\frac{1}{n}\right)$ of that of a single driven rod due to the mutual screening.

The screening coefficient η for n electrodes in parallel is defined as,

$$\eta = \frac{\text{Resistance of one electrode}}{(\text{Resistance of n electrodes in parallel}) \times n}$$

11.12 Grounding Grids

The low ground resistance in case of high voltage substations can be obtained with the use of interconnected ground grids. In a typical grounding grid system, a number of interconnected bare solid copper conductors are buried at a depth of 0.3 to 0.6 m and spaced in a grid pattern. It provides common earth for all devices and metallic structures in the substation.

At each of the junction point, the conductors are bonded together. This system is usually supported by a number of vertical rods about 3 m long at some joints.

If a is cross-sectional area of copper, in circular miles, t is the fault duration in seconds, T_m is the maximum allowable temperature and T_a is the ambient temperature then the size of grid conductors required which prevents fusing under the fault current is given as,

$$a = I\sqrt{\frac{76t}{ln\left[\frac{234+T_m}{234+T_a}\right]}}$$

If the grid depth is less than 0.25 m then the earthing resistance of the grid is given by,

$$R = \frac{\rho}{4}\sqrt{\frac{\pi}{a}} + \frac{\rho}{L}$$

Here R = Grid resistance in ohms

a = Ground area occupied by grid in m^2

L = Total length of buried conductors in m

But when the grid depth is greater than 0.25 m then earthing resistance is given by,

$$R = \rho\left[\frac{1}{L} + \frac{1}{\sqrt{20\,A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right]$$

The effective grounding of the equipment is possible through the grid. Also the voltage gradiant at the surface of the earth can be controlled at safe value for human contacts with the addition of ground rods, the ground resistance further reduces when soil resistivity in the upper layer is more than the soil underneath.

11.13 Design Principles of Substation Grounding System

The most important factor in the substation is its grounding. The system neutral is connected to the ground through grounding. The discharge path for surge arrestors and safety of operating personnels can also be achieved through grounding.

The grounding gives low resistance path to earth and reduces rise in ground potential which is dependent on magnitude of fault current and resistance of grounding system. The low resistance for substation ground can not be obtained in deserts and rocky areas.

The convenient way for getting proper ground connection is through grids. If the ground rods are used in addition then it reduces the ground resistance. Depending on the size of the substation, nature of soil and the grounding resistance required, the size of grid and number along with length of driven rods can be determined.

Under the fault condition, the potential of earth and its gradient over the surface out from the electrode is dependent on the ground resistance. The systems with higher values for maximum ground fault current, it is not possible to have lower values for ground resistance so as to have rise in grounding system potential to safe value.

The practical solution for grounding at substation yards is through grid or mat. The grid consists of a number of meshes and connected to several earth electrodes driven at intervals.

The total number of electrodes required is determined by using the expression

$$\text{Number of electrodes} = \frac{\text{Maximum Fault Current}}{500}$$

The grounding resistance for a grounding grid or mat is calculated from the following expression,

$$R_g = \frac{\rho_s}{4r} + \frac{\rho_s}{L}$$

Here ρ_s is resistivity of soil in Ω-m, L is total length of buried conductor in metres and r is radius of circular plate in metres.

The size of grounding conductor should be appropriate so as to have thermal stability for ground fault current and it should be mechanically strong. The minimum cross section for the grounding conductor having required thermal stability is determined from the following expression,

$$A_{min} = I_F \frac{\sqrt{t}}{C}$$

where I_F is fault current in amperes while t is time in seconds for the operation of protective relays including circuit breaker tripping time. C is a constant. Its value is 70 for steel having temperature rise of 400°C while for copper with temperature rise of 300°C, its value is 165.

The minimum size required for proper mechanical strength in case of steel is 61 mm^2. For copper it is 107.2 mm^2 while in case of aluminium it is 195 mm^2.

In case of grounding conductors made up of steel, its size should be checked for corrosion. If the soil is moderately or severely corrosive then the steel strip of minimum thickness 6 mm and minimum cross section area should be 200 mm^2.

The earthing grid system is normally extended over the total substation yard and in few cases, several metres beyond it. The grounding conductors should have low impedance. They should be able to carry prospective fault current without getting fused or damaged. They must take account the future expansion of connected power system.

Examples with Solutions

➡ **Example 11.1 :** *Determine the inductance of Peterson coil to be connected between the neutral and ground to neutralize the charging current of overhead line having the line to ground capacitance of 0.15 μF. If the supply frequency is 50 Hz and the operating voltage is 132 kV, Find the kVA rating of the coil.*

Solution : In case of Peterson coil we have,

$$L = \frac{1}{3\omega^2 C}$$

$$\omega = 2\pi f = 2 \times \pi \times 50 = 100 \times \pi = 314.159 \text{ r/s}$$

$$C = 0.15 \ \mu F = 0.15 \times 10^{-6} \ F$$

Inductance,

$$L = \frac{1}{3 \times (314.159)^2 \times (0.15 \times 10^{-6})}$$

$$\therefore \quad L = \frac{1}{0.0444} = 22.51 \ H$$

$$\text{kVA rating of coil} = \frac{V_{ph}^2}{\omega L}$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{132 \times 10^3}{\sqrt{3}} = 76210.23 \text{ V}$$

$$\text{kVA rating of coil} = \frac{(76210.23)^2}{314.159 \times 22.51} = 821.29$$

Example 11.2 : *In a 50 Hz overhead line, the capacitance of one line to earth was 1.6 μF. It was decided to use an earth fault neutralizer. Calculate the reactance to neutralize the capacitance of i) 100% of the length of line ii) 90% of the length of the line iii) 95% of the length of the line.*

Solution :

$$\omega = 2\pi f = 2\pi \times 50 = 100\pi = 314.159 \text{ r/s}$$

$$C = 1.6 \text{ μF} = 1.6 \times 10^{-6} \text{ F}$$

i) For 100% length of the line

We have inductance of Peterson coil given by,

$$L = \frac{1}{3\omega^2 C} = \frac{1}{3(314.159)^2 (1.6 \times 10^{-6})} = 2.11 \text{ H}$$

The inductance required to neutralize is 2.11 H

Reactance $X_L = 2\pi fL = \omega L = (314.159)(2.11)$

$\therefore$ $X_L = 663.14 \ \Omega$

ii) Capacitance for 90% of the length of the line is

$$1.6 \times 0.9 = 1.44 \text{ μF} = 1.44 \times 10^{-6}$$

Inductance, $L = \dfrac{1}{3\omega^2 C} = \dfrac{1}{3(314.159)^2 (1.44 \times 10^{-6})}$

$\therefore$ $L = 2.34$ H

Inductive Reactance, $X_L = \omega L = (314.159)(2.34) = 736.82 \ \Omega$

iii) Capacitance for 95% of the length of the line is,

$$1.6 \times 0.95 = 1.52 \text{ μF} = 1.52 \times 10^{-6}$$

Inductance, $L = \dfrac{1}{3\omega^2 C} = \dfrac{1}{3(314.159)^2 (1.52 \times 10^{-6})} = 2.22 \text{ H}$

$\therefore$ $L = 2.22$ H

Inductive Reactance, $X_L = \omega L = (314.159)(2.22) = 698.04 \ \Omega$

Review Questions

1. *Explain in brief isolated neutral system*
2. *What are the advantages of neutral earthing ?*
3. *State the methods adopted for non-effectively grounded systems.*
4. *What do you mean by effectively grounded and non-effectively grounded systems ?*
5. *Write a note on solid grounding.*
6. *Explain resistance earthing.*
7. *What are the advantages of resistance earthing ?*
8. *How reactance earthing is achieved ?*
9. *Write a note on resonant grounding.*
10. *Derive the expression for the reactance of the Peterson coil.*
11. *Explain the working of arc supression coil.*
12. *Write short notes on i) voltage transformer earthing ii) Earthing transformer.*
13. *What are the various factors on which soil resistivity depends ?*
14. *Write a note on grounding grids.*
15. *Explain the principles of design of substation grounding.*
16. *A 33 kV, 3 phase, 50 Hz overhead line 50 km long has a capacitance earth line equal to 0.019 μF per km.*

    Determine the inductance and kVA rating of the arc supression coil. **(6.75 H, 169.3 kVA)**
17. *In a 50 Hz, overhead line, the capacitance of one line to earth was 1.5 μF. It was decided to use an earth fault neutralizer. Calculate the reactance to neutralize the capacitance of i) 100% of the length of the line ii) 90% of the length of the line iii) 95% of the length of the line.*

    ((i) 2.25 H (ii) 2.5 H (iii) 2.37 H)
18. *Determine the value of reactance to be connected in the neutral connection to neutralize the capacitance current of a overhead line to ground capacitance of each line equal to 0.015 μF. The frequency is 50 Hz.* **(22.6 H)**

❑❑❑

12 Protection Against Overvoltage

12.1 Introduction

The voltage waves having magnitude more than its normal value and which remains for a very short duration are called overvoltage surges or transient overvoltages. For any electrical equipment, its insulation requirements are decided by these transient overvoltages.

The overvoltages in the system occur due to various reasons such as lightning surges, switching surges, faults and travelling waves. There is high rate of rise and high peak value in transient overvoltages which is dangerous for the insulation and hence protection is required against these overvoltages.

12.2 Lightning Phenomenon

A lightning stroke on any overhead line or on outdoor equipment causes lightning surges. Before studying the protection against these lightning surges, let us study the mechanism of lightning.

An electrical discharge in the air between clouds, between the separate charge centres in the same cloud or between cloud and the earth is nothing but lightning. It produces the large spark accompanied by the light. This discharge of electricity through the air from the clouds under turbulent conditions is always abrupt and discontinuous. The serious hazards may take place sometimes if this discharge terminate on the earth.

There are various theories which explain the potentials required for lightning strokes, are built up. However we will assume that because of some process taking place in the atmosphere under the turbulent conditions there is accumulation of charges in the clouds. With the dielectric medium as the air the cloud and the ground form plates of a capacitor. If the lower part of the cloud is negatively charged, the earth is positively charged by induction.

For lightning discharge to take place, it requires breakdown of air between the cloud and the earth. With increase in the charge, the potential between the cloud and the earth increases. As a result of this the potential gradient in the air increases. The potential gradient required for the breakdown of air is 30 kV/cm peak. But there is large moisture content in the air and because of lower pressure at high altitude, the breakdown of air takes place at 10 kV/cm. The process of lightning discharge is shown in the Fig. 12.1.

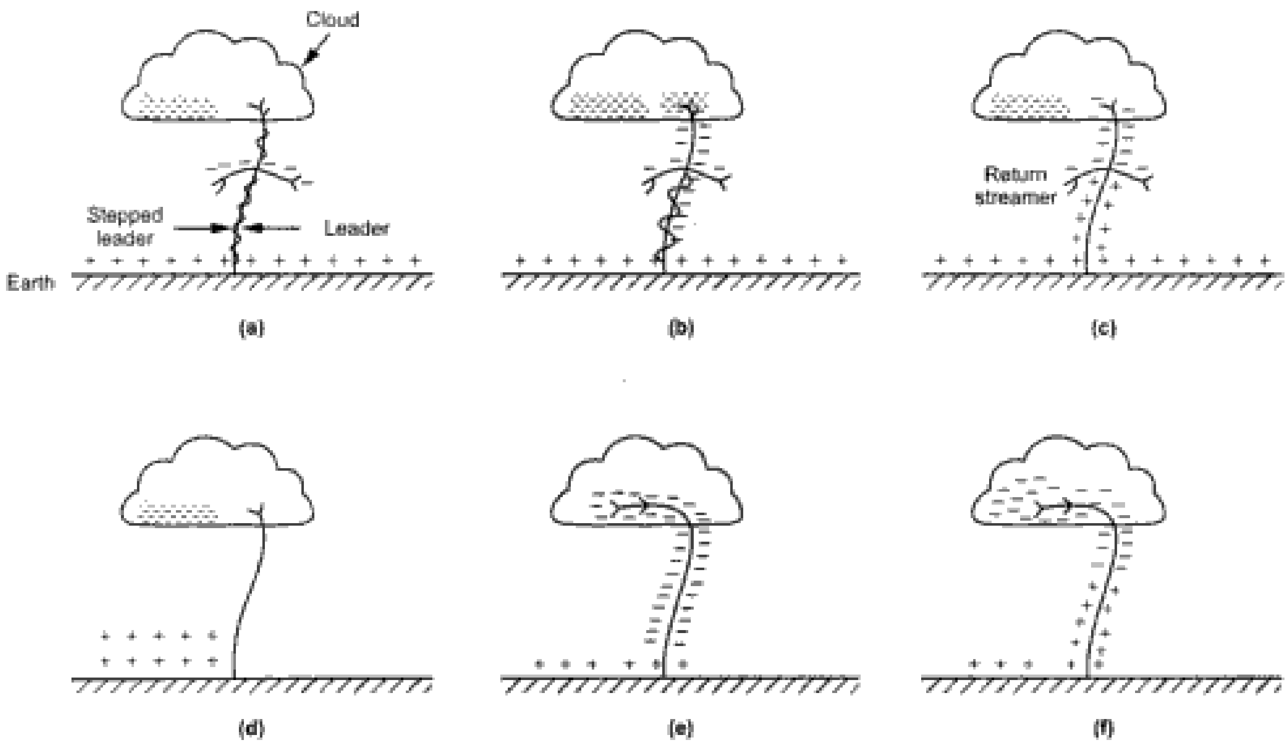


Fig. 12.1

When charge increases there is difference in potential between cloud and earth which also increases resulting in increase of potential gradient of air which is non-uniformly distributed. The potential gradient is more at the centre of charge in the cloud. This gradient appears across some part of the air and when it is more than breakdown strength of air, this air breaks down. A streamer called pilot streamer or leader streamer starts from cloud towards the earth and carries the charge with it as shown in the Fig. 12.1 (a). Till the time the cloud through which this stream is initiated supplies enough charge to maintain the potential gradient at the tip of the leader streamer above the breakdown strength of air, the leader streamer continues to travel towards the earth. With the loss of this gradient, the streamer stops without reaching to the earth. The charge dissipated without forming the complete stroke. The lightning stroke may start with the potentials of the order of 5×10^6 V to 20×10^6 V between cloud and earth while the current of the leader streamer is low, typically less than 100 A and its propagation velocity is 0.05 % of that of velocity of light.

Many times the streamer travels towards the earth until it is reached to the earth or some object on earth. As the initial streamer moves towards earth, it is accompanied by points of luminescence which travel in jumps giving rise to stepped leaders. In one step the distance travelled is about 50 m while the velocity of stepped leader exceeds one sixth of that of light. The stepped leaders results in first visual phenomenon of discharge.

The electrostatic field and potential gradient at earth's surface is high as this streamer reaches to the earth. When it becomes sufficiently large then a short upward streamer called return streamer rises form the earth as shown in the Fig. 12.1 (c). When the contact of leader is made with the earth then a sudden spark may be appeared. This contact is similar to closing of a switch between two opposite charges, the downward leader with negative charge and upward streamer with positive charge. Due to this sudden sparks appearing which causes the most neutralisation of negative charges on the cloud. This is called **lightning**. Any further discharge from the cloud must be originated form other portion of it.

When lightning occurs then it is associated with high current followed by lower current for significant duration as the charge in the cloud is neutralised. The upward streamer carries high current with a speed of propagation of about 30 m/ µsec which is faster than the speed of the leader streamer. The current rises sharply within microseconds and then decays slowly compared to its rise. This is similar to discharge of a capacitor through a circuit but it is not periodic. The experiments conducted in the laboratories show that when the charge in the channel is near exhaustion, there is smooth transition in current into its low value which is associated with the remaining charge in the cloud.

When the streamer reaches the earth and much of charge in the cloud from which it was originated, is neutralised then potential pertaining to point of charge centre reduces. But there may exist high potential between this original charge centre and other charge centres. Due to this, there may be discharge from other charge centres into the region where the leader streamer was originated. Thus subsequent discharges takes place alongwith the original stroke to the earth. Many strokes can be observed which contains more than one current peak which are called **multiple** or **repetitive**. Separate peaks are termed as **components**.

In summary we can say that lightning is a phenomenon of breakdown of air and discharge which can be seen by eye as a single flash but contains number of separate strokes that travels with same path practically. The variation of time interval between them is from 0.5 msec to 500 msec. 87 % of the lightning strokes originate from negatively charged clouds while remaining 13 % originate from positively charged clouds. Lightning discharge current magnitude lies in the range of 10 kA to 90 kA.

Some values for the lightning stroke are given below in the Table 12.1 for the information:

Voltage	200 MV (peak)
Current	10 to 90 kA (discharge)
Duration	10 μ sec
Power	8×10^9 kW
Energy	22 kWh

Table 12.1

We should also consider the case of statically induced charges and various lightning strokes. When a charged clouds come above the conductor, the charges are statically induced on the conductor which are released by travelling either side in the form of travelling waves when clouds go away from their place. These surges are not prevented by earthwire.

It can also be seen that the paths travelled by lightning strokes are unpredictable in certain cases. Usually these strokes try to travel and reach to the earth. These strokes are interrupted by lightning rods, trees, tall structures etc. But sometimes these strokes does not obey any rule and travels horizontally in all sorts of haphazard fashion.

B type strokes originate due to sudden change in charge between two clouds. As a result of this there is sudden change in charge in other (third cloud in its vicinity) cloud which discharges to the earth. This B type stroke does not hit lightning rod or earth wire. Thus overhead lines can not be protected against such strokes.

12.2.1. Waveform of Lightning Current

A generalized waveform for lightning current is shown in the Fig. 12.2.

It consists of a peak value called crest. The time taken by the wave to reach this peak is called front time. The time span from origin to a point where is the voltage or current has decayed to one half of its peak value is represented by T_2.

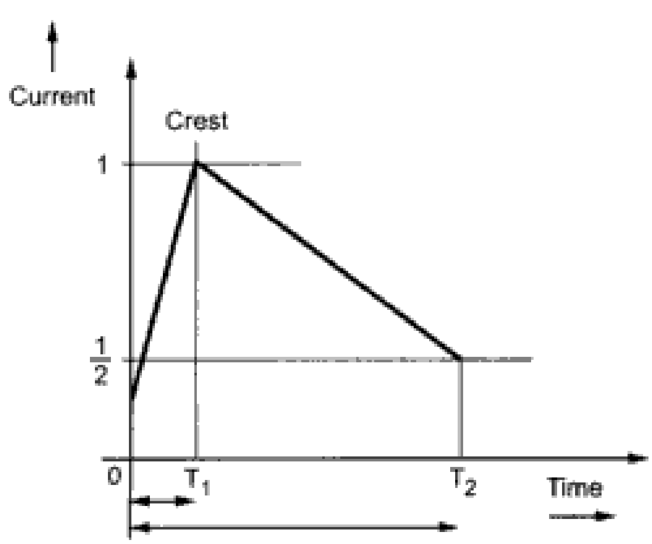


Fig. 12.2

Time T_1 varies from 1 to 10 μsec while T_2 varies from 10 to 100 μsec. 25 % of the lightning strokes carry current less than 10 kA. 86% strokes are with currents less than 50 kA. In case of 11% strokes the current lies in between 50 and 100 kA. While 2 % strokes carry current in between 100 and 150 kA. Only 0.5 % strokes carry currents more than 150 kA whereas the measured highest value is 400 kA. The total duration of lightning in some strokes may be up to 1 second.

12.3 Types of Lightning Strokes

There are two main types of lightning strokes that appear on various equipments in the power system. They are viz. Direct Stroke and Indirect Stroke. Direct stroke may appear on line conductor, on tower top or on the ground wire indirect stroke may appear on overhead line conductors.

12.3.1 Direct Stroke on Overhead Conductors

These strokes are most dangerous as their effects are most severe and harmful. In this type of stroke, the discharge or the current path is directly from the cloud to the overhead line. From the line, the current path may be over the insulators down the pole to the ground. The voltage set up is in millions which can cause flash over and puncture of insulators. The insulators may get shattered till the surge is sufficiently dissipated and it travels to both sides. The wave may reach to the substation and damage the equipments because of excessive stress produced.

If a overhead line conductor is struck by lightning then the rise in voltage at the point is given by,

$$V_x = I_{stroke} \times \frac{Z_L}{2}$$

where, I_{stroke} = current in the lightning stroke

Z_L = surge impedance of the line.

The term $\frac{Z_L}{2}$ is used in the above expression as the charge on the conductor flows to the both sides of the conductor in the form of travelling waves.

If we consider $Z_L = 1000\ \Omega$, $I_{stroke} = 40$ kA as representative figures then voltage developed will be,

$$V_x = (40\times10^3)(\frac{1000}{2}) = 20\times10^6 = 2\times10^7 \text{ volts}$$

This is the amount of voltage that is produced during a stroke. If this lightning stroke appears at a point away from a substation or generating station then this overvoltage and the current flows along the line in both the directions shattering the insulators and even wrecking poles until the energy present is dissipated completely in the paths towards earth. If it occurs near a plant or substation then the damage is sure. But these types of direct strokes are not frequent in occurrence.

Due to this lightning stroke, neighbouring lines are also subjected to overvoltages due to electromagnetic coupling. These high voltages may cause flash over in case of insulators.

All high voltage overhead lines are protected from lightning strokes by use of earth conductors. With the use of overhead network of earth conductors, the outdoor switchyards are protected.

A direct stroke is shown in the Fig. 12.3.

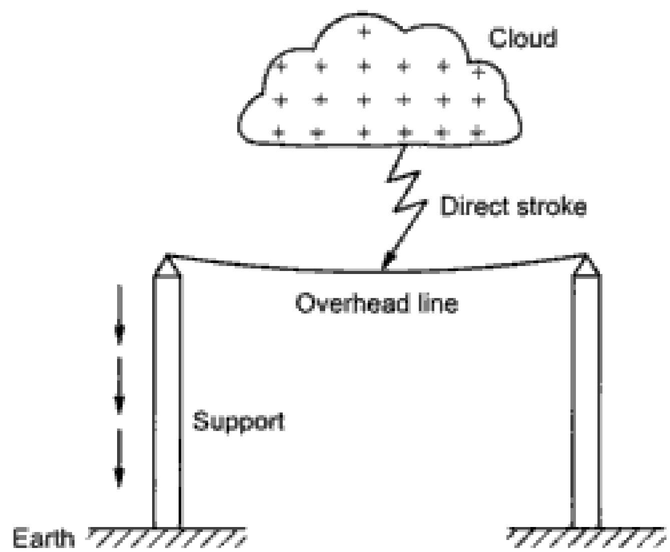


Fig. 12.3

The cloud will induce opposite charge on the overhead line by induction. When the potential between the cloud and line is more than breakdown strength of air, the lightning discharge takes place between cloud and the line.

There may be other type of direct stroke that may occur on the overhead line which is illustrated in the Fig. 12.4.

This type of stroke is produced because of sudden change in charge conditions in the clouds. Consider, for example, three clouds viz. cloud 1, cloud 2 and cloud 3 having positive, negative and positive charges respectively. If cloud 1 is shifted towards cloud 2 then discharge may take place between them and charge on them will be neutralised. Thus charge on clouds 1 and 2 may be disappeared quickly. As a result charge on cloud 3 is suddenly free as its bonding with cloud 2 has been broken. Due to this, rapid discharge from cloud 3 may take place to the earth ignoring tall objects. Thus protection against these strokes is difficult while protection against other type of direct stroke is possible as the direct stroke we have discussed above will occur on tall objects.

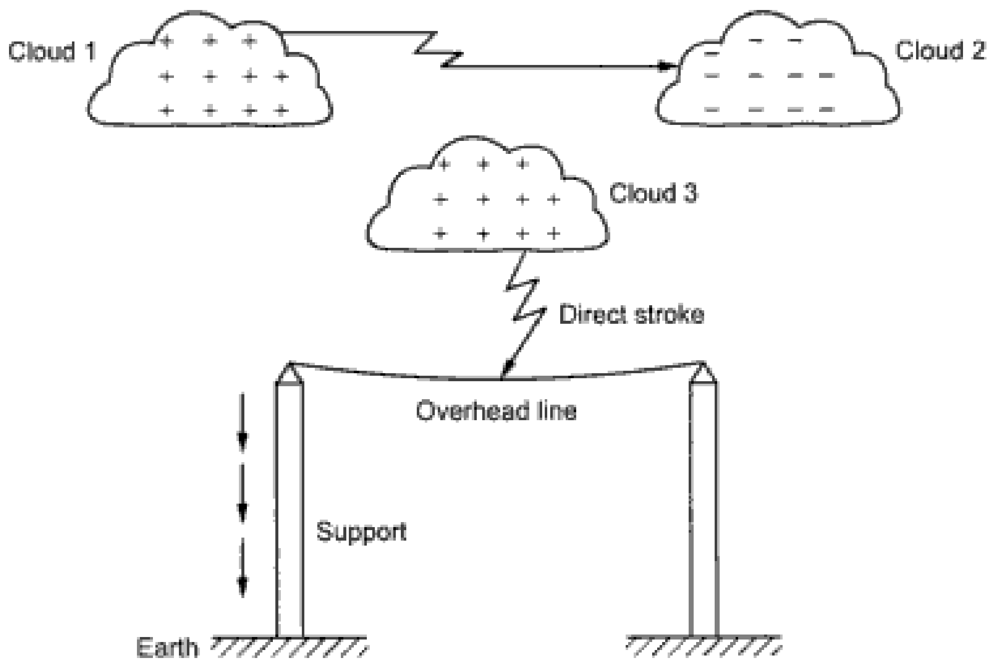


Fig. 12.4

12.3.1.1 Director Stroke on Tower

If there is a direct lightning stroke on the tower then its voltage is increased. Its value is given by

$$V_{stroke} = L_T \frac{di}{dt} + R_T \, i$$

where V_{stroke} = Voltage surge between top of tower and earth

L_T = Inductance of tower

R_T = Resistance of tower

i = current flowing through tower because of stroke.

For example if we consider $R = 10\ \Omega$, $i = 30$ kA, $\frac{di}{dt} = 10$ kA / μs

$$L = 10\ \mu H$$

$$\therefore \quad V_{stroke} = (10)(10) + (10)(30) = 400 \text{ kV}$$

This is the voltage that will appear between top of tower and earth. If this voltage is more than impulse flash over level then flash over may occur between tower and line conductor.

Due to this travelling waves may also be formed in both the directions of conductor which may reach to substation equipments to cause their damage. A direct stroke on the ground wire in its middle span may also cause a flash over between line conductor and earthwire or line conductor and tower.

12.3.2 Indirect Strokes

The effect of indirect strokes is similar to that of direct strokes. Their effect is more severe in case of distribution lines than in case of high voltage lines. These strokes are due to electrostatically induced charges on the conductors due to presence of charged clouds. Sometimes currents may be induced electromagnetically due to lightning discharge in the immediate vicinity of line which results in indirect stroke. It is shown in the Fig. 12.5.

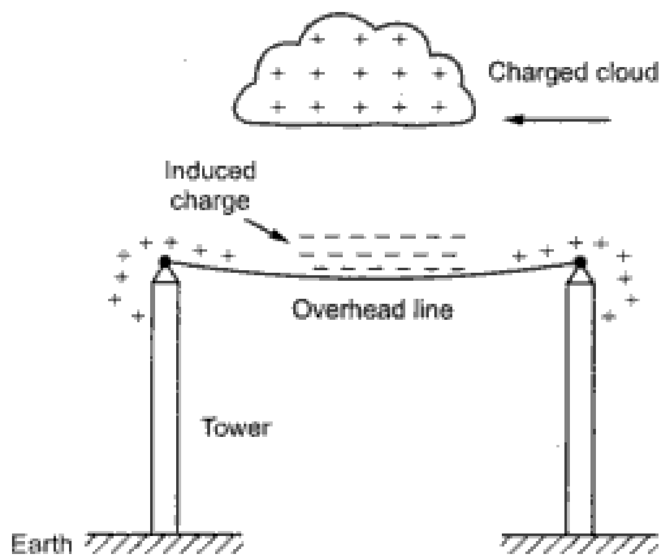


Fig. 12.5

Consider that a positively charged cloud is above the line. It induces negative charge on the line by electromagnetic induction which is present in that portion of the line which is under the cloud while the other portions of line are positively charged as shown in the Fig. 12.5. The induced positive charges slowly leak to the earth through the insulators. Whenever there is discharge from the cloud to earth or to another cloud, the negative charge on the wire is isolated as it can not move quickly to the earth over the insulators. Due to this, negative charge goes along the line in both directions in the form of travelling waves. Maximum surges in a transmission line are caused by indirect lightning strokes. The same action may take place but with opposite charges if the cloud is negatively charged.

12.4 Effects of Lightning

Because of direct or indirect type of lightning strokes, a steep fronted voltage wave is produced on the line. Its peak value may reach to about 2000 kV in about 1 μsec while it decays to half its peak value in about 5 μsec. Because of this voltage, travelling waves are initiated along the line in both the directions. The velocity of these travelling waves depend upon the inductance (L) and capacitance (C) of the transmission line. The harmful effects of lightning are discussed below.

i) The travelling waves which are generated on account of lightning surges shatter the insulators and may even wreck poles.

ii) If these traveling waves reach towards the windings of generator or the alternator then it may cause its appreciable damage. The inductance associated with the windings opposes the sudden change in charge through it. Because of this, excessive pressure may be developed between the windings which also cause insulation breakdown. After insulation breakdown, the line voltage may be sufficient to maintain the arc which is produced resulting in ultimate damage to machine.

iii) When the arc is initiated due to lightning stroke then it will set up disturbing oscillations in the line. Due to this other equipments connected to the system may be damaged.

12.5 Protection Against Lightning

Proper protection must be provided to the power stations, substations, overhead transmission lines from the direct lightning strokes while the electrical apparatus must be protected from indirect strokes in the form of travelling waves. Already we have seen that the lightning strokes can cause severe damage than other types of switching surges or transients. Hence protection against lightning strokes is an important consideration in the system design.

Commonly used equipments for protection against lightning strokes are as given below.

1. Earthing screen.
2. Overhead ground wires
3. Lightning arresters or surge diverters.

To protect the generating stations and the substations from direct strokes, earthing screen is used. Overhead ground wires protect the overhead transmission line from direct lightning strokes. The protection against both kinds of strokes direct and indirect in the form of travelling waves is provided with the help of lightning arresters.

Sometimes lightning or earth rods are mounted on tall buildings. These rods are connected to the earth. On the sharp points of this rod, positive charges are accumulated which attracts the lightning strokes. The earth wire placed above the overhead line is grounded at every tower and positive charges are accumulated on this wire. The negatively charged strokes are attracted by earth wire. If this wire is not present, there would be flash over in the line as lightning strokes will strike directly on the line.

The earth wire does not provide 100 % protection as weak strokes and B type of strokes are not attracted by this wire. The earth wire is a good solution for the most dangerous direct strokes. It has a shielding angle which is the angle made by outermost conductor in the line at the ground wire. This angle should be as lower as possible to give more protection. Whatever line conductors come under the shielded zone are well protected against direct strokes. This angle is normally between 30° to 40°. Its typical satisfactory and economical value is 35°.

12.6 Protection of Generating Stations and Substations Against Direct Strokes

Generally the generating stations are housed in big buildings while the substations are housed in switchyard or outdoor. To protect these structures from direct strokes, three important requirements viz. interception, conduction and dissipation must be fulfilled. It requires an object in good electrical connection with the earth having low impedance path to attract the leader stroke. It also requires a low resistance connection with the body of the earth.

For having a good electrical connection, the upper portion of metal structure may be used. Instead of this, a separate metallic system called shield mounted on the structure or near to it may be used. The total switchyard is provided with earthed overhead shielding screen.

The earthing screen consists of a network of copper conductors mounted all over the electrical equipment in the plant or substation. This shield is appropriately connected to the earth on atleast two points with the help of low impedance path. Occurrence of any direct stroke is directly diverted to the earth as the shield provides low resistance path. Thus the costly station equipments are protected from damage. This is designed in such a way that out of 1000 strokes, 999 will be diverted to earth through this shield while only 1 stroke may strike on the protected equipment which is called 0.1 % exposure.

Transmission line conductors are protected with the help of overhead earthed shield. A vertical line if drawn from the earth wire and angle α is plotted on its both sides then this angle α is called shielding angle while envelope within angle 2α is called zone of protection. The clearance between line conductor and overhead shielding should be more than minimum clearance between phase and earth. Lightning mast is an independent structure which is installed at specific locations in the switchyard.

In outdoor switchyards, lightning masts are preferred up to 33 kV. With increase in voltage, it becomes tall and uneconomical. In this case, overhead shielding wires are employed as height of the structure required is less.

12.7 Protection of Transmission Lines Against Direct Strokes

The transmission lines are effectively protected against direct lightning strokes with the use of ground wires. The ground wire is a conductor which runs in parallel with the line conductor. It is placed at the top of tower structure. For horizontal configuration of line conductors there are two ground wires whereas for vertical configuration there is only one ground wire.

The ground wire is made up of galvanised steel or recently ACSR conductor of the same size as that of line conductor is used. The material and size of conductor required for ground wire needs more mechanical considerations in its design rather than the electrical. With the help of simple and economical methods, the effective resistance of the ground wire can be decreased.

The use of ground wire is to provide shielding of line conductors against direct lightning strokes. Also whenever a stroke appears on a tower, the ground wire on both sides of tower provide parallel paths for stroke reducing effective impedance and the potential at tower top is comparatively less. As the ground wire and power line conductors are coupled electrically and magnetically, chances of failure of insulation are significantly reduced.

For the sake of simplicity and understanding, one ground wire and one conductor is shown in the Fig. 12.6.

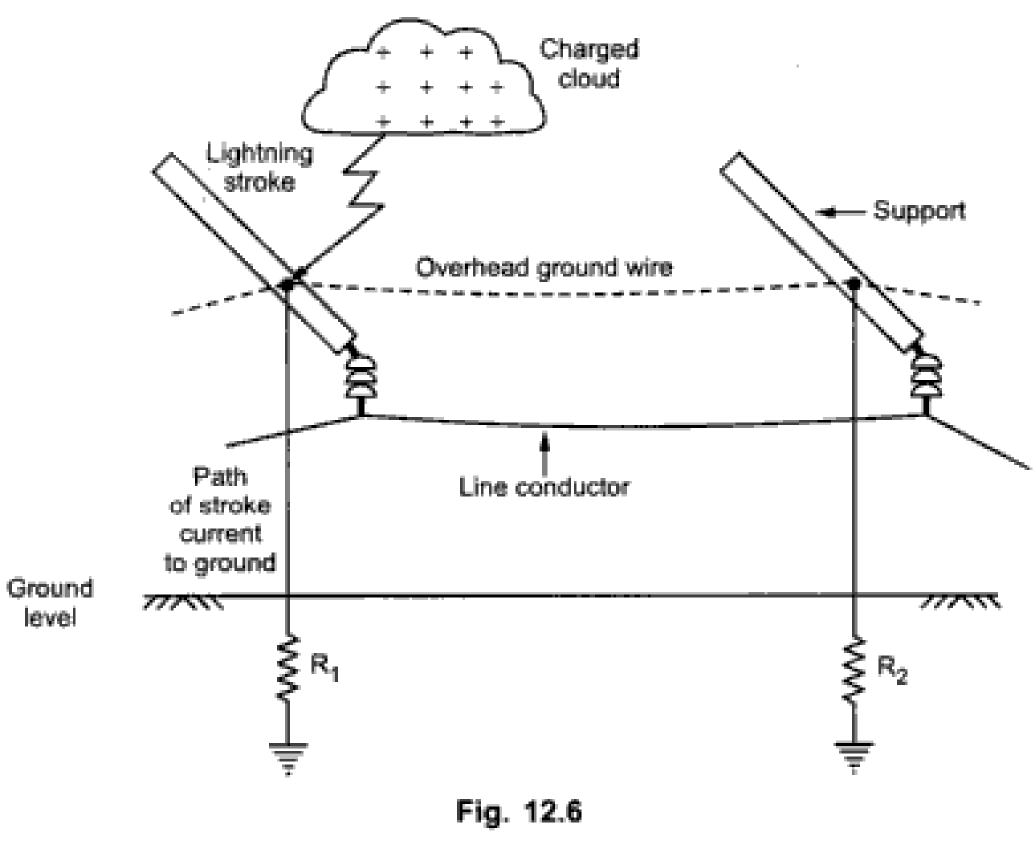


Fig. 12.6

The height of ground wire is such that practically all the lightning strokes are intercepted by them. These ground wires are earthed at every tower or pole through low resistance.

Whenever any stroke strikes on the line, it will be taken up by ground wire. The heavy current flows to the ground from the ground wire. The extent to which protection is provided by the ground wire depends on footing resistance of the tower. Let us consider this resistance as say R_1 and the lightning stroke current is say I_{stroke}, then potential of the tower top V_{Tower} with respect to earth is given by,

$$V_{Tower} = I_{stroke} \cdot R_1$$

This is the approximate voltage between tower and line conductor which also appears across string of insulators present on the tower. If this voltage is less than that required for insulator flash over then no damage or harmful effects can be observed. But if its value is greater then insulator flash over may take place resulting in its damage. Hence the footing resistance of the tower should be kept as low as possible to limit the value of voltage which will avoid flash over of insulator.

It is important to consider that the voltage to which the tower is raised during lightning stroke, is not dependent on the system voltage. Hence the design of transmission line against lightning for specific performance has nothing to do with the system voltage.

12.7.1 Requirements of Ground Wire

The requirements for the design of the line against lightning strokes are given below.

i) The ground wires used for protection of transmission line should be mechanically strong and should be suitably located to provide the protection.

ii) There must be sufficient clearance between power line conductors and ground wire for the given system voltage.

iii) The footing resistance of the tower should be as low as possible and economically justifiable.

The first requirement is met by use of galvanised steel wire or ACSR wire and the protective angle or shielding angle decides the location of ground wire for effective shielding. Protective angle is the angle between the vertical line passing through the ground wire and the line passing through the outermost line conductor. It is shown in the Fig. 12.7.

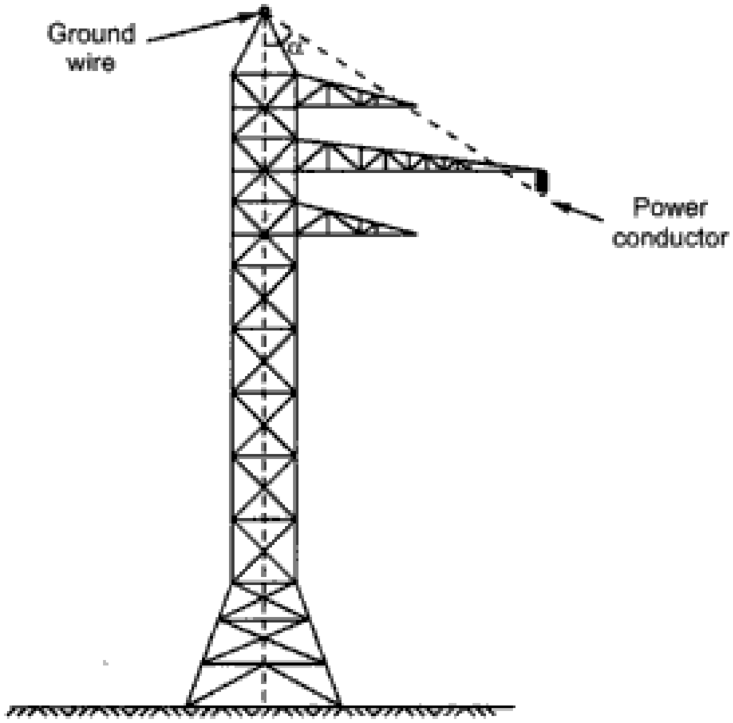


Fig. 12.7

If two or more than two ground wires are used then the protective zone between the two adjacent wires can be taken as semi-circle with diameter as a line joining the two ground wires. Experiments by research scientists show that a single wire provides effective shielding to a line conductor that lies below a quarter circle with its centre at the height of ground wire and radius equal to height of ground wire from the groundlevel. The proved shielding angle for adequate protection is about 30° for plain areas while it decreases by an amount of slope of hill in case of hilly regions.

The second requirement of sufficient clearance between tower and conductor is met by suitable design of cross arm in such a way that when a string of insulators is given a swing of about 30° towards the tower structure then the air gap between the conductor and tower structure should be in such a way as to withstand the switching voltage (normally four times line to ground voltage) that may appear on the system. The clearances between conductors can also be adjusted by adjusting the sag in such a way as to avoid the midspan flash overs.

The third requirement is already discussed earlier. For 66 kV line, the standard acceptable value of footing resistance is nearly 10 Ω. It increases as the system voltage rises. For a line with operating voltage of 400 kV, its typical value is 80 Ω. The tower footing resistance is its value when measured at a frequency of supply which is 50 Hz in our country. The performance of the line in context with lightning stroke depends on impulse value of resistance which is a function of soil resistivity, critical breakdown gradient of soil, length and type of driven grounds and magnitude of stroke current.

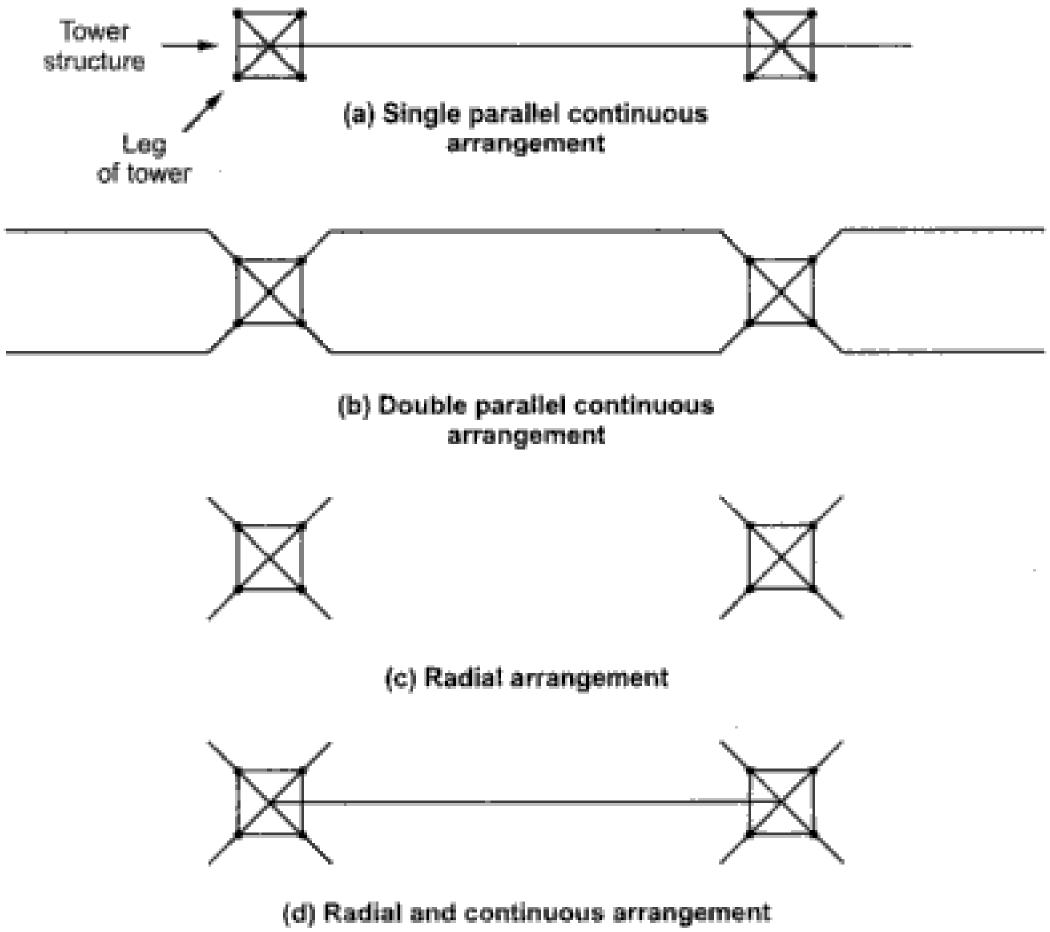


Fig. 12.9 Various counterpoises arrangements

The ground wire in addition to give protection against direct strokes also provides electrostatic screening by reducing the voltage induced in the conductors by discharge of a neighbouring cloud. Consider C_X as capacitance of cloud to line while C_Y as capacitance of line to ground as shown in the Fig. 12.10.

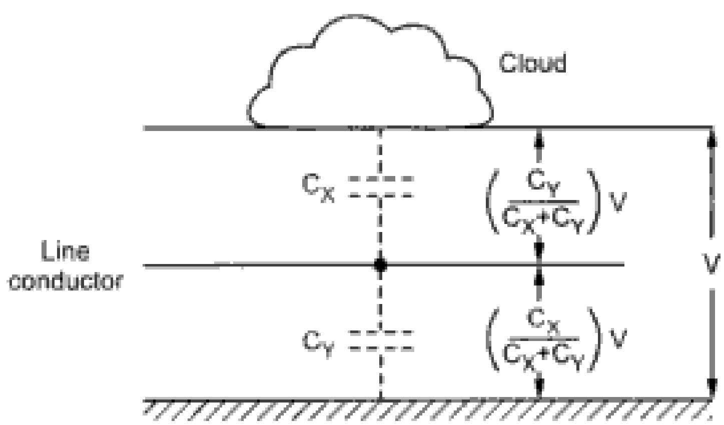


Fig. 12.10

The voltage across the line and the ground is $\left(\frac{C_Y}{C_X + C_Y}\right)$ V. V is the cloud voltage. As the ground wire is above the line conductor, there will be appreciable increase in C_Y which results in reduction of line induced voltage.

With a single ground wire the induced voltage is reduced to half of that without ground wire. With two ground wires, this reduction is about one third while for three ground wires, it is one fourth. These results are at favourable conditions of good earths and low impedance of earth connection as obtained by conducting experiments in the laboratory. The ground wire is also helpful in attenuating any travelling waves which may set up in the lines by acting short circuited secondary of line conductors.

12.7.4 Advantages of Ground Wire

i) Direct lightning strokes on the transmission line are well protected by ground wire.

ii) There is damping effect of the ground wire on the disturbance travelling along the line as it acts as a short circuited secondary.

iii) For external fields, it provides electrostatic shields to certain extent which reduces the voltage induced in the line conductors due to discharge of a neighbouring cloud.

12.7.5 Disadvantages of Ground Wire

i) It requires extra cost.

ii) It may be possible that due to breaking of ground wire and falling on the line conductors can cause a direct short-circuit fault. But this situation is rare to occur as mechanically strong galvanized steel stranded conductors are used. Due to this the ground wires bear sufficient strength.

12.7.6 Use of Ground Wire

Ground wires are extensively used for protection against direct lightning strokes for voltages ranging from 110 kV to 500 kV. They are used on all the important transmission lines and on all sections of transmission lines running through regions which subject to frequent lightning storms.

12.8 Protection of Transmission Line by Auxiliary Devices

The alternative way of protecting transmission line against lightning is by making use of auxiliary devices. In these ways of protection, discharge path is controlled and some device is used to extinguish the arc so formed. The most commonly used device is protector tube which consists of fibre tube with an electrode in each end. It is shown in the Fig. 12.11.

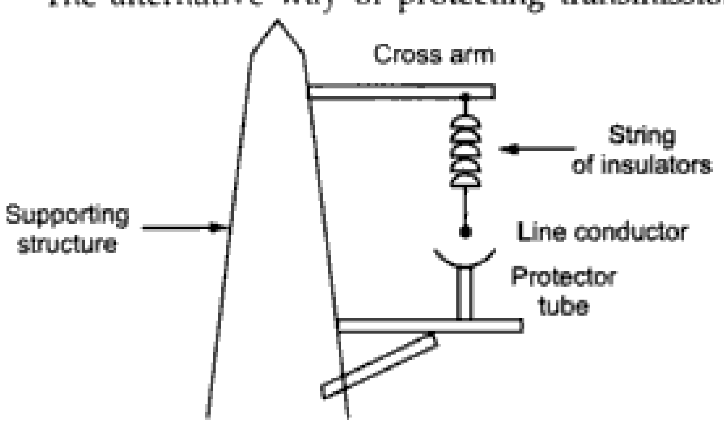


Fig. 12.11

It is mounted below each line in such a way that the upper electrode is connected to horn which is arc shaped at appropriate distance below the line forming a series gap with it. The lower electrode is effectively grounded.

With the appearance of the surge on the line the series gap is spanned. An arc is formed between the electrodes in the tube. Some of the fibre of tube walls is vapourized due to heat in the arc. The natural gas from this reaction violently enters into the arc to deionize it which prevents restriking of the arc after first zero point of the current.

12.9 Protection of Electrical Apparatus Against Travelling Waves (Indirect Strokes)

The earthing screen and the ground wire discussed earlier provide protection against direct lightning strokes but does not provide any protection against travelling waves which may reach the electrical apparatus. The lightning arresters or the surge arresters are the one who provide protection against the travelling waves.

There are basically two main sources of causing overvoltages viz. external overvoltages mainly due to lightning and internal overvoltages due to switching operations. The protection against external overvoltages due to lightning can be provided by methods which are known as shielding methods.

The shielding methods do not allow an arc path to form between line and ground thus giving protection in line design. For protection against internal overvoltages non-shielding methods are employed which allow an arc path between line and ground. There is special provision of extinction of arc in these methods.

Use of ground wire for protection that has been described earlier is a shielding method while use of spark gaps and lightning arresters are non-shielding methods. Sometimes the non-shielding methods are also used for giving protection against external overvoltages.

The non shielding methods are based on the principle of insulation breakdown. When the overvoltage is incident on protective device, a part of energy content in it is discharged to ground through the protective device.

The breakdown of insulation is function of voltage as well as time of its application alongwith shape and size of the electrodes used. More steeper is the voltage wave, the larger will be magnitude of voltage required for breakdown as expenditure of energy is required for breakdown of dielectric in any form requires time. This energy criterion for different insulators can be compared with the help of term called Impulse ratio which is defined as the ratio of breakdown voltage due to impulse of specified shape to the breakdown voltage at power frequency. For sphere

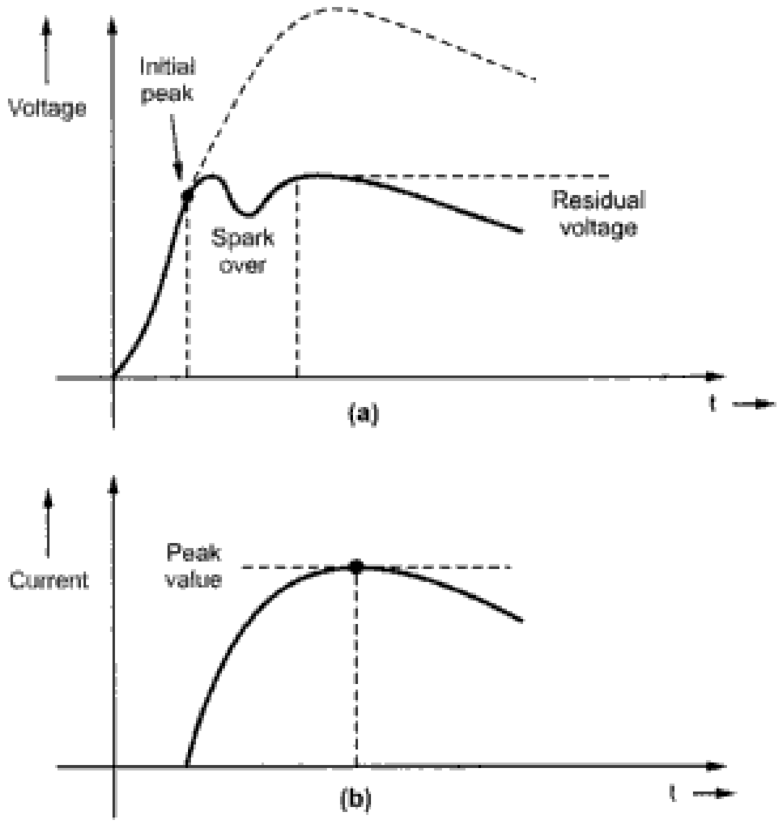


Fig. 12.13

The most commonly employed protective device against travelling waves is a surge diverter which is connected between line and earth at the substation. The travelling waves are diverted to the earth with this diverter. The travelling voltage wave after reaching near the diverter sparks over at a certain prefixed voltage. It is shown in the Fig. 12.13 (a) and (b) respectively.

This provides a conducting path of low impedance between line and earth. The residual or discharge voltage will be controlled to a safe value which could be withstood by insulation by the flow of current to earth through surge impedance of the line.

It is clear that the path of low impedance exists only when overvoltage occurs in case of surge diverter while it comes to normal state immediately to offer high impedance for normal working system voltage.

12.10 Requirements of Surge Diverter

The ideal surge diverter has following requirements.

i) It should not carry any current at normal system voltage i.e. its breakdown voltage should be above any normal or abnormal fundamental frequency voltage that may occur on the system.

ii) The transient voltage wave whose peak value is greater than the spark over or breakdown voltage of surge diverter should breakdown as fast as possible to provide path for surge to earth.

iii) After the breakdown, the surge diverter should be capable of carrying discharge current without damage to it and the voltage should not be more than its breakdown value.

iv) When the transient voltage reduces below its breakdown value, the power frequency current flowing through the diverter should be interrupted as quickly as possible.

12.11 Operation of a Typical Surge Diverter (Lightning Arrester)

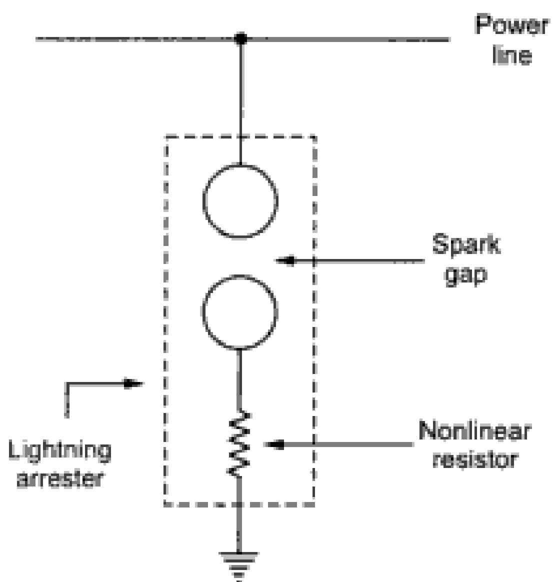


Fig. 12.14 (a)

The basic form of any type of surge diverter is shown in the Fig. 12.14 (a).

It consists of a spark gap which is in series with a non linear resistor. The terminal of the protected equipment is connected on end of the diverter. The other end of the diverter is solidly grounded through non-linear resistor.

The length of a spark gap is set in such a way that the normal system voltage is not sufficient to initiate arc across the gap while very high voltage will cause break down of air insulation and arc is initiated.

The non-linear resistor bears a property of decrease in its resistance as the voltage increases and vice versa. The volt-amp characteristics for a non linear resistor is shown in the Fig. 12.14 (b).

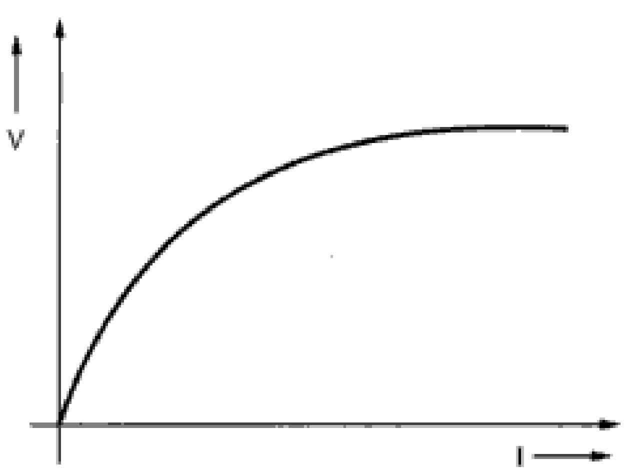


Fig. 12.14 (b)

Under normal condition, the diverter is off without conducting any current or very small negligible current due to capacitive effect (Non-linear resistor offers very high resistance to this current hence it is negligible) Hence the gap is not conducting.

Whenever high voltage occurs, there is breakdown of air insulation initiating the arc. Thus a low resistance path is offered for the surge to the earth. Excess charge on the line because of surge is conducted to the earth through the arrester which prevents the surge being sent back on line.

As there is breakdown of spark gap due to over voltage, the arc would be short circuit on the system and may cause power follow current in the diverter. After the surge is over, the resistor offers very high resistance to prevent the effect of short circuit which makes the spark gap non-conducting.

It should be observed that the arc in the gap should immediately cease after the surge is over to avoid the current flowing through gap and resistor which would be damaged otherwise. The voltage drop across the arrester should be less than the breakdown strength of the insulation of the equipment to be protected.

Presently following types of surge arresters are commonly used.

1. Valve type or gapped silicon-carbide surge arresters consisting of silicon carbide discs in series with spark gap units.
2. Zinc oxide gapless arresters or metal oxide arresters. These are gapless and consisting of ZnO (Zinc Oxide) discs in series. These arresters are having good volt-amp characteristics. The energy absorption level is also high and these arresters are preferred for EHV and HVDC installations.

12.12 Classification of Surge Arresters

Based on current, voltage and energy capability the surge arresters are classified as follows.

1) Station type surge arresters :

This type of arrester has the highest capacity for energy dissipation while lowest level of protection. The peak discharge current that can carry is 10 kA while its voltage range for operation is 3.3 kV to 245 kV (rms). They are employed normally in large power stations and substations.

2) Line type surge arresters :

These arresters are mainly used for protection of large transformers, intermediate sub stations and medium and large power stations. They are smaller than station transformers. The standard discharge current carried safely by them is about 5 kA while the working voltage range is 3.3 kV to 123 kV (rms).

3) Distribution type and secondary type surge arresters :

These type of arresters are used for protection of distribution transformers in distribution circuits mounted on poles. The standard peak discharge current for its operation is 2.5 kA and 1.5 kA. While its voltage range is up to 3.3 kV (rms).

There are three general types of surge diverters with each having its field of application. They are

i) the rod gap

ii) the protector tube or Expulsion type lightning arrester

iii) the conventional valve type lightning arrester.

12.13 Terms and Specifications used in Surge Arresters

Following terms and specifications are generally used in reference with surge arrester.

i) Non-linear resistor :

This is a part of arrester offering low resistance to the flow of discharge current of the surge limiting the voltage across arrester terminals while offering high resistance to the flow of power frequency currents (inoperative for normal power frequency voltage).

ii) Rated voltage of the arrester :

It is defined as the maximum permissible power frequency RMS voltage between the line terminal and earth terminal of the arrester as specified by the manufacturer at which surge arrester can perform its rated duty. Generally for all other equipments rated voltage is between phase to phase while for surge arresters it is between phase and ground.

iii) Follow current :

It is defined as the current that flows from connected power source through lightning arrester following the passage of the discharge current.

iv) Normal discharge current :

It is defined as that current which is flowing through the surge arrester after the spark over. It is expressed as crest or peak value for a specified wave. These values are given for various types of lightning arresters described in previous section.

v) Discharge current :

The surge current which flows through the arrester after the spark over is called discharge current.

vi) Power frequency spark over voltage :

It is defined as the rms value of power frequency voltage that is applied between line and earth terminals of the arrester causing the spark over of the series gap.

vii) Impulse spark over voltage :

The highest value of the voltage attained during an impulse of given polarity of specified wave shape applied between line terminal and earth terminal of an arrester before the flow of discharge current is called impulse spark over voltage.

viii) Residual or discharge voltage :

It is defined as the voltage which appears across line and earth terminal during the flow or passage of discharge current.

ix) Rated current :

It is the maximum impulse current at which the peak discharge residual voltage is determined.

x) Co-efficient of Earthing :

It is defined as the ratio of highest rms voltage of healthy phase to earth to the phase to phase normal voltage. Mathematically it is given by,

$$\text{Coefficient of earthing} = \frac{\text{Highest rms voltage of healthy phase to earth}}{\text{Phase to phase normal rms voltage}} \times 100$$

12.14 Horn Gap Arrester

This type of arrester has two horn shaped metal rods separated by a small distance. One end is connected to the line while the other is connected to the earth. It is shown in the Fig. 12.15.

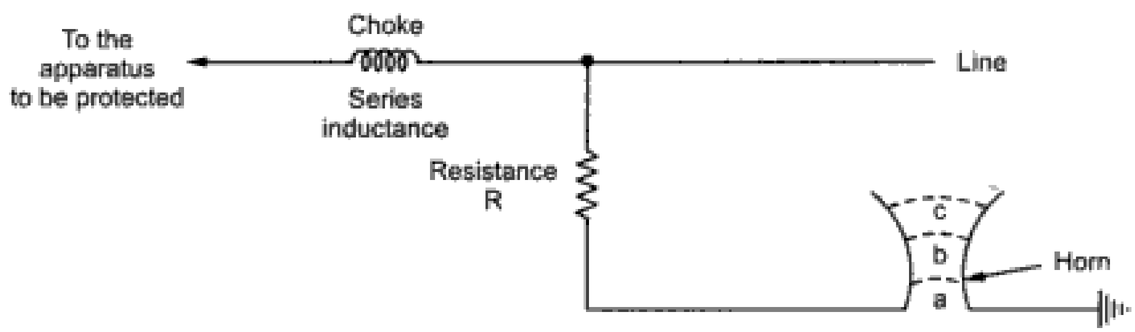


Fig. 12.15 Horn gap arrester

The horns are constructed in such manner that the distance between them gradually increases towards the top. The horns are mounted on porcelain insulators. The resistance R limits the follow current to a small value. The choke connected between equipment to be protected and horn gap is designed in such a way as to offer small reactance at normal power frequency while high reactance at transient frequency. Hence the choke does not allow any transients to enter the apparatus to be protected. By using the choke the steepness of the wave incident on the equipment to be protected is reduced. While the choke also reflects the voltage surge back on to the horn. The gap between the horns is adjusted in such a way that normal supply voltage will not be sufficient to initiate arc across the gap.

Under normal conditions, the gap is non-conducting whenever there is an overvoltage in the system and its value is more then breakdown value of gap, spark over takes place across small gap. The arc formed may be maintained by the normal voltage also. The heated air around the arc and the magnetic effect of the arc cause it to move up in the gap. The arc acts like a flexible conductor. The arc moves gradually through positions a, b, c respectively. At some position (say c), lengthening of arc takes place as distance between the horns is too large. Thus the voltage is not enough to maintain the arc and it is extinguished. The excessive charge on the line is therefore travelled to the earth through the arrester.

12.14.1 Advantages

1. After the surge is over, this type of arrester does not cause short circuiting of the system as the arc is cleared by itself.
2. The follow current is maintained to a small value with the help of series resistance.

12.14.2 Disadvantages

1. If the gap is bridged due to some external factors (such as birds) the device will not work properly.
2. The setting of horn gap is required to be changed due to corrosion and pitting which can affect its performance.
3. The time required for its operation is relatively more (about 3 seconds) than recent fast operating devices.
4. It is harmful to employ this type of arrester on isolated neutral system.

Due to above limitations, the horn gap arrester is rarely used in practice. Also it has low reliability and hence used as secondary protection.

12.15 Rod Gap Arrester or Spark Gap Arrester

It is the simplest, cheapest and most rugged form of surge diverter used for protection of insulators in line, equipments and bushings. It is shown in the Fig. 12.16.

Please refer Fig. 12.16 on next page.

The conducting rods are provided between the line terminal and earthed terminal of the insulator with an adjustable gap. The medium present in the gap is air. The rods are either square or round with diameter approximately 12 mm and bent at right angles. One rod is connected to the line circuit while the other rod is connected to the earth. The gap between the rods may be in the form of horns or arcing rings.

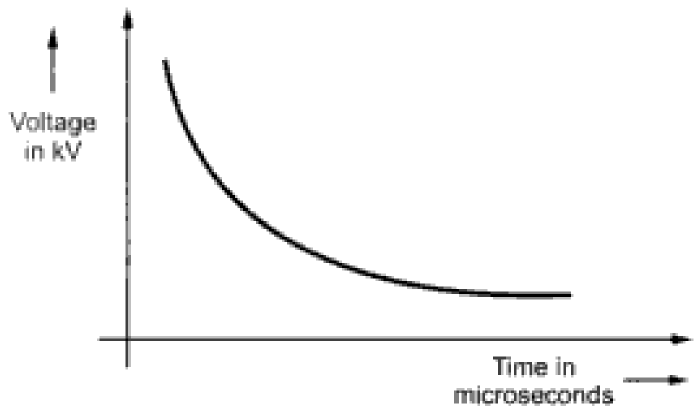


Fig. 12.17

Under normal operating conditions the gap is non-conducting. When the high voltage surge occurs on the line, there is spark over in the gap and current in surge is diverted to the earth. Thus excessive charge on the line is passed to the earth through this arrester. The volt-time characteristics for a rod gap is shown in the Fig. 12.17.

With the given gap and the wave shape of the voltage, the time required for the breakdown varies inversely with the voltage. The time for flash over for positive polarity is less than that for negative polarity. Upto certain extent the flash over voltage depends on the length of grounded rod. There is considerable difference between positive and negative flash over voltages for low values of this length. If the length is about 1.5 to 2 times the gap spacing then it is sufficient to reduce this difference applicably. The gap setting is in such a way that its breakdown voltage should be more than 30% below the voltage level of the equipment to be protected that it can withstand.

12.15.1 Limitations

Following are limitations of rod gap arrester.

1. Precise protection is not achieved and is not reliable so it can not be used as main protection against surge in high voltage systems. But as it is cheap it can be a good choice for second line of defence.
2. It gives protection against waves with comparatively small sloping front. Also the breakdown voltage varies with polarity, steepness and waveshape. The performance is affected by polarity of surge.
3. The rods may get damaged due to excess heat produced by arc. This is an important consideration in high voltage systems.
4. The performance is affected adversely due to climatic conditions such as humidity, temperature pressure.
5. The power frequency follow current is not interrupted by this type of arrester and it continues, to flow even after the high voltage surge is over. This creates a line to ground (or earth fault) fault which is to be interrupted by circuit breaker. Thus the operation of rod gap results in interruption of supply and breakers must operate to de-energize the circuit to clear the flash over. The

arc set up across the gap due to surge current ionizes the surrounding air which affects the insulation strength of the gap. Also sufficient time must be provided for deionization of arc path before the reclosure of circuit breaker for restoring supply. Hence it is generally used as back up protection.

There are some improvements in rod gap such as fused gap and control gap which are also used in practice sometimes. The fused gap is simply a rod gap along with a fuse in series with it to cut the power follow current. But it requires replacement and maintenance of fuse. Also for its effective operation it requires proper co-ordination between blowing of fuse and adjacent relay timing.

The control gap consists of a double gap arrangement to get sphere gap characteristics. Compared to rod gap its volt-time characteristics are better. It can be used with or without fuses and used as a back up or secondary protection.

12.16 Multigap Arrester

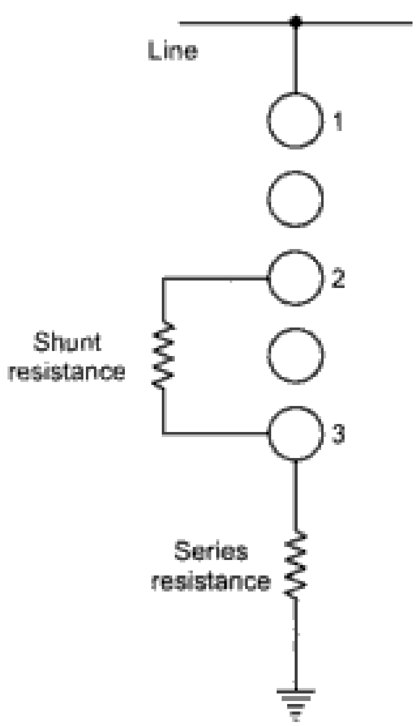


Fig. 12.18

It consists of a series of metallic cylinders made up of alloy of zinc generally insulated from one another and separated by small air gaps as shown in the Fig. 12.18.

Cylinder 1 is connected in series with the line while cylinder 3 is connected to earth through a series resistance. The series resistance limits the arc. The protection against travelling waves is reduced due to series resistance. To overcome this difficulty shunt resistance is included in some of the gaps.

Under normal operating conditions, cylinder 2 is at earth potential and it is not possible to breakdown the series gaps by normal voltage.

When overvoltage occurs, there is breakdown of the gap between 1 and 2. The large current will pass through the gaps instead of choosing an alternate path through shunt resistance and will divert to the earth.

After the surge is over, there is no arc in between 2 and 3, the power follow current is limited by shunt and series resistances as they are now in series. The current is not enough to maintain arc in the gap between 1 and 2 and normal conditions are restored. These arresters are used for system voltages upto 33 kV.

iii) The internal gap inside the tube.

iv) It has an open vent at the bottom for releasing the gases.

It consists of a series gap in series with internal gap inside a fibre tube. This gap in the fibre tube is made up of two electrodes. The upper electrode is connected to the series gap while the lower electrode is connected to the earth. One such arrester is placed under each line conductor. It is required that the breakdown voltage of the tube should be less than that of the insulation for which it is used.

Whenever Over voltage occurs on the line, there is breakdown in the series gap and arc is formed between the electrodes in the tube. Thus providing a low impedance path for lightning current to earth.

The heat produced by the arc vapourizes some of the organic material in the tube. The resulting natural gas builds up high pressure in short time and expelled out through the bottom vent after producing lot of turbulance in the tube. After the gas leaving from the tube violently, it carries ionized air around the arc.

Due to this strong de-ionizing effect, the arc is extinguished without restriking making current zero. The arc extinction time is about one or two half cycles which is very short interval for protective relays to act. Hence circuit breakers remain closed and line is kept in operation. After the expelling of gases and arc suppression, the tube is ready for new operation. The power follow current is safely interrupted by this type of arrester.

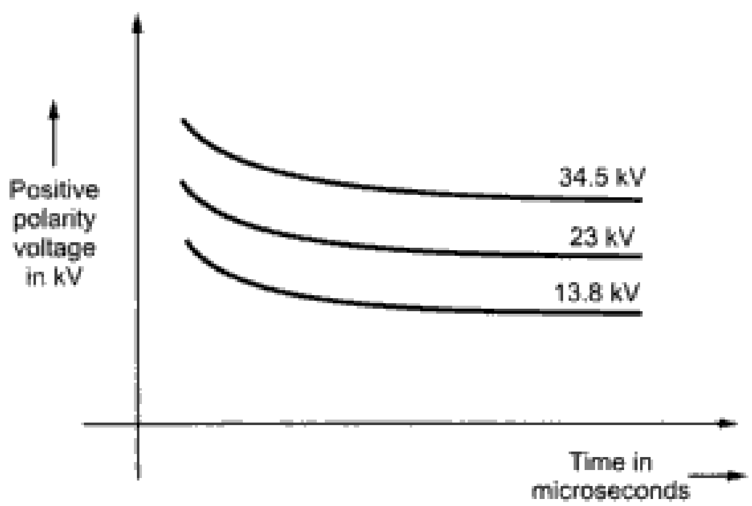


Fig. 12.20

With each operation of the tube the diameter of the fibre tube is increased as some part of fibre lining is vapourized every time which lowers insulation characteristics of tube. The volt-time characteristics are better than rod gap type and are shown in the Fig. 12.20.

Excessive current flowing through the tube may cause its bursting while a small current will be insufficient for producing necessary pressure to extinguish the arc. Also as the gas producing material is utilized each time when arrester operates, there is limitation of number of operations which can be safely carried by this arrester. Since there is gaseous discharge, it is not suitable for mounting near other equipments.

12.17.1 Advantages

1) They are cheaper and can be installed easily.
2) They are capable of interrupting power follow current immediately after the surge is over.

12.17.2 Disadvantages

1) The volt-amp characteristics for this arrester is poor and hence can not be used for protection of expensive station equipments.
2) It can not be mounted in an enclosed equipment because of discharge of gas during its operation.
3) It can perform limited number of operations as some of the fibre is used in every operation to produce gas for extinguishing the arc.

These type of lightning arresters are used on transmission towers near to the stations in certain cases to make the station lightning arrester free from its duty to certain extent by reducing the magnitude of surges coming on the line.

They are also used for protection against surges for transformers in rural areas as they are cheap than valve type arresters. These arresters are also employed in some special cases such as transmission towers with more height wherein there are more chances of lightening strokes.

Expulsion type arresters are either transmission type used for transmission line insulators or distribution type for the protection of distribution transformer and similar apparatus on distribution networks.

12.18 Valve Type Lightning Arrester

It is an expensive surge diverter also known as non-linear surge diverter. The details of this arrester are shown in the Fig. 12.21. (See Fig. 12.21 on next page)

As shown in the figure, there are two assemblies viz.

i) series spark gaps
ii) non linear resistor discs made up of material such as thyrite or matrosil in series.

The non linear elements are in series with the gap. Both these assemblies are contained in tight porcelain container for reliable protection against moisture, humidity and condensation.

The interrupting capacity of the spark gaps unit can be increased with the help of grading resistors. Under normal working conditions, the leakage current is always less than 0.1 mA approximately which flow through the resistors. This is sufficient to maintain the enclosures at specified temperature above ambient so as to prevent the effect of moisture into enclosure.

12.18.2 Non Linear Resistors

The non-linear resistors are made of an inorganic compound viz. Thyrite or Metrosil. These discs are in series to form a block. With the increase in applied voltage and current, the resistance decreases quickly. The residual voltage is hence maintained though current is high within limit. The non-linear resistors have the property of providing high resistance to current flow of normal system voltage but low resistance to flow of high surge currents i.e. its resistance decreases with increase in current and vice versa. Hence the power follow current after the surge is over can be easily interrupted with the help of resistor blocks by spark gaps at first current zero.

12.18.3 Working

Under normal operating conditions, the system voltage is not enough to cause breakdown of air gap assembly. Under the condition of over voltage, there is breakdown of series spark gaps and the surge current quickly reaches to ground through non linear resistors. The non-linear resistors will offer very small resistance to the flow of surge current whose magnitude is large. Thus the surge is prevented from sending back over the line. After the surge is over, the resistor blocks offers high resistance to the flow of power follow current and the current is interrupted. After approaching towards the equipment to be protected , the surge takes around 0.25 μsec to reach to the arrester and the whole operation of arrester takes place in a very short interval of time in about 20 to 30 μsec. The arc is extinguished at first current zero by cooling and lengthening of arc and also the voltage and current are almost in phase.

The volt-ampere characteristics of valve type lightning arrester is shown in the Fig. 12.22.

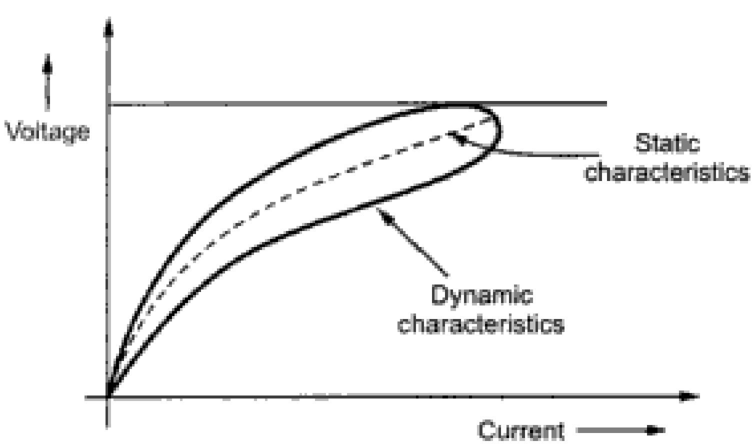


Fig. 12.22

The closed curve represents the dynamic characteristics corresponding to application of voltage surge while the dotted line showing static characteristics. The horizontal tangent drawn to the dynamic characteristics gives the voltage known as residual voltage and is the peak voltage during discharge of surge current.

Depending upon the type of the arrester i.e. either line type or station type discharge voltage varies from 3 kV to 6 kV. This voltage is also affected by magnitude and waveshape of discharge current.

The impulse ratio of unity is obtained for this arrester according to design of spark gaps. Hence high values of surge currents can not be interrupted. The impulse breakdown strength is smaller than residual voltage which decides the protection level for insulation co-ordination.

The volt-current relationship for one type of thyrite disc (non-linear resistor) is given by,

$$V = K I^{\alpha}$$

$$\text{Resistance of the arrester} = \frac{V}{I} = \frac{K I^{\alpha}}{I} = \frac{K}{I^{1-\alpha}} = \frac{K}{I^{\beta}} = K I^{-\beta}$$

Typical values of K and β are 4650 and 0.72.

With N number of thyrite discs,

$$\text{Resistance,} \quad R = \frac{NK}{I^{\beta}} = NK I^{-\beta}$$

$$\therefore \quad R I^{\beta} = NK = \text{constant}$$

12.18.4 Advantages

i) The operation of this arrester is very fast within a fraction of second.

ii) They are suitable for effective protection of transformers and cables against surges.

12.18.5 Disadvantages

i) Very steep wave front type of surges are not being protected by these arresters. Fortunately the lightning surges on the transmission system are attenuated as they travel over the line towards the substations and they are within the reach of protection circuits in the substations. But proper care should be taken to prevent surges of severe intensity and efficient form of shielding should be used.

ii) The performance of this type of arrester may be affected if there is entry of moisture in the enclosure. This problem can be solved by sealing the container hermetically or enclosures are filled by inert gas and contain some form of de-humidifier or allowing the leakage current to pass to maintain the temperature within limits.

12.18.6 Applications

The valve type arrester is classified in following types.

i) Station type :

These arresters are efficient and expensive which are used for protection of important equipments with rating from 2.2 kV to 400 kV and higher. It has highest capability for dissipation of energy.

ii) Line type :

The term "Line" is misleading as these arresters are not used for protection of lines. Unlike station type, these are also used for protection of plants and substations which are comparatively less important and economy is to be achieved. They are used upto 66 kV except in some cases beyond it. They are smaller in cross section, weight and cost than station type. They provide protection against higher surge voltages than station type but have less surge current capacity. Typical ratings of these arresters are upto 5 kA to use in large transformers and intermediate substations.

iii) Arrester for protecting Rotating Machines :

These are specially used for protection of generators and motors with voltage range from 2.2. kV to 22 kV.

iv) Distribution type arrester :

These are generally used for protection of pole mounted distribution substations and are available in the voltage range from 2.2 kV to 15 kV.

v) Secondary arresters :

These are used for protection of low voltage apparatus with the range of 120 V to 750 V.

12.19 Metal Oxide Lightning Arresters

This is a new type of lightning arrester developed and used. It consists of non-linear resistor block and main element of the arrester is metal oxide or normally zinc oxide (ZnO) which is economical compared to thyrite arresters. There are no series gap and its degree of non-linearity is more than that of thyrite arrester.

The ZnO type of arrester provides better surge protection with more stable protection characteristics and has simple construction similar to valve type but the valve element is a dense ceramic body made up of ZnO and other metallic oxides.

12.20 Location of Lightning Arresters

The lightning arresters are normally located near the equipment to be protected. Because of this, the chances of surges to enter the circuit between the protective equipment (arrester) and the equipment to be protected are reduced. Secondly if there is distance between arrester and protected equipment then a steep fronted wave after being incident on lightning arresters, after spark over at the appropriate sparkover voltage, enters the transformer after travelling over the lead between two and suffers reflection at the terminal. The total voltage at the terminal of transformer is sum of incident and reflected voltage which is approximately twice the incident voltage. If the arrester is not at correct location then transformer may experience a surge of twice the magnitude that on arrester. With L as the inductance of the lead between arrester and equipment, the voltage incident at transformer terminal is given by,

$$V = IR + L\frac{di}{dt}$$

where, $\frac{di}{dt}$ = Rate of change of surge current

If a capacitor is connected at the terminals of protected equipment then steepness of wave is reduced which decreases rate di/dt which results in less distribution of stress on winding of protected equipment.

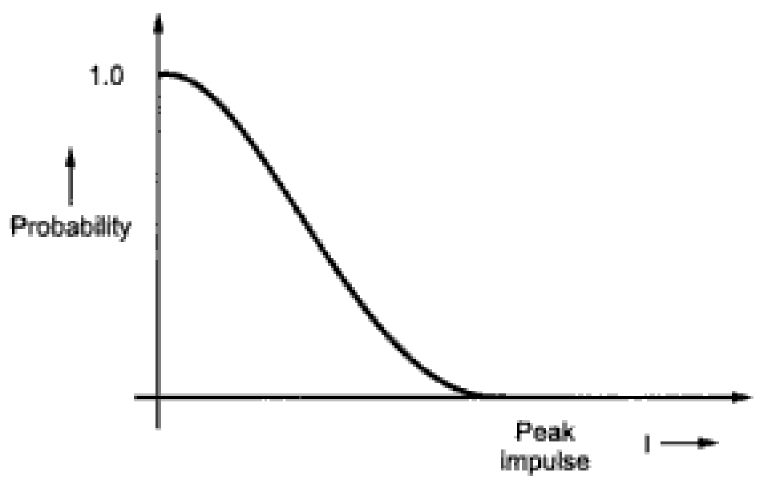


Fig. 12.23

The location of an arrester in a substation depends on what is the probability of flashover on the line per one hundred kilometers in a span of one year. The typical probability curve of peak impulse current is shown in the Fig. 12.23.

The crest or peak value of surge and the characteristics of arresters are also important. It will not be economical and necessary also to install one arrester near to each equipment in the substation. The optimum use of arrester to serve the intended purpose is to install it at the entry of incoming line.

For indoor substations, the requirement of lightning arrester is comparatively less as equipments there are connected by cables which attenuate the surges. Hence the duty of arrester in case of medium voltage range indoor substation is reduced considerably.

12.21 Rating of Lightning Arrester

The discharge current in the surge is very large which is passed through the arrester. But the time of discharge is less hence the energy dissipated is small. Hence the important factor in selection of lightning arrester is the line to ground voltage that the arrester is subjected during operation for any condition.

Generally 5 % allowance is taken to consider the no-load condition of the line and sudden loss of load on generators. Thus an arrester of 105% rating is used on a system where line to ground voltage may reach line to line value during ground fault.

The rated voltage is maximum permissible rms value of power frequency voltage which is supported by the arrester across its line and earth terminals while still carrying out effectively and without damage the automatic extinction of follow up current.

The voltage rating of the arrester must be greater than normal phase to ground voltage to avoid high current flowing through arrester causing terminal overloading. In order to get the maximum voltage which can occur on system phases and ground during fault on one of the phases, it is required to know system highest voltage and co-efficient of earthing.

The highest voltage of the system is normally taken as 110 % of nominal system voltage.

Now, $$\text{Coefficient of earthing} = \frac{\text{Highest rms voltage of healthy phase to earth}}{\text{Phase to phase normal rms voltage}}$$

$\therefore$ Voltage rating of arrester = Highest phase to phase rms voltage × coefficient of earthing

$\therefore$ Voltage rating of arrester = 1.1 × Phase to phase rms voltage × coefficient of earthing

For effectively earthed system, the co-efficient of earthing is 0.8.

If system voltage is 400 kV,

$$\therefore \quad \text{Rating of arrester} = 1.1 \times 400 \times 0.8 = 352 \text{ kV}$$

For non-effectively earthed systems, isolated or unearthed neutral system, arresters are rated at 100 % of system highest voltage.

If phase to phase rms voltage = 400 kV with isolated or unearthed neutral system

$$\therefore \quad \text{Rating of arrester} = 1.1 \times 400 = 440 \text{ kV}$$

The nominal discharge current must have specific wave shape and crest value to classify arrester with reference to its durability and protection characteristics. Different ratings are tabulated as below. The wave shape for these ratings is 8/20 μs.

Sr. No.	Current Rating (kA)	Application
1	10	Protection of important and main power and substations in areas which are prone to lightning strokes more frequently with system voltages above 66 kV.
2	5	Protection of other power and substations with system voltages above 66 kV
3	2.5	Protection of small substations where diverters of higher ratings are uneconomical with system voltages upto 22 kV
4	1.5	Protection of rural distribution system where it is necessary to install diverters more frequently for protecting small transformers with system voltages not more than 22 kV

Table 12.3

As per American practice, the wave shape is specified as 10/20 μs.

The power frequency spark over voltage should be 1.6 times the rated voltage of arrester to avoid frequent sparking over of arrester due to internal over voltages of insufficient magnitude. The maximum impulse spark over voltage is the magnitude of 1/50 μsec voltage wave on which the arrester sparks over 5 times out of 5. The residual or discharge voltage depends , for type and nominal voltage of arrester, on waveform gradient (di/dt) and magnitude of current. For determining this voltage, it is recommended to use a current wave denoted by 8/20 μsec. The discharge voltages are fixed for a current of 5 kA or 10 kA. Maximum discharge current is referred to a wave shape given by 5/20 μsec.

12.22 Tests on Lightning Arrester

Various tests are performed on lightning arresters to evaluate its performance. Some of the tests are listed below :

1. 1/50 impulse spark over test
2. Wave front impulse spark over test
3. Peak discharge residual voltage at rated diverter current
4. Impulse current withstand test
5. Switching impulse voltage test
6. Peak discharge residual voltage at low current

7. Discharge capacity of durability
8. Transmission line discharge test
9. Low current long duration test
10. Power duty cycle test
11. Pressure relief test

12.23 Surge Absorber

The steepness of wave front of travelling waves can cause damage to the apparatus in addition to magnitude of wave. More steeper is the travelling wave, the damage to the apparatus is more. Thus to reduce the steepness of wave front of the surge, surge absorber is used.

The surge absorber is a protective device which can reduce the steepness of wave front of a surge and absorbs energy contained in travelling wave. Though surge diverter and surge absorber eliminate the surge, the way in which it is done is different in two devices. The surge diverter diverts the surge to the earth while surge absorber absorbs energy contained in the surge.

A capacitor connected between line and earth can reduce the steepness of wave front. Similarly as the impedance of capacitor is inversely proportional to its frequency, it gives protection against low voltage high frequency waves. Thus it can be considered that the lines are connected to the earth so far as discharge at high frequency is considered.

The capacitor is used for the protection of transformer winding to make it free from very high stresses that may be set up in the turns. A pure capacitor can not dissipate the energy in wave front or in high frequency discharge but it just reflects the energy away from the equipment to be protected while the energy is dissipated in the resistance of line conductors and earthing resistances. With a series combination of resistor and capacitor, a part of energy is dissipated in the series combination in addition to prevent it from approaching to the equipment. The arrangement is shown in the Fig. 12.24 (i) and (ii). At normal power frequency, the reactance of capacitor is high and practically no current flows to the ground.

The surge absorber may also be in the form similar to air cored transformer with low inductance primary and single turn short circuited secondary to act for energy dissipation. When the travelling wave is incident on the absorber, a part of energy is dissipated as heat due to transformer action and by eddy currents. Because of series inductances, the wave front steepness is reduced.

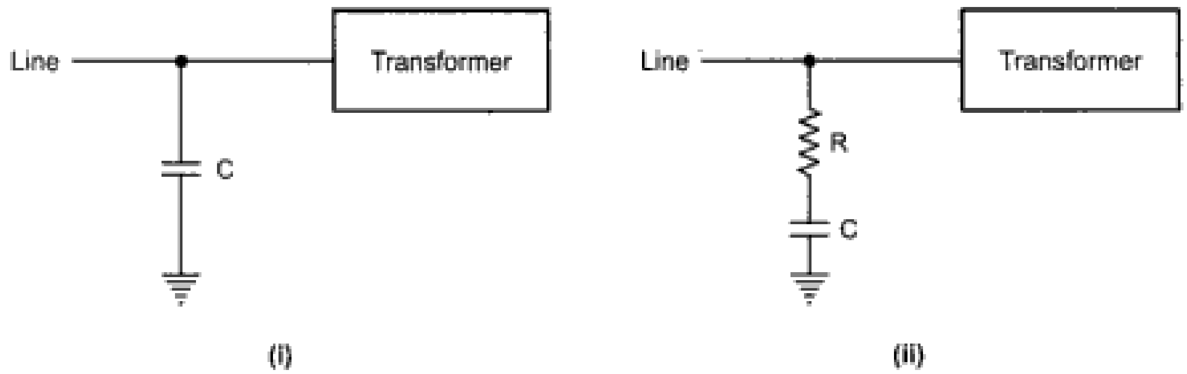


Fig. 12.24 Surge absorber using capacitor

In another type of surge absorber, a parallel combination of resistance and inductance is used as shown in the Fig. 12.25 . This combination is placed in series with the line steep wave fronts or high frequency discharges to find the inductive path to have more reactance and are forced through resistance where they are dissipated. The power frequency currents find inductive path of minimum impedance ($X_L = 2 \pi f L$ i.e. $X_L \propto f$) and pass through it without much loss.

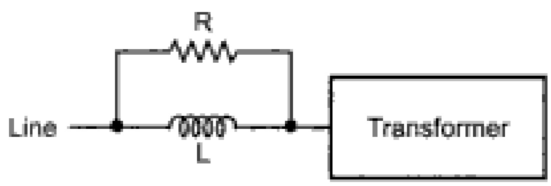


Fig. 12.25

The Ferranti surge absorber consists of inductive coil magnetically coupled but not electrically to a metal shield and the steel tank containing it. The coil is cylindrical and currents are induced in metal shield. The absorber is enclosed cylindrical boiler plate tank and is vacuum impregnated. It is similar to transformer with short circuited secondary. The inductor is primary while metallic shield acts as short circuited secondary dissipator. The energy is dissipated as heat generated in a dissipator due to transformer action. It is used for the protection of transformer. It is shown in the Fig. 12.26.

Due to filter effect, the high frequency currents are prevented from passing freely through the absorber, The energy transferred through mutual induction is dissipated in the form of heat in the dissipator.

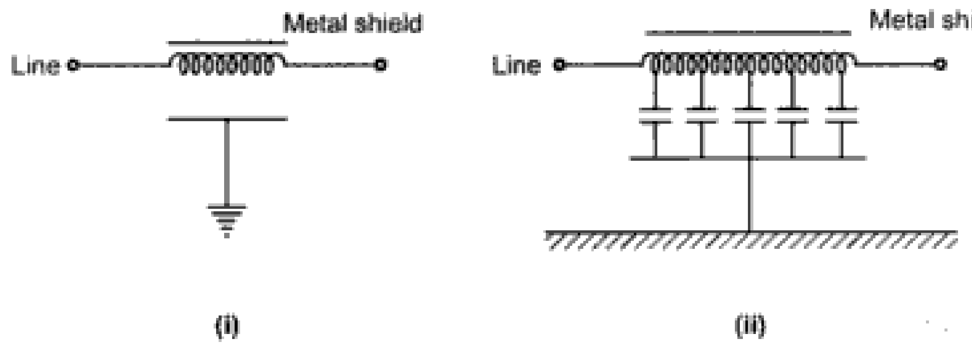


Fig. 12.26 Ferranti surge absorber

12.24 Summary of Protective Devices Against Lightning Surges

Sr. No.	Device	Field of application
1	Rod gap type	Bushing Insulator, Support Insulator, Across Insulator String
2	Overhead earthed ground wires	Above overhead transmission lines , In the substation area
3	Vertical masts	Substations
4	Earthed lightning rods	Above tall buildings or structures
5	Lightning or surge arresters	Incoming lines in substations, Near terminals of transformers and generators, Pole mounted distribution systems
6	Surge absorbers	Near rotating machines or switchgear, Across series reactors

Table 12.3

Review Questions

1. *Explain the phenomenon of lightning discharge.*
2. *What are various types of lightning strokes ? Explain them in detail.*
3. *What are the harmful effects of lightning strokes on substation equipments ?*
4. *What are various methods of protection against lightning strokes ?*
5. *How do earthing screen and ground wires provide protection against direct lightning strokes ?*
6. *What is a surge diverter ? What is basic principle of operation of surge diverter ? How are they classified ?*
7. *Write short notes on the following types of arresters :*

   i) Horn gap arrester *ii) Rod gap arrester* *iii) Multigap arrester*

   iv) Expulsion type arrester *v) Valve type arrester*

8. *Explain clearly how rating of lightning arrester is selected. How the location of lightning arrester is decided ?*

9. *Explain the following terms related to the lightning arrester :*
   a) Rated voltage b) Follow current c) Discharge current
   d) Power frequency spark over voltage e) Impulse spark over voltage
   f) Residual voltage g) Rated current

10. *What is tower footing resistance ? What are the methods to reduce this resistance ?*

11. *What is a ground wire ? Discuss its location with respect to the line conductors.*

12. *Explain the operation of various types of surge absorbers.*

13. *What do yo mean by coefficient of earthing ?*

14. *What are the basic requirements of a good lightning arrester ?*

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