

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

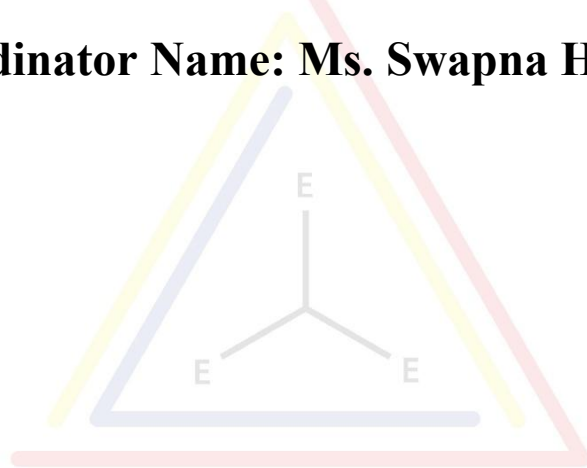
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Academic Year: 2026-27

Course Code: BEE701

Course Title: Switch Gear & Protection

Course Co-ordinator Name: Ms. Swapna H



Department of EEE
Emitting Elite Energy

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Vision of the Institute Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources. Mission of the Institute • To keep pace with advancements in knowledge and make the students competitive and capable at the global level. • To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torch-bearers of tomorrow's society. • To strive to attain ever-higher benchmarks of educational excellence	Vision of the Department To create Electrical and Electronics Engineers who excel to be technically competent and fulfil the cultural and social aspirations of the society. Mission of the Department • To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development. • To offer outcome based technical education. • To encourage faculty in training & development and to offer consultancy through research & industry interaction.
Program Educational Objectives (PEO's) • PEO1: To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society. • PEO2: To make graduates continuously acquire and enhance their technical and socio-economic skills. • PEO3: To aspire graduates on R&D activities leading to offering solutions and excel in various career paths. • PEO4: To produce quality engineers who have the capability to work in teams and contribute to real time projects.	Program Specific Outcomes (PSO's) • PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of power systems and also to control industrial drives using power electronics. • PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning.

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Program Outcomes (PO's)

PO1: Engineering Knowledge: Apply knowledge of mathematics, natural science, computing, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to develop to the solution of complex engineering problems.

PO2: Problem Analysis: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions with consideration for sustainable development. (WK1 to WK4)

PO3: Design/Development of Solutions: Design creative solutions for complex engineering problems and design/develop systems/components/processes to meet identified needs with consideration for the public health and safety, whole-life cost, net zero carbon, culture, society and environment as required. (WK5)

PO4: Conduct Investigations of Complex Problems: Conduct investigations of complex engineering problems using research-based knowledge including design of experiments, modelling, analysis & interpretation of data to provide valid conclusions. (WK8).

PO5: Engineering Tool Usage: Create, select and apply appropriate techniques, resources and modern engineering & IT tools, including prediction and modelling recognizing their limitations to solve complex engineering problems. (WK2 and WK6)

PO6: The Engineer and The World: Analyze and evaluate societal and environmental aspects while solving complex engineering problems for its impact on sustainability with reference to economy, health, safety, legal framework, culture and environment. (WK1, WK5, and WK7).

PO7: Ethics: Apply ethical principles and commit to professional ethics, human values, diversity and inclusion; adhere to national & international laws. (WK9)

PO8: Individual and Collaborative Team work: Function effectively as an individual, and as a member or leader in diverse/multi-disciplinary teams.

PO9: Communication: Communicate effectively and inclusively within the engineering community and society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations considering cultural, language, and learning differences

PO10: Project Management and Finance: Apply knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, and to manage projects and in multidisciplinary environments.

PO11: Life-Long Learning: Recognize the need for, and have the preparation and ability for i) independent and life-long learning ii) adaptability to new and emerging technologies and iii) critical thinking in the broadest context of technological change. (WK8)

Module -1

Introduction for Power System Protection, Relay Construction and Operating Principles

- 1.0 Need for protective systems
- 1.1 Nature and causes of faults
- 1.2 Types of faults
- 1.3 Effects of faults
- 1.4 Zones of protection
- 1.5 Primary and back-up protection
- 1.6 Desirable qualities of protective relaying
- 1.7 Protective relays
- 1.8 Instrument transformers
- 1.9 Auto-reclosing
- 1.10 Classification of protective relays
- 1.11 Electromechanical relays
- 1.12 Time–current characteristics, current setting, time setting

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Module -1 Introduction for Power System Protection

Course objectives: To discuss performance of protective relays, components of protection scheme and relay terminology & to explain relay construction and operating principles

1.0 NEED FOR PROTECTIVE SYSTEMS

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

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

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

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

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

Thus, the occurrence of a major fault is prevented. If the gas evolves rapidly, the Buchholz relay trips the circuit breaker instantly.

Protective relaying is teamwork of the following Components for the protection of equipment these include: protective current transformers and voltage transformers, protective relays, time-delay relays, auxiliary relays, secondary circuits; trip circuits, auxiliaries and accessories, etc. Each component is important.

1.1 Nature and causes of Faults

Equipment	Cause of fault	% of Total Faults
1. Overhead lines	Lightning strokes Storms, earthquakes, icing Birds, trees, kites aeroplanes, snakes, etc. Internal over-voltages.	30—40
2. Underground cables	Damage during digging Insulation failure due to temperature rise Failure of joints	8—10
3. Alternators (Generator)	Stator faults Rotor faults Abnormal conditions Faults in associated equipment Faults in protective system	6—8
4. Transformers	Insulation failure Faults in tap-changer Faults in bushing Faults in protection circuit Inadequate protection Overloading, over voltage.	10—12
5. CT, PT	Over-voltages Insulation failures Breaking of conductors Wrong connections	15—20
6 Switchgear	Insulation failure Mechanical defect Leakage of air/oil/gas Inadequate rating Lack of maintenance.	10—12

Statistics of fault on overhead lines

Types of fault	% of occurrence
Line to ground faults	80-90%
Double line faults	6-10%
Double line to ground faults	3-7%
Triple line faults	2% or less

1.2 TYPES OF FAULTS

Two broad classifications of faults are

- Symmetrical faults
- Unsymmetrical faults

Symmetrical Faults

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

Unsymmetrical Faults

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

Single-phase to Ground (L-G) Fault

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

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

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

Phase-to-Phase (L-L) Fault

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

Open-circuited Phases

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

Winding Faults

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

Simultaneous Faults

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

1.3 EFFECTS OF FAULTS

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

- Heavy short circuit current may cause damage to equipment or any other element of the system due to overheating and high mechanical forces set up due to heavy current.
- Arcs associated with short circuits may cause fire hazards. Such fires, resulting from arcing, may destroy the faulty element of the system. There is also a possibility of the fire spreading to other parts of the system if the fault is not isolated quickly.
- There may be reduction in the supply voltage of the healthy feeders, resulting in the loss of industrial loads.
- Short circuits may cause the unbalancing of supply voltages and currents, thereby heating rotating machines.
- There may be a loss of system stability. Individual generators in a power station may lose synchronism, resulting in a complete shutdown of the system. Loss of stability of interconnected systems may also result. Subsystems may maintain supply for their individual zones but load shedding would have to be resorted in the sub-system which was receiving power from the other subsystem before the occurrence of the fault.
- The above faults may cause an interruption of supply to consumers, thereby causing a loss of revenue.

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

1.4 ZONES OF PROTECTION

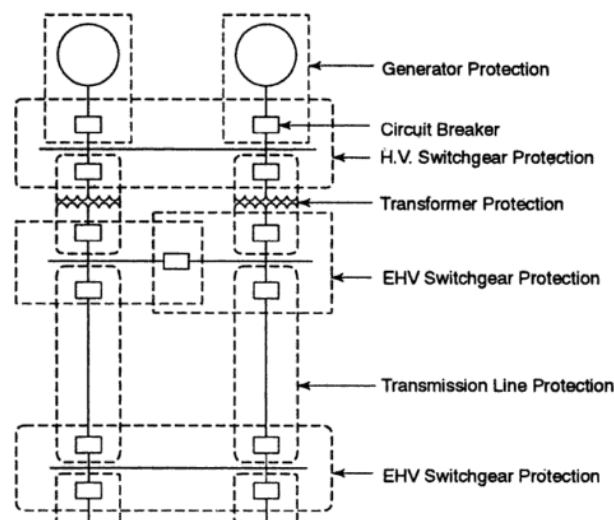


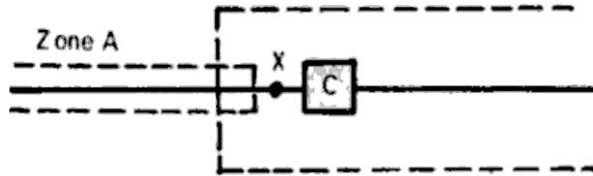
FIGURE 1.1 Zones of protection

The protected zone is that part of a power system guarded by a certain protection Scheme and usually contains one or at the most two elements of the power system. The zones are arranged to overlap so that no part of the system remains unprotected. Figure (1.1) shows a typical arrangement of overlapping zones of protection.

A power system contains generators, transformers, bus bars, transmission and distribution lines, etc. There is a separate protective scheme for each piece of equipment or element of the power system, such as generator protection, transformer protection, transmission line protection, bus bar

protection, etc.

Neighboring zones overlap so that no ‘dead spot’ are left in the protected system



It can be seen that for a fault at X the circuit breakers of ‘Zone B’ including breaker C will be tripped; however, this does not interrupt the flow of fault current from ‘Zone A’, the relaying equipment of ‘Zone B’ must also trip certain breaker in zone ‘Zone A’

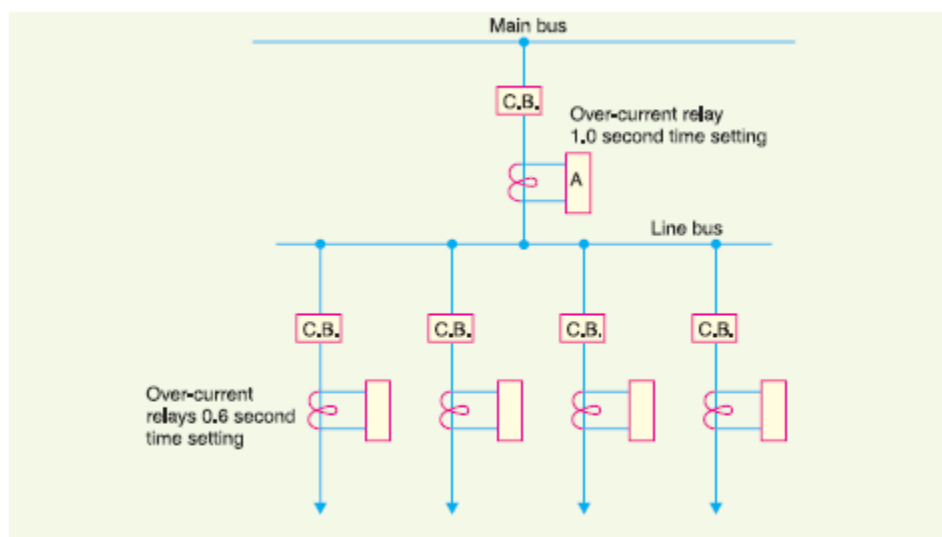
This is all right for fault at X, but for faults in zone B to the right of breaker C the operation of breakers in zone A is not useful. How far this unnecessary operation can be tolerated will depend on the particular application .

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1.5 PRIMARY AND BACK-UP PROTECTION

Primary protection (Main protection) is the essential protection provided for protecting an equivalent/machine. As a precautionary measure, an additional protection is generally provided and is called 'Back-up Protection'. The primary protection is the first to act and the Back-up Protection is the next in the line of defense-meaning, if primary protection fails, the back-up protection comes into action and removes the faulty part from the healthy system. Back-up protection is provided for the following reasons:

If due to some reason, the Main protection fails, the Back-up protection serves the purpose of protection. Main protection can fail due to failure of one of the components in the protective system such as relay, auxiliary relay CT, PT, trip circuit, circuit-breaker, etc. If the primary protection fails, there must be an additional protection; otherwise the fault may remain uncleared, resulting in a disaster.



Back-up protection. It is the second line of defence in case of failure of the primary protection. It is designed to operate with sufficient time delay so that primary relaying will be given enough time to function if it is able to. Thus referring to above Fig., relay A provides back-up protection for each of the four lines. If a line fault is not cleared by its relay and breaker, the relay A on the group breaker will operate after a definite time delay and clear the entire group of lines. It is evident that when back-up relaying functions, a larger part is disconnected than when primary relaying functions correctly. Therefore, greater emphasis should be placed on the better maintenance of primary relaying.

As a measure of economy, Back-up protection is given against short-circuit protection and generally not for other abnormal conditions. The extent to which back-up protection is provided, depends upon economic and technical considerations

The back-up relays are made independent of those factors which might cause primary relays to fail. A back-up relay operates after a time delay to give the primary relay sufficient time to operate. When a back-up relay operates, a larger part of the power system is disconnected from the power source, but this is unavoidable.

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

1. **Relay Back-up.** Same breaker is used by both main and back-up protection, but the protec-

- tive systems are different. Separate trip coils may be provided for the same-breaker.
2. **Breaker Back-up.** Different breakers are provided for main and back-up protection, both the breakers being in the same station
 3. **Remote back-up.** The main and Back-up protections provided at different stations and are completely independent.

1.6 DESIRABLE QUALITIES OF PROTECTIVE RELAYING

Protective relaying should have certain qualities. Some of these quantities cannot be expressed in form of a mathematical expression, however, they are important. The qualities of protective relaying are named as

- Selectivity & discrimination.
- Fast Operation.
- Sensitivity.
- Stability.
- Reliability.
- Adequateness.

The qualities should be carefully considered while selecting protection schemes for power system protection. Cost is also equally important. A better protective system costs more

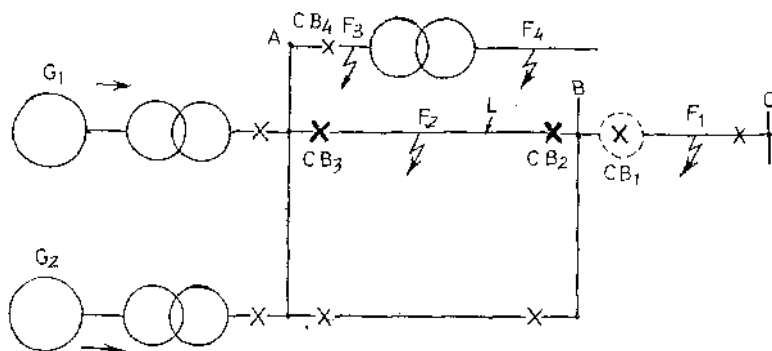
Selectivity & discrimination.

This is the property by which only the faulty element of the system is isolate and remaining healthy section should are left intact.

Discrimination is 'the act Discriminating' or 'distinguishing the difference between' the following:

Normal Condition & Abnormal condition

The protective system should operate only during abnormal conditions and should not operate under normal condition. In other words, the protective relaying system should discriminate between normal condition and abnormal condition. It should select and disconnect only faulty part without disconnecting the remaining healthy part.



Explaining Selectivity ('X' mark indicate CB)

Protective relaying should be inoperative and stable during faults and abnormal conditions beyond its protective zone. It should not operate for faults, abnormal conditions beyond its protective zone. Referring to below Fig, if a fault occurs on transmission line, the protective relaying should isolate only the faulty line without tripping the neighbouring line or the transformer. For fault F1, only

circuit-breaker CB1 should open. For fault F2, both CB2 and CB3 should open.

If protective relaying is not selective, and operates for faults beyond its protective zones, a larger portion of the system gets disconnected unnecessarily, causing embarrassment to supplier and consumers

Fast Operation

A protective system should be fast enough to isolate the faulty element of the system as quickly as possible to minimise damage to the equipment and to maintain the system stability.

Fault clearing time is the time between the instant of fault and instant of final arc interruption (in circuit breaker).

Fault clearing time is the sum of relay-time and circuit breaker-time.

Remember the time events

$$\text{Fault Clearing Time} = [\text{Relay Time}] + [\text{Breaker Time}]$$

Fault Instant to Closing of relay contacts	+	Closing of relay contacts to Final Arc-extinction in C.B.
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The relay-time is the time between the instant of occurrence of fault and the instant of closure of relay contacts. Or, it is the time between the instant when the operating quantity reaches the pick-up value and the instant of closure of relay contacts.

The circuit breaker time is the total of time taken by operating mechanism to open to circuit breaker contacts and the arcing time. It is also called total break time.

The fault clearing time is significant due to the following reasons:

1. Rapid fault clearing minimizes the damage. During short circuit tests on bus bars, with fault duration of 0.07 second, with 60 kA R.M.S. value of current, no damage was observed after the tests. With fault duration of 7 seconds, however, the bus bars were completely destroyed.
2. Rapid fault clearing improves power system stability. For the reason, the slow relays and slow circuit breakers should not be preferred for protection, where stability is important. This applies to protection of EHV transmission lines, protection of large machines like important generator, large transformer, large-motors, etc., and protection in important generating stations and receiving stations

Though fast fault clearing is desirable, time lag is purposely provided in majority of protection systems for the following purposes:

- To permit discrimination between main and back-up protection.
- To prevent the operation of relay during transients, starting currents, permissible load fluctuations, etc.

The relay-time of fast relays is of the order of a few cycles and that of inverse time relays can be adjusted between about 6 seconds to 60 seconds. The circuit-breaker time of slow circuit-breakers is of the order of 5 cycles and that of fast circuit-breakers is of the order of 2 cycles to 3 cycles.

Sensitivity

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

Reliability

A protective relay must operate reliably when a fault occurs. The reliability of a protective relay should be very high, a typical value being 95%.

Reliability means trustworthiness. The protective relaying should not fail to operate in the event of faults in the protected zone. Secondly, there should not be any fault in the components of protective system. Protective system should not operate unnecessarily. Reliability of protective systems is assessed from statistical data.

The protective system is teamwork of several components. A failure or defect in any one of them can result in failure of protection system. Hence the basic requirement of reliable protection is reliability of each component including circuit-breaker, relays, CT's, PT's secondary cables, trip circuit, battery system accessories, etc.

To achieve a high degree of reliability, greater attention should be given to the design, installation, maintenance and testing of the various elements of the protective system. Robustness and simplicity of the relaying equipment also contribute to reliability.

Stability

This is the ability of the protective system to remain inoperative under all load conditions, and also in case of external faults. The relay should remain stable when a heavy current due to an external fault is flowing through it

OR

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

Adequateness

There can be many abnormal conditions and providing protection against every abnormal condition is economically impossible. However, the protection provided for any machine, should be adequate.

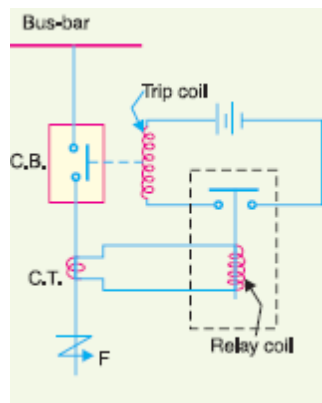
The adequateness of protection is judged by considering the following aspects :

- Rating of the protected machine.
- Location of the protected machine.
- Probability of abnormal condition due to internal and external causes.
- Cost of the machine, important.
- Continuity of supply as affected by failure of machine.

for low voltage machine/equipment, at the remote end of the system, an elaborate and costly protective system is not necessary. For example, distribution transformers below, say 500 kVA are protected simply by drop-out fuses. Motors below 100 kW are protected by thermal over-load relays and HRC fuses. In these cases, the cost of CT's and protective relays, circuit-breakers, etc. is not generally justified. Whereas for a large machine, say generator, a very complex protective scheme is necessary. The adequateness of protection should be assessed while planning the protection scheme. Each installation generally needs particular attention, as the protective relaying needs are influenced by local conditions

1.7 Protective Relays

A protective relay is a device that detects the fault and initiates the operation of the circuit breaker to isolate the defective element from the rest of the system. The relays detect the abnormal conditions in the electrical circuits by constantly measuring the electrical quantities which are different under normal and fault conditions. The electrical quantities which may change under fault conditions are voltage, current, frequency and phase angle. Through the changes in one or more of these quantities, the faults signal their presence, type and location to the protective relays. Having detected the fault, the relay operates to close the trip circuit of the breaker. This results in the opening of the breaker and disconnection of the faulty circuit. A typical relay circuit is shown in Fig. 21.1. This diagram shows one phase of 3-phase system for simplicity. The relay circuit connections can be divided into three parts viz.



- (i) First part is the primary winding of a current transformer (C.T.) which is connected in series with the line to be protected.
- (ii) Second part consists of secondary winding of C.T. and the relay operating coil.
- (iii) Third part is the tripping circuit which may be either a.c. or d.c. It consists of a source of supply, the trip coil of the circuit breaker and the relay stationary contacts. When a short circuit occurs at point F on the transmission line, the current flowing in the line increases to an enormous value. This results in a heavy current flow through the relay coil, causing the relay to operate by closing its contacts. This in turn closes the trip circuit of the breaker, making the circuit breaker open and isolating the faulty section from the rest of the system. In this way, the relay ensures the safety of the circuit equipment from damage and normal working of the healthy portion of the system.

1.8 Instrument transformers. The lines in sub-stations operate at high voltages and carry current of thousands of amperes. The measuring instruments and protective devices are designed for low voltages (generally 110 V) and currents (about 5 A). Therefore, they will not work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing instrument transformers on the power lines. The function of these instrument transformers is to transfer voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays. There are two types of instrument transformers viz.

- (i) Current transformer (C.T.)
- (ii) Potential transformer (P.T.)

(i) Current transformer (C.T.). A current transformer is essentially a step-down transformer which steps down the current to a known ratio. The primary of this transformer consists of one or more turns of thick wire connected in series with the line. The secondary consists of a large number of turns of fine wire and provides for the measuring instruments and relays a current which is a constant fraction of the current in the line. Suppose a current transformer rated at 100/5 A is connected in the line to measure current. If the current in the line is 100 A, then current in the secondary will be 5A. Similarly, if current in the line is 50A, then secondary of C.T. will have a current of 2.5 A. Thus the C.T. under consideration will step down the line current by a factor of 20.

(ii) Voltage transformer. It is essentially a step down transformer and steps down the voltage to a known ratio. The primary of this transformer consists of a large number of turns of fine wire connected across the line. The secondary winding consists of a few turns and provides for measuring instruments and relays a voltage which is a known fraction of the line voltage. Suppose a potential transformer rated at 66kV/110V is connected to a power line. If line voltage is 66kV, then voltage across the secondary will be 110 V.

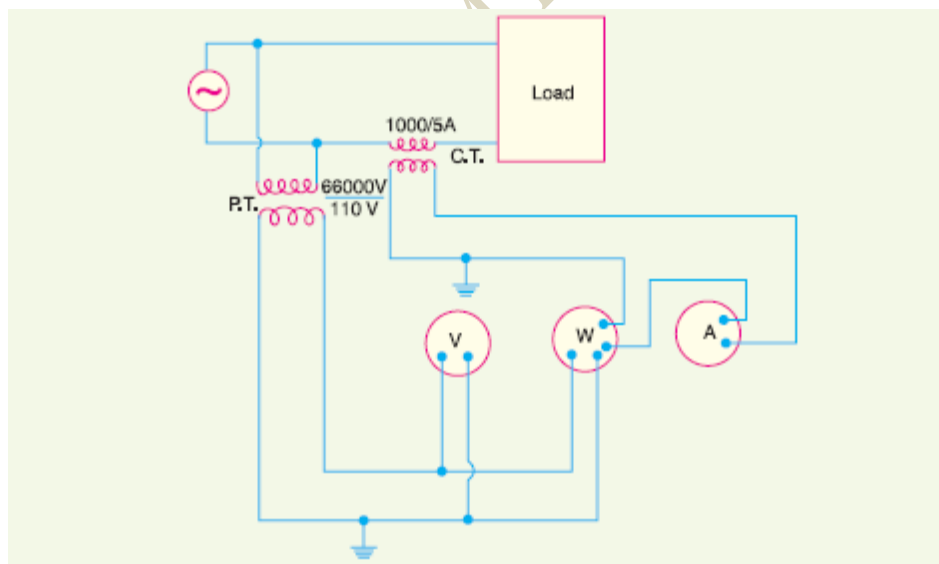


Fig. above shows the use of instrument transformers. The *potential transformer rated 66,000/110V provides a voltage supply for the potential coils of voltmeter and wattmeter. The current transformer rated 1000/5 A supplies current to the current coils of wattmeter and ammeter. The use of instrument transformers permits the following advantages:

- (a) They isolate the measuring instruments and relays from high-voltage power circuits.
- (b) The leads in the secondary circuits carry relatively small voltages and currents. This permits to use wires of smaller size with minimum insulation.

1.9 Auto-Reclosing

Faults on overhead lines fall into one of three categories:

- A. transient
- B. semi-permanent
- C. permanent

80-90% of faults on any overhead line network are transient in nature. The remaining 10%-20% of faults are either semi-permanent or permanent

Most of the faults on overhead lines are transient in nature. About 80% to 90% of faults are momentary and caused by tree branches, lightning, birds etc. These conditions result in arcing faults which last for very small duration and clear after that moment. The arc generated can be extinguished and the line can be re-energized. For this momentary fault, which recovers on its own, normal circuit breaker operation of opening the faulty part is not advisable. Some provision should be permitted in circuit breakers to close the breaker contacts if the fault is cleared momentarily. This fact is employed as a basis for auto-reclosures.

In this scheme, after the relays of both ends have picked up, the circuit breakers are tripped as far as possible at the same time and reclosed after time has been allowed for deionization. The fault disappears if it is transient and the line is restored to normal service after the reclosure. If the fault is not cleared after the first reclosure, a double or triple attempt of separation and reclosure is made. If the fault still persists, the breaker may permanently open till it is manually reset.

Auto reclosures may be single or three phase type. Mostly single phase auto reclosing breakers are preferred as most of the transmission faults are single phase to ground faults. Auto reclosures of single pole type improve the stability of the system as power remains transmitted through the remaining two healthy phases when a fault on one phase occurs.

The breakers may be rapid auto reclosing type (about 20 cycles or 0.4 sec) or delayed auto reclosing (5 to 30s) type. For rapid reclosing type, it is not required to check synchronism while reclosing; however, for delay reclosing, synchronism should be checked before reclosing. For this purpose, synchronous relays are employed.

Use of an auto-reclose scheme to re-energise the line after a fault trip permits successful re-energisation of the line. Sufficient time must be allowed after tripping for the fault arc to de-energise prior to reclosing; otherwise, the arc will re-strike. Such schemes have been the cause of a substantial improvement in continuity of supply. A further benefit, particularly to EHV systems, is the maintenance of system stability and synchronism.

The most important parameters of an auto-reclose scheme are:

1. dead time
2. reclaim time
3. single or multi-shot

These parameters are influenced by: **a.** type of protection **b.** type of switchgear **c.** possible stability problems **d.** effects on the various types of consumer loads

Dead Time

Several factors affect the selection of system dead time as follows:

- a.** system stability and synchronism
- b.** type of load
- c.** CB characteristics
- d.** fault path de-ionisation time

e. protection reset time

Reclaim time

Factors affecting the setting of the reclaim time are

- Type of protection
- Spring winding time

Number of Shots Factors affecting the setting of the reclaim time are

- Circuit breaker limitations
- System conditions

A typical single-shot auto-reclose scheme is shown in below Figure. The fig. shows a successful reclosure in the event of a transient fault,

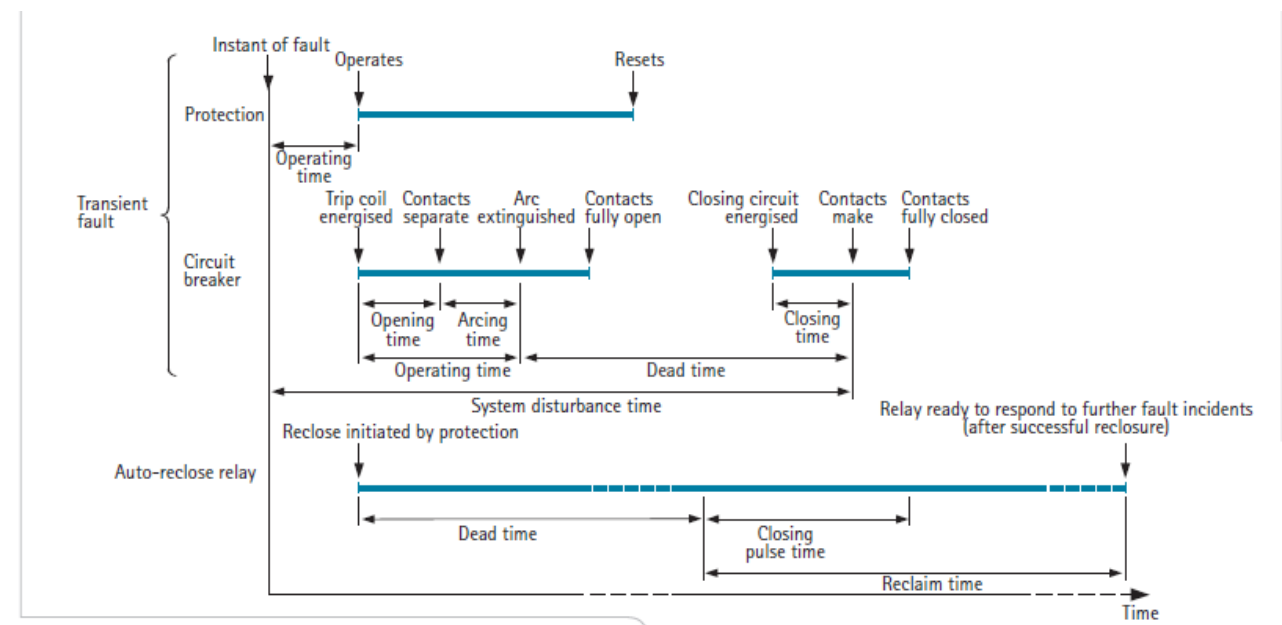


Figure: Single-shot auto-reclose scheme operation for a transient fault

On HV distribution networks, auto-reclosing is applied mainly to radial feeders where problems of system stability do not arise, and the main advantages to be derived from its use can be summarised as follows:

- reduction to a minimum of the interruptions of supply to the consumer
- instantaneous fault clearance can be introduced, with the accompanying benefits of shorter fault duration, less fault damage, and fewer permanent faults

As 80% of overhead line faults are transient, elimination of loss of supply from this cause by the introduction of auto-reclosing gives obvious benefits through:

- improved supply continuity
- reduction of substation visits

1.10 CLASSIFICATION OF PROTECTIVE RELAYS

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

Classification of Protective Relays Based on Technology

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

1. Electromechanical relays
2. Static relays
3. Numerical relays
4. Microprocessor-based relay
5. Microcontroller-based relay

Electromechanical Relays

Electromechanical relays are further classified into two categories, i.e.

- (i) Electromagnetic relays, and
- (ii) Thermal relays.

- **Electromagnetic relays:**

- Operate on the electromagnetic principle i.e. an electromagnet attracts magnetic moving part or a force is exerted on a current carrying conductor when placed in the magnetic field or a force is produced by the principle of induction, etc. Moving iron, moving coil, attracted armature, induction disc and induction cup type relays come under this group of relays

- **Thermal relays**

- Utilize the electro thermal effect of the actuating current for their operation.

Static Relays

These are solid state relays and employ semiconductor diodes, transistors, thyristors, logic gates, ICs, etc. The measuring circuit is a static circuit and there are no moving parts. In some static relays, a slave relay which is a D.C. polarised relay is used as the tripping device

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

Numerical Relays

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

At present microprocessor/ microcontroller-based numerical relays are widely used. These relays use different relaying algorithms to process the acquired information. Microprocessor/microcontroller-based relays are called numerical relays specifically if they calculate the algorithm numerically. The term 'digital relay' was originally used to designate a previous-generation relay with analog measurement circuits and digital coincidence time measurement (angle measurement) using microprocessors. Now a days the term 'numerical relay' is widely used in place of 'digital relay'. Sometimes, both terms are used in parallel. Similarly, the term 'numerical protection' is widely used in place of 'digital protection'. Sometimes both these terms are also used in parallel.

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

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

Microprocessor-based relay:

A microprocessor is used to perform all functions of a relay. It measures electrical quantities, makes comparisons, performs computations, and sends tripping signals. It can realize all sorts of relaying characteristics, even irregular curves which cannot be realised by electromechanical or static relays easily.

Microcontroller-based relay:

A microcontroller is used for performing all the function of the relay. It measures the electrical quantities by acquiring them in digital form through a data acquisition system, makes comparisons, processes the digital data to calculate the fault discriminants and make trip decisions. It can realised all sorts of relaying characteristics

Classification of Protective Relays Based on their Function

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

- Over current relays
- Under voltage relays
- Impedance relays
- Under frequency relays
- Directional relays

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

CLASSIFICATION OF PROTECTIVE RELAYS BASED ON SPEED OF OPERATION.

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

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

Instantaneous Relays

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

Time-delay Relays

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

High-speed Relays

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

Ultra High-speed Relays

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

CLASSIFICATION OF PROTECTIVE SCHEMES

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

- Over current protection
- Distance protection
- Differential protection

Over current Protection

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

Distance Protection

Distance protection is used for the protection of transmission or sub-transmission lines; usually 33 kV, 66 kV and 132 kV lines. It includes a number of distance relays of the same or different types. A distance relay measures the distance between the relay location and the point of fault in terms of impedance, reactance, etc. The relay operates if the point of fault lies within the protected section of the line. There are various kinds of distance relays. The important types are impedance, reactance and mho type. An impedance relay measure the line impedance between the fault point and relay location; a reactance relay measures reactance, and a mho relay measures a component of admittance .

Differential Protection

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

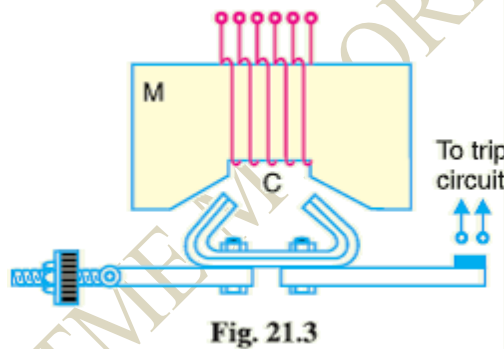
1.11 Electromechanical Relays

Most of the relays in service on electric power system today are of electro-mechanical type. They work on the following two main operating principles:

- (i) Electromagnetic attraction
- (ii) Electromagnetic induction

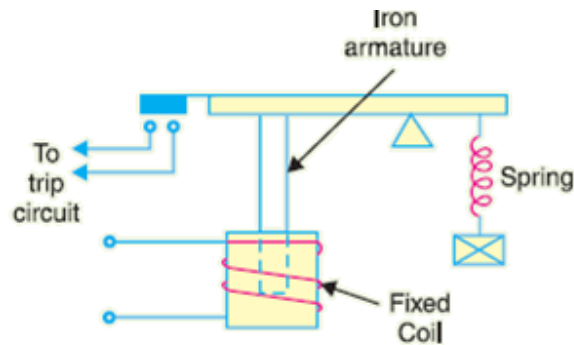
Electromagnetic Attraction Relays

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

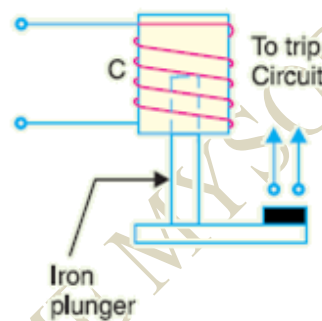


(i) Attracted armature type relay. Fig. shows the schematic arrangement of an attracted armature type relay. It consists of a laminated electromagnet M carrying a coil C and a pivoted laminated armature. The armature is balanced by a counterweight and carries a pair of spring contact fingers at its free end. Under normal operating conditions, the current through the relay coil C is such that counterweight holds the armature in the position shown. However, when a short-circuit occurs, the current through the relay coil increases sufficiently and the relay armature is attracted upwards. The contacts on the relay armature bridge a pair of stationary contacts attached to the relay frame. This completes the trip circuit which results in the opening of the circuit breaker and, therefore, in the disconnection of the faulty circuit. The minimum current at which the relay armature is attracted to close the trip circuit is called pickup current. It is a usual practice to provide a number of tapings on the relay coil so that the number of turns in use and hence the setting value at which the relay operates can be varied.

(ii) Solenoid type relay. Below Fig. shows the schematic arrangement of a solenoid type relay. It consists of a solenoid and movable iron plunger arranged as shown. Under normal operating conditions, the current through the relay coil C is such that it holds the plunger by gravity or spring in the position shown. However, on the occurrence of a fault, the current through the relay coil becomes more than the pickup value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, thus opening the circuit breaker and disconnecting the faulty circuit.



(iii) Balanced beam type relay. Below Fig. shows the schematic arrangement of a balanced beam type relay. It consists of an iron armature fastened to a balance beam. Under normal operating conditions, the current through the relay coil is such that the beam is held in the horizontal position by the spring. However, when a fault occurs, the current through the relay coil becomes greater than the pickup value and the beam is attracted to close the trip circuit. This causes the opening of the circuit breaker to isolate the faulty circuit



Electromagnetic Induction Relays

Electromagnetic induction relays operate on the principle of induction motor and are widely used for protective relaying purposes involving a.c. quantities. They are not used with d.c. quantities owing to the principle of operation. An induction relay essentially consists of a pivoted aluminium disc placed in two alternating magnetic fields of the same frequency but displaced in time and space. The torque is produced in the disc by the interaction of one of the magnetic fields with the currents induced in the disc by the other.

To understand the production of torque in an induction relay, refer to the elementary arrangement shown in Fig.(i). The two a.c. fluxes ϕ_2 and ϕ_1 differing in phase by an angle α induce e.m.f.s' in the disc and cause the circulation of eddy currents i_2 and i_1 respectively. These currents lag behind their respective fluxes by 90° . Referring to Fig.(ii) Where the two a.c. fluxes and induced currents are shown separately for clarity,

$$\text{let } \phi_1 = \phi_{1\text{max}} \sin \omega t$$

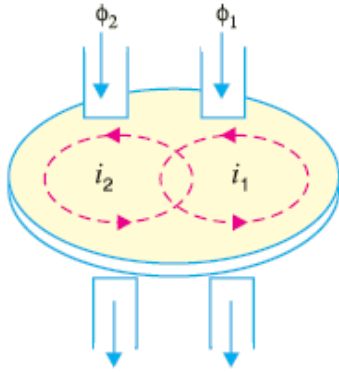
$$\phi_2 = \phi_{2\text{max}} \sin (\omega t + \alpha)$$

where ϕ_1 and ϕ_2 are the instantaneous values of fluxes and ϕ_2 leads ϕ_1 by an angle α .

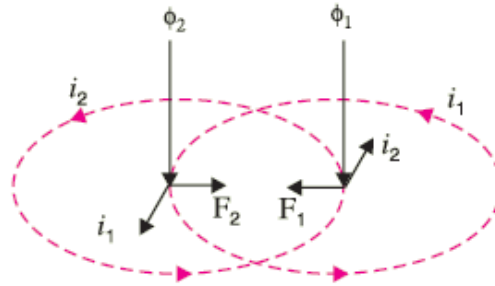
Assuming that the paths in which the rotor currents flow have negligible self-inductance, the

rotor currents will be in phase with their voltages.

$$\therefore i_1 \propto d(\phi_{1\max} \sin \omega t) / dt \propto \phi_{1\max} \cos \omega t$$



(i)



(ii)

$$\text{and } i_2 \propto d\phi_2 / dt \propto \phi_{2\max} \cos(\omega t + \alpha)$$

Now, $F_1 \propto \phi_1 i_2$ and $F_2 \propto \phi_2 i_1$

Fig. (ii) shows that the two forces are in opposition.

$\therefore$ Net force F at the instant considered is

$$\begin{aligned} F &\propto F_2 - F_1 \\ &\propto \phi_2 i_1 - \phi_1 i_2 \\ &\propto \phi_{2\max} \sin(\omega t + \alpha) \phi_{1\max} \cos \omega t - \phi_{1\max} \sin \omega t \phi_{2\max} \cos(\omega t + \alpha) \\ &\propto \phi_{1\max} \phi_{2\max} [\sin(\omega t + \alpha) \cos \omega t - \sin \omega t \cos(\omega t + \alpha)] \\ &\propto \phi_{1\max} \phi_{2\max} \sin \alpha \\ &\propto \phi_1 \phi_2 \sin \alpha \quad \dots (i) \end{aligned}$$

where ϕ_1 and ϕ_2 are the r.m.s. values of the fluxes

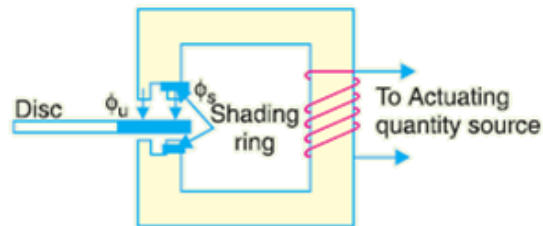
The following points may be noted from exp. (i):

- (a) The greater the phase angle α between the fluxes, the greater is the net force applied to the Disc. Obviously, the maximum force will be produced when the two fluxes are 90° out of phase.
- (b) The net force is the same at every instant. This fact does not depend upon the assumptions made in arriving at exp. (i).
- (c) The direction of net force and hence the direction of motion of the disc depends upon which flux is leading.

The following three types of structures are commonly used for obtaining the phase difference in the fluxes and hence the operating torque in induction relays :

- (i) shaded-pole structure
- (ii) watt-hour-meter or double winding structure
- (iii) induction cup structure

(i) Shaded-pole structure. The general arrangement of shaded-pole structure is shown in below Fig. It consists of a pivoted aluminium disc free to rotate in the air-gap of an electromagnet. One half of each pole of the magnet is surrounded by a copper band known as shading ring. The alternating flux ϕ_s in the shaded portion of the poles will, owing to the reaction of the current induced in the ring, lag behind the flux ϕ_u in the unshaded portion by an angle α . These two a.c. fluxes differing in phase will produce the necessary torque to rotate the disc. As proved earlier, the driving torque T is



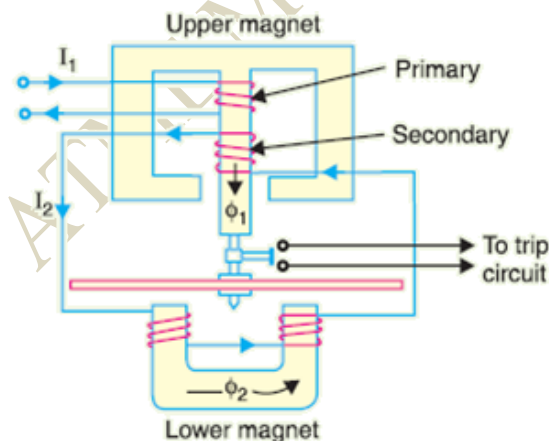
$$T \propto \phi_s \phi_u \sin \alpha$$

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

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

This shows that driving torque is proportional to the square of current in the relay coil

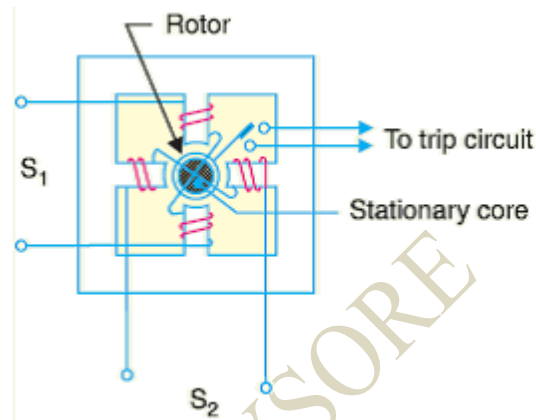
(ii) Watthour-meter structure. This structure gets its name from the fact that it is used in watthour meters. The general arrangement of this type of relay is shown in Fig. It consists of a pivoted aluminium disc arranged to rotate freely between the poles of two electromagnets. The upper electromagnet carries two windings ; the primary and the secondary. The primary winding carries the relay current I_1 while the secondary winding is connected to the winding of the lower magnet. The primary current induces e.m.f. in the secondary and so circulates a current I_2 in it. The flux ϕ_2 induced in the lower magnet by the current in the secondary winding of the upper magnet will lag behind ϕ_1 by an angle α . The two fluxes ϕ_1 and ϕ_2 differing in phase by α will produce a driving torque on the disc proportional to $\phi_1 \phi_2 \sin \alpha$.



An important feature of this type of relay is that its operation can be controlled by opening or closing the secondary winding circuit. If this circuit is opened, no flux can be set by the lower magnet however great the value of current in the primary winding may be and consequently no torque will be produced. Therefore, the relay can be made inoperative by opening its secondary winding circuit

Induction cup structure. Fig. shows the general arrangement of an induction cup structure. It most closely resembles an induction motor, except that the rotor iron is stationary, only the rotor conductor portion being free to rotate. The moving element is a hollow cylindrical rotor which turns on its axis. The rotating field is produced by two pairs of coils wound on four poles as shown.

The rotating field induces currents in the cup to provide the necessary driving torque. If ϕ_1 and ϕ_2 represent the fluxes produced by the respective pairs of poles, then torque produced is proportional to $\phi_1 \phi_2 \sin \alpha$ where α is the phase difference between the two fluxes. A control spring and the back stop for closing of the contacts carried on an arm are attached to the spindle of the cup to prevent the continuous rotation. Induction cup structures are more efficient torque producers than either the shaded-pole or the watt-hour meter structures. Therefore, this type of relay has very high speed and may have an operating time less than 0.1 second



1.12 Time-current Characteristics, Current Setting, Time Setting

Relay Definitions

- Operating force or torque: A force or torque which tends to close the contacts of the relay.
- Restraining (Control) force or torque: A force or torque which opposes the operating force/ torque.
- Actuating quantity: An electrical quantity (current, voltage, etc) to which relay responds
- PICK-UP:
When the relay operates, we say, the relay has picked-up. It simply means that the relay with normally open contacts, has closed its contacts.

The pick-up value or pick-up level is the minimum value of operating quantity at which the relay is one the verge of operation, e.g., consider an over current relay. The current injected in the relay coil is very gradually increased. At a current value of 2.51 amperes, the relay has not operated, at a value of 2.52 amperes, the relay begins to operate. Then, 2.52 amperes is the pick-up value.

In induction disc relays, the pick-up value corresponds to plug-setting (described later). If plug setting is 2.5 A, the relay starts operating at 2.5 A. If plug setting is 3.5 A, relay starts operating at 3.5 A and so on. However, in such relays the pick-up value is not exact, within about 5% of plug setting. The relay may not pick-up exactly at the plug setting value due to errors introduced by dust, friction, adjustment errors; and because operating torque is minimum at pick-up value.

- RESET OR DROP-OFF LEVEL:

Now, we are talking about the relay which has already operated, and the actuating current is still flowing in the relay coil. As the operating quantity is gradually reduced, at some maximum value, the relay value, the relay contacts which have closed, start opening. This condition is called Reset or Drop off.

The value of operating quantity at which the relay (normally open) contacts which were closed due to relay operation, start opening and coming to original state (open).

- Plug Setting and Time Setting in Induction Disc Relays

In these relays, there is a facility for selecting the plug setting and time setting such that the same relay can be used for a wide range of current, time and characteristics.

- Time Setting in Induction Disc Relays

Time multiplier setting is generally in the form of an adjustable back-stop which decides the arc-length through which the disc travels, by reducing the length of travel, the time is reduced. The time multiplier setting is marked from about 0.1 to 1, with major divisions marked in between. If relay takes a certain time, say S seconds with time multiplier setting 1, the same relay will take time equal to T x S seconds for time multiplier setting T, other conditions remaining the same.

I.e. Actual Operating Time of Relay = Time multiplier setting x Trip Time (Time required to close the contacts)

- Plug Setting in Induction Disc Relays

It should be possible to use the same relay for a certain range of current/voltage. Hence a plug setting bridge is provided with electromagnetic relays. The plug setting refers to the reference value of operating quantity at which the relay starts operating. If by inserting the plug, setting of 2.5 is selected, the relay will start operating when the current in relay coil (secondary current of (CT) is about 2.5 A or more. Plug setting determines the number of turns tapped from the relay coil. The current-time characteristic for various plug setting is generally same, provided time setting remains unchanged. Such performance is achieved by matching the plug-setting and corresponding number of turns tapped from the coil such that the Ampere-turns remains same for various plug-settings

The arrangement is such that for various plug settings, the ampere-turns (amperes of plug setting x turns of coil corresponding to the plug setting) are constant for various plug settings. Thereby, the relay characteristics remains the same for various plug settings, for a given time setting. Actually, the relay should start operating at current equal to plug setting. However, due to friction, dust etc, the operations may not take

place at exact plug setting value.

The relay characteristic is plotted with multiples of plug setting as an abscissa (log scale) and time in seconds (log scale) as ordinate. Suppose, current injected in relay coil is 10 Amp and plug setting is 2.5 Amp, then plug setting multiplier will be $10 / 2.5 = 4$.

Plug-setting multiplier and represents the number of times the relay current is in excess of the current setting

$$\text{PSM} = \text{Current injected in relay coil (secondary current of (CT))} / \text{plug setting}$$

Or

$$\text{PSM} = \text{Primary fault current} / (\text{Relay Setting Current} * \text{C.T ratio})$$

Plug setting bridge is provided with induction disc relays and it provides a wide range of current settings. The plug setting refers to the magnitude of current at which the relay starts to operate. The plug setting bridge comprises connections tapped from relay coil. By inserting the plug, in a particular gap in the bridge, a certain number of turns of the relay coil are brought into circuit

Fig. 1 illustrates typical characteristics of induction disc relays, on log scales.

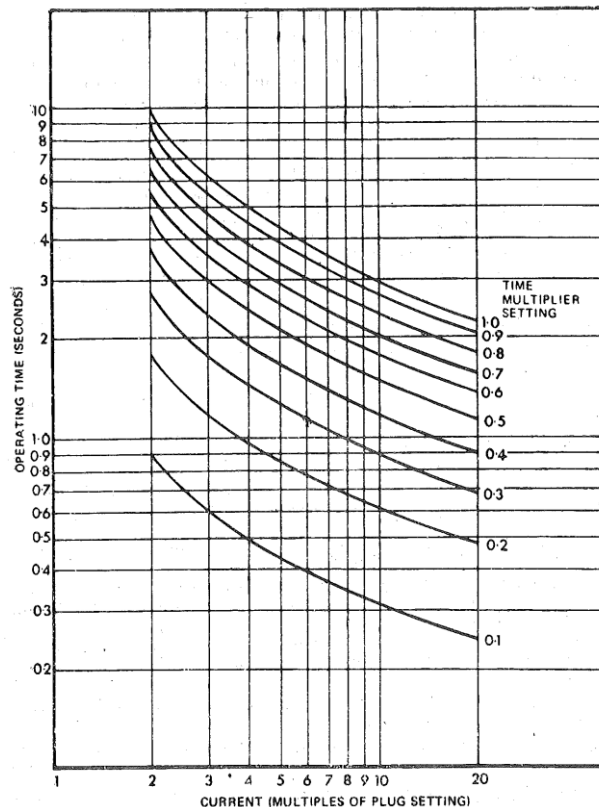


Fig 1, Inverse Characteristics of induction disc relay on log scale

The time / current Characteristics of induction disc relay is Inverse Characteristics, the time reduces as current increases.

Effect of Time-setting

By reducing the time multiplier, the characteristic is shifted to lower side, indicating that operating time is reduced (Fig. 1)

➤ **Operating time:** It is the time which elapses from the instant at which the actuating quantity exceeds the relays pick-up value to the instant at which the relay closes its contacts.

➤ **Burden (Power consumption):** The power consumed by the relay circuitry at the rated current or voltage is known as its burden expressed in volt ampere in a.c and in watts in d.c circuit

➤ Directional or reverse power relay: A directional relay is able to detect whether the point of fault lies in the forward or reverse direction with respect to the relay location. It is able to sense the direction of power flow, i.e. whether the power is flowing in the normal direction or the reverse direction

The operating time of all over current relays tends to become asymptotic (Straight Line) to a definite minimum value with increase in the value of current. This is inherent in electromagnetic relays due to saturation of the magnetic circuit. So by varying the point of saturation different characteristics are obtained; these are:

- Definite time.
- Inverse characteristics
- Inverse definite minimum time (IDMT).
- Very inverse.
- Extremely inverse

These characteristics are obtained by induction disc and induction cup relays.

The torque of these relays as shown earlier is proportional to $\phi_1 \cdot \phi_2 \cdot \sin \alpha$ where ϕ_1 and ϕ_2 are the two fluxes cutting the disc or cup and α is the angle between them. Where both fluxes are produced by the same quantity, as in current or voltage operated relays, then below saturation the torque is proportional to I^2 , the coil current, or $T = KI^2$. If the core is made to saturate at very early stage with the result that by increasing I , K decreases so that the time of operation remains same over the working range, the characteristics is shown by curve (a) in fig1 and is known as definite minimum time characteristics i.e. (DMT) irrespective of the magnitude of the current above the pickup value, the operating time is the same (i.e. the time of operation is almost definite), however, DMT relay has also a slightly inverse characteristics.

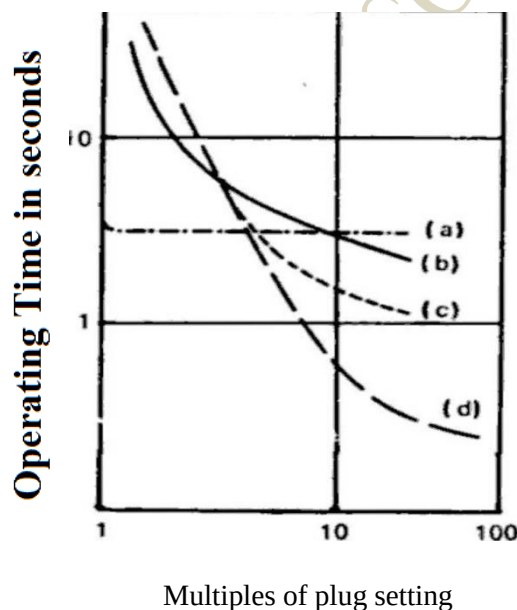


FIGURE 1 Characteristics of various overcurrent relays: (a) definite time ;(b) IDMT; (c) Very inverse; (d) extremely inverse

In the case of inverse time characteristics, the relay operating time decreases as the current above the pickup value increases (i.e. time is inversely proportional to current)

Now if the core is made to saturate at a later stage the characteristics assume the shape of curve (b) Fig 1, known as IDMT (inverse definite minimum time (IDMT) characteristic)

The characteristics of DMT & of inverse time characteristics type is called inverse definite minimum time (IDMT) characteristics as show in fig

In case of inverse definite minimum time (IDMT) Relay, the operating characteristics will be inverse time

characteristics at lower value of the fault current and DMT characteristics at higher values of fault current.

Now if the core saturation occurs at a still later stage the characteristics assume the shape shown by the curve (C) in fig 1 known as very inverse. The time-current characteristic is inverse over a greater range and after saturation tends to definite time.

The curve (d) in fig 1 shows extremely inverse characteristics i.e. the saturation occurs at a very late stage and the equation of the curve is roughly of the form $I^2t=k$ where I is the operating current and t is the time of operation.

Example Determine the time of operation of a 5-ampere, 3-second overcurrent relay having a current setting of 125% and a time setting multiplier of 0.6 connected to supply circuit through a 400/5 current transformer when the circuit carries a fault current of 4000 A. Use the curve (TMS = 1) shown in Fig. 21.16.

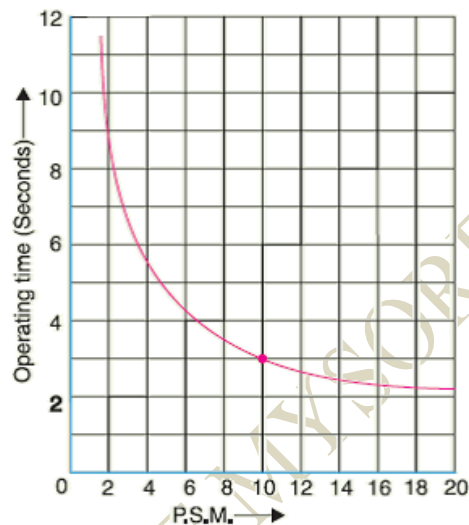


Fig. 21.16

Solution.

Rated secondary current of C.T. = 5 A

Pickup current = $5 \times 1.25 = 6.25$ A

Fault current in relay coil = $4000 \times \frac{5}{400} = 50$ A

$\therefore$ Plug-setting multiplier (P.S.M.) = $50 / 6.25 = 8$

Corresponding to the plug-setting multiplier of 8 (See Fig. 21.16), the time of operation is 3.5 seconds.

$\therefore$ Actual relay operating time = $3.5 \times \text{Time-setting multiplier} = 3.5 \times 0.6 = 2.1$ seconds

Course outcomes : Interpret performance of protective relays, components of protection scheme and relay terminology & over current protection

Further Readings

1. <http://nptel.ac.in/downloads/108101039/>
2. <https://www.electrical4u.com/protection-system-in-power-system/>
3. <http://electrical-engineering-portal.com>

Module 2

Induction Type Relay

Course objectives: - To explain relay construction and operating principles.

- To explain over current protection using electromagnetic and static relays
- To discuss types of distance relays.

NON-DIRECTIONAL OVER-CURRENT OR EARTH-LEAKAGE (INDUCTION TYPE) RELAY

The over current relay operates when the current in the circuit exceeds a certain preset value.

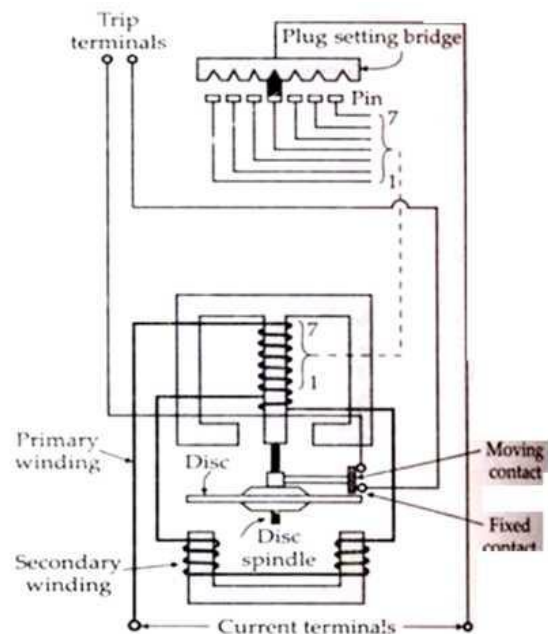
Such a relay consists of a metallic disc which is free to rotate between the poles of two electromagnets (Shown in below Fig) The spindle of this disc carries a moving contact which bridges two fixed contacts when the disc rotates through an angle which is adjustable between 0° and 360° . By adjusting this angle the travel of the moving contact can be adjusted so that the relay can be given any desired time setting which is indicated by a pointer on a time setting dial. The dial is calibrated from 0 to 1. These figures do not represent the actual operating times but are multipliers to be used to convert the time known from the relay name plate curve into the actual operating time.

The upper electromagnet has a primary and a secondary winding. The primary is connected to the secondary of a C.T. in the line to be protected and is provided with tappings. (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), These tappings are connected to a plug setting bridge which is usually arranged to give seven selections of tapping, the over current range being 50 per cent to 200 per cent in steps of 25% and the earth fault 10% to 70% or 20% to 80% in steps of 10%. These values are percentages of the current rating of the relay.

Thus a relay may have a current rating of 5 A, indicating that it is suitable for use on CT having a secondary current rating of 5 A but with a setting of 50% the relay would start to operate at 2.5 A. similarly, if set at 200% it would start to operate at any desired tapping and, therefore, current setting can be selected by inserting a pin between the spring loaded jaws of the bridge type socket at the appropriate tap due.

When the pin is withdrawn for the purpose of hanging the setting while the relay is in service, the relay automatically adopts a high setting, thus, ensuring that the C.T. secondary is not open circuited and that the relay remains operative for faults during the process of changing the settings.

The secondary winding on the central limb of upper magnet is connected in series with the lower electro magnet winding. This secondary winding is energized by the induction from primary winding so by this arrangement the leakage flux of both the magnet are sufficiently displacement in phase, The torque exerted on the disc is due to the interaction of eddy currents produced therein by means of the leakage flux from the upper electromagnet and the flux from the lower electromagnet: the control torque is produce by spiral spring.

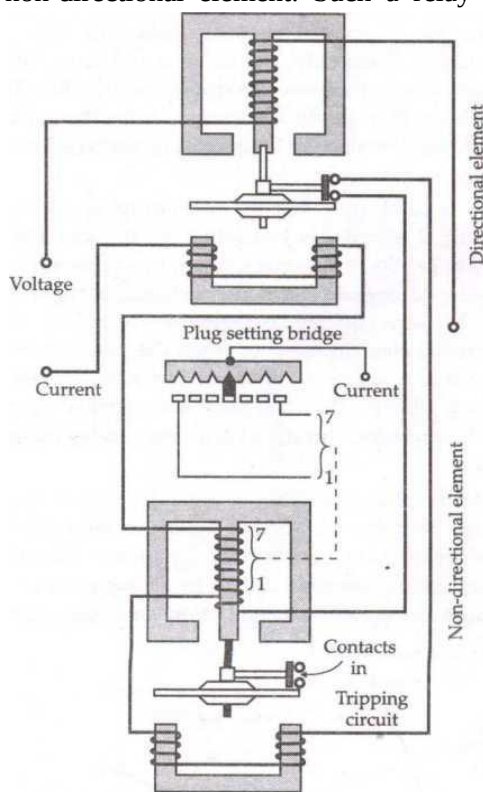


The torque is produced due to induction principle, as explained above. This torque is opposed by Control torque produced by spiral springs **under normal conditions the Control force is more than driving force hence disc remains stationary**. Under fault conditions when current becomes high, the disc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

DIRECTIONAL RELAY (OVERCURRENT OR EARTH FAULT RELAY)

Construction and Operating Principle

The non-directional relay discussed above can operate for fault flow in either direction. In order to achieve operation for the fault flowing in a specific direction, it is necessary to add a directional element to the non-directional element. Such a relay which responds to fault flow in a particular direction is called a directional relay. Fig. shows a schematic arrangement of such a directional relay



The upper magnet of the directional element carries a winding connected through a potential transformer (not shown) to the system voltage. This is called the voltage coil of the relay. The lower magnet of the same element carries another winding (current coil of the relay) which is energised, through a C.T. by the fault current. This winding is carried over the upper magnet of the non-directional element. The contacts of the directional element are connected in series with another winding over the lower magnet of the non-directional element.

When a fault takes place, the fault current flows through current coil of the relay which produces a flux in the lower magnet of the directional element while the current in the voltage coil produces another flux in this upper-magnet of the directional element. The two fluxes produce a torque tending to close its contacts (directional element contacts).

The relay current also flows through the winding over the upper magnet of the non-directional element and therefore produces a flux in this magnet. This flux induces an e.m.f in the winding over the lower magnet of the non-directional element. Since this winding provides a closed path, the induced e.m.f

circulates a current which, therefore, produces another flux. The two fluxes then produce a torque on the disc of the non-directional element to close the contacts in the trip circuit

It is to be seen that the movement of the non-directional element is controlled by the directional element i.e., the directional element must operate first in order to operate the non-directional element. As will be seen in the paragraphs to follow, the directional element operates when the power flow is in a definite designed direction. The non-directional element will operate when there is a sufficient torque i.e., the operating current is sufficient ($\sim$ relay current setting).

In the phasor diagram of below Fig, 'V' is the relay voltage. In directional relays, voltage is taken as the reference quantity. Let 'I' be the relay current. Here it is shown leading the relay voltage by an angle θ .

V and I produce flux Φ_v and Φ_I respectively.

Φ_v lagging V by an angle Φ

And Φ_I being in phase with current 'I'

Torque, therefore, is $T \propto \Phi_v \cdot \Phi_1 \cdot \sin(\Phi + \theta)$, where $\Phi_v \propto V$ and $\Phi_1 \propto I$ so
So that the torque equation for the directional element of the relay is

$$T \propto V \cdot I \cdot \sin(\Phi + \theta),$$

Maximum torque occurs when $\sin(\theta + \Phi)$ is a maximum i.e., when $(\theta + \Phi) = 90^\circ$, the condition shown by the dotted line in above Fig.

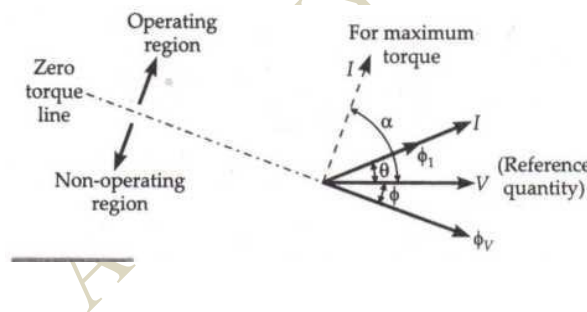
Zero torque will occur when $\sin(\theta + \Phi) = 0$ i.e., $(\theta + \Phi) = 0$ or 180° this being satisfied when the relay current phasor lies along the chain dotted line which is at right angles to the maximum torque line.

The directional elements will therefore operate provided the current phasor lies within $\pm 90^\circ$ of the maximum torque line, if the current phasor is displaced by more than 90° the element will restrain. The operating and the non-operating region are shown in the above Fig.

Angle α in the figure is the relay maximum torque angle (MTA) and is defined as the angle by which the current supplied to the relay leads the voltage supplied to the relay for maximum relay torque. It may be seen that

$\alpha = 90 - \Phi$, so that $\Phi = 90 - \alpha$, equation becomes $T = K \cdot V \cdot I \sin(\theta + 90 - \alpha) = KVI \cos(\theta - \alpha)$

It may be noted that though the system current in general lags the system voltage the relay current is made to lead the relay voltage, by suitable connections, ensure that the relay operates correctly for all types of faults under all system conditions



Induction Type Directional Power Relay

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

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

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

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

The interaction of fluxes ϕ_1 and ϕ_2 with the eddy currents induced in the disc produces a driving torque given by : $T \propto \phi_1 \phi_2 \sin \alpha$

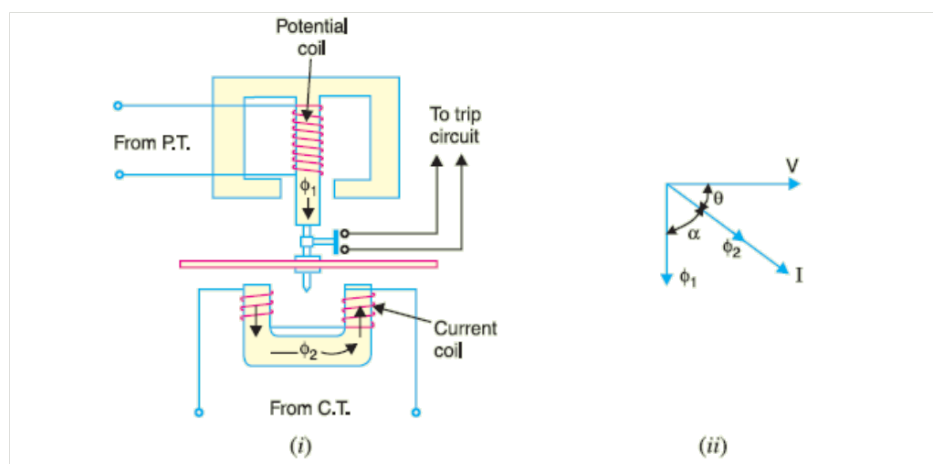
Since $\phi_1 \propto V$, $\phi_2 \propto I$ and $\alpha = 90 - \theta$

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

$\propto V I \cos \theta$

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

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



Protection of Lines

The probability of faults occurring on the lines is much more due to their greater length and exposure to atmospheric conditions. This has called for many protective schemes which have no application to the comparatively simple cases of alternators and transformers. The requirements of line protection are :

- (i) In the event of a short-circuit, the circuit breaker closest to the fault should open, all other circuit breakers remaining in a closed position.
- (ii) In case the nearest breaker to the fault fails to open, back-up protection should be provided by the adjacent circuit breakers.
- (iii) The relay operating time should be just as short as possible in order to preserve system stability, without unnecessary tripping of circuits.

The protection of lines presents a problem quite different from the protection of station apparatus such as generators, transformers and busbars. While differential protection is ideal method for lines, it is much more expensive to use. The two ends of a line may be several kilometres apart and to compare the two currents, a costly pilot-wire circuit is required. This expense may be justified but in general less costly methods are used. The common methods of line protection are :

- (i) Time-graded overcurrent protection
- (ii) Differential protection
- (iii) Distance protection

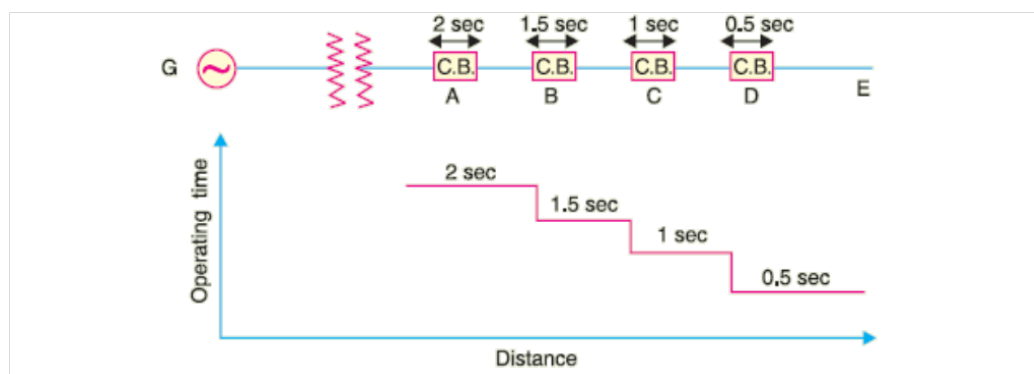


Fig. . shows the symbols indicating the various types of relays.

Time-Graded Overcurrent Protection

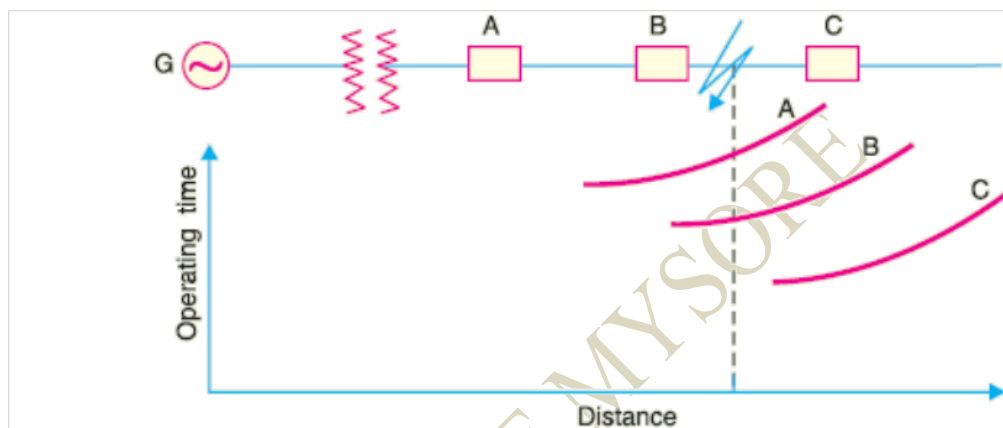
In this scheme of overcurrent protection, time discrimination is incorporated. In other words, the time setting of relays is so graded that in the event of fault, the smallest possible part of the system is isolated. We shall discuss a few important cases.

Radial feeder. The main characteristic of a radial system is that power can flow only in one direction, from generator or supply end to the load. It has the disadvantage that continuity of supply cannot be maintained at the receiving end in the event of fault. Time-graded protection of a radial feeder can be achieved by using (i) definite time relays and (ii) inverse time relays



(i) Using definite time relays. Above Fig. shows the overcurrent protection of a radial feeder by definite time relays. The time of operation of each relay is fixed and is independent of the operating current. Thus relay *D* has an operating time of 0.5 second while for other relays, time delay* is successively increased by 0.5 second. If a fault occurs in the section *DE*, it will be cleared in 0.5 second by the relay and circuit breaker at *D* because all other relays have higher operating time. In this way only section *DE* of the system will be isolated. If the relay at *D* fails to trip, the relay at *C* will operate after a time delay of 0.5 second i.e. after 1 second from the occurrence of fault. The disadvantage of this system is that if there are a number of feeders in series, the tripping time for faults near the supply end becomes high (2 seconds in this case). However, in most cases, it is necessary to limit the maximum tripping time to 2 seconds. This disadvantage can be overcome to a reasonable extent by using inverse-time relays.

(ii) Using inverse time relays. below Fig. shows overcurrent protection of a radial feeder using inverse time relays in which operating time is inversely proportional to the operating current. With this arrangement, the farther the circuit breaker from the generating station, the shorter is its relay operating time. The three relays at *A*, *B* and *C* are assumed to have inverse-time characteristics. A fault in section *BC* will give relay times which will allow breaker at *B* to trip out before the breaker at *A*.



Parallel feeders. Where continuity of supply is particularly necessary, two parallel feeders may be installed. If a fault occurs on one feeder, it can be disconnected from the system and continuity of supply can be maintained from the other feeder. The parallel feeders cannot be protected by non-directional overcurrent relays only. It is necessary to use directional relays also and to grade the time setting of relays for selective trippings

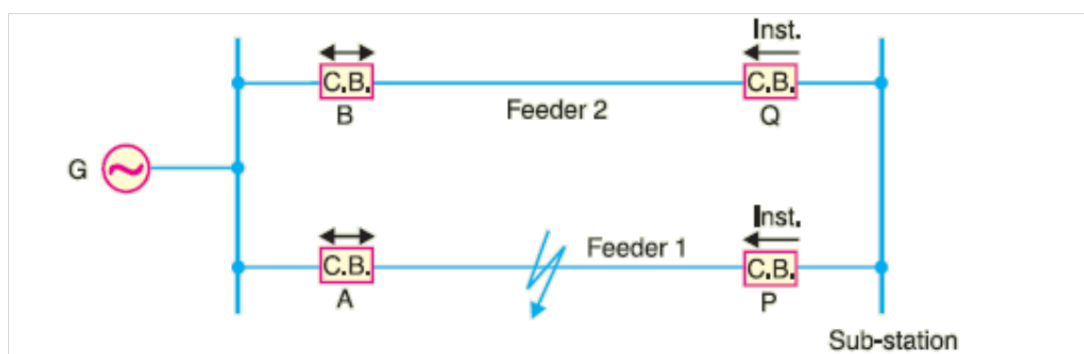


Fig. 23.6 shows the system where two feeders are connected in parallel between the generating station and the sub-station. The protection of this system requires that

- (i) each feeder has a non-directional overcurrent relay at the generator end. These relays should have inverse-time characteristic.
- (ii) each feeder has a reverse power or directional relay at the sub-station end. These relays should be instantaneous type and operate only when power flows in the reverse direction i.e. in the direction of arrow at P and Q. Suppose an earth

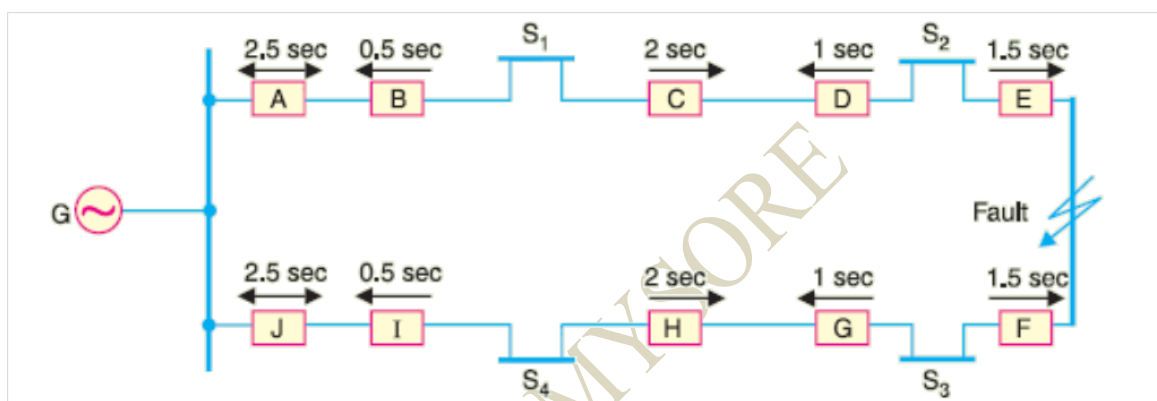
fault occurs on feeder 1 as shown in Fig. 23.6. It is desired that only circuit breakers at A and P should open to clear the fault whereas feeder 2 should remain intact to maintain the continuity of supply. In fact, the above arrangement accomplishes this job. The shown fault is fed via two routes, viz.

(a) directly from feeder 1 via the relay A

(b) from feeder 2 via B, Q, sub-station and P

Therefore, power flow in relay Q will be in normal direction but is reversed in the relay P. This causes the opening of circuit breaker at P. Also the relay A will operate while relay B remains inoperative. It is because these relays have inverse-time characteristics and current flowing in relay A is in excess of that flowing in relay B. In this way only the faulty feeder is isolated.

Ring main system. In this system, various power stations or sub-stations are interconnected by alternate routes, thus forming a closed ring. In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the ring, thereby maintaining continuity of supply



Above Fig. shows the single line diagram of a typical ring main system consisting of one generator G supplying four sub-stations S1, S2, S3 and S4. In this arrangement, power can flow in both directions under fault conditions. Therefore, it is necessary to grade in both directions round the ring and also to use directional relays. In order that only faulty section of the ring is isolated under fault conditions, the types of relays and their time settings should be as follows :

(i) The two lines leaving the generating station should be equipped with non-directional overcurrent relays (relays at A and J in this case).

(ii) At each sub-station, reverse power or directional relays should be placed in both incoming and outgoing lines (relays at B, C, D, E, F, G, H and I in this case).

(iii) There should be proper relative time-setting of the relays. As an example, going round the loop GS1 S2 S3 S4G ; the outgoing relays (viz at A, C, E, G and I) are set with decreasing time limits e.g.

A = 2.5 sec, C = 2 sec, E = 1.5 sec G = 1 sec and I = 0.5 sec

Similarly, going round the loop in the opposite direction (i.e. along G S4 S3 S2 S1 G), the outgoing relays (J, H, F, D and B) are also set with a decreasing time limit e.g.

J = 2.5 sec, H = 2 sec, F = 1.5 sec, D = 1 sec, B = 0.5 sec.

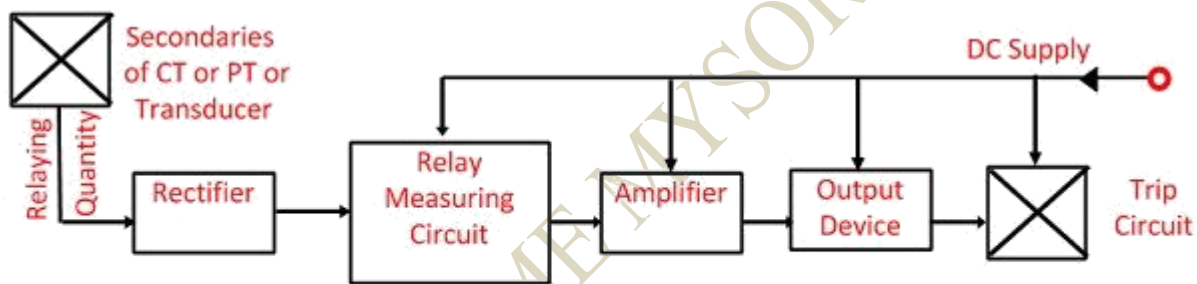
Suppose a short circuit occurs at the point as shown in Fig. 23.7. In order to ensure selectivity, it is desired that only circuit breakers at E and F should open to clear the fault whereas other sections of the ring should be intact to maintain continuity of supply. In fact, the above arrangement accomplishes this job. The power will be fed to the fault via two routes viz (i) from G around S1 and S2 and (ii) from G around S4 and S3. It is clear that relays at A, B, C and D as well as J, I, H and G will not trip. Therefore, only relays at E and F will operate before any other relay operates because of their lower time-setting.

Static Relays

These are solid state relays and employ semiconductor diodes, transistors, thyristors, logic gates, ICs, etc. The measuring circuit is a static circuit and there are no moving parts. In some static relays, a slave relay which is a D.C. polarised relay is used as the tripping device

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

The component of the static relay is shown in the figure below. The input of the current transformer is connected to the transmission line, and their output is given to the rectifier. The rectifier was rectifying the input signal and pass it to the relaying measuring unit.



Block Diagram of Static Relay

Circuit Globe

The rectifying measuring unit has the comparators, level detector and the logic circuit. The output signal from relaying unit obtains only when the signal reaches the threshold value. The output of the relaying measuring unit acts as an input to the amplifier.

The amplifier amplifies the signal and gives the output to the output devices. The output device activates the trip coil only when the relay operates. The output is obtained from the output devices only when the measurand has the well-defined value. The output device is activated and gives the tripping command to the trip circuit.

The static relay only gives the response to the electrical signal. The other physical quantities like heat temperature etc. is first converted into the analogue and digital electrical signal and then act as an input for the relay.

Advantages of Static Relay

The following are the benefits of static relays.

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

7. The static relay can easily operate in earthquake-prone areas because they have high resistance to shock.

Limitations of Static Relay

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

For integrated protection and monitoring systems programmable microprocessor controlled static relays are preferred.

ATME MYSORE

Numerical Relays

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

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

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

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

Microprocessor-based relay:

A microprocessor is used to perform all functions of a relay. It measures electrical quantities, makes comparisons, performs computations, and sends tripping signals. It can realize all sorts of relaying characteristics, even irregular curves which cannot be realised by electromechanical or static relays easily.

Microcontroller-based relay:

A microcontroller is used for performing all the function of the relay. It measures the electrical quantities by acquiring them in digital form through a data acquisition system, makes comparisons, processes the digital data to calculate the fault discriminants and make trip decisions. It can realised all sorts of relaying characteristics

Microprocessor-based over current relay

An over current relay is the simplest form of protective relay which operates when the current in any circuit exceeds a certain predetermined value, i.e. the pick-up value. It is extensively used for the protection of distribution lines, industrial motors and equipment. Using a multiplexer, the microprocessor can sense the fault currents of a number of circuits. If the fault current in any circuit exceeds the pick-up value, the microprocessor sends a tripping signal to the circuit breaker of the faulty circuit. As the microprocessor accepts signals in voltage form, the current signal derived from the current transformer is converted into a proportional voltage signal using a current to voltage converter. The a.c.

voltage proportional to the load current is converted into D.C. using a precision rectifier. Thus, the microprocessor accepts D.C. voltage proportional to the load current.

The block schematic diagram of the relay is shown in Fig. (a). the output of the rectifier is fed to the multiplexer. The microcomputer sends a command to switch on the desired channel of the multiplexer to obtain the rectified voltage proportional to the current in a particular circuit. The output of the multiplexer is fed to the A/D converter to obtain the signal in digital form. The A/D converter ADC0800 has been used for this purpose. The microcomputer sends a signal to the ADC for starting the conversion.

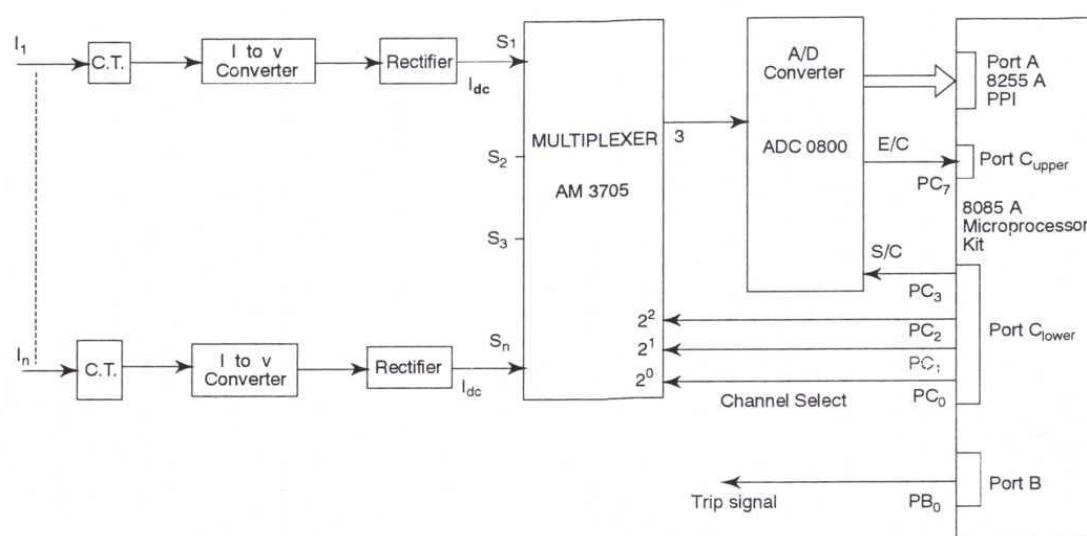
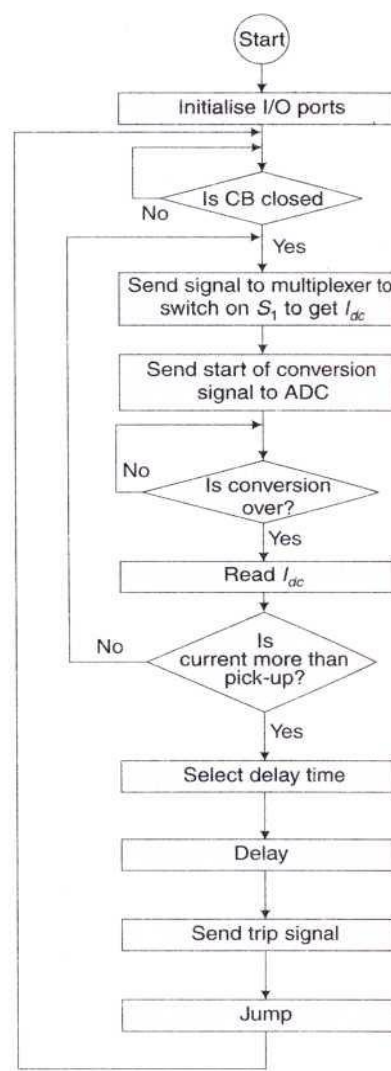


FIGURE (a) Block schematic diagram of overcurrent relay

The microcomputer reads the end of conversion signal to examine whether the conversion is over or not. As soon as the conversion is over, the microcomputer reads the current signal in digital form and then compares it with the pick-up value.

In the case of a definite time over current relay, the microcomputer sends the tripping signal to the circuit breaker after a predetermined time delay if the fault current exceeds the pick-up value. In case of instantaneous over current relay there is no intentional time delay. In order to obtain inverse-time characteristics, the operating times for different values of currents are noted for a particular characteristic. These values are stored in the memory in tabular form. The microcomputer first determines the magnitude of the fault current and then selects the corresponding time of operation from the look-up table. A delay subroutine is started and the trip signal is sent after the desired delay. Using the same program, any characteristic such as IDMT, very inverse or extremely inverse can be realised by simply changing the data of the look-up table according to the desired characteristic to be realised. The microcomputer continuously measures the current and moves in a loop and if the measured current exceeds the pick-up value, it compares the measured value of the current with the digital values of current given in the look-up table in order to select the corresponding count for a time delay. Then it goes in delay subroutine and sends a trip signal to the circuit breaker after the predetermined time delay. The program flowchart is shown in Fig. (b).

In order to avoid false tripping of an over current relay due to transients the program can be modified slightly. When the fault current exceeds the pick-up value, the fault current is measured once again by the microprocessor to confirm whether it is a fault current or transient. In case of any transient of short duration, the measured current above pick-up value will not appear in the second measurement. But if there is an actual fault, it will again appear in the second measurement also, and then the microprocessor will issue a tripping signal to disconnect the faulty part of the system .



Distance Protection

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

Distance relay group is perhaps the most interesting and versatile family of relays. Principle types of distance relays are

- impedance relay
- Reactance relay
- Admittance or mho relay

Distance relay differ in principle from other forms of protection in that their performance is not governed by the magnitude of the current or the voltage in the protected circuit but rather on the ratio of these two quantities. Distance relays are actually actuating relays with one coil energized by voltage and the other by current. The current element produces a positive or pick up torque while the voltage element produces a negative or reset torque. The relay operates only when the V/I ratio falls below a predetermined value (or set value). During a fault on a transmission line the fault current increases and the voltage at the fault point decreases the V/I ratio is measured at the location of CTs and PTs. The voltage of the PT location depends on the distance between PT and fault. If the fault is nearer, the measured voltage is lesser and if the fault is farther, measured voltage is more. Hence assuming constant fault impedance each value of V/I measure from relay location corresponds to distance between relaying point and the fault along the line. Hence such protection is called the distance protection or impedance protection.

Distance protection is non-unit type protection; the protected zone is not exact. The distance protection is high speed protection and is simply to apply. It can be employed as primary as well as back up protection. Distance protection is very commonly used in protection of transmission line. Distance relay is used where overcurrent relaying is too slow and is not so selective. Distance relays are used for both phase fault and ground fault protection and they provide high speeds for clearing faults than overcurrent relays. Distance relay is also independent of changes in magnitude of the short-circuit currents and hence they are not much affected by changes in the generation capacity and the system configuration. Thus they eliminate long clearing times of faults near the power source required by overcurrent relays if used for the purpose.

Distance protection schemes are commonly employed for providing the primary or main protection and backup protection for AC transmission and distribution line against 3 phase faults, phase to phase fault and phase to ground faults.

In some schemes for short lines, the phase to ground fault protection sensing may be by distance relay and measurement by overcurrent relays because distance protection for shorter lines are susceptible to errors due to arc fault resistance. In general, choice of type of distance protection depends on length of line, tripping time required and coordination requirements

Application of Distance Protection Relay

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

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

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

Impedance Type Distance Relay

Definition: The relay whose working depends on the distance between the impedance of the faulty section and the position on which relay installed is known as the impedance relay or distance relay. It is a voltage controlled equipment. The relay measures the impedance of the faulty point, if the impedance is less than the impedance of the relay setting, it gives the tripping command to the circuit breaker for closing their contacts. The impedance relay continuously monitors the line current and voltage flows through the CT and PT respectively. If the ratio of voltage and current is less than the relay starts operating then the relay starts operating.

Principle of Operation of Impedance Relay

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

The figure below explains the impedance relay in much easier way. The potential transformer supplies the voltage to the transmission line and the current flows because of the current transformer. The current transformer is connected in series with the circuit.

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

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

Operating Characteristic of an Impedance Relay

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

$$T = k_1 I^2 - k_2 V^2 - k_3$$

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

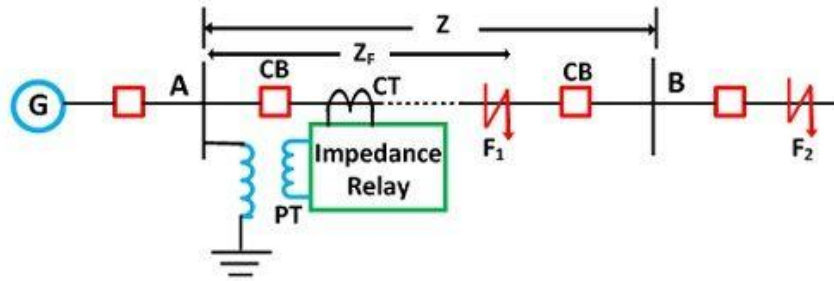
$$k_2 V^2 = k_1 I^2 - k_3$$

$$\frac{V}{I} = Z = \sqrt{\frac{k_1}{k_2} - \frac{k_3}{k_2 I^2}}$$

If the spring control effect becomes neglected, the equation becomes

$$Z = \sqrt{\frac{k_1}{k_2}} = \text{Constant}$$

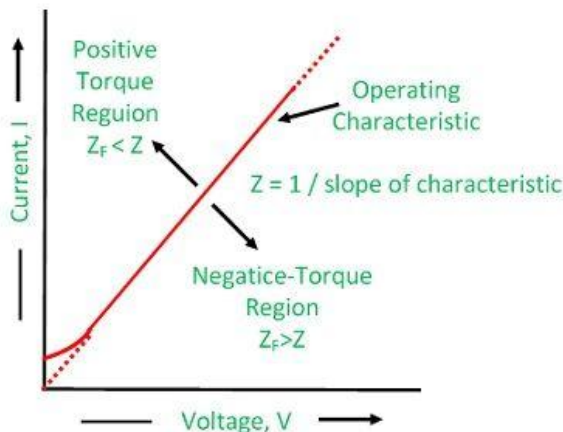
The operating characteristic concerning the voltage and current is shown in the figure below. The dashed line in the image represents the operating condition at the constant line impedance.



Principle of operation of an Impedance Relay

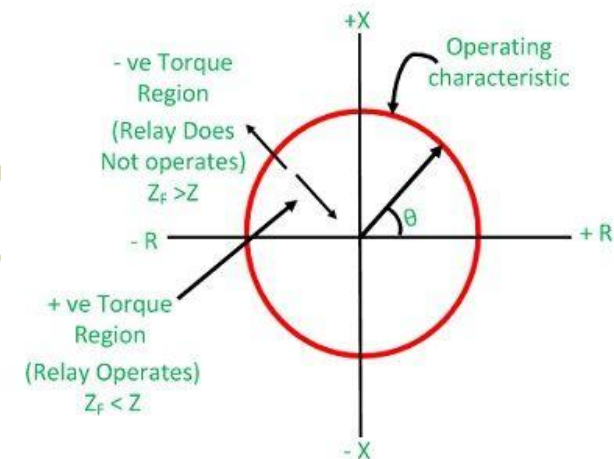
Circuit Globe

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



Operating Characteristic of an Impedance Relay

Circuit Globe



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

Circuit Globe

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

Drawbacks of Plan Impedance Relay

The following are the disadvantages of the impedance relay.

1. It gives the response on both the side of the CT and PT. Thus, it becomes difficult for the breaker to determine whether the fault is external or internal.
2. The relay is easily affected by the arc resistance of the line.
3. It is very sensitive to the power swing. The powerful winds generate the faults on the line because of which the impedances of the line vary.

The relay always operates when the impedance of the line is less than the relay settings. This type of relay is called the high-speed relay.

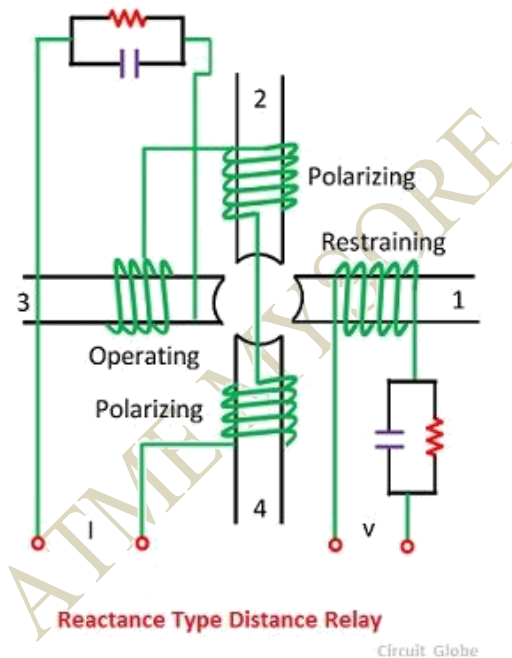
Reactance Relay

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

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

Construction of Reactance Relay

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



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

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

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

$$T = K_1 I^2 - K_2 \sin \theta - K_3$$

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

$$K_1 I^2 - K_2 V I \cos(\theta - 90^\circ) - K_3$$

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

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

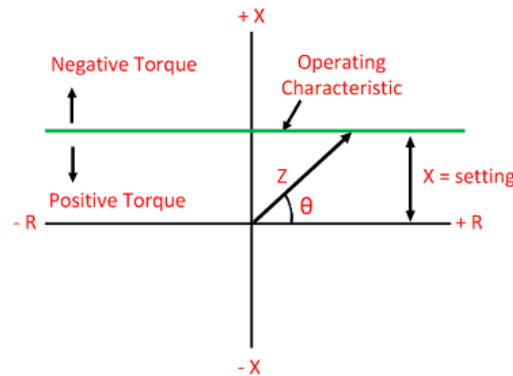
$$\frac{V}{I} \sin \theta = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$

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

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

Operating Characteristic of Reactance Relay

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



Operating Characteristic of Reactance Type Distance Relay

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

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

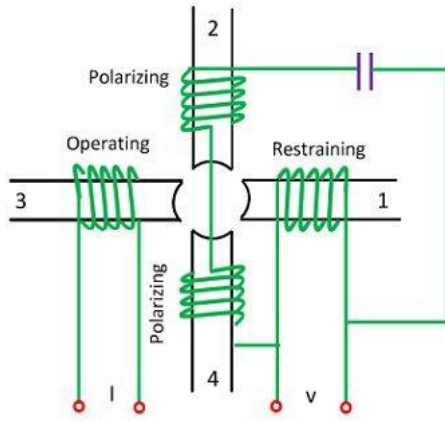
This type of relay is not capable of selecting whether the fault has taken place in the section where the relay is located, or it has taken place in the adjoining section when used on the transmission line. The directional unit used with the reactance relay will not be same as used with the impedance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

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

Mho Relay

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

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



Schematic Diagram of Mho Relay

Circuit Globe

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

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

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

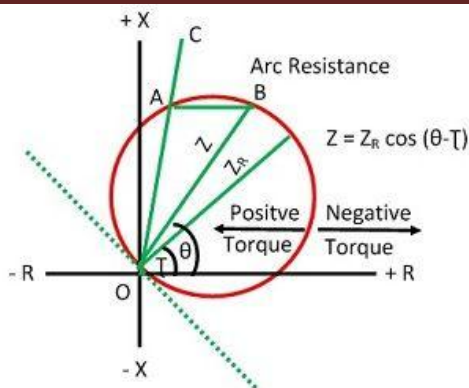
$$K_1 VI \cos(\theta - \tau) - K_2 V^2 - K_3 = 0 \quad \frac{K_1}{K_2} \cos(\theta - \tau) - \frac{K_3}{K_2 VI} = \frac{V}{I} = Z$$

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

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

Operating Characteristic of Mho Relay

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



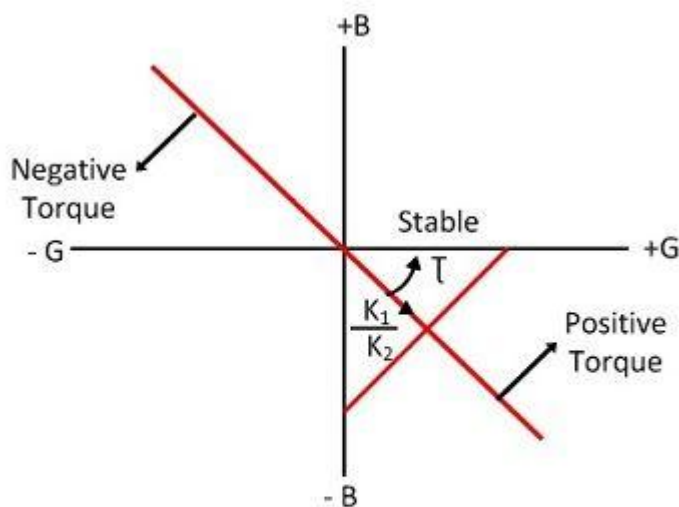
Operating Characteristic of Mho Relay

Circuit Globe

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

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

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



Characteristic of Mho Type Relay on Admittance Diagram

Circuit Globe

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

Angle Impedance Relay

Angle Impedance Relay measures a component of the impedance of the line at the relay location. It is also called as ohm relay. Its Characteristic on R-X diagram is a straight line and is inclined to R-Axis at any angle as shown in below fig. the reactance relay is a particular case of reactance relay. The Angle Impedance Relay is used in conjunction with others relay, for example it is used to limit the area of MHO relay on the R-X Diagram to make it less sensitive to power surges

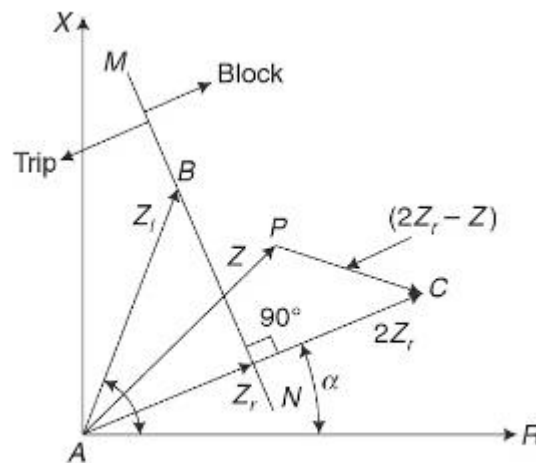
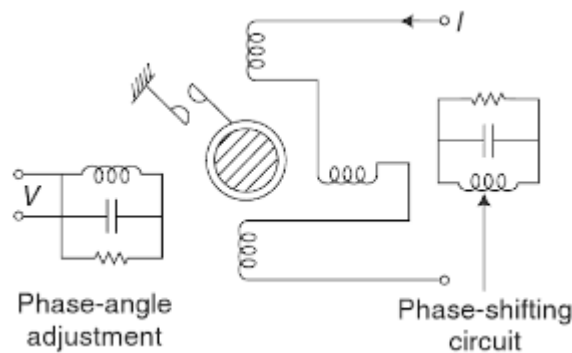


Fig. Characteristic of angle-impedance relay

Electro Mechanical Angle Impedance Relay

For this kind of relay, an induction cup construction as show in below fig. is used



the torque equation of the relay is given by
$$T = K_1 I^2 - K_2 VI \cos (\phi - \alpha) - K_3$$

In case of reactance relay $\alpha=90^\circ$. But in case of angle impedance relay, it may have any value which governs the inclination of Characteristic with respect to the R-axis.

Course Outcome: Interpret the working of distance relays and the effects of arc resistance, power swings, line length and source impedance on performance of distance relays.

Further Readings

1. <http://nptel.ac.in/downloads/108101039/>
2. <https://www.electrical4u.com/protection-system-in-power-system/>
3. <http://electrical-engineering-portal.com>

Module 3

Pilot Relaying Schemes:

3.0 Introduction,

3.1 Wire Pilot Protection,

3.2 Carrier Current Protection

Differential Protection

3.3 Differential Relays,

3.4 Differential Protection of 3 Phase Circuits

3.5 Percentage or Biased Differential Relay,

3.6 Balanced (Opposed) Voltage Differential Protection.

3.8 Transformer Protection,

3.9 Protection of Generators

4.0 Protection of Motor

4.1 Buszone Protection

4.2 Frame Leakage Protection

ATME MYSORE

Module 3 Pilot Relaying Schemes, Differential Protection, Rotating Machines Protection, Transformer and Buszone Protection

- To discuss pilot protection; wire pilot relaying and carrier pilot relaying.
- To discuss construction, operating principles and performance of various differential relays for Differential protection.
- To discuss protection of generators, motors, Transformer and Bus Zone Protection

3.0 Introduction- Pilot Relaying Scheme

A protection scheme which employs communications to send a signal from one station to another to allow high speed tripping (permission) or to prevent high speed tripping (blocking). Pilot protection allows over-reaching zones of protection to ensure full protection of the line as well as high speed tripping

Pilot Relaying Scheme Directional Comparison Blocking (DCB) A communications based protection scheme where high speed over-reaching tripping is allowed unless a block signal is received.

Permissive over-reaching transfer trip (POTT) A communications based protection scheme where high speed over-reaching tripping is allowed only if a permissive signal is received

3.1 Wire Pilot Protection

Pilot relaying is an adaptation of the principles of differential relaying for the protection of transmission-line sections

The term “pilot” means that between the ends of a transmission line there is an interconnecting channel of some sort over which information can be conveyed. Three different types of such a channel are presently in use, and they are called “wire pilot”, “carrier-current pilot” and “microwave pilot”. A wire pilot consists generally of a two-wire circuit of the telephone-line type, either open wire or cable. A wire pilot is generally economical for distances up to 8 or 15 km, beyond which a carrier-current pilot usually becomes more economical. Microwave pilots are employed when the number of services requiring pilot channels exceeds the technical or economic capabilities of carrier current.

The differential pilot-wire protection is most satisfactory and is widely employed on account of the advantages such as simplicity, flexibility, a high stability ratio, rapid fault clearance (a time varying between 0.1 and 0.5 second according to the “break time” of the circuit breaker).

The differential pilot-wire protection is based upon the principle that the currents compared at each end of the line or feeder by the use of pilot wires should be same under normal operating conditions and the equality is lost only when there is a fault in between the two ends. The system is quite similar to that employed for the protection of alternators and transformers and the difference lies only in the length of pilot wires.

3.2 Carrier-Current Protection:

In modern high-power electrical systems it is necessary to have quick-acting protections on long transmission lines. The requirements to be met by such protections are fully satisfied by the circulating current differential protection with its high sensitivity, quick action and independence upon the settings of the adjoining-section protections. Notwithstanding this, owing to the need for installing interconnecting conductors (cables), circulating current differential protections are confined to lines up to 8 or 15 km long.

It is, however, possible to make use of the main line conductors as the interconnecting conductors of a circulating current differential protection. The need for special interconnecting conductors (cables) then disappears and it hence becomes possible to set up a circulating current differential protection on transmission lines of any length. This is the basis of what are called carrier-current protections. The essential difference between carrier current protection and the voltage balance (Translay) pilot-wire protection is that, in the former, only the phase angles of the currents at the two ends of a line are compared instead of actual currents as in the latter case and this phase angle decides whether the fault is internal or external.

To make possible the transmission of commercial-frequency (50 Hz) load current, and at the same time use the main line conductors as the interconnecting conductors of the differential protection, it is necessary to use a current of higher frequency in order to be able to transmit current impulses from one end of the line to the other. High frequency signals in the range of 50 kHz to 400 kHz, commonly known as the carrier, are transmitted over the conductors of the protected line.

To inject the carrier signal and to restrict it within the protected section of the line suitable coupling apparatus and line traps are used at both ends of the protected section. This obviously makes this protection scheme quite expensive and justifies its application only in transmission lines of 110kV and above.

The main elements of the carrier channel are:

- (i) Transmitter
- (ii) Receiver
- (iii) Coupling equipment and
- (iv) Line trap.

Here we need not to go through the details of carrier current transmitters or receivers, all we need to know is that when a voltage of positive polarity is impressed on the control circuit of transmitter, it generates a high frequency output voltage. This output voltage is impressed between one phase conductor of the transmission line and the earth.

Each carrier-current receiver receives carrier current from its local transmitter as well as from the transmitter at the distant end of the line. In effect, the receiver converts the received carrier current into a dc voltage that can be used in a relay or other circuit to perform any desired function. The voltage is zero when carrier current is not being received.

Line trap unit is inserted between the bus-bar and connection of coupling capacitor to the line. It is a parallel LC network tuned to resonance at the high frequency. It hence presents high impedance to the high-frequency carrier current, but relatively low impedance (less than $0.1\ \Omega$) to the power-frequency (50 Hz) current. Traps are employed to confine the carrier currents to the protected section so as to avoid interference with or from other adjacent carrier current channels, and also to avoid loss of the carrier current signal in adjoining power circuits for any reason whatsoever, external short circuit being a principal reason. Consequently, carrier current can flow only along the line section between the traps.

The coupling capacitor (CC) connects the high frequency (carrier) equipment to one of the line conductors and simultaneously serves to isolate the carrier equipment from the high power-line voltage. It presents a relatively low reactance to the high frequency currents (about $150\ \Omega$ at 500 kHz) and a high reactance to the power frequency (about $1.5\ \text{M}\ \Omega$ at 50 Hz). To reduce impedance further a low inductance is connected in series with the coupling capacitors to provide a resonance at carrier frequency.

It is thus evident that the commercial-frequency current will be able to flow only through the line conductors, while the high-frequency carrier current will circulate, when the receiver-transmitter operate, over the line conductor fitted with the high-frequency traps, through the coupling capacitors and through ground (the return conductor).

Methods of Carrier-Current Protection:

There are different methods of carrier current protection and basic forms of carrier protection are:

- (i) Directional Comparison Protection and
- (ii) Phase-Comparison Carrier Protection.

(i) Directional Comparison Protection:

The protection operates on the basis of comparison of the fault-power flow directions at the two ends of the protected line. Operation takes place only when the flow of power at both ends of the line is in the bus-to-line direction, a condition which will evidently only arise in event of a fault on the protected section of the line. With directional-comparison relaying, the carrier pilot informs the equipment at one end of the line how a directional relay at the other end responds to a short circuit.

The conditions for internal and external faults are illustrated in Fig. 5.17. The relays at both ends of the protected section respond to fault power flowing away from the bus (tripping direction). For faults in the protected section, power flows in the tripping direction at both ends. For external faults power flow will be in opposite directions. A simple signal through carrier pilot is transmitted from one end to the other during faults.

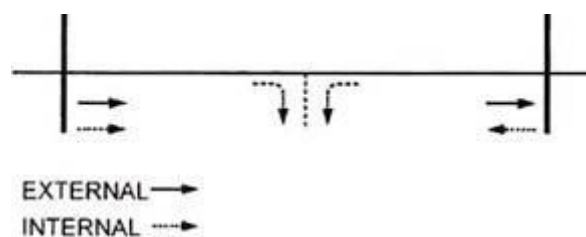


Fig. 5.17. Direction of Current Flow For External and Internal Faults

The pilot scheme can be employed for transmitting either blocking, or permitting signals. Thus possible carrier protections are of two types viz., carrier-blocking scheme and carrier-permitting scheme.

In a carrier-blocking protection scheme, the presence of carrier prevents or blocks operation of the protection. Carrier is, therefore, transmitted only upon the occurrence of a fault and is employed to prevent tripping in the event of an external fault. In carrier-permitting scheme the presence of carrier permits operation of the protection. The carrier blocking scheme is more reliable than carrier-permitting scheme. This is because a failure in the carrier-permitting signal equipment will mean a failure in isolating the fault, whereas a failure in carrier-blocking signal equipment isolates the section on which no fault exists. However, such false operation is preferable to the failure to clear a faulted section.

In a carrier-permitting protection scheme, normally no pilot signal is transmitted from any terminal. Should a short circuit occur in an immediately adjacent line section, a pilot signal is transmitted from any terminal where short-circuit current flows out of the line (i.e., in the non-tripping direction). While any station is transmitting a pilot signal, tripping is blocked at all other stations. But should a short circuit occur on the protected section of the line, no pilot signal is transmitted and tripping occurs at any terminal where short-circuit current flows. Therefore, the pilot is blocking pilot, since the reception of a pilot signal is not required of permit tripping.

Directional comparison protection scheme (carrier blocking type) is illustrated in Fig. 5.18. The operation of the directional element provided on each breaker is indicated by the arrow and the non-operation by the letter O. Occurrence of fault activates relays on each of the breakers near the fault. This relay unless blocked from operation, causes tripping of breakers. The blocking signal is controlled by the directional relays on each breaker, and is transmitted from one end of a protected section to the other by carrier.

If a directional element determines that the fault is external to the protected section, a signal is transmitted blocking the operation of breakers at both ends of the section. In case the directional elements at both ends determine that fault is in the protected section, no blocking signal is transmitted from either end, and both breakers trip. The sequence of event for a fault at F is made clear by illustration in Fig. 5.18.

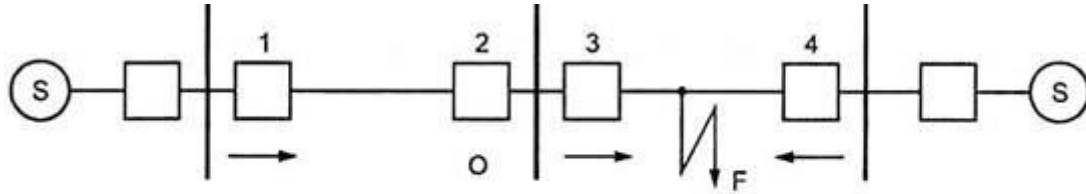


Fig. 5.18. Illustration of Directional Comparison Protection of a Power System

At breaker 1 the directional element shows that the fault may be in the section 1-2. This breaker trips if no blocking signal is received. No blocking signal is transmitted to breaker 2. At breaker 2 the directional element shows that the fault is not in section 1-2. A carrier signal is transmitted that blocks tripping of both the breakers 1 and 2.

At breakers 3 and 4 the directional elements show that the fault may be in section 3-4. No blocking signal is transmitted and after a very short time delay (1 to 3 cycles), both the breakers 3 and 4 trip.

(ii) Phase-Comparison Carrier Protection:

Phase-comparison relaying equipment uses its pilot to compare the phase relation between current entering in the protected zone and the current leaving the protected zone. The current magnitudes are not compared. Phase comparison protection provides only main or primary protection, backup protection must be provided in addition.

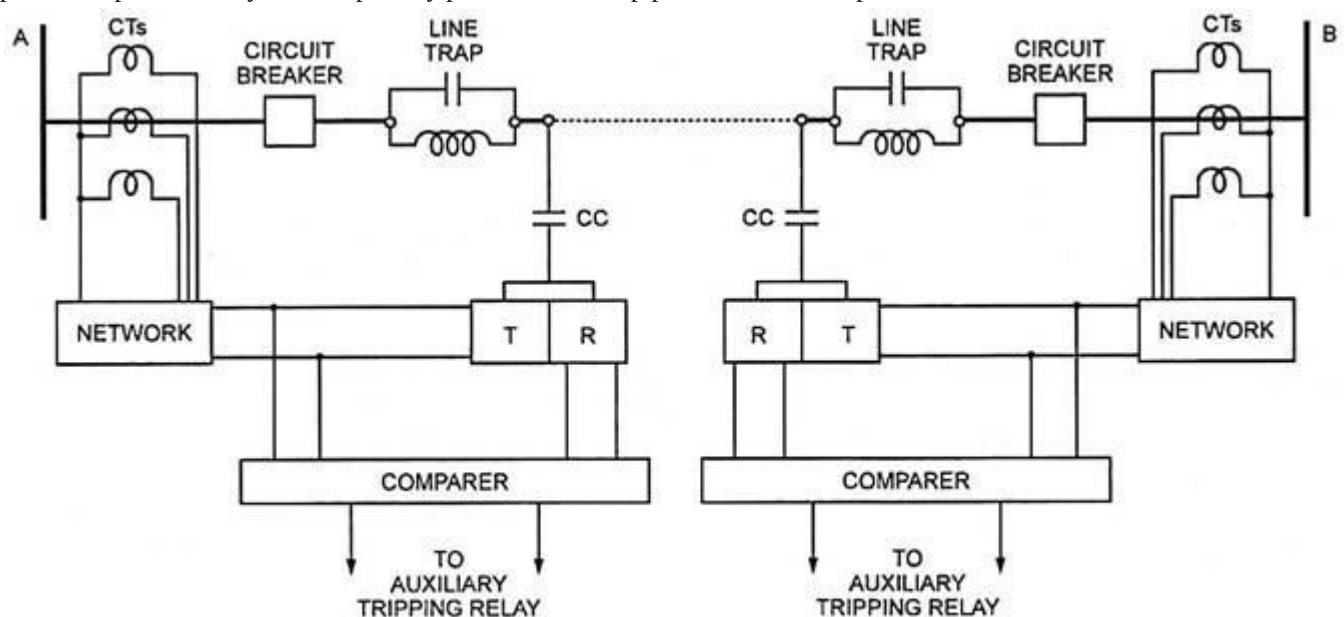


Fig. 5.19. Schematic Representation of Phase-Comparison Carrier Protection

Figure 5.19 shows schematically the principal elements of the equipment provided at both ends of a two-terminal transmission line, employing a carrier-current pilot. As in ac wire-pilot protection, the transmission-line CTs feed a network that transforms the CT output currents into a single-phase sinusoidal output voltage. This voltage is applied to a carrier-current transmitter and to a 'comparer'.

The output of a carrier-current receiver is also applied to the comparer. The comparer controls the operation of an auxiliary relay for tripping the transmission-line circuit breaker. These elements provide means for transmitting and receiving carrier-current signals for comparing at each end of the relative phase relations of the transmission-line current at both ends of the line.

For examining the relations between the network output voltages at both ends of the line and also the carrier-current signals that are transmitted during external and internal fault conditions refer to Fig. 5.20. For an external fault at point D in Fig. 5.20, the network output voltages at stations A and B (waves a and c) are 180° out of phase.

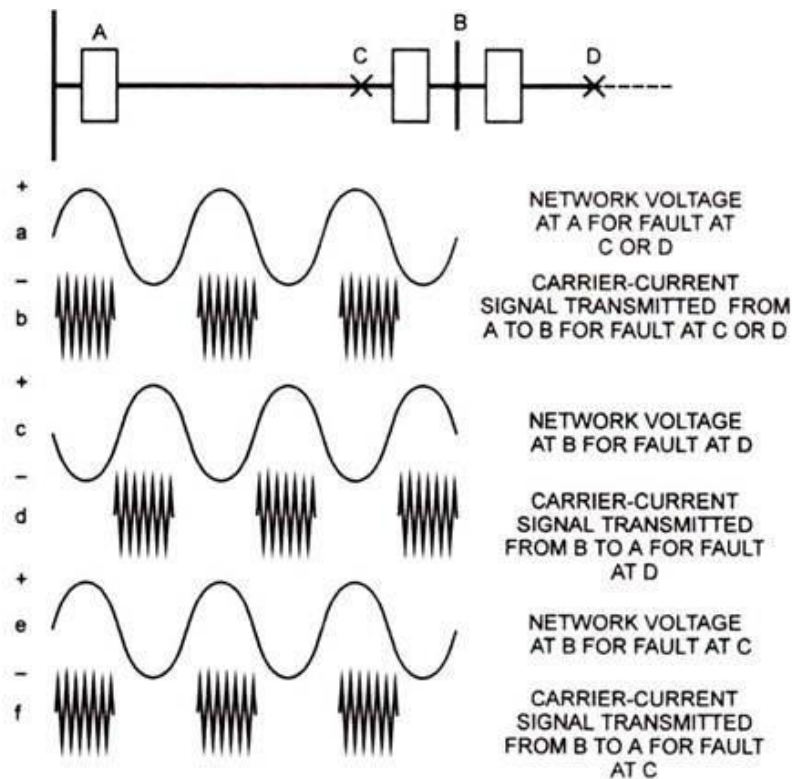


Fig. 5.20. Relations Between Network Output Voltages and Carrier-Current Signals

This is because the connections of CTs at the two stations are reversed. Since an ac voltage is used to control the transmitter, carrier-current is transmitted only during the half cycles of the voltage wave when the polarity is positive. The carrier-current signals transmitted from stations A and B (waves b and d) are displaced in time, so that there is always a carrier-current signal being sent from one end or the other.

For internal fault at point C, the network output voltage at station B reverses because of reversal of power-line currents at station B, the carrier-current signals (waves b and d) are concurrent, and there is no signal from either station every other half cycle.

Phase-comparison relaying acts to block tripping at both terminals whenever the carrier-current signals are displaced in time so that there is little or no time interval when a signal is not being transmitted from one end or the other. When the carrier-current signals are approximately concurrent, tripping will occur whenever there is sufficient short-circuit current flowing. This is shown in Fig. 5.21 where network output voltages are superimposed, and the related tripping and blocking tendencies are illustrated.

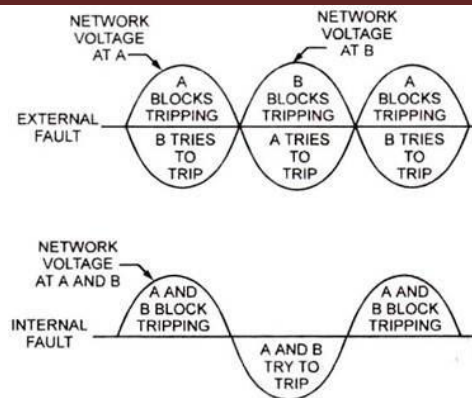


Fig. 5.21. Relation of Tripping and Blocking Tendencies To Network Output Voltages

As shown in Figs. 5.20 and 5.21, the equipment at one station transmits a blocking carrier-current signal during one half cycle, and then stops transmitting and tries to trip during the next half cycle, if carrier current is not received from the other end of the line during this half cycle, the equipment operates to trip its breaker. But, if carrier current is received from the other end of the line during the interval when the local carrier-current transmitter is idle, tripping does not occur.

Advantages of Carrier-Current Protection:

Carrier current over the power line provides simultaneous tripping of circuit breakers at both ends of the line in one to three cycles. Thereby high speed fault clearing is obtained, which improves the power system stability. Besides, there are several other advantages of carrier-current protection.

These are:

1. Fast, simultaneous operation of circuit breakers at both ends.
2. Auto-reclosing simultaneous reclosing signal is sent thereby simultaneous (1 to 3 cycles) reclosing of circuit breaker is obtained.
3. Fast clearing prevents shocks to systems.
4. Tripping due to synchronising power surges does not occur, yet during internal fault clearing is obtained.
5. For simultaneous faults, carrier-current protection provides easy discrimination.
6. Carrier-current relaying is best suited for fast relaying in conjunction with modern fast circuit breakers.
7. No separate wires are required for signalling, as the power lines themselves carry power as well as communication signalling. Hence the capital and operating costs are smaller.

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

3.3 Differential Protection

“A differential relay responds to vector difference between two or more similar electrical quantities”.

From this definition the following aspects are known:

1. The differential relay has at least two actuating quantities say i_1, i_2 .
2. The two or more actuating quantities should be similar i.e. current/current.
3. The relay responds to the vector difference between the two i.e. to $i_1 - i_2$, which includes magnitude and/or phase angle difference.

Differential protection is generally unit protection. The protected zone is exactly determined by location of CT's or VTs. The vector difference is achieved by suitable connections of current transformer or voltage transformer secondaries.

APPLICATIONS OF DIFFERENTIAL PROTECTION

Most differential relays are current differential relays in which vector difference between the current entering the winding and current leaving the winding is used for sensing and relay operation.

Differential protection principle is used in the following applications

- Protection of Generator, Protection of Generator-Transformer Unit.
- Protection of Transformer.
- Protection of Feeder (Transmission Line) by Pilot wire differential protection.
- Protection of transmission Line by Phase Comparison Carrier Current Protection.
- Protection of large motors.
- Bus-zone protection.

PRINCIPLE OF CIRCULATING CURRENT DIFFERENTIAL (MERZ-PRIZE) PROTECTION.

Fig (a) illustrates the principle of differential protection of generator and transformer. X is the winding of the protected machine. When there is no internal fault, the current entering in X is equal in phase and magnitude to current leaving X, the CT's are of such a ratio that during the normal conditions or for external faults (Through Faults) the secondary currents of CT's are equal. These currents say i_1 and i_2 circulate in the pilot wires. The polarity connections are such that the currents i_1 and i_2 are in the same direction in pilot wires, during normal conditions or external faults

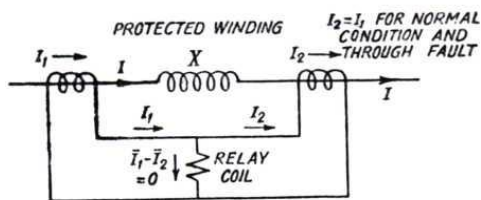


Fig. a). Principle of circulating current relay of generators, transformers.

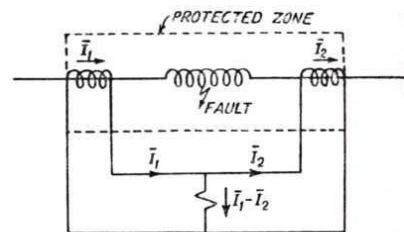


Fig. (b). Internal Fault : $I_1 - I_2 \neq 0$.

Relay operating coil is connected at the middle of pilot wires. Relay unit is of over current type.

During normal condition and external fault the protection system is balanced and the CTs ratios are such that secondary currents are equal. These currents circulate in pilot wires. The vector

differential current $i_1 - i_2$ which flows through the relay coil is zero
 $i_1 - i_2 = 0$ (normal condition or external faults)

This balance is disturbed for internal faults. When fault occurs in the protected zone, the current entering the protected winding is no more equal to the leaving the winding because some current flows to the fault. The differential $i_1 - i_2$ flows through the relay operating coil and the relay operates if the operating torque is more than restraining torque.

The currents i_1 and i_2 circulate in the secondary circuit. Hence CT's does not get damaged. Polarities of CT's are considered. CT's are connected such that the circulating currents i_1 and i_2 are as shown in Fig. (a) For normal condition

DIFFICULTIES IN DIFFERENTIAL PROTECTION

Difference in pilot wire lengths. The current transformers and machine to be protected are located at different sites and normally it is not possible to connect the relay coil to the equipotential points. The difficulty is overcome by connecting adjustable resistors in series with the pilot wires. These are adjusted on site to obtain the equipotential points.

CT Ratio errors during short-circuits. The current transformer may have almost equal ratio at normal currents. But during short-circuit conditions, the primary currents are unduly large. The ratio errors of CT's on either sides differ during these conditions due

- 1) Inherent difference in CT characteristic arising out of difference in magnetic circuit, saturation conditions etc.
- 2) Unequal D.C. components in the short circuit-currents.

Tap-changing. The tap-changing causes change in transformation ratio of a transformer. Thereby the CT ratios do not match with the new-tap settings, resulting in current in pilot wires even during healthy condition. This aspect is taken care of by biased differential relay

3.4 Differential Protection for 3-Phase Circuits:

The above principle can be extended to a system element having several connections. A three-phase circuit is only necessary, as before, that all the CTs have the same ratio, and that they be connected so that the differential relay carries no current when the total current entering the circuit is vectorially equal to that current leaving the circuit.

During normal operating conditions the three secondary currents of CTs are balanced and no current flows through the relay coil. But during fault in the protected zone, the balance is disturbed and differential current flows through the relay operating coil and when the differential current exceeds the relay's pick-up value, the relay operates.

The principle can still be applied for the protection of a 3-phase power transformer, but in this case, the ratios and connections of the CTs on the opposite sides of the power transformer must be such as to compensate for the magnitude and phase-angle change between the power transformer currents on either side.

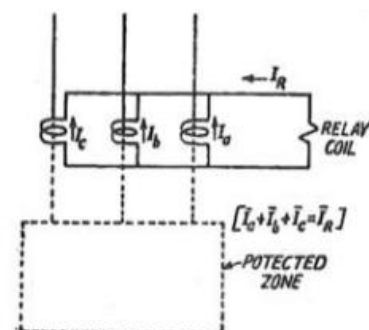


Fig. 2. Differential Protection of 3-phase circuit.

3.5 BASED OR PERCENT DIFFERENTIAL RELAY

The reason for using this modification is circulating current differential relay is to overcome the trouble arising out of values of external short-

differences in CT ratios for high circuit currents.

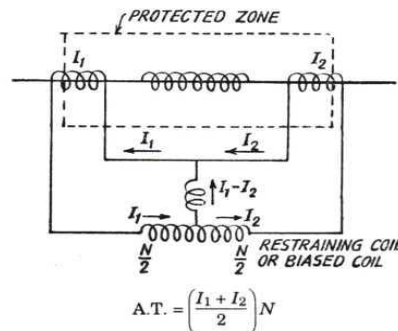


Fig. Per cent Differential Relay.
(Biased Differential Relay.)

The percentage differential relay has an additional restraining coil connected in the pilot wire as shown in Fig.

In this relay the operating coil is connected to the mid-point of the restraining coil.

The differential current in operation coil is $(i_1 - i_2)$,

While current in restraining coil is $\frac{i_1 + i_2}{2}$

If the Number of turns on the restraining coil is 'N', the total ampere turn are $\frac{I_1 N}{2} + \frac{I_2 N}{2}$, which is same as if $\frac{I_1 + I_2}{2}$ were to flow through whole coil.

For external faults both I_1 and I_2 increase and thereby the restraining torque increases which prevents the mal-operation.

The operating characteristic of such a relay is given in Fig.

Except for the effect of the control spring at low current the ratio of differential operating current to average restraining current is Fixed Percentage. Hence the relay is called 'Percentage Differential Relay'.

The relay is also called 'Based Differential Relay' because the restraining coil is also called a biased coil as it provides additional flux.

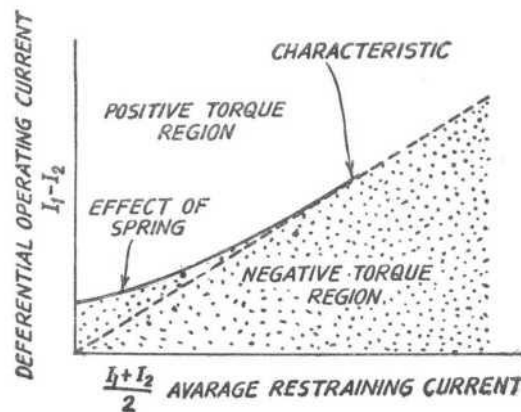
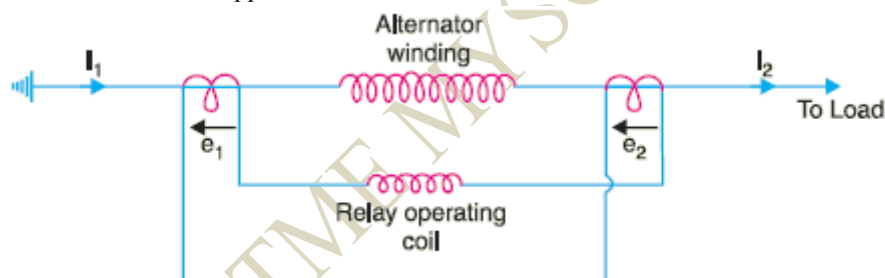


Fig. Operating characteristic of differential relay.

The percentage of biased differential relay has a rising pick-up characteristic. As the magnitude of through current increases, the restraining current increases

3.6 Balanced (Opposed) Voltage Differential Relay

Below fig shows the arrangement of voltage balance protection. In this scheme of protection, two similar current transformers are connected at either end of the element to be protected (e.g. an alternator winding) by means of pilot wires. The secondaries of current transformers are connected in series with a relay in such a way that under normal conditions, their induced e.m.f.s' are in opposition.



Under healthy conditions, equal currents ($I_1 = I_2$) flow in both primary windings. Therefore, the secondary voltages of the two transformers are balanced against each other and no current will flow through the relay operating coil. When a fault occurs in the protected zone, the currents in the two primaries will differ from one another (i.e. $I_1 \neq I_2$) and their secondary voltages will no longer be in balance. This voltage difference will cause a current to flow through the operating coil of the relay which closes the trip circuit.

Disadvantages

The voltage balance system suffers from the following drawbacks :

- (i) A multi-gap transformer construction is required to achieve the accurate balance between current transformer pairs.
- (ii) The system is suitable for protection of cables of relatively short lengths due to the capacitance of pilot wires. On long cables, the charging current may be sufficient to operate the relay even if a perfect balance of current transformers is attained.

Course outcome: Interpret pilot protection; wire pilot relaying and carrier pilot relaying, Interpret construction, operating principles and performance of differential relays for differential protection

Future Readings

1. <http://nptel.ac.in/downloads/108101039/>
2. <https://www.electrical4u.com/protection-system-in-power-system/>
3. <http://electrical-engineering-portal.com>

Module 4 CIRCUIT BREAKERS

- 4.0 Introduction
- 4.1 Fault Clearing Time of a Circuit Breaker
- 4.2 Arc Voltage
- 4.3 Restriking Voltage and Recovery Voltage
- 4.4 Arc Interruption
- 4.5 Current Chopping
- 4.6 Classification of Circuit Breakers
- 4.7 Air – Break Circuit Breakers
- 4.8 Oil Circuit Breakers
- 4.9 Air –Blast Circuit Breakers
- 4.10 SF6 Circuit Breakers
- 4.11 Vacuum Circuit Breakers
- 4.12 High Voltage Direct Current Circuit Breakers
- 4.13 Rating of Circuit Breakers
- 4.14 Testing of Circuit Breakers

ATME MYSORE

Module 4 CIRCUIT BREAKERS

Course objectives: To explain the principle of circuit interruption and different types of circuit breakers.

4.0 Introduction

The **electric arc** is a type of electric discharge between electrodes. The arc formation between the contacts of CB is entirely due to Ionization process such as ionization by collision, photo ionization, thermal ionization, etc in circuit-breakers, the arc persists during the brief period after separation of current carrying contacts. The circuit-break should be capable of extinguishing the arc without getting damaged. The interruption of D.C. arcs is relatively more difficult than a.c. arcs. In a.c. arcs, as the current becomes zero during the regular wave, the arc vanishes and it is prevented from restriking.

4.1 Fault clearing time is the time between the instant of fault and instant of final arc interruption (in circuit breaker).

Fault clearing time is the sum of relay-time and circuit breaker-time.

Remember the time events

$$\text{Fault Clearing Time} = [\text{Relay Time}] + [\text{Breaker Time}]$$

Fault Instant to Closing of relay contacts	+	Closing of relay contacts to Final Arc-extinction in C.B.
---	---	--

The relay-time is the time between the instant of occurrence of fault and the instant of closure of relay contacts. Or, it is the time between the instant when the operating quantity reaches the pick-up value and the instant of closure of relay contacts.

The circuit breaker time is the total of time taken by operating mechanism to open to circuit breaker contacts and the arcing time. It is also called total break time.

The fault clearing time is significant due to the following reasons:

1. Rapid fault clearing minimizes the damage. During short circuit tests on bus bars, with fault duration of 0.07 second, with 60 kA R.M.S. value of current, no damage was observed after the tests. With fault duration of 7 seconds, however, the bus bars were completely destroyed.
2. Rapid fault clearing improves power system stability. For the reason, the slow relays and slow circuit breakers should not be preferred for protection, where stability is important. This applies to protection of EHV transmission lines, protection of large machines like important generator, large transformer, large-motors, etc., and protection in important generating stations and receiving stations

Though fast fault clearing is desirable, time lag is purposely provided in majority of protection

systems for the following purposes:

- To permit discrimination between main and back-up protection.
- To prevent the operation of relay during transients, starting currents, permissibly load fluctuations, etc.

The relay-time of fast relays is of the order of a few cycles and that of inverse time relays can be adjusted between about 6 seconds to 60 seconds. The circuit-breaker time of slow circuit-breakers is of the order of 5 cycles and that of fast circuit-breakers is of the order of 2 cycles to 3 cycles.

4.2 ARC VOLTAGE

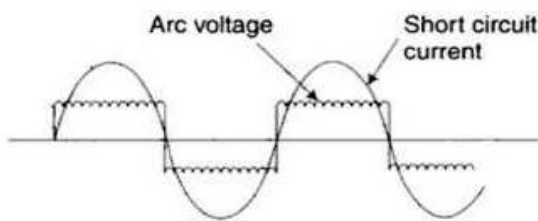


Fig 1, Short Circuit current and arc voltage

Above figure shows the wave shape of arc voltage. The voltage drop across the arc is called arc voltage. As the arc path is purely resistive, the arc voltage is in phase with the arc current. The magnitude of the arc voltage is very low, amounting to only a few per cent of the rated voltage. A typical value may be about 3 per cent of the rated voltage

4.3 Restriking Voltage and Recovery Voltage

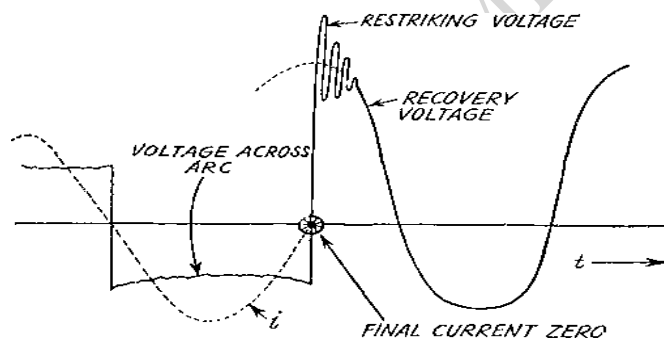


Fig 2, Restriking Voltage and Recovery Voltage Final Current Zero

The voltage across the contacts of circuit breaker is arc voltage when the arc exists. This voltage becomes system voltage (power frequency voltage (50Hz)) when the arc is completely interrupted. The arc is extinguished at the instant of Current Zero, the voltage across the breaker terminal does not normalise instantaneously but it oscillates and there is a transient condition. At the instant of arc getting interrupted a high frequency voltage appears across the contacts (Breaker pole) which is superimposed on power frequency (50 Hz) system voltage. It is known as **restriking voltage**.

This high frequency transient voltage tries to restrike the arc; hence it is called **restriking voltage or transient recovery voltage (TRV)**. Such voltage has a power frequency component plus

an oscillatory component, the oscillatory transient component is due to inductance and capacitance in ckt, power frequency component is due to system voltage(refer above figure)

The frequency of transient component is given by
$$F_n = \frac{1}{2\pi\sqrt{LC}}$$

F_n =frequency of transient voltage, Hz

L =EQUIVANT INDUCTANCE, Henry , C = EQUIVANT Capacitance, farad

This transient oscillatory component subsides (vanishes) after few micro sec(less than 0.1 mill sec) and the normal frequency system voltage is established after arc is completely extinguished, this voltage which appear across breaker contact after arc is finally extinguished is called **recovery voltage**.

4.4 Arc Interruption

These circuit- breakers employ various techniques to extinguish the arc resulting from separation of the current- carrying contacts. The mode of arc extinction is either 'high resistance interruption' or 'zero-point interruption'

The techniques adopted for the arc extinction can be classified into the following three categories:

1. High resistance interruption. The resistance of the arc (current path) is increased with time rapidly so as to reduce the current to value insufficient to maintain the arc.

The arc resistance can be increased by lengthening, splitting, cooling the arc, the main drawback with this type of interruption is that energy dissipated is high and so it is only used in low and medium power ac C.B and in dc circuit breaking.

In this method the length of the arc is increased so as to increase the voltage across the arc. The voltage of the arc is increased till it more than the system voltage across the contacts; At this point the arc gets extinguished.

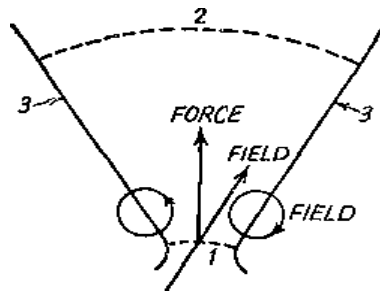
$$R_{arc} = V_{arc} / i_{arc}$$

Assuming arc current (i_{arc}) to be constant the resistance of the arc can be increased by increasing voltage V_{arc} . The arc voltage hence the arc resistance can be increased by increasing length of the arc.

The method is used in low and medium voltage a.c. (air break cb) and D.C. circuit breakers.

The arc resistance is increased by the following methods

Lengthening the arc by means of arc runners



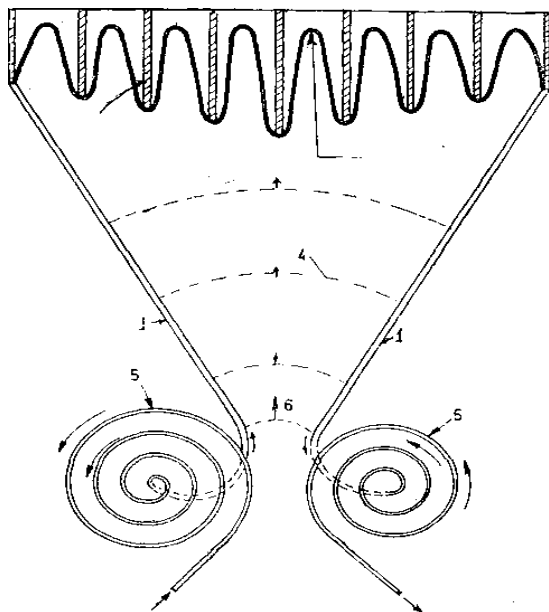
1. Initial position of arc
2. Final position of arc.
3. Arc runners (in vertical plane)
4. Field (in horizontal plane)
5. Force due to electrodynamic forces (in vertical plane)

Function of the arc runners.

Arc runners are horn-like blades of conducting material, which are connected to arcing contacts with their tips radiating upwards in 'V' shape. The arc originates at the bottom and blows upwards by electromagnetic force. The tips of the arc move upwards along arc runners or arc horns rapidly. The length of the arc increases and the arc is extinguished (Interrupted).

Splitting of Arc

The arc is elongated and split by arc splitters. These are specially made plates of resin bonded fiber glass. These are placed in the path perpendicular to the arc and the arc is pulled into them by electromagnetic force experienced by the arc by means of magnetic field applied in proper direction so as to pull the arc upwards. When the arc is pulled in space between the plates, it gets elongated constrained split and cooled. By virtue of these effects the arc gets extinguished.



1. Arc runner (metallic)
2. Arc splitters
3. Elongated arc
4. Arc in process of travelling
5. Blow-out coils (metallic)
6. Origin of Arc

Cooling of Arc. Cooling of the arc brings about recombination of ionized particles, cooling is brought by bringing the arc (ionized gas) in contact with cooler air.

If a gas containing positive ions and electrons there is a tendency for these to come together and combine to form a neutral atom. This phenomenon is termed as recombination. Recombination takes place directly in gas, and is important in the process of arc extinction

2. Current zero interruption. This method is employed in a.c arc interruption. The arc is interrupted at natural current zero of the alternating current wave and the dielectric strength of the contact-gap is increased to such an extent that it can withstand the voltage stress across it. This method is employed in a.c. arc interruption. Actually the alternating current passes through zero 100 times per second in 50 cycle's current wave. At every current zero the arc vanishes for a brief moment.

However, the arc restrike (appears) again with the rising current wave, to stop this process it is necessary to remove the ionized gas b/w the contacts or to recombine electrons in ionized gas at a rate greater than that at which they are being released, by either method the resistance of the arc-path rapidly increases until the path again becomes an insulator. In a.c. circuit-breakers the arc is interrupted at a current zero as zero current position offers most favourable situation for this where residual ionization is small. At current zero, the space between contacts is deionized quickly by introducing fresh unionized medium such as oil or fresh air, or SF₆ gas, between the contacts. The dielectric strength of the contact space increases to such an extent that the arc does not continue after current zero. A high voltage may appear across the contacts. The voltage may re-establish the arc if the dielectric strength of gap is less than the restriking voltage. In that case the arc continues for another half cycle and may get extinguished at next current zero.

In various types of circuit-breaker designs, the provision is made to remove the hot gases from the contact space immediately after the arc so as to fill the contact space by fresh dielectric medium of high dielectric strength.

Expression for Restriking Voltage and Rate of Rise of Restriking Voltage (RRRV)

The rate of rise of restriking voltage usually abbreviated by R.R.R.V. is a rate expressed in volts per micro-second,

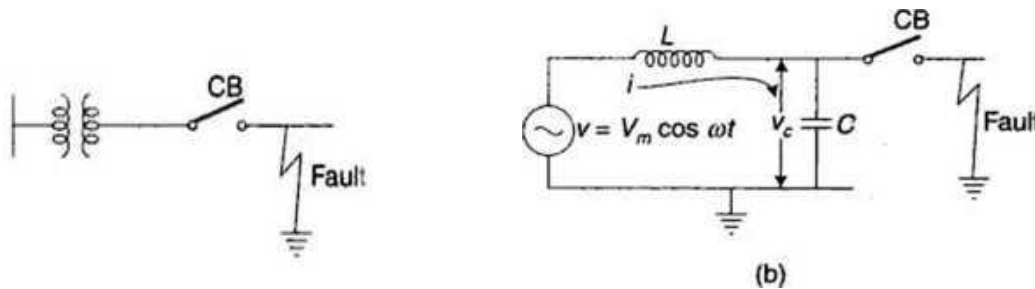


Fig (a) Fault on a feeder near circuit breaker (b) Equivalent electrical circuit for analysis of restriking voltage

The above figure (a) shows a short circuit on a feeder beyond the location of the circuit breaker. Figure (b) shows an equivalent electrical ckt where L and C are the inductance and Capacitance per phase of the system upto the point of CB location.

When the circuit breaker is closed, the short circuit current flows through R , L and the contact of CB, the capacitance C being short-circuited by the fault. Hence, the circuit of Fig (b) becomes completely reactive and the fault current is limited entirely by inductance of the system.

When the circuit-breaker contacts are opened and the arc is extinguished, the current 'I' is diverted through the capacitance C , resulting in a transient condition. The inductance and the capacitance form a series oscillatory circuit. The voltage across the capacitance which is restriking voltage, rises and oscillates, as shown in Fig. 2

The frequency of transient component is given by
$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

f_n = frequency of transient voltage, Hz

L = Inductance/ Phase, Henry

C = Capacitance b/w Phase and earth / phase, farad

The voltage across the capacitance which is the voltage across the contacts of the circuit breaker can be calculated in terms of L , C , f_n and system voltage.

$$L \frac{di}{dt} + \frac{1}{C} \int i dt = E$$

where E is the system voltage at the instant of arc interruption. As the transient oscillation is a fast phenomenon, E can be regarded as a constant for a short duration.

$$i = \frac{dq}{dt} = \frac{d(Cv_c)}{dt}, \quad \text{where } v_c = \text{voltage across the capacitor.}$$

Therefore,

$$\frac{di}{dt} = \frac{d^2(Cv_c)}{dt^2} = C \frac{d^2v_c}{dt^2}$$

$$\int \frac{idt}{C} = \frac{q}{C} = v_c$$

Substituting these values in the equation given above, we get

$$LC \frac{d^2v_c}{dt^2} + v_c = E$$

Taking Laplace Transform of both sides of the equation, we get

$$LC S^2 v_c(S) + v_c(S) = \frac{E}{S}$$

where $v_c(S)$ is the Laplace Transform of v_c .

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

or

$$v_c(S) [LCS^2 + 1] = \frac{E}{S}$$

or

$$v_c(S) = \frac{E}{S[LCS^2 + 1]} = \frac{E}{LCS \left(S^2 + \frac{1}{LC} \right)}$$

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

or

$$v_c(S) = \frac{w_n^2 E}{S(S^2 + w_n^2)} = \frac{w_n E}{S} \left(\frac{w_n}{S^2 + w_n^2} \right)$$

Taking the inverse Laplace, we get

$$v_c(t) = w_n E \int_0^t \sin w_n t$$

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

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

$$v_c(t) = E (1 - \cos \omega_n t) \quad \text{or} \quad v_c(t) = E \left(1 - \cos \frac{1}{\sqrt{LC}} t\right)$$

= Restriking voltage

The maximum value of restriking voltage = $2 E_{\text{peak}}$

= $2 \times$ peak value of the system voltage

The Rate of Rise of Restriking voltage (RRRV)

$$= \frac{dE}{dt} (1 - \cos \omega_n t)$$

$$= \omega_n E \sin \omega_n t$$

The maximum value of RRRV = $\omega_n E$

$$= \omega_n E_{\text{peak}}$$

For a 132 kV system, the reactance and capacitance up to the location of the circuit breaker is 3 ohms and 0.015 μF , respectively. Calculate the following:

- The frequency of transient oscillation.
- The maximum value of restriking voltage across the contacts of the circuit breaker.
- The maximum value of RRRV.

Solution

- The frequency of transient oscillation

$$L = \frac{3}{2\pi 50}, \quad f = 50, \text{ the system frequency}$$

$$= \frac{3}{100\pi} = 0.00954 \text{ H}$$

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

$$= \frac{1}{2\pi\sqrt{0.00954 \times 0.015 \times 10^{-6}}}$$

$$= \frac{10^5}{2\pi \times 1.1962} = \frac{10^5}{7.5241} = 13.291 \text{ kHz}$$

- The restriking voltage

$$v_c = E [1 - \cos \omega_n t]$$

The maximum value of the restriking voltage = $2 E_{\text{peak}}$

$$= 2 \times \frac{132}{\sqrt{3}} \sqrt{2} = 215.56 \text{ kV}$$

(c) The maximum value of RRRV = $\omega_n E_{\text{peak}}$

$$= 2\pi f_n \times \frac{132}{\sqrt{3}} \times \sqrt{2} \times 1000$$

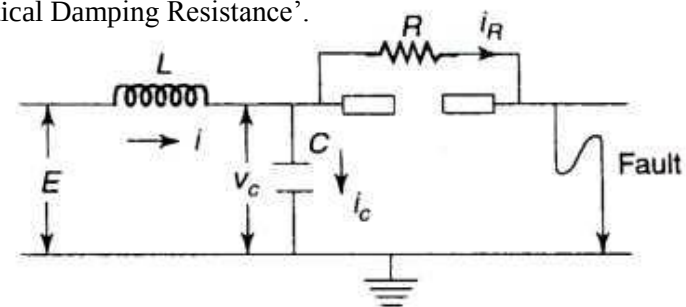
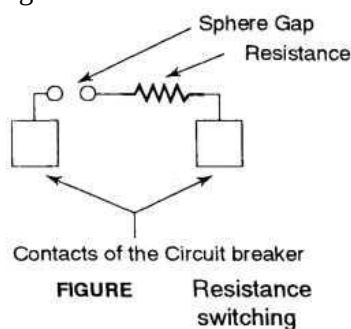
$$= 2\pi \times 13.291 \times 1000 \times \frac{132}{\sqrt{3}} \times \sqrt{2} \times 1000 \text{ V/s}$$

$$= 9010.45 \times 10^6 \text{ V/s} = 9.01045 \text{ kV}/\mu\text{s}$$

Resistance Switching

To reduce the restriking voltage, RRRV and severity of the transient oscillations, a resistance is connected across the contacts of the circuit breaker. This is known as resistance switching. The resistance is in parallel with the arc. A part of the arc current flows through this resistance resulting in a decrease in the arc current and increase in the deionisation of the arc path and resistance of the arc. This process continues and the current through the shunt resistance increases and arc current decreases. Due to the decrease in the arc current, restriking voltage and RRRV are reduced. The resistance may be automatically switched in with the help of a sphere gap as shown in Fig. The resistance switching is of great help in switching out capacitive current or low inductive current.

The analysis of resistance switching can be made to find out the critical value of the shunt resistance to obtain complete damping of transient oscillations. Below Figure shows the equivalent electrical circuit for such an analysis. The value of resistance R at which the frequency of Restriking voltage becomes zero is called "Critical Damping Resistance".



Let us see the effect of such a resistance on the frequency of restriking voltage transient

The voltage equation is given by

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

Therefore, the above equation become

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

or

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

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

Therefore,

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

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

Substituting these values in the main equation, we get

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

Taking Laplace Transform, we get

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

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

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

$$\text{or} \quad v_c(S) = \frac{E}{SLC \left[S^2 + \frac{1}{RC} S + \frac{1}{LC} \right]}$$

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

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

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

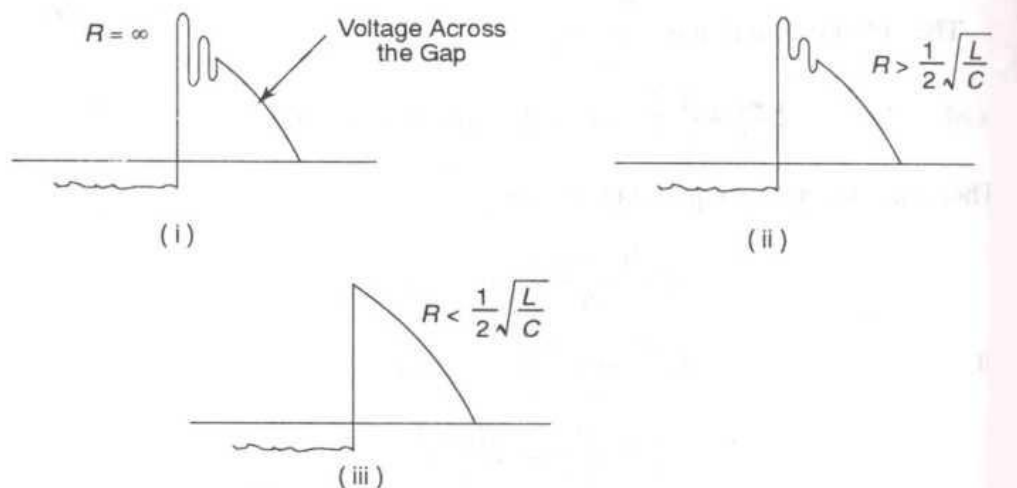


FIGURE Transient oscillations for different values of R

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

Therefore, if the value of the resistance connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2} \sqrt{L/C}$ there will be no transient oscillation. If $R > \frac{1}{2} \sqrt{L/C}$, there will be oscillation. $R = \frac{1}{2} \sqrt{L/C}$ is known as critical resistance. Figure 9.9 shows the transient conditions for three different values of R . The frequency of damped oscillation is given by

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

In a 220 kV system, the reactance and capacitance up to the location of circuit breaker is $8 \, \Omega$ and $0.025 \, \mu\text{F}$, respectively. A resistance of 600 ohms is connected across the contacts of the circuit breaker. Determine the following:

- Natural frequency of oscillation.
- Damped frequency of oscillation.
- Critical value of resistance which will give no transient oscillation.
- The value of resistance which will give damped frequency of oscillation, one-fourth of the natural frequency of oscillation.

Solution

$$L = \frac{8}{2\pi 50} = \frac{8}{100\pi} = 0.02544 \, \text{H}$$

$$\begin{aligned} \text{(i) Natural frequency of oscillation} &= \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \\ &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}}} \end{aligned}$$

(ii) Frequency of damped oscillation is given by

$$\begin{aligned}
 f &= \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}} \\
 &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times (600)^2}} \\
 &= \frac{1}{2\pi} \sqrt{\frac{10^{10}}{6.36} - \frac{10^{10}}{9}} = 3.413 \text{ kHz}
 \end{aligned}$$

(iii) The value of critical resistance

$$R = \frac{1}{2} \sqrt{\frac{L}{C}} = \frac{1}{2} \sqrt{\frac{0.02544}{0.025 \times 10^{-6}}} = 504.35 \Omega$$

(iv) The damped frequency of oscillation is $\frac{1}{4} \times 6.304 \text{ kHz} = 1576 \text{ Hz}$

$$\begin{aligned}
 1576 &= \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}} \\
 &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times R^2}} \\
 \text{or } 1576 &= \frac{1}{2\pi} \sqrt{\frac{10^{10}}{6.36} - \frac{10^{16}}{25R^2}}
 \end{aligned}$$

Therefore, $R = 520.8 \Omega$.

4.5 Interruption of Low Magnetizing Current (Current Chopping)

The necessity of interrupting small inductive current arises while disconnecting transformers on no load. No-load currents of transformer, i.e. magnetizing currents are almost at zero power factor lag, the current is smaller than normal current rating of the breaker. The breaking of such a low current presents a severe duty on the circuit-breaker

When interrupting low inductive currents such as magnetizing currents of transformer, shunt reactor, **the rapid deionization of contact space and blast effect may cause, the current to be interrupted before its natural zero. This phenomenon of the interruption of current before its natural zero is called current chopping.**

In such a situation, the energy stored in the Inductance (magnetic field) appears in the form of high voltage across the stray capacitance at the moment of current Interruption, which will cause restriking of the arc.

$$\frac{1}{2} Li^2 = \frac{1}{2} CV^2 \text{ Joules}$$

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

The frequency of transient Oscillation is given by $F_n = \frac{1}{2\pi\sqrt{LC}}$

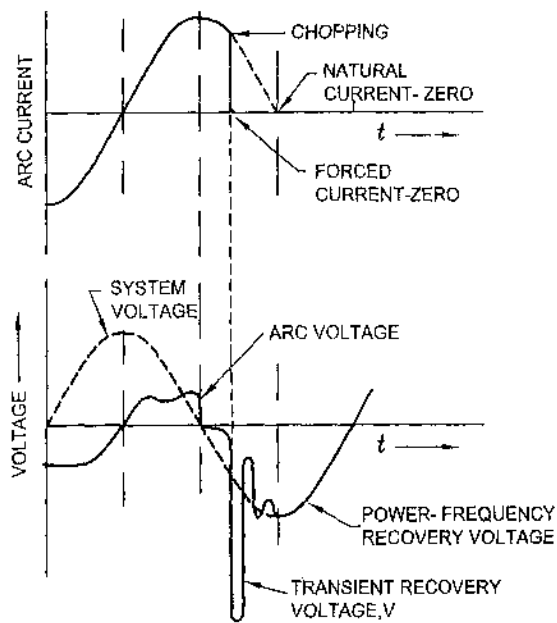
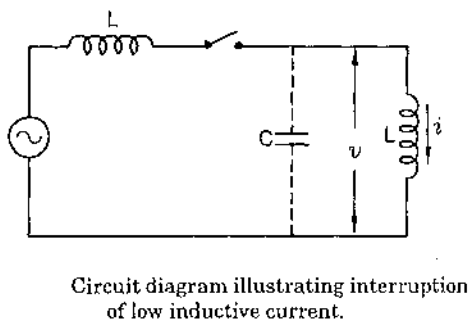


Fig. Interruption of low magnetizing currents.

Such a transient voltage having high RRRV appears across the contacts, unless the arc continues. If it restrikes a further, chop may, occur or several chops may occur before the current is finally interrupted, circuit-breaker in ay fails to clear the fault.

If the restrike does not occur; the severe voltage appears across the CB contacts and on the system.

Resistance switching is adopted to overcome the effect of over-voltages due to current Chopping

A circuit breaker interrupts the magnetising current of a 100 MVA transformer at 220 kV. The magnetising current of the transformer is 5% of the full load current. Determine the maximum voltage which may appear across the gap of the breaker when the magnetising current is interrupted at 53% of its peak value. The stray capacitance is 2500 μ F. The inductance is 30 H.

Solution The full load current of the transformer

$$= \frac{100 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 262.44 \text{ A}$$

$$\text{Magnetising current} = \frac{5}{100} \times 262.44 = 34.44 \text{ A}$$

$$\text{Current chopping occurs at } 0.53 \times 34.44\sqrt{2} = 25.83 \text{ A}$$

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

$$\therefore \frac{1}{2} \times 30 \times (25.83)^2 = \frac{1}{2} \times 2500 \times 10^{-6} v^2$$

$$\therefore v = 2829 \text{ kV}$$

4.6 CLASSIFICATION of Circuit Breaker

The a.c circuit-breakers can be classified on the basis of rated voltages. Circuit-breakers below rated voltage of 1000 V are called low voltage circuit-breakers and above 1000 V are called high voltage a.c. circuit-breakers.

The type of the circuit-breaker is usually identified according to the medium of arc extinction the classification of the circuit breakers based on the medium of arc extinction is as follows:

1. Air break circuit-breaker/Miniature circuit-breaker.
2. Air blast circuit-breaker
3. Oil circuit-breaker (tank type of bulk oil)
4. Minimum oil circuit-breaker.
5. Sulphur hexafluoride circuit-breaker. (Single pressure or Double Pressure).
6. Vacuum circuit-breaker.

The construction of the circuit-breakers depends upon its type (arc-quenching medium), voltage rating and structural form.

Air-break Circuit-breakers. Utilize air at atmospheric pressure for arc-extinction

Air-blast Circuit-breakers. Utilize high pressure compressed air for arc, they need compressed air plant.

Bulk-oil and Minimum-oil Circuit-breakers. Utilize Dielectric oil (Transformer oil) for an extinction. In Bulk-oil circuit breakers, the contacts are separated inside a steel tank filled with dielectric oil. In minimum oil circuit-breakers the contacts are separated in an insulating housing (interrupter) filled with dielectric oil,

SF6 Circuit-breakers. Sulphur-hexa-fluoride gas is used for arc extinction. There are two types:

Single Pressure puffer type SF6 Circuit-breakers, in which the entire circuit-breaker is filled with SF6 gas at single pressure (4 to 6 kgf/cm²). The pressure and gas flow required for arc extinction is obtained by piston action.

Double pressure type SF6 Circuit-breaker, in which the gas from high-pressure system is released into low pressure system over the arc during the arc quenching process

4.7 AIR BREAK CIRCUIT BREAKER

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

In air-break circuit breakers, the principle of high resistance is employed for arc interruption. The arc resistance is increased by lengthening, splitting and cooling the arc. The arc length is rapidly increased employing arc runners and arc chutes. The arc moves upward by both electromagnetic and thermal effects. It moves along the arc runner and then it is forced into a chute. It is split by arc splitters. A blow-out coil is employed to provide magnetic field to speed up arc movement and to direct the arc into arc splitters. The blow-out coil is not connected in the circuit permanently. It comes in the circuit by the arc automatically during the breaking process. The arc interruption is assisted by current zero in case of ac air break circuit breakers. High resistance is obtained near current zero.

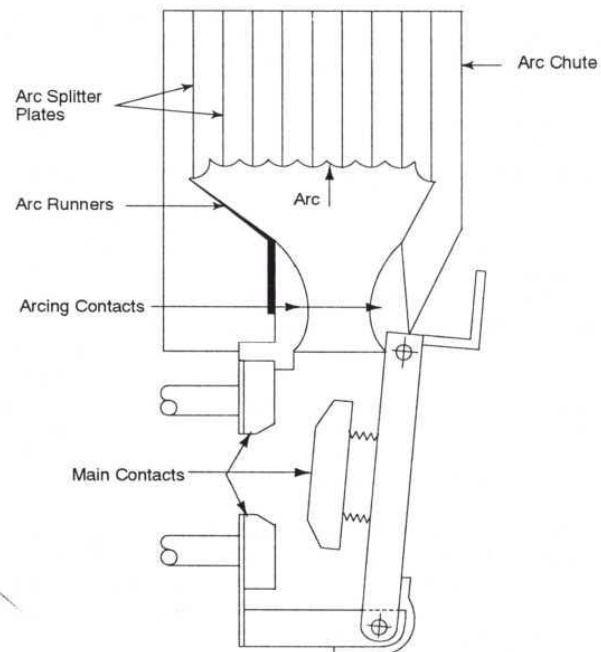


FIGURE Air-break circuit breaker

AC air-break circuit breakers are available in the voltage range 400 to 12 kV. They are widely used in low and medium voltage system. They are extensively used with electric furnaces, with large motors requiring frequent starting, in a place where chances of fire hazard exist, etc. Air-break circuit breakers are also used in dc circuit up to 12 kV.

4.8 OIL CIRCUIT BREAKER

Mineral oil has better insulating properties than air. Due to this very reason it is employed in many electrical equipment including circuit breakers. Oil has also good cooling property. In a circuit breaker when arc is formed, it decomposes oil into gases. Hence, the arc energy is absorbed in decomposing the oil. The main disadvantage of oil is that it is inflammable and may pose a fire hazard. Other disadvantages include the possibility of forming explosive mixture with air and the production of carbon particles in the oil due to heating, which reduces its dielectric strength.

Bulk oil Circuit Breaker

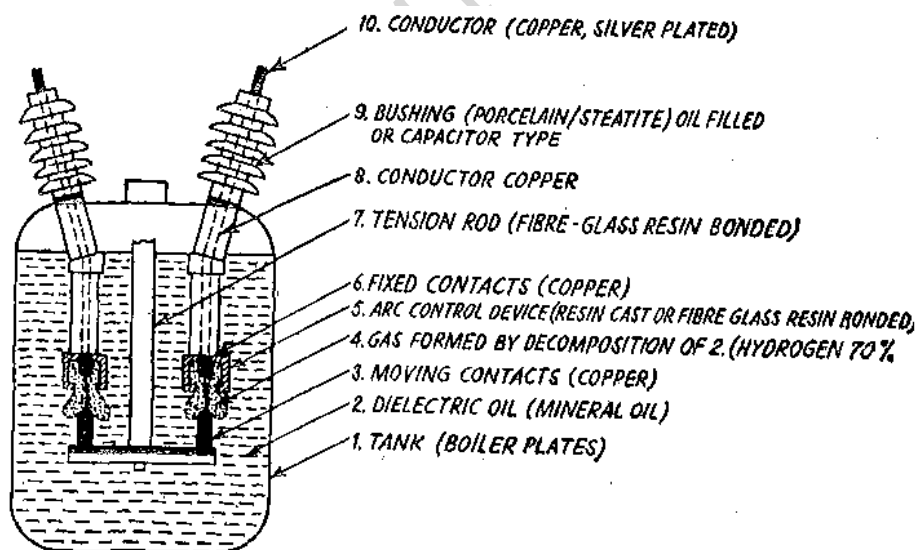
Plain oil circuit breaker (Double break)

The bulk oil circuit breakers generally employed in our power systems are of this type. In these the gases produced during arcing are confined to small volumes by the use of an insulating, rigid arc chamber (Arc Control Device or arc control pots) surrounding the contacts. Thus, higher pressures can be developed to force the oil and gas through or around the arc to extinguish it. These small, high pressure resistant chambers are known as arc control pots or sometimes as explosion pots.

With the improvement in the design of the arc control pots, great reductions have been effected both in arc duration and total break time

The main features that have an important bearing upon the performance of a plain-break oil circuit breaker are:

- Length of break.
- Speed of contact movement.
- Head of oil above contacts.
- Clearance to earthed metal adjacent to contacts.



Bulk oil circuit-breaker with arc control device.

In plain-break oil circuit breaker there is a fixed and a moving contact immersed in Bulk oil. The metal tank is strong, weather tight to keep moisture out and earthed.

Figure shows a double break plain oil circuit breaker. When contacts separate there is a severe arc which struck between the contact decomposes the oil into gases. The gas obtained is mainly hydrogen. The volume of gases produced is about one thousand times that

of the oil decomposed. Hence, the oil is pushed away from arc and the gaseous medium surrounds the arc. The arc interrupting factors are as follows

- Elongation of the arc.
- Formation of gaseous medium in between the fixed and moving contacts. This has a high heat conductivity and high dielectric strength.

A large gaseous pressure is developed because a large amount of energy is dissipated within the tank. Therefore, the tank of the circuit breaker is made strong to withstand such a large pressure. When gas is formed around the arc, the oil is displaced. To accommodate the displaced oil, an air cushion between the oil surface and the tank is essential. The air cushion also absorbs the mechanical shock produced due to upward oil movement of oil.

Sufficient level of oil above the contacts is required to provide substantial oil pressure at the tank so it prevent escape of liberated hydrogen gas from oil to air, thus prevent formation of explosive mixture,

Certain gap between the contacts must be created before the arc interruption occurs. To achieve this speed of the break should be as high as possible, Welding of contacts may result on short-circuit interruption if the speed of contact movement is slow

The Double breaks in series provide rapid arc elongation (increases the length of the arc such that arc resistance increases), but this arrangement has the disadvantage of unequal voltage distribution across the breaks.

To assist arc interrupting process arc control device are fitted to fixed contact, this arc control device are semi-enclosed chamber made up of insulating material, the performance of Ocb depends on effectiveness of arc control device

The operating mechanism i.e. opening and closing of breaker contacts are obtained by lowering and rising tension rod. the arc control device are normally connected to fixed contact such that contact separation take place inside the semi-enclosed chamber the gas produced in the chamber produces very high pressure in it, This arc is extinguished by the oil and by the gases formed by the decomposition of oil, there by the arc interruption is very quick. . As the moving contacts leave the arc control Plain break bulk oil circuit-breaker.

The trapped gas gets released from the arc control device, while doing so, the arc is extinguished by blast effect

Disadvantages

- Contacts may get welded during arc interruption process if the speed of contacts movement is slow.
- Large amount of oil for higher voltage is necessary in bulk oil circuit-breakers through only a small quantity is necessary for arc extinction. The large quantity is

necessary to provide insulation between the live parts and earthed steel tank. If the container is made of ceramic material, the size of container could be made small.

- Decomposition of oil produce carbon particle which result in contamination and decrees of dielectric strength of transformer oil.
- The entire oil in the tank is likely to get deteriorated duo to sludge formation in the proximity of arc. Then the entire oil needs replacement

Minimum oil circuit breaker.

This type is also known as poor oil or small oil circuit-breaker. In minimum oil circuit- breakers the current interruption takes place inside ‘interrupter’. The enclosure of the interrupter is made of insulating material like porcelain. Hence the clearance between the live parts and the enclosure can be reduced and lesser quantity of oil require for internal insulation. There are two chambers separated from each other, but both filled with oil. The upper chamber is arc extinction chamber. The oil from this chamber does not mix with that in the lower chamber. Lower chamber acts like a dielectric support.

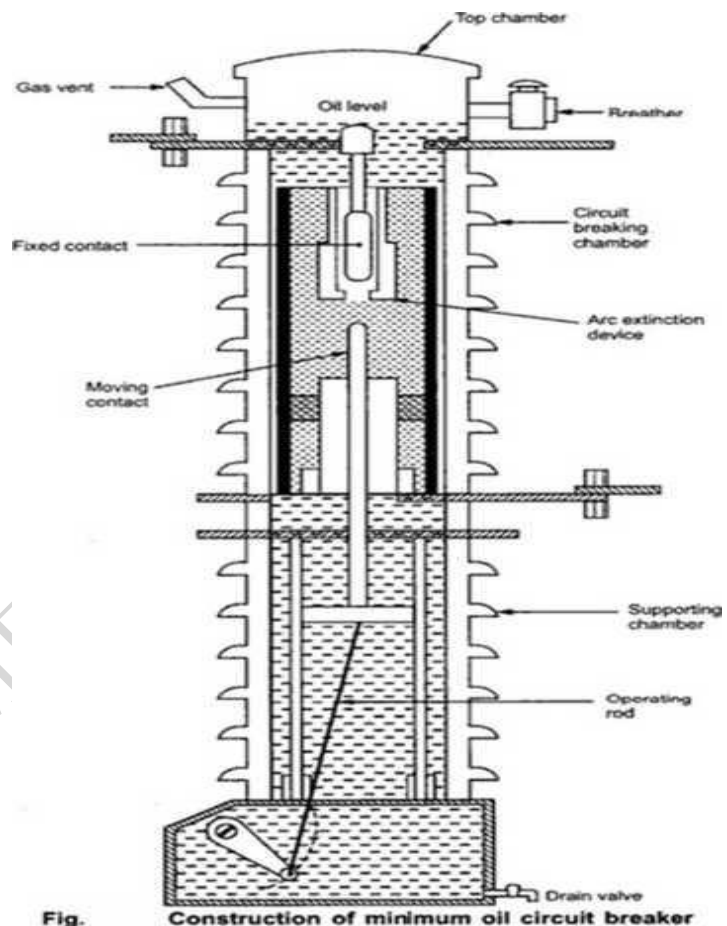


Fig. Construction of minimum oil circuit breaker

PRINCIPLE OF ARC-EXTINCTION ON OIL BREAKERS

As the current carrying contacts are separated under oil, the heat of the arc causes decomposition of the oil. The gases formed due to the decomposition expand, causing increase in pressure. The pressure built-up and the flow of gases is influenced by the design of arc-control device speed of contact travel, the energy liberated by the arc, etc. The gas flowing near the contact zone causing cooling and splitting of the arc. The contact space is filled with fresh dielectric oil after the final arc interruption at a current zero.

The advantages of minimum oil circuit breaker arc

- The quantity of oil required is small.
- The space requirement is reduced.
- The risk of fire is reduced.

Disadvantages

- Due to smaller quantity of oil, the degree of carbonisation is increased.
- The gases are difficult to remove from the contact space in time.
- The dielectric strength of the oil deteriorates rapidly as degree of carbonisation is high

4.9 Air Blast Circuit Breaker

Air blast circuit breakers are suitable for operating voltages of 132 kV and above. They have also been used in 11 kV-33 kV range for certain applications. At present, SF₆ circuit breakers are preferred for 132 kV and above. Vacuum circuit breakers are preferred for 11 kV-33 kV range. Therefore, the air blast circuit breakers are becoming obsolete.

In air blast circuit-breaker (also called compressed air circuit-breaker) high pressure air (at 20-30 kg/cm) is used as an arc quenching medium, this high pressure is forced over the arc through a nozzle at the instant of contact separation. The ionized gas between the contacts is blown away by the blast of the air. After the arc extinction the chamber is filled with high pressure air, which prevents restrike of arc.

PRINCIPLE OF ARC QUENCHING IN ABCBs

The air blast circuit-breaker needs an auxiliary compressed air system which supplies air to the air receiver of the breaker. For opening operation, the air is admitted in the arc extinction chamber. It pushes away the moving contacts. In doing so the contacts are separated and the air blast takes away the ionized gases along with it and assists arc extinction. Within one or two cycles the arc is extinguished by the air blast and the arc extinction chamber is filled with high pressure air has higher dielectric strength than that of atmospheric pressure. Hence small contact gap of few centimetres is enough the flow of air around contacts is guided by the nozzle shaped contacts. It may be axial cross or a suitable combination

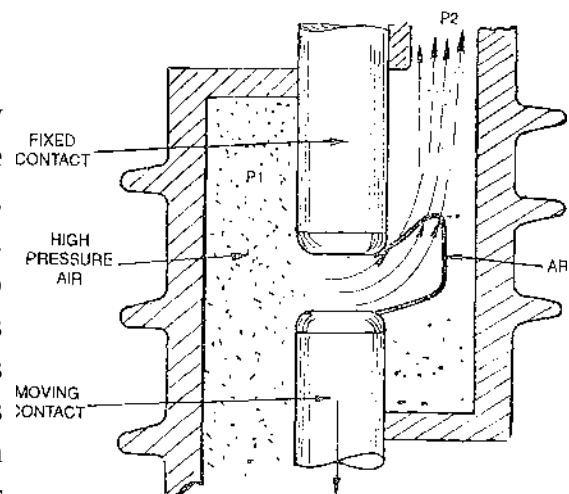


Fig. Flow of air in Air-blast C.B.

In the axial blast type air flow shown in Fig. (a) The flow of air is longitudinal along the arc

In axial blast type air flow, the air flows from high pressure reservoir to the atmosphere through a convergent divergent nozzle. The difference in pressure and the design of nozzle is such that as the air expands into the low-pressure zone, it attains almost supersonic velocity. The flow of air through the nozzle is governed by the parameters like pressure ratio, area of throat, exit area of nozzle, and is influenced by the diameter of the arc itself

The air flowing at a high speed axially along the arc causes removal of heat from the periphery of the arc and the diameter of the arc reduces to a low value at current zero. At this instant the arc is interrupted and the contact-space is flushed with fresh air flowing through the nozzle. Resistance switching is employed in axial blast type to reduce RRRV.

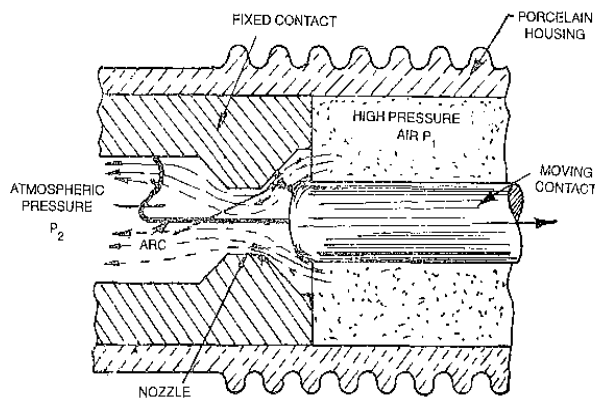
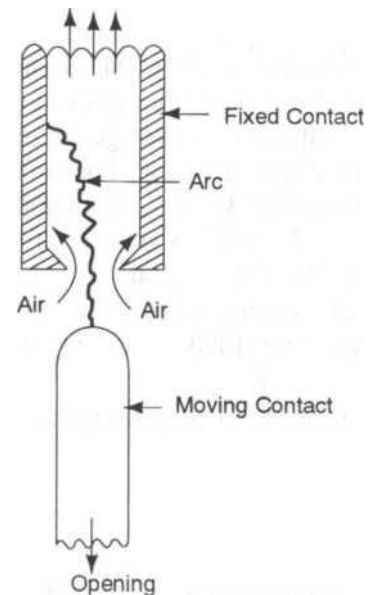
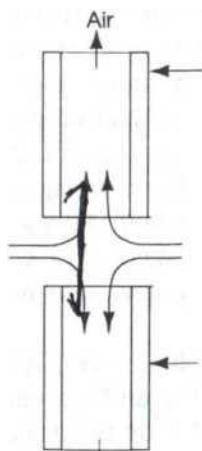


Fig. (a) Axial Flow.



(b)

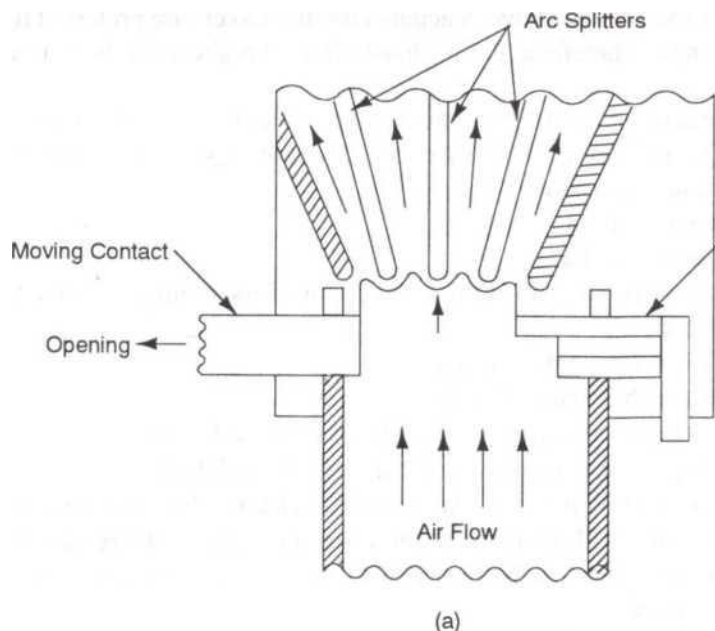


(c)

(b) Single blast type axial-blast circuit breaker (c) Double blast type (or radial-blast type) axial- blast circuit breaker

Cross-blast circuit breaker

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



The advantages of air blast circuit breakers over oil circuit breakers are:

- Cheapness and free availability of the interrupting medium, chemical stability and inertness of air.
- High speed operation.
- Elimination of fire hazard.
- Short and consistent arcing time and therefore, less burning of contacts.
- Less maintenance.
- Suitability for frequent operation.
- Facility for high speed reclosure.

The disadvantages of an air blast circuit breaker are as follows.

- An air compressor plant has to be installed and maintained, Required more auxiliary components.
- Upon arc interruption the air blast circuit breaker produces a high-level noise when air is discharged to the open atmosphere. In residential areas, silencers need to be provided to reduce the noise level to an acceptable level, not suitable in residential area
- Problem of current chopping.
- Problem of restriking voltage.

4.10 SF6 Circuit Breakers

Sulphur hexafluoride (SF₆) is heavy gas its density is five times that of air, having good dielectric strength and excellent arc quenching (Interrupting) property.

Properties of SF₆

It is an chemically inert and it does not attack metals or glass, Colourless, odourless, Nontoxic, Pure SF₆ gas is not harmful to health, nontoxic, and non-flammable. At atmospheric pressure, its dielectric strength is about 2.5 times that of air. At 3 atmospheric pressure its dielectric strength is equal to that of transformer oil.

Advantages are it is an **electronegative gas**, i.e. it has high affinity for electrons. When a free electron comes in collision with a neutral SF₆ gas molecule, the electron is absorbed by the neutral gas molecule and a negative ion is formed. As the negative ions so formed are heavy they do not (Ionize easily) attain sufficient energy to contribute to ionisation of the gas, thus prevent breakdown of SF₆ gaseous Insulator, This property gives a good dielectric property.

Electro negativity of the gas gives **lower arc-time constant**. The time required for the medium to regain its dielectric strength after final current zero is called arc-time constant. The arc-time constant of SF₆ gas is of the order of a few Microseconds

The gas has an excellent property of recombination after the removal of the source which energizes the arc. This gives an excellent arc quenching property. The gas has also an excellent heat transfer property. Its thermal time constant is about 1000 times shorter than that of air.

Major disadvantage is that the SF₆ gas liquefies at certain low temperatures, the temperature at which SF₆ changes to liquid depends on the pressure. The liquefaction temperature increases with pressure. At 15 atm. pressure, the gas liquefies at a temperature of about 10°C. Hence, SF₆ breakers are equipped with thermostatically controlled heaters wherever such low ambient temperatures are encountered.

However, it decomposes to SF_4 , SF_2 , S_2 , F_2 , S and F at temperatures of the order of 1000°C after arc extinction, the products of decomposition recombine in a short time, within about 1 microsecond. In the presence of moisture, the decomposition products can attack contacts, metal parts and rubber sealing's in SF_6 circuit breakers. Therefore, the gas in the breaker must be moisture-free. To absorb decomposition products, a mixture of soda lime ($\text{NaOH} + \text{CaO}$) and activated alumina can be placed in the arcing chamber.

SF_6 is now being very widely used in electrical equipment like high voltage metal enclosed cables; high voltage metal clad switchgear, bushings, circuit- breakers, current transformers, etc.

SF_6 circuit breakers are manufactured in the voltage range 3.6 kV to 765 kV. However, they are preferred for voltages 132 kV and above. The dielectric strength of SF_6 gas increases rapidly after final current zero. SF_6 circuit breakers can withstand severe RRRV and are capable of breaking capacitive current without restriking. Problems of current chopping is minimised. Electrical clearances are very much reduced due to high dielectric strength of SF_6

Preparation of SF_6 Gas

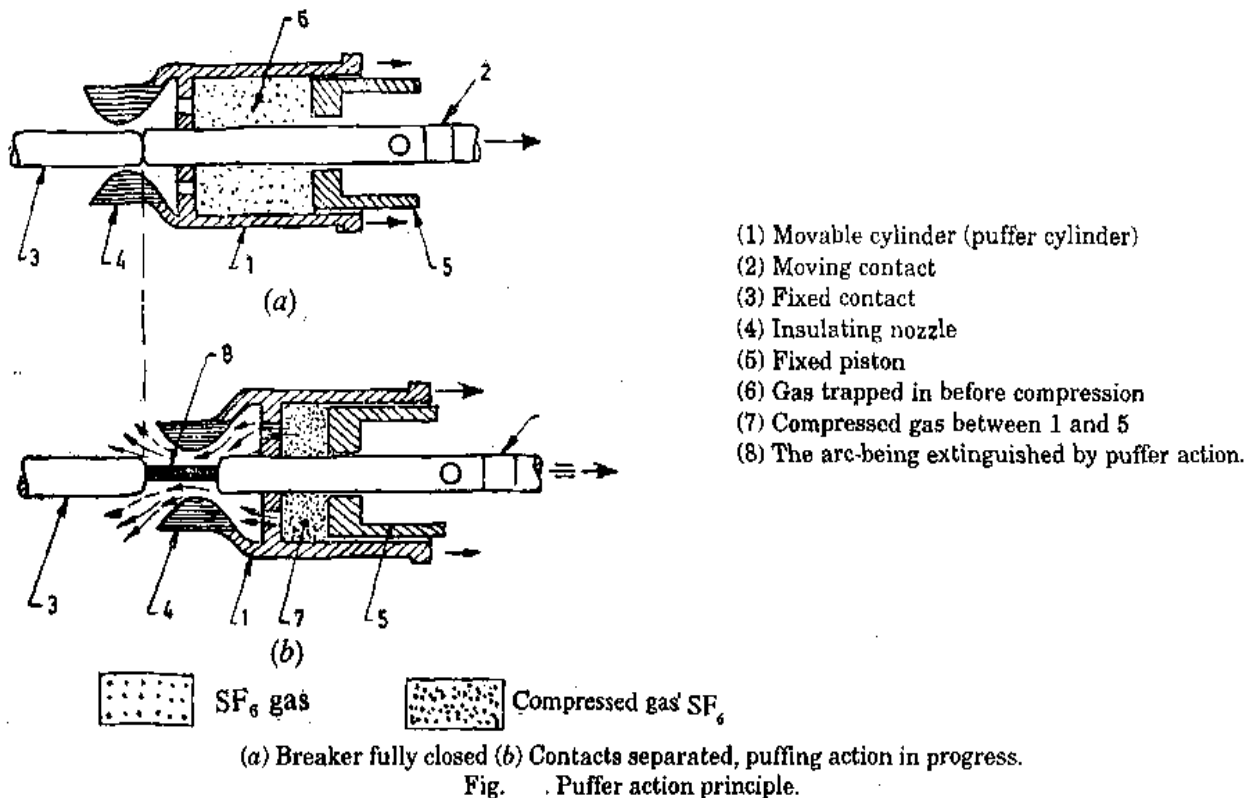
Sulphur hexafluoride gas is prepared by burning coarsely crushed roll sulphur in fluorine gas, in a steel box, provided with staggered horizontal shelves, each bearing about 4 kg of sulphur. The steel box is made gas-tight. The gas thus obtained contains other fluorides such as S_2F_{10} , SF_4 and must be purified further SF_6 gas is generally supplied by chemical firms. The cost of gas is low if manufactured on a large scale.

The gas is transported in liquid form in cylinders. Before filling the gas, the circuit-breaker is evacuated to the pressure of about 4 mm of mercury so as to remove the moisture and air. The gas is then filled in the circuit-breaker. The gas can be reclaimed by the gas-handling unit

Types of SF₆ Circuit Breakers

Puffer-type SF₆ circuit breakers

This type of circuit breakers are also sometimes called single-pressure or impulse type SF₆ circuit breakers. In this type of breakers, gas is compressed by a moving cylinder system and is released through a nozzle to quench the arc.



These circuit-breakers employ a principle of puffer action illustrated in above Fig

Fig (a) illustrates the fully closed position of the interrupter. The moving cylinder (1) is coupled with the movable conductor (2) against the fixed piston (5) and there is a relative movement between (1) and (5) and the gas is compressed in the cavity (6). This trapped gas is released through the nozzle (4), during arc extinction process. During the travel of the moving contact (2) and movable cylinder (1) the gas puffs over the arc and reduces the arc diameter by axial convection and radial dissipation. At current zero, the arc diameter becomes too small and the arc gets extinguished. The puffing action continues for some time even after the arc extinction and the contact space is filled with cool, fresh gas.

MERITS OF SF₆ CIRCUIT-BREAKERS

- Outdoor SF₆ CB is simple less costly, maintenance free
- Due to outstanding arc quenching property of SF₆ the arcing time is very small. This reduces contact erosion
- During arcing of SF₆ breaker, no carbon dioxide is formed and hence no reduction of dielectric strength
- SF₆ breaker is compact in size and electrical clearances are drastically reduced
- The gas is non-inflammable and chemically stable. The decomposition products are not explosive. Hence there is no danger of fire or explosion.
- Same gas is recirculated in the circuit. Hence requirement of SF₆ gas is small
- Ample overload margin. For the same size of conductors, the current carrying ability of SF₆ circuit-breakers is about 1.5 times that of air blast circuit-breakers because of superior heat transferability of SF₆ gas.
- The breaker is silent and does not make sound like air-blast-circuit breaker during operation.
- The sealed construction avoids the contamination by moisture, dust, sand etc. No costly compressed air system like Air Blast CB.
- The maintenance required is minimum, the breaker may need maintenance once in four to ten years!
- Ability to interrupt low and high fault currents, magnetising currents, capacitive current, without excessive over-voltages. The SF₆ gas circuit-breaker can perform the various duties like clearing short-line faults, opening unloaded transmission lines capacitor switching transformer, reactor switching etc. much smoothly.
- Excellent insulating arc extinguishing physical and chemical properties of SF₆ gas is the greater advantage of SF₆ breakers. No frequent contact replacement.

SOME DEMERITS OF SF₆ CIRCUIT-BREAKER

- Sealing problems arise. Imperfect joints lead to leakage of gas.
- In this case of leakage in the breaker tank, this gas, being heavier than air settles in the surroundings and may lead to suffocation of the operating personnel. However, it is non-poisonous
- Arced SF₆ gas is poisonous and should not be inhaled or let-out.
- Influx of moisture in the breaker is very harmful to SF₆ gas circuit-breakers. Several failures reported due to this cause.
- Mechanism of higher energy level is necessary for puffer type SF₆ breakers. Lower speeds due to friction, misalignment can cause failure of breaker.
- The internal parts should be cleaned thoroughly during periodic maintenance under clean, dry environment. Dust of Teflon and sulfides should be removed.

- Special facilities are needed for transporting the gas, transferring the gas and maintaining the quality of gas. The deterioration of quality of the gas affects the reliability of the SF₆ circuit breaker.

Non Puffer Type SF₆ Circuit Breaker

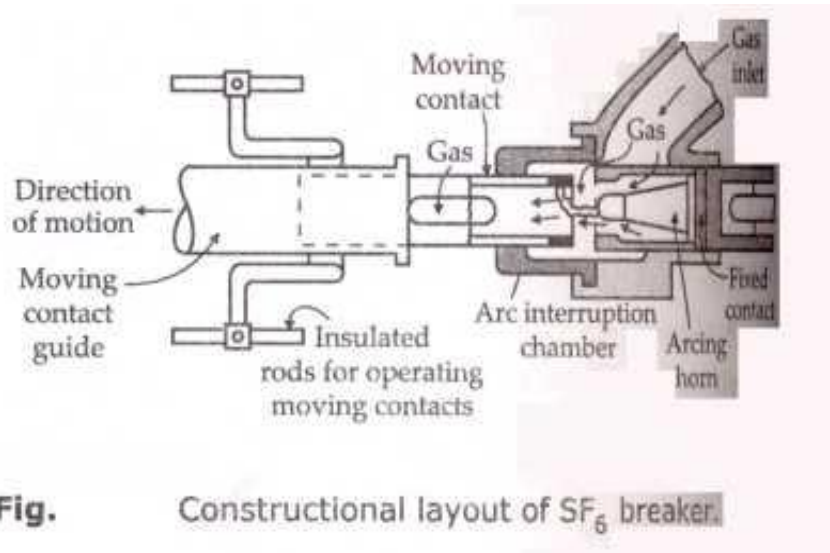


Fig. Constructional layout of SF₆ breaker.

It consists of a fixed current carrying hollow cylindrical contact fitted with an arcing horn. The moving portion consists of another hollow cylinder with rectangular holes in the sides so that gas after blowing along and across the arc is let out through these apertures. The moving contact of each interrupter is so mounted on two insulated rods that all the moving contacts operate simultaneously. Generally three interrupted units are mounted in series. (Above shown is one interrupter) When the breaker closed the current passes from the fixed contact into the side wall of the moving contact. From the moving contact the current is conducted to the adjacent fixed contact through the moving contact guide. In this way the current is conducted in each interrupter in the closed position. An arcing horn is placed inside the fixed contact. Its head projects into the moving contact when the breaker operates, an arc is struck between the fixed contact and the moving contact but it quickly transfers from the fixed contact to the arcing horn and greatly reduces the burning and pitting at the fixed contacts. The tips of the fixed contact, arcing horn and the moving contact are coated with copper tungsten arc resistance material.

The interruption of the arc is achieved by the action of sulphur hexafluoride gas forcing gas at high pressure flows through tubes leading to interrupter units at a high speed and producing both axial and cross blast effects.

A closed system is used for the gas. Since the gas is costly, it is reconditioned and reclaimed after each operation of the breaker. Necessary auxiliary system is therefore provided for this purpose.

4.11 Vacuum Circuit Breaker

The dielectric strength and arc interrupting ability of high vacuum is superior to those of porcelain, oil, air and SF₆ at atmospheric pressure. SF₆ at 7 atm. pressures and air at 25 atm. pressure have dielectric strengths higher than that of high vacuum. The pressure of 10⁻⁵ mm of mercury and below is considered to be high vacuum. Low pressures are generally measured in terms of torr; 1 torr being equal to 1 mm of mercury. It has now become possible to achieve pressures as low as 10⁻⁸ torr.

In high vacuum, of the order of 10⁻⁵ mm of mercury, the mean free path (Collision Path B/W Molecules) of the residual gas molecules becomes very large. It is of the order of a few metres. Therefore, when contacts are separated by a few mm in high vacuum, an electron travels in the gap without making collision.

In vacuum CB the formation of arc is due to metal vaporisation, not from the gaseous medium b/w electrode contacts as in case of other CB, in vacuum arc electrons and ions do not come from the medium in which the arc is drawn but they come from the electrodes due to the evaporation of their surface material. The breakdown strength is independent of gas density (Gas evolved from electrodes surface). It depends only on the gap length and surface condition and the material of the electrode. The breakdown strength of highly polished and thoroughly degassed electrodes is higher. Copper-bismuth, silver-bismuth, silver-lead and copper-lead are good materials for making contacts of the breaker

When contacts are separated in high vacuum, an arc is drawn between them. The arc does not take place on the entire surface of the contacts but only on a few spots. The contact surface is not perfectly smooth. It has certain micro projections. At the time of contact separation, these projections form the last points of separation. The current flows through these points of separation resulting in the formation of a few hot spots. These hot spots emit electrons and act as cathode spots. In addition to thermal emission, electrons emission may be due to field emission and secondary emission

Operation (Arc extinction in vacuum interrupters)

The arc interruption process in vacuum interrupters is quite different from that in other types of circuit-breakers. The vacuum as such is a dielectric medium and arc cannot persist in ideal vacuum. However, the separation of current carrying contacts causes the vapour to be released from the contacts surface giving rise to plasma. Thus, as the contacts separate, the contact space is filled with vapour of positive ions liberated from the contact material. The vapour density depends on the current in the arc. During the decreasing mode of the current wave the rate of release of the vapour reduces and after the current zero, the medium regains the dielectric strength provided vapour density around Contacts has substantially reduced.

Construction

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

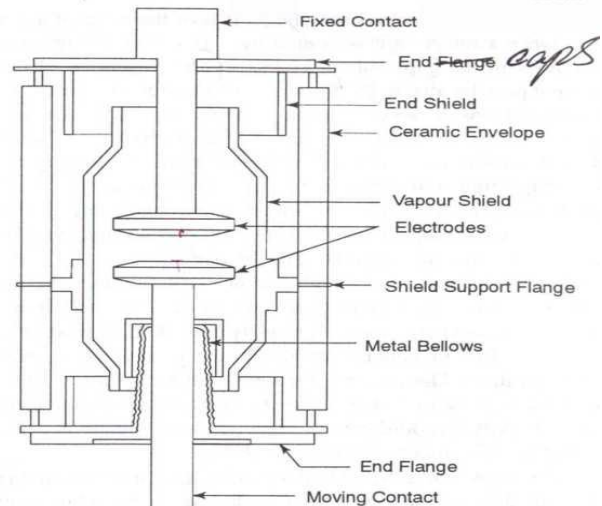


FIGURE Vacuum circuit breaker

Advantages

The vacuum circuit breaker is very simple in construction compared to other types of circuit breaker. The contact separation is about 1 cm which is adequate for current interruption in vacuum. As the breaker is very compact, power required to close open its contacts is much less compared to other types of breaker. It is capable of interrupting capacitive and small inductive currents, without producing excessive transient over voltages. Vacuum circuit breakers have other advantages like suitability for repeated operations, least maintenance, silent operation, long life, silent operation, high speed of dielectric recovery, less weight of moving parts, highest insulation strength etc.

Vacuum circuit breakers have now become popular for voltage ratings up to 36 kV. Up to 36 kV they employ a single interrupter

Disadvantage

- Erosion of contact surface, material is lost from the surface
- Contact welding under either momentary condition of closing or short circuit.

- In the event of loss of vacuum due to transit damage or failure, the entire interrupter is rendered useless. It cannot be repaired at site.
- For interruption of low magnetising currents in certain range, additional surge suppressors are required in parallel with each phase of a VCB

4.12 High Voltage DC Circuit Breakers

HVDC transmission lines are used for point to point transmission of large power over long distances. Such lines have many advantages over ac transmission lines such as lower cost, less stability problems, less corona loss and less radio interference, etc. The current in HVDC lines is controlled by controlling the firing circuits of the thyristors employed in rectifiers and inverters. Switching operations are performed from ac side with the help of ac circuit breakers

In ac circuits, current passes through natural current zeros, and hence it is possible to design ac circuit breakers to interrupt large currents. This feature is not available in dc. If a high current is suppressed abruptly in dc, a very high transient voltage appears across the contacts of the circuit breakers. Therefore, in dc circuit breakers, some external circuits have to be provided to bring down the current from full value to zero, smoothly without suppressing it suddenly

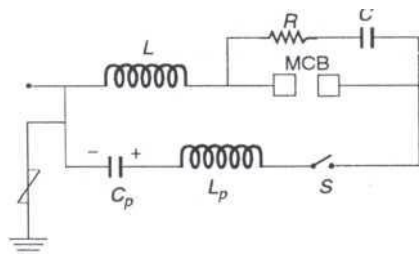
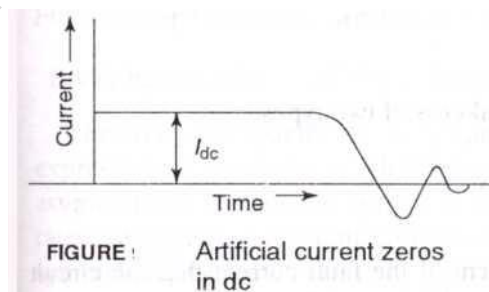


FIGURE: HVDC circuit breaker



The additional circuit creates artificial current zeros which are utilized for arc interruption as shown in above Fig

Figure shows the schematic diagram of a HVDC circuit breaker. It consists of a main circuit breaker MCB and a circuit to produce artificial current zero and to suppress transient voltage

The main circuit breaker MCB may either be an SF6 or vacuum circuit breaker. R and C are connected in parallel with the main circuit breaker to reduce dv/dt after the final current zero. L is a saturable reactor in series with the main circuit breaker. It is used to reduce di/dt before current zero. Cp and Lp are connected in parallel to produce artificial current zero after the separation of the contacts in the main circuit breaker MCB. A non-linear resistor is used

to suppress the transient overvoltage which may be produced across the contacts of the main circuit breaker.

Switch S, which is a triggered vacuum gap, is switched immediately after the opening of the contacts of the main circuit breaker. The capacitor 'C' is precharged in the direction as shown in the figure. When S is closed, the precharged capacitor C_p discharges through the main circuit breaker and sends a current in opposition to the main circuit current. This will force the main circuit current to become zero with a few oscillations. The arc is interrupted at a current zero.

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4.13 Rating of Circuit Breaker

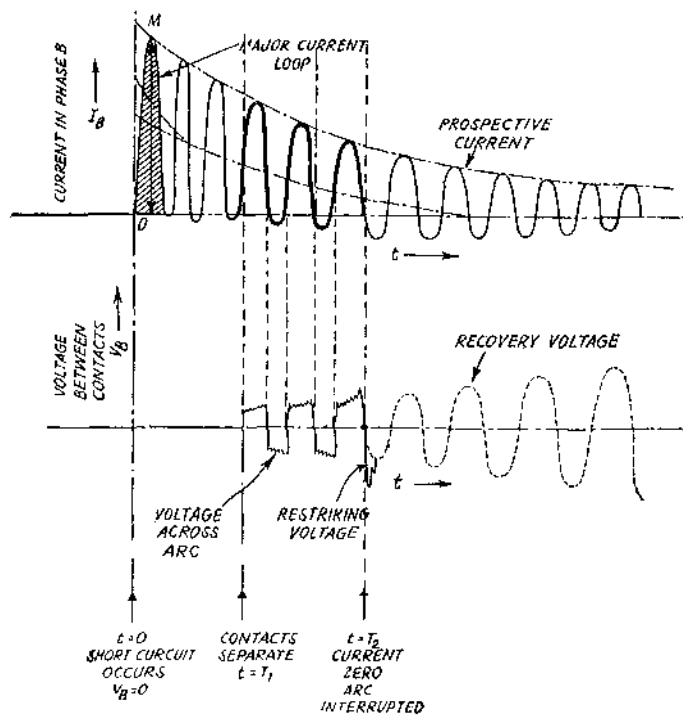


Fig. Oscillogram of current and voltage during fault-clearing.

Rated Short Circuit-Breaking Current

As the Short circuit occurs, the short circuit current attains high value, the CB contact start separating after the operation of relay. The contact of CB separate during transient state, the RMS value of current at the instant of contact separation is called **breaking current of CB** & Expressed in KA

The rated short-circuit breaking-current of a circuit-breaker is highest RMS value of short-circuit current which the circuit-breaker is capable of breaking under specified conditions of transient recovery voltage and power frequency voltage. It is expressed in kA R.M.S. at contact separation.

Referring to above Fig. the short-circuit current has a certain value at the instant of contact separation, ($t = T_1$), the breaking current refers to value current at the instant of the contact separation

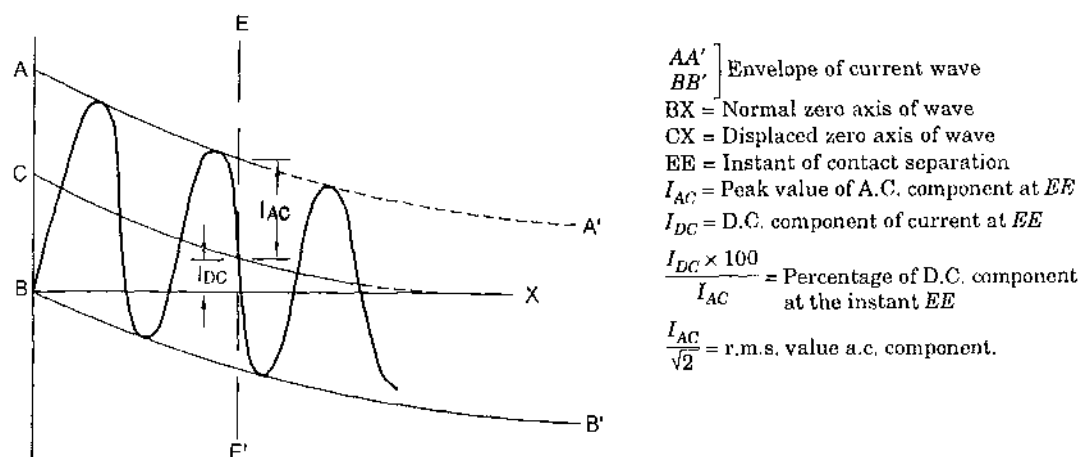


Fig. Determination of breaking current.

The breaking current is expressed by two values :

- (1) the r.m.s. value of a.c. component at the instant of contact separation EE , given by

$$\frac{I_{AC}}{\sqrt{2}}$$

- (2) the percentage d.c. component at the instant of contact separation given by

$$\frac{I_{DC} \times 100}{I_{AC}}$$

The r.m.s. values of a.c. components are expressed in kA, the standard values being 8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100 kA.

The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of MVA given as follows:

$$MVA = \sqrt{3} \text{ kV} \times \text{kA}$$

where MVA = Breaking capacity of a circuit-breaker

kV = Rated voltage

kA = Rated breaking current.

Rated Short-circuit Making Current

If a CB closes on clearing the fault the current would increase to high value during 1st half cycle (first current loop). The highest peak value is reached during 1st current loop, this peak value is called **making current**

It may so happen that circuit-breaker may close on an existing fault. In such cases the current increase to the maximum value at the peak of first current loop. The circuit-breaker should be able to close without hesitation as contacts touch. The circuit-breaker should be able to withstand the high mechanical forces during such a closure. These capabilities are proved by carrying out making

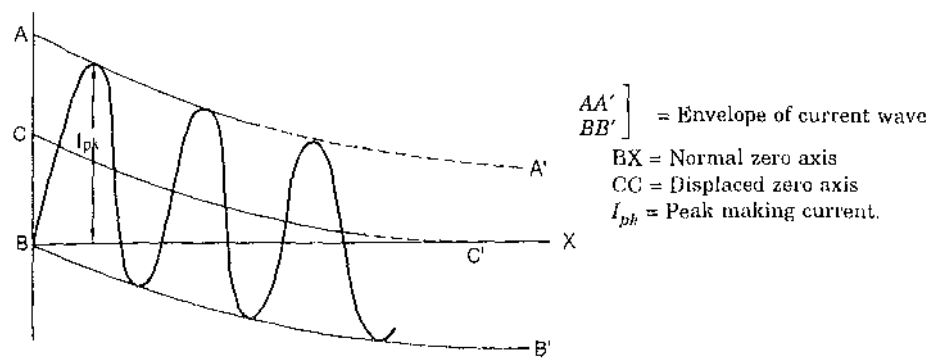


Fig. 1. Determination of peak making current.

current test. The rated short-circuit making current of a circuit-breaker in the peak value of first current loop of short-circuit current (I_{pk}) which the circuit-breaker is capable of making at its rated voltage

The rated short-circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current.

$$\begin{aligned} \text{Rated making current} &= 1.8 \times \sqrt{2} \times \text{Rated short-circuit breaking} \\ &= 2.5 \times \text{Rated short-circuit breaking current.} \end{aligned}$$

the factor $\sqrt{2}$ converts the r.m.s. value to peak value. Factor 1.8 takes into account the doubling effect of short-circuit-current during the first quarter cycle. with consideration to slight drop in current

Short-time Current Rating

The circuit breaker must be capable of carrying short-circuit current for a short period while another circuit breaker (in series) is clearing the fault. The rated short-time current is the rms value (total current, both A.C. and D.C. components) of the current that the circuit breaker can carry safely for a specified short period

Rated Voltage, Current and Frequency

In a power system, the voltage level at all points is not the same. It varies, depending upon the system operating conditions. Due to this reason manufacturers have specified a rated maximum voltage at which the operation of the circuit breaker is guaranteed. The specified voltage is somewhat higher than the rated nominal voltage.

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

The rated frequency is also mentioned by the manufacturer. It is the frequency at which the circuit breaker has been designed to operate. The standard frequency is 50 Hz. If a circuit breaker is to be used at a frequency other than its rated frequency, its effects should be taken into consideration.

Selection of Circuit Breakers

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

<i>Type</i>	<i>Arc Quenching Medium</i>	<i>Voltage Range and Breaking Capacity</i>
Miniature circuit breakers	Air at atmospheric pressure	400-600V; for small current rating
Air-break circuit breakers	Air at atmospheric pressure	400 V-11 kV; 5-750 MVA
Minimum oil circuit breakers	Transformer oil	3.3 kV-220 kV; 150-25000 MVA
Vacuum circuit breakers	Vacuum	3.3 kV-33 kV; 250-2000 MVA
SF ₆ circuit breakers	SF ₆ at 5 kg/cm ² pressure	3.3-765 kV; 1000-50,000 MVA
Air blast circuit breakers	Compressed air at high pressure (20-30 kg/cm ²)	66 kV-1100 kV; 2500-60,000 MVA

Earlier oil circuit breakers were preferred in the voltage range of 3.3 kV- 66 kV. Between 132 kV and 220 kV, either oil circuit breakers or air blast circuit breakers were recommended. For voltages 400 kV and above, air blast circuit breakers were preferred. The present trend is to recommend vacuum Circuit Breaker.

<i>Rated Voltage</i>	<i>Choice of Circuit Breakers</i>	<i>Remark</i>
Below 1 kV	Air-break C.B.	
3.3 kV-33 kV	Vacuum C.B., SF ₆ C.B., minimum oil C.B.	Vacuum preferred
132 kV-220 kV	SF ₆ C.B, air blast C.B, minimum oil C.B.	SF ₆ preferred
400 kV-760 kV	SF ₆ C.B., air blast C.B.	SF ₆ is preferred

4.14 Testing of Circuit Breakers

INDIRECT TESTING

The short-circuit power available in testing stations (of the order of 4000 MVA in laboratory type testing station) is not sufficient to test a complete breaker (which is of rated breaking capacity of the order of 10,000 MVA at 245 kV). Even single pole of an EHV circuit-breaker cannot be tested by direct testing method. As all EHV circuit-breaker are with several arc interrupter units tested per pole each unit can be separately tested. This is called Unit Testing. From tests on one unit, the capacity of the 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 of capacity 5, times that of the plant.

The important indirect Testing Methods include the following :

Unit Testing. Which means testing one or more units separately.

Synthetic Testing. In which the current source providing short circuit current and voltage source supplying restriking and recovery voltage are different.

Substitution Tests. These are conducted for oil circuit breaker; the characteristics of current versus time are obtained for different voltages. The performance beyond the tested values is determined by approximation.

Compensation Tests. Which are conducted on oil circuit-breakers in critical range of low current by a suitable compensation such as increased frequency, increase restriking voltages etc.

Capacitance Tests. The capacitor which is charged by a voltage source is discharged through the breaker. An oscillatory circuit provides restriking voltage

UNIT TESTING OR ELEMENT TESTING

Almost all modern EHV circuit-breakers, minimum oil, Air Blast, SF6 etc. consist of two or more identical units (or interrupters) per pole. These interrupters operate (open or close) simultaneously and share the voltage across the pole almost equally. The breaking capacity in M.V.A. is also shared equally. Hence by testing one unit, the results can be applied to the capacity of the pole. This is known as Unit Testing or Element Testing.

While applying unit test the voltage must be reduced by factor a and all the impedances should be reduced by factor a to get test voltage across the unit same as that following expressions

$$a = \frac{1}{n} \text{ when one unit is tested together.}$$

$$a = \frac{m}{n} \text{ when } m \text{ units are tested together.}$$

where n is number of units per pole.

For example consider 3 pole, 230 kV circuit-breaker with three units per pole. Test is to be conducted at normal voltage i.e. 230 kV between poles. Voltage across one pole is $230/\sqrt{3} = 133$ kV.

$$a = \frac{1}{n}, n = 3$$

$\therefore$ Voltages required for testing one unit

$$= a \times 133 = \frac{1}{3} \times 133 = 44.33 \text{ kV}$$

Further : L and C of test circuit should be reduced to get same natural frequency as that direct testing, i.e.

$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ in Direct Testing}$$

$$f_n = \frac{1}{2\pi\sqrt{aL \times \frac{C}{a}}} = \frac{1}{2\pi\sqrt{LC}}$$

The natural frequency of transient restriking voltage remains unchanged. Time scale also remains unchanged.

With breakers in which the voltage distribution across the pole is not evenly distributed amongst the units, some units will be stressed more and the others less. The test should be performed so as to test the highest stress coming over the unit. Hence correction must be made in unit testing results. Statistically, unit testing has been established as a reliable method of testing.

SYNTHETIC TESTING

In this method of testing, there are two sources of power supply for the testing, a current source and a voltage source. The current source is a high current, low voltage source. It supplies short-circuit current during the test. The voltage source is a high voltage, low current source. It provides restriking and recovery voltage

There are two methods of synthetic testing- parallel current injection method and series current injection method. Parallel current injection method is widely used as it is capable of providing RRRV and recovery voltage as required by various standards

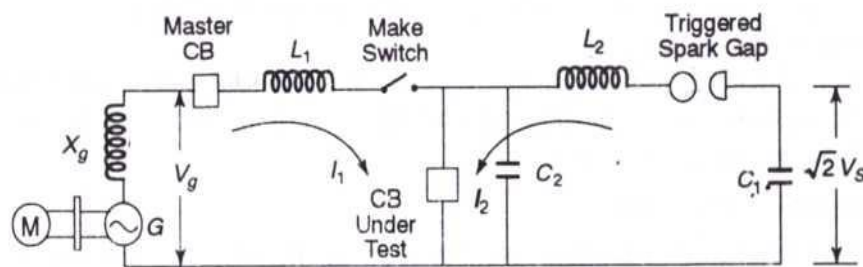


FIGURE Synthetic testing of circuit breaker

Figure shows a circuit for synthetic testing. It is a circuit for parallel current injection method of synthetic testing. The high current source is a motor driven generator. It injects a high short-circuit current I_1 into the circuit breaker under test at a relatively reduced voltage, V_g . The inductance L_1 is to control the short-circuit current. The master circuit breaker and the circuit breaker under test are tripped before current I_1 reaches its natural zero. These circuit breakers are fully opened by the time t_0 . The capacitor C is a high voltage source to provide recovery voltage. It is charged prior to the test, to a voltage $\sqrt{2}V_s$. This voltage is equal to the peak power frequency voltage which will appear across the contacts at the moment the circuit breaker under test interrupts the current. L_2 and C_2 control transient recovery voltage and RRRV. The triggered spark gap is fired at t_1 slightly before the short-circuit current I_1 reaches its natural zero, it is done to properly simulate the pre-current zero zone during the test. There is a control circuit to fire the triggered spark gap at the appropriate moment. Below Figure shows waveforms during synthetic testing.

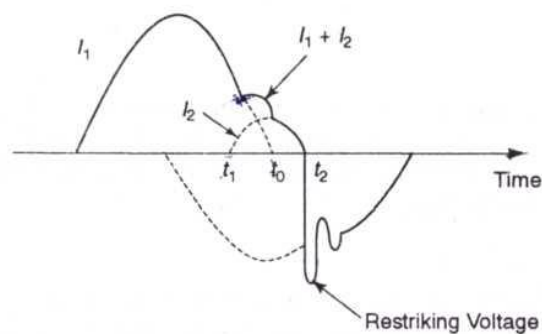


FIGURE Waveform during synthetic testing

Capacitance test

In this test a capacitor is charged by a D.C. voltage source. Capacitor is connected in series with an inductor and making switch. The breaker is connected across the capacitor. C and L from oscillatory circuit. The circuit-breaker under test is opened and voltage across the capacitor is discharged through the arc. The arc gets extinguished at a current zero. This test is used for investigating the behaviour of the breaker towards restriking voltage.

Compensation test

Oil circuit-breakers have internal source of extinguishing energy. For low currents extremely difficult extinguishing conditions may be experienced because of insufficient pressure build up. The characteristics of the breaker in critical range are ascertained by compensation test. These tests are conducted in critical range. In the test, the pressure in the arc extinction device, lengths and durations of arc etc. are recorded, test being conducted at reduced voltage. The reduction in voltage is-compensated by some other factor such as:

- Increased frequency.
- Applying impulse voltage at current zero.
- The pressure in the tank of an oil circuit breaker is given by $P = K V^{0.5} I^{0.2}$

The effect of reduced voltage can therefore be compensated by increasing current

SUBSTITUTION TEST

In substitution test a number of tests at closely graduated capacities are conducted on the breaker with internal source of extinguishing energy. Characteristics of arc duration and current to interrupted are plotted. These are development tests.

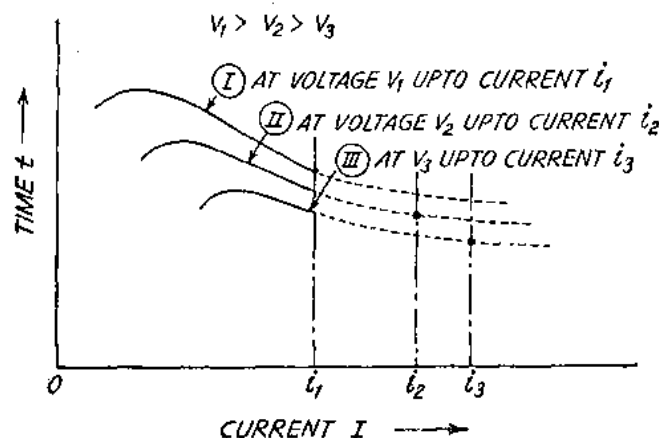


Fig. Substitution test characteristics.

The substitution test is conducted as follows:

1. Test the breaker at full voltage and upto current permitted by the capacity of the plant, i.e. current i_1 of characteristic I.
2. Test the breaker at reduced voltage upto current i_2 permitted by the test plant at reduced voltage V_2 obtain the time required for various current upto i_2 and plot characteristic II
3. Likewise, plot characteristics III at voltage V_3 upto current i_3 , characteristic IV at voltage V_4 upto current i_1 etc where V_1 is the highest test voltage $V_1 > V_3 > V_4$ etc. i_1 is the current at voltage V_1 permitted by test plant.

On plotting the characteristic I, II, III, etc, these are extended by approximation as shown by the dotted lines. From the extended line the breaker performance can be predicated for values of current beyond range of testing station.

Course outcome: Interpret the principle of circuit interruption in different types of circuit breakers

Future readings

1. <http://nptel.ac.in/downloads/108101039/>
2. <https://www.electrical4u.com/protection-system-in-power-system/>
3. <http://electrical-engineering-portal.com>

Module 5 Fuses, Protection against Overvoltages, Modern Trends in Power System Protection

5.0 Fuses: Introductions

5.1 Definitions

5.2 Fuse Characteristics

5.3 Types of Fuses

5.4 Applications of HRC Fuse

5.5 Discrimination

Protection against Overvoltages:

5.6 Causes of Overvoltages

5.7 Lightning phenomena

5.8 Protection against Lightning

Protection of Transmission Lines against Direct Lightning Strokes,

Protection of Stations and Sub –Stations from Direct Strokes

Protection against Travelling Waves,

5.9 Insulation Coordination,

5.10 Basic Impulse Insulation Level (BIL).

5.11 Gas insulated substation/switchgear (GIS).

Course objective

To explain the principle of circuit interruption and different types of circuit breakers.

To describe the construction and operating principle of different types of fuses and to give the definitions of different terminologies related to a fuse.

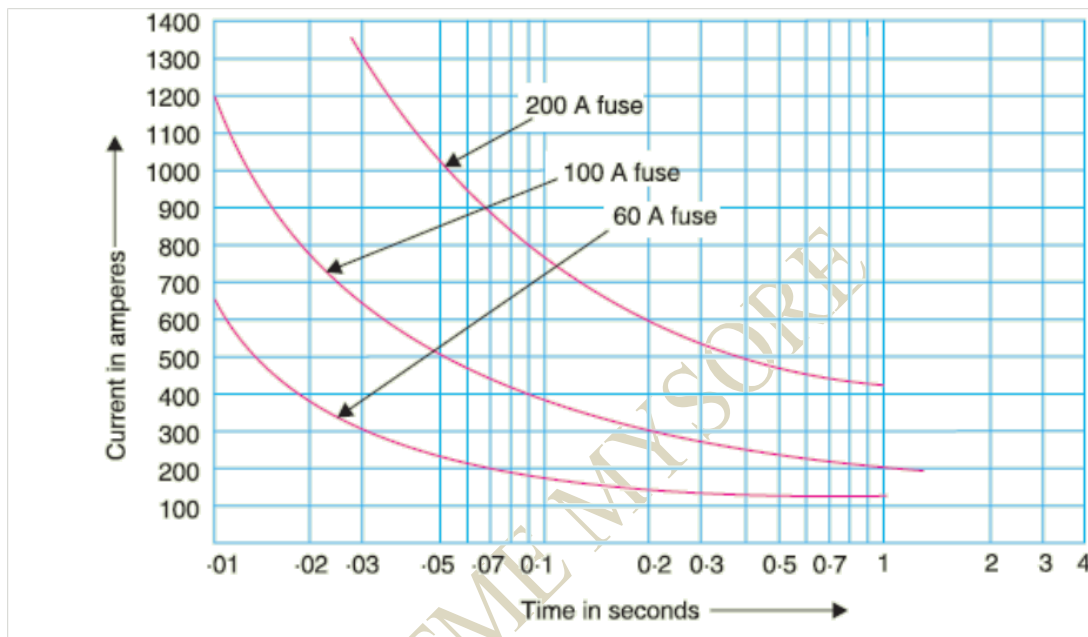
To discuss protection Against Overvoltages and Gas Insulated Substation (GIS).

Module 5

Fuses

5.0 Introductions

Fuse is a short piece of metal, inserted in the circuit, which melts when excessive current flows through it and thus breaks the circuit. The fuse element is generally made of materials having low melting point, high conductivity and least deterioration due to oxidation e.g., silver, copper etc. It is inserted in series with the circuit to be protected. Under normal operating conditions, the fuse element is at a temperature below its melting point. Therefore, it carries the normal current without overheating. However, when a short-circuit or overload occurs, the current through the fuse increases beyond its rated value. This raises the temperature and fuse element melts (or blows out), disconnecting the circuit protected by it. In this way, a fuse protects the machines and equipment from damage due to excessive currents.



The time required to blow out the fuse depends upon the magnitude of excessive current. The greater the current, the smaller is the time taken by the fuse to blow out. In other words, a fuse has inverse time-current characteristics as above shown in Fig. Such a characteristic permits its use for overcurrent protection

Advantages

- (i) It is the cheapest form of protection available.
- (ii) It requires no maintenance.
- (iii) Its operation is inherently completely automatic unlike a circuit breaker which requires an elaborate equipment for automatic action.
- (iv) It can break heavy short-circuit currents without noise or smoke.
- (v) The smaller sizes of fuse element impose a current limiting effect under short-circuit conditions.
- (vi) The inverse time-current characteristic of a fuse makes it suitable for overcurrent protection.
- (vii) The minimum time of operation can be made much shorter than with the circuit breakers.

Disadvantages

- (i) Considerable time is lost in rewiring or replacing a fuse after operation.
- (ii) On heavy short-circuits, *discrimination between fuses in series cannot be obtained unless there is sufficient difference in the sizes of the fuses concerned.
- (iii) The current-time characteristic of a fuse cannot always be co-related with that of the protected Apparatus

Desirable Characteristics of Fuse Element

The function of a fuse is to carry the normal current without overheating but when the current exceeds its normal value, it rapidly heats up to melting point and disconnects the circuit protected by it. In order that it may perform this function satisfactorily, the fuse element should have the following desirable characteristics :

- (i) low melting point e.g., tin, lead.
- (ii) high conductivity e.g., silver, copper.
- (iii) free from deterioration due to oxidation e.g., silver.
- (iv) low cost e.g., lead, tin, copper.

The above discussion reveals that no material possesses all the characteristics. For instance, lead has low melting point but it has high specific resistance and is liable to oxidation. Similarly, copper has high conductivity and low cost but oxidises rapidly. Therefore, a compromise is made in the selection of material for a fuse

Fuse Element Materials

The most commonly used materials for fuse element are lead, tin, copper, zinc and silver. For small currents upto 10A, tin or an alloy of lead and tin (lead 37%, tin 63%) is used for making the fuse element. For larger currents, copper or silver is employed. It is a usual practice to tin the copper to protect it from oxidation. Zinc (in strip form only) is good if a fuse with considerable time-lag is required i.e., one which does not melt very quickly with a small overload.

The present trend is to use silver despite its high cost due to the following reasons:

- (i) It is comparatively free from oxidation.
- (ii) It does not deteriorate when used in dry air.
- (iii) The coefficient of expansion of silver is so small that no critical fatigue occurs. Therefore, the fuse element can carry the rated current continuously for a long time.
- (iv) The conductivity of silver is very high. Therefore, for a given rating of fuse element, the mass of silver metal required is smaller than that of other materials. This minimises the problem of clearing the mass of vapourised material set free on fusion and thus permits fast operating speed.
- (v) Due to comparatively low specific heat, silver fusible elements can be raised from normal temperature to vapourisation quicker than other fusible elements. Moreover, the resistance of silver increases abruptly as the melting temperature is reached, thus making the transition from melting to vapourisation almost instantaneous. Consequently, operation becomes very much faster at higher currents.
- (vi) Silver vapourises at a temperature much lower than the one at which its vapour will readily ionise. Therefore, when an arc is formed through the vapourised portion of the element, the arc path has high resistance. As a result, short-circuit current is quickly interrupted

5.1 DEFINITIONS

Operation of fuse-link. Process of pre-arcing and arcing resulting in blowing/melting of fuse-link.

Cut-off. The melting of fuse-element before the current reaches the prospective peak (fault current peak value). The value of current at which the cut-off (Melting) occurs is called cut-off current. Cut-off current measured as an instantaneous value.

Pre-arcing Time-Time between beginning of the prospective current loop and the cut-off

Arcing Time-Time between cut-off and final current zero.

Total Operating Time-Pre-arcing time plus arcing time.

Fuse element-The part of the fuse which is designed to melt when the fuse operates.

Fuse link-The part of the fuse which needs replacement when the fuse blows out.

SPECIFICATION OF A FUSE LINK

Voltage Rating. This is specified by the manufacturer. The rated voltage of the fuse should be equal to or more than:

1. Voltage of the circuit in a single phase a.c. or two wire circuit.
2. Line voltage in case of three phase a.c. circuit.
3. Voltage between two outer wires in three wire d c circuits

Frequency. A fuse link suitable for 50 c/s may not have same rating for other frequencies of D.C. circuits

Current Rating. This rating is stated by the manufacturer. It is R.M.S. value of current which the fuse can carry continuously without melting.

Minimum Fusing Current. The minimum current at which the fuse will melt.

Fusing Factor. The ratio of minimum fusing current to the current rating,

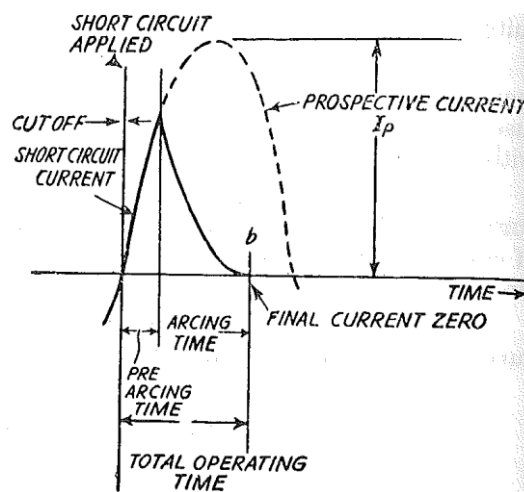
Fusing factor = Minimum fusing current / current rating of fuse, this factor is more than 1

Prospective current of a circuit. The short circuit current that would flow in the circuit if the fuse were absent (replaced by a link of negligible impedance).

Prospective peak current of the circuit- Peak value of first current loop of short circuit current, It is measured in terms of the rms value of the A.C Component.

5.2 Fuse characteristic

Cut-off characteristic of fuse (HRC)

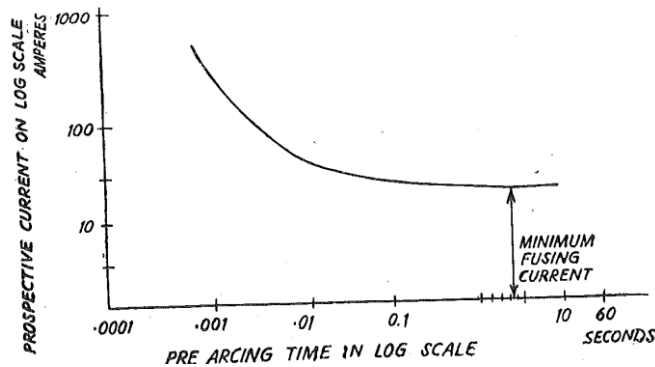


On occurrence of short circuit, the current starts increasing. It would have reached a peak of the prospective current (I_p), if no fuse were there to protect. But fuse does not allow current to reach I_p . Because of sufficient heat energy generated by the fault current, the fuse element is cut-off at I_c and arc is initiated and after a brief arcing time the current is interrupted. The cut-off value depends upon (1) normal current rating of the fuse; (2) prospective current (3) the asymmetry of circuit waveform.

Cut-off property has a great advantage that the short circuit current does not reach the prospective peak, Hence the circuit is not subjected to electrodynamic stresses corresponding to peak prospective current. Hence the bus bar design is considerably simplified because the maximum value of current for design purposes in cut-off value.

Time-current characteristics of fuse

A fuse being a Thermal device possesses inverse time-current characteristic, i.e. operating time decreases as fault current increases.



Typical Time-Current characteristic of a fuse

Normally the characteristics give pre-arcing time plotted against prospective currents upto the rupturing capacity rating of the fuse. Both the axis are plotted on logarithmic axis.

It is observed that as the prospective current increases, the pre-arcing time reduces. Further the characteristic becomes asymmetry and there is a minimum current below which the fuse does not operate. For currents near the minimum fusing current, the operating time is long

Fuse Law

Fuse law determines the current carrying capacity of a fuse wire. The law can be established in the following way. At steady state condition, that is when fuse carry normal current without increasing its temperature to the melting limit. That means at this steady state condition, heat generated due to current through fuse wire is equal to heat dissipated from it, so there is an Equilibrium condition and fuse don't melt at normal rated current. But during abnormal condition as fault current increases the heat generate is not equal to heat dissipated

$$\text{Heat generated} = I^2 \cdot R$$

Where R is the resistance of the fuse wire

$$= I^2 \cdot \rho \cdot \frac{l}{a}$$

Where ρ is the resistivity, l is the length and a is the cross sectional area of fuse wire

$$= I^2 \cdot \rho \cdot \frac{L}{\pi d^2/4}$$

Where d is the diameter of fuse wire

$$= I^2 \cdot K_1 \cdot \frac{L}{d^2} \dots\dots\dots(i)$$

Where K_1 is a constant

Heat lost $\propto$ surface area of fuse wire $\propto \pi d \cdot l$

Therefore, heat lost = $K_2 \cdot d \cdot l \dots\dots\dots(ii)$

Where K_2 is a constant

Now, equating (i) & (ii), we get,

$$I^2.K_1.\frac{1}{d^2} = K_2.d.l$$

$$\Rightarrow I^2 = K.d^3$$

Where $K = \frac{K_2}{K_1}$ is another constant

$$\Rightarrow I = K.d^{3/2}$$

$$\Rightarrow I = K.d^{1.5}$$

This is known as **fuse law**, where 'I' is an approximate value of the minimum fusing current for a round fuse wire, given by $I = K.d^{3/2}$ where k is a constant depending upon the material of the fuse wire, and 'd' is the diameter of the wire.

5.3 Types of Fuses

In general, fuses may be classified into: (i) Low voltages fuses (ii) High voltage fuses

Low Voltage Fuses

Low voltage fuses can be subdivided into two classes viz., (i) semi-enclosed rewirable fuse (ii) high rupturing capacity (H.R.C.) cartridge fuse

Semi-enclosed rewirable fuse. Rewirable fuse (also known as kit-kat type) is used where low values of fault current are to be interrupted. It consists of (i) a base and (ii) a fuse carrier. The base is of porcelain and carries the fixed contacts to which the incoming and outgoing phase wires are connected. The fuse carrier is also of porcelain and holds the fuse element (tinned copper wire) between its terminals. The fuse carrier can be inserted in or taken out of the base when desired. When a fault occurs, the fuse element is blown out and the circuit is interrupted. The fuse carrier is taken out and the blown out fuse element is replaced by the new one. The fuse carrier is then reinserted in the base to restore the supply. This type of fuse has two advantages. Firstly, the detachable fuse carrier permits the replacement of fuse element without any danger of coming in contact with live parts. Secondly, the cost of replacement is negligible.

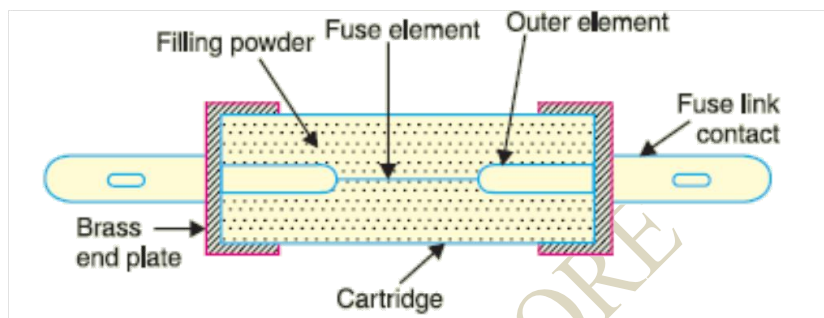
Disadvantages

- (i) There is a possibility of renewal by the fuse wire of wrong size or by improper material.
- (ii) This type of fuse has a low-breaking capacity and hence cannot be used in circuits of high fault level.
- (iii) The fuse element is subjected to deterioration due to oxidation through the continuous heating up of the element. Therefore, after some time, the current rating of the fuse is decreased *i.e.*, the fuse operates at a lower current than originally rated.
- (iv) The protective capacity of such a fuse is uncertain as it is affected by the ambient conditions.
- (v) Accurate calibration of the fuse wire is not possible because fusing current very much depends upon the length of the fuse element.

Semi-enclosed rewirable fuses are made upto 500 A rated current, but their breaking capacity is low *e.g.*, on 400 V service, the breaking capacity is about 4000 A. Therefore, the use of this type of fuses is limited to domestic and lighting loads.

High-Rupturing capacity (H.R.C.) cartridge fuse. The primary objection of low and uncertain breaking capacity of semi-enclosed rewirable fuses is overcome in H.R.C. cartridge fuse. Fig. shows the essential parts of a typical H.R.C. cartridge fuse. It consists of a heat resisting ceramic body having metal end-caps to which is welded silver current-carrying element. The space within the body surrounding the element is completely packed with a filling powder. The filling material may be chalk, plaster of paris, quartz or marble dust and acts as an arc quenching and cooling medium.

Under normal load conditions, the fuse element is at a temperature below its melting point. Therefore, it carries the normal current without overheating. When a fault occurs, the current increases and the fuse element melts before the fault current reaches its first peak. The heat produced in the process vapourises the melted silver element. The chemical reaction between the silver vapour and the filling powder results in the formation of a high resistance substance which helps in quenching the arc.



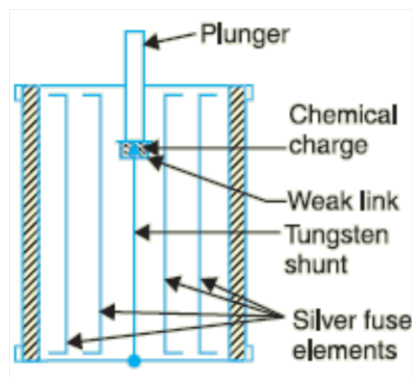
Advantages

- (i) They are capable of clearing high as well as low fault currents.
- (ii) They do not deteriorate with age.
- (iii) They have high speed of operation.
- (iv) They provide reliable discrimination.
- (v) They require no maintenance.
- (vi) They are cheaper than other circuit interrupting devices of equal breaking capacity.
- (vii) They permit consistent performance.

Disadvantages

- (i) They have to be replaced after each operation.
- (ii) Heat produced by the arc may affect the associated switches.

H.R.C. fuse with tripping device. Sometime, H.R.C. cartridge fuse is provided with a tripping device. When the fuse blows out under fault conditions, the tripping device causes the circuit breaker to operate. Fig. shows the essential parts of a H.R.C. fuse with a tripping device. The body of the fuse is of ceramic material with a metallic cap rigidly fixed at each end. These are connected by a number of silver fuse elements. At one end is a plunger which under fault conditions hits the tripping mechanism of the circuit breaker and causes it to operate. The plunger is electrically connected through a fusible link, chemical charge and a tungsten wire to the other end of the cap as shown. When a fault occurs, the silver fuse elements are the first to be blown out and then current is transferred to the tungsten wire. The weak link in series with the tungsten wire gets fused and causes the chemical charge to be detonated. This forces the plunger outward to operate the circuit breaker. The travel of the plunger is so set that it is not ejected from the fuse body under fault conditions.



Advantages. H.R.C. fuse with a tripping device has the following advantages over a H.R.C. fuse without tripping device :

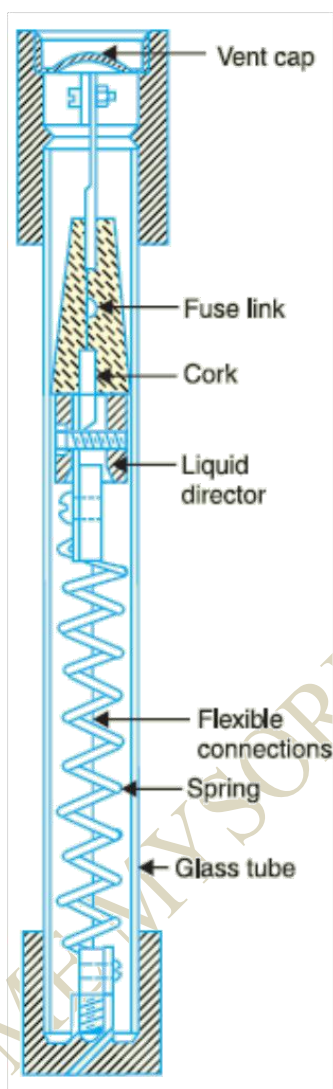
- (i) In case of a single phase fault on a three-phase system, the plunger operates the tripping mechanism of circuit breaker to open all the three phases and thus prevents “single phasing”.
- (ii) The effects of full short circuit current need not be considered in the choice of circuit breaker. This permits the use of a relatively inexpensive circuit breaker.
- (iii) The fuse-tripped circuit breaker is generally capable of dealing with fairly small fault currents itself. This avoids the necessity for replacing the fuse except after highest currents for which it is intended. Low voltage H.R.C. fuses may be built with a breaking capacity of 16,000 A to 30,000 A at 440V. They are extensively used on low-voltage distribution system against over-load and shortcircuit conditions.

High Voltage Fuses

The low-voltage fuses discussed so far have low normal current rating and breaking capacity. Therefore, they cannot be successfully used on modern high voltage circuits. Intensive research by the manufacturers and supply engineers has led to the development of high voltage fuses. Some of the high voltage fuses are :

(i) **Cartridge type.** This is similar in general construction to the low voltage cartridge type except that special design features are incorporated. Some designs employ fuse elements wound in the form of a helix so as to avoid corona effects at higher voltages. On some designs, there are two fuse elements in parallel ; one of low resistance (silver wire) and the other of high resistance (tungsten wire). Under normal load conditions, the low resistance element carries the normal current. When a fault occurs, the low-resistance element is blown out and the high resistance element reduces the short-circuit current and finally breaks the circuit. High voltage cartridge fuses are used upto 33 kV with breaking capacity of about 8700 A at that voltage. Rating of the order of 200 A at 6.6 kV and 11 kV and 50 A at 33 kV are also available.

(ii) **Liquid type.** These fuses are filled with carbon tetrachloride and have the widest range of application to h.v. systems. They may be used for circuits upto 100 A rated current on systems upto 132 kV and may have breaking capacities of the order of 6100 A. Fig. 20.5 shows the essential parts of the liquid fuse. It consists of a glass tube filled with carbon tetrachloride solution and sealed at both ends with brass caps. The fuse wire is sealed at one end of the tube and the other end of the wire is held by a strong phosphor bronze spiral spring fixed at the other end of the glass tube. When the current exceeds the prescribed limit, the fuse wire is blown out. As the fuse melts, the spring retracts part of it through a baffle (or liquid director) and draws it well into the liquid. The small quantity of gas generated at the point of fusion forces some part of liquid into the passage through baffle and there it effectively extinguishes the arc.



Difference Between a Fuse and Circuit Breaker

It is worthwhile to indicate the salient differences between a fuse and a circuit breaker in the tabular form.

S. No.	Particular	Fuse	Circuit breaker
1.	<i>Function</i>	It performs both detection and interruption functions.	It performs interruption function only. The detection of fault is made by relay system.
2.	<i>Operation</i>	Inherently completely automatic.	Requires elaborate equipment (<i>i.e.</i> relays) for automatic action.
3.	<i>Breaking capacity</i>	Small	Very large
4.	<i>Operating time</i>	Very small (0.002 sec or so)	Comparatively large (0.1 to 0.2 sec)
5.	<i>Replacement</i>	Requires replacement after every operation.	No replacement after operation.

5.4 Applications of HRC Fuse

Applications of High-voltage high rupturing capacity fuses are used for short circuit protection in high-voltage switchgear for the 50 to 60 Hz frequency range Distribution transformers up to 2000 kVA High-voltage motors up to 3 MW Capacitors up to 1200 kvar MV voltage transformers Cable feeders

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5.5 Discrimination: - Discrimination between two fuses is said to occur if on the occurrence of a short-circuit or overcurrent fault, only the desired fuse operates

Figure 15.34 shows a single –line diagram of a distribution network. It is very clear from the figure that a 60A fuse must operate for the fault at F. A 200A fuse should act as a back-up in case of failure of a 60A fuse. The characteristics of two fuses have to be coordinated as shown in fig 15.35

Discrimination between Two Fuses

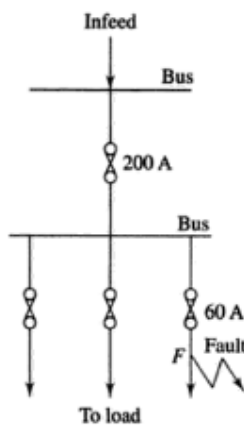


Fig. 15.34

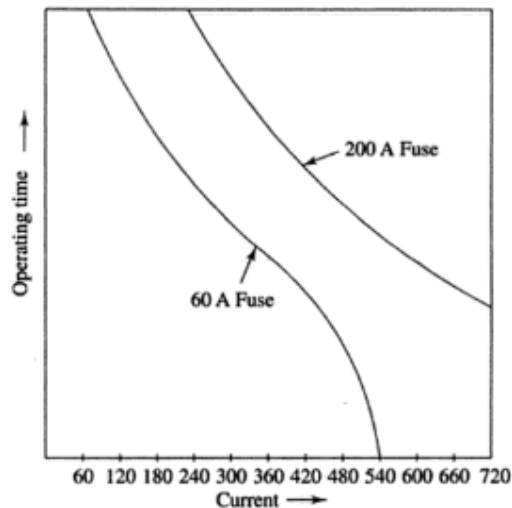


Fig. 15.35

Discrimination between a fuse and over current relay

Fig 15.36 shows a single line diagram of an 11kV feeder supplying a pole-mounted transformer. The drop-out fuse is for the protection of transformer only. Hence, the overcurrent relay has to be coordinated with kit-kat fuse. The characteristic of both the relay and fuse are plotted in fig 15.37 considering the transformer ratio.

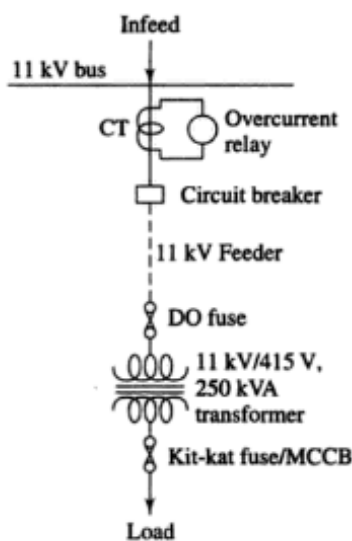


Fig. 15.36

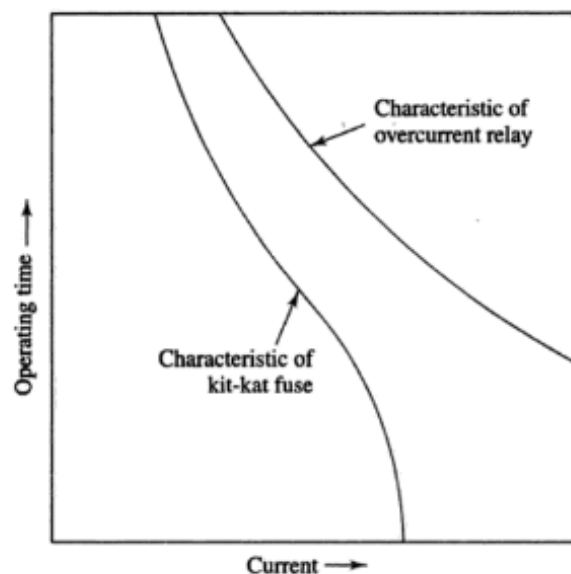


Fig. 15.37

5.6 Causes of Overvoltages

The Overvoltages on a power system may be broadly divided into two main categories viz.

1. Internal causes

(i) Switching surges (ii) Insulation failure (iii) Arcing ground (iv) Resonance

2. External causes i.e. lightning

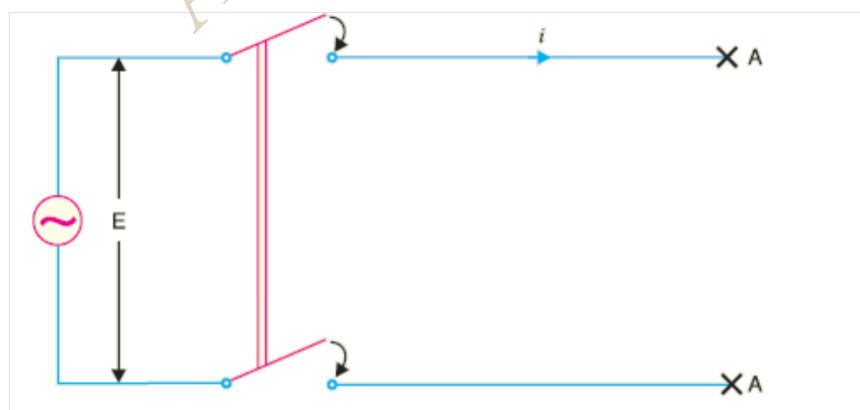
Internal causes do not produce surges of large magnitude. Experience shows that surges due to internal causes hardly increase the system voltage to twice the normal value. Generally, surges due to internal causes are taken care of by providing proper insulation to the equipment in the power system. However, surges due to lightning are very severe and may increase the system voltage to several times the normal value. If the equipment in the power system is not protected against lightning surges, these surges may cause considerable damage. In fact, in a power system, the protective devices provided against overvoltages mainly take care of lightning surges

Internal Causes of Overvoltages

Internal causes of overvoltages on the power system are primarily due to oscillations set up by the sudden changes in the circuit conditions. This circuit change may be a normal switching operation such as opening of a circuit breaker, or it may be the fault condition such as grounding of a line conductor. In practice, the normal system insulation is suitably designed to withstand such surges. We shall briefly discuss the internal causes of overvoltages.

1. Switching Surges. The overvoltages produced on the power system due to switching operations are known as switching surges. A few cases will be discussed by way of illustration:

(i) Case of an open line. During switching operations of an unloaded line, travelling waves are set up which produce overvoltages on the line. As an illustration, consider an unloaded line being connected to a voltage source as shown in Fig.



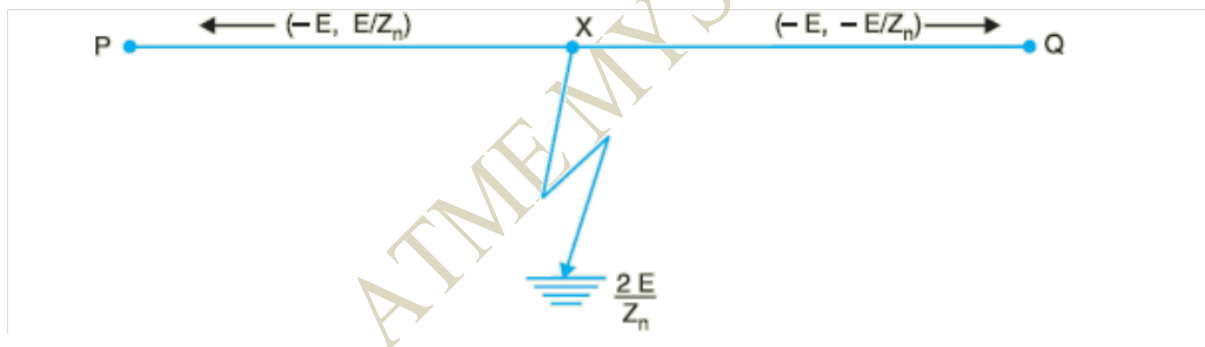
When the unloaded line is connected to the voltage source, a voltage wave is set up which travels along the line. On reaching the terminal point A, it is reflected back to the supply end without change of sign. This causes voltage doubling i.e. voltage on the line becomes twice the normal value. If $E_{r.m.s.}$ is the supply voltage, then instantaneous voltage which the line will have to withstand will be $2\sqrt{2} E$. This overvoltage is of temporary nature. It is because the line losses attenuate the wave and in a very

short time, the line settles down to its normal supply voltage E . Similarly, if an unloaded line is switched off, the line will attain a voltage of $2\sqrt{2} E$ for a moment before settling down to the normal value.

(ii) Case of a loaded line. Overvoltages will also be produced during the switching operations of a loaded line. Suppose a loaded line is suddenly interrupted. This will set up a voltage of $2 Z_n i$ across the break (i.e. switch) where i is the instantaneous value of current at the time of opening of line and Z_n is the natural impedance of the line. For example, suppose the line having $Z_n = 1000\Omega$ carries a current of 100 A (r.m.s.) and the break occurs at the moment when current is maximum. The voltage across the breaker (i.e. switch) = $2 \sqrt{2} \times 100 \times 1000 / 1000 = 282.8$ kV. If V_m is the peak value of voltage in kV, the maximum voltage to which the line may be subjected is $(V_m + 282.8)$ kV

(iii) Current chopping. Current chopping results in the production of high voltage transients across the contacts of the air blast circuit breaker as detailed in chapter 19. It is briefly discussed here. Unlike oil circuit breakers, which are independent for the effectiveness on the magnitude of the current being interrupted, air-blast circuit breakers retain the same extinguishing power irrespective of the magnitude of this current. When breaking low currents (e.g. transformer magnetising current) with air-blast breaker, the powerful de-ionising effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is called current chopping and produces high transient voltage across the breaker contacts. Overvoltages due to current chopping are prevented by resistance switching

Insulation failure. The most common case of insulation failure in a power system is the grounding of conductor (i.e. insulation failure between line and earth) which may cause overvoltages in the system. This is illustrated in Fig.



Suppose a line at potential E is earthed at point X . The earthing of the line causes two equal voltages of $-E$ to travel along XQ and XP containing currents $-E/Z_n$ and $+E/Z_n$ respectively. Both these currents pass through X to earth so that current to earth is $2 E/Z_n$.

3. Arcing ground. In the early days of transmission, the neutral of three phase lines was not earthed to gain two advantages. Firstly, in case of line-to-ground fault, the line is not put out of action. Secondly, the zero sequence currents are eliminated, resulting in the decrease of interference with communication lines. Insulated neutrals give no problem with short lines and comparatively low voltages. However, when the lines are long and operate at high voltages, serious problem called arcing ground is often witnessed. The arcing ground produces severe oscillations of three to four times the normal voltage. The phenomenon of intermittent arc taking place in line-to-ground fault of a 3 phase system with consequent production of transients is known as **arcing ground**. The transients produced due to arcing ground are cumulative and may cause serious damage to the equipment in the power system by causing breakdown of insulation. Arcing ground can be prevented by earthing the neutral

4. Resonance. Resonance in an electrical system occurs when inductive reactance of the circuit becomes equal to capacitive reactance. Under resonance, the impedance of the circuit is equal to resistance of the circuit and the p.f. is unity. Resonance causes high voltages in the electrical system. In the usual transmission lines, the

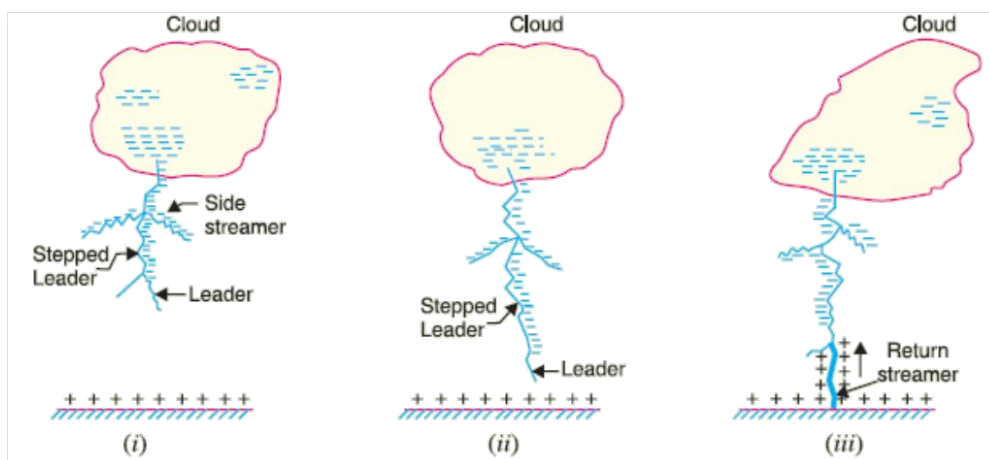
capacitance is very small so that resonance rarely occurs at the fundamental supply frequency. However, if generator e.m.f. wave is distorted, the trouble of resonance may occur due to 5th or higher harmonics and in case of underground cables too

5.7 Lightning phenomena

An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as **lightning**. Lightning is a huge spark and takes place when clouds are charged to such a high potential (+ve or -ve) with respect to earth or a neighbouring cloud that the dielectric strength of neighbouring medium (air) is destroyed. There are several theories which exist to explain how the clouds acquire charge. The most accepted one is that during the uprush of warm moist air from earth, the friction between the air and the tiny particles of water causes the building up of charges. When drops of water are formed, the larger drops become positively charged and the smaller drops become negatively charged. When the drops of water accumulate, they form clouds, and hence cloud may possess either a positive or a negative charge, depending upon the charge of drops of water they contain. The charge on a cloud may become so great that it may discharge to another cloud or to earth and we call this discharge as lightning. The thunder which accompanies lightning is due to the fact that lightning suddenly heats up the air, thereby causing it to expand. The surrounding air pushes the expanded air back and forth causing the wave motion of air which we recognise as thunder.

Mechanism of Lightning Discharge

Let us now discuss the manner in which a lightning discharge occurs. When a charged cloud passes over the earth, it induces equal and opposite charge on the earth below it. Fig. 24.4 shows a negatively charged cloud inducing a positive charge on the earth below it. As the charge acquired by the cloud increases, the potential between cloud and earth increases and, therefore, gradient in the air increases. When the potential gradient is sufficient (5 kV/cm to 10 kV/cm) to break down the surrounding air, the lightning stroke starts. The stroke mechanism is as under: (i) As soon as the air near the cloud breaks down, a streamer called leader streamer or pilot streamer starts from the cloud towards the earth and carries charge with it as shown in Fig. (i). The leader streamer will continue its journey towards earth as long as the cloud, from which it originates feeds enough charge to it to maintain gradient at the tip of leader streamer above the strength of air. If this gradient is not maintained, the leader streamer stops and the charge is dissipated without the formation of a complete stroke. In other words, the leader streamer will not reach the earth. Fig.(i) shows the leader streamer being unable to reach the earth as gradient at its end cloud not be maintained above the strength of air. It may be noted that current in the leader streamer is low ($<100 \text{ A}$) and its velocity of propagation is about 0.05% that of Velocity of light. Moreover, the luminosity of leader is also very low.



(ii) In many cases, the leader streamer continues its journey towards earth [(ii)] until it makes contact with earth or some object on the earth. As the leader streamer moves towards earth, it is accompanied by points of luminescence which travel in jumps giving rise to stepped leaders. The velocity of stepped leader exceeds one-sixth of that of light and distance travelled in one step is about 50 m. It may be noted that stepped leaders have sufficient luminosity and give rise to first visual phenomenon of discharge.

(iii) The path of leader streamer is a path of ionisation and, therefore, of complete breakdown of insulation. As the leader streamer reaches near the earth, a return streamer shoots up from the earth [(iii)] to the cloud, following the same path as the main channel of the downward leader. The action can be compared with the closing of a switch between the positive and negative terminals; the downward leader having negative charge and return streamer the positive charge. This phenomenon causes a sudden spark which we call lightning. With the resulting neutralisation of much of the negative charge on the cloud, any further discharge from the cloud may have to originate from some other portion of it. The following points may be noted about lightning discharge :

(a) A lightning discharge which usually appears to the eye as a single flash is in reality made up of a number of separate strokes that travel down the same path. The interval between them varies from 0.0005 to 0.5 second. Each separate stroke starts as a downward leader from the cloud.

(b) It has been found that 87% of all lightning strokes result from negatively charged clouds and only 13% originate from positively charged clouds.

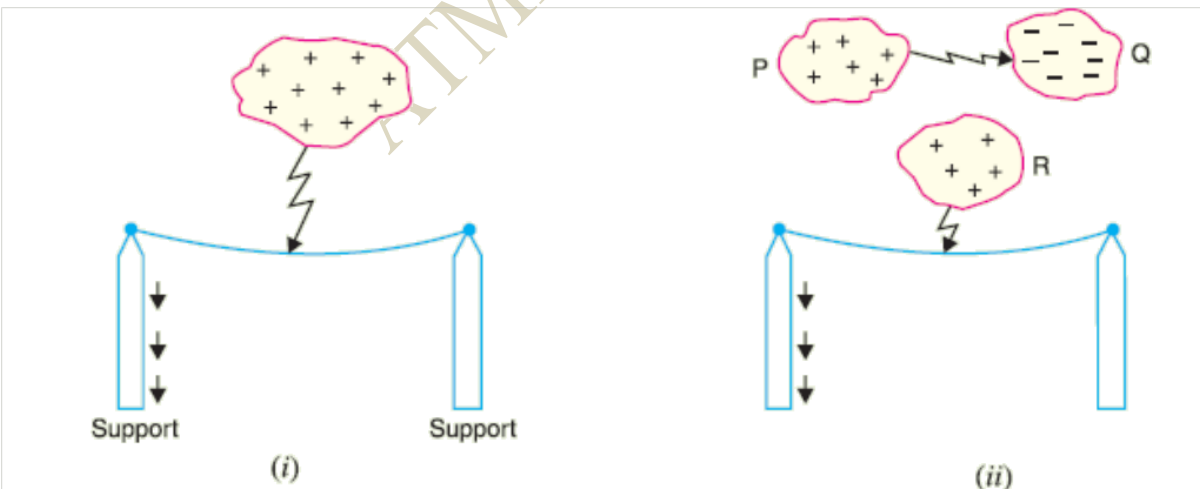
(c) It has been estimated that throughout the world, there occur about 100 lightning strokes per second.

(d) Lightning discharge may have currents in the range of 10 kA to 90 kA.

Types of Lightning Strokes

There are two main ways in which a lightning may strike the power system (e.g. overhead lines, towers, substations etc.), namely; 1. Direct stroke 2. Indirect stroke

1. Direct stroke. In the direct stroke, the lightning discharge (i.e. current path) is directly from the cloud to the subject equipment e.g. an overhead line. From the line, the current path may be over the insulators down the pole to the ground. The overvoltages set up due to the stroke may be large enough to flashover this path directly to the ground. The direct strokes can be of two types viz. (i) Stroke A and (ii) stroke B



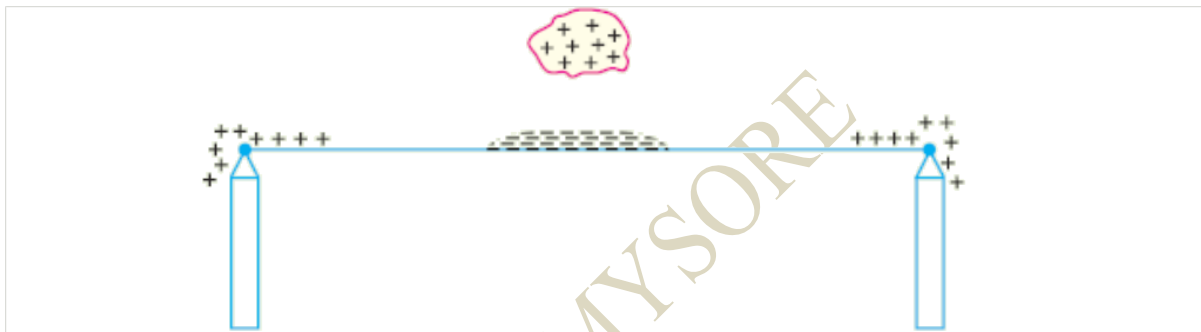
(i) In stroke A, the lightning discharge is from the cloud to the subject equipment i.e. an overhead line in this case as shown in Fig. (i). The cloud will induce a charge of opposite sign on the tall object (e.g. an overhead line in this case). When the potential between the cloud and line exceeds the breakdown value of air, the lightning discharge occurs between the cloud and the line.

(ii) In stroke B, the lightning discharge occurs on the overhead line as a result of stroke A between the clouds as shown in Fig. (ii). There are three clouds P, Q and R having positive, negative and positive charges respectively. The charge on the cloud Q is bound by the cloud R. If the cloud P shifts too near the cloud Q, then lightning

discharge will occur between them and charges on both these clouds disappear quickly. The result is that charge on cloud *R* suddenly becomes free and it then discharges rapidly to earth, ignoring tall objects.

Two points are worth noting about direct strokes. Firstly, direct strokes on the power system are very rare. Secondly, stroke *A* will always occur on tall objects and hence protection can be provided against it. However, stroke *B* completely ignores the height of the object and can even strike the ground. Therefore, it is not possible to provide protection against stroke *B*.

2. Indirect stroke. Indirect strokes result from the electrostatically induced charges on the conductors due to the presence of charged clouds. This is illustrated in Fig. A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. This negative charge, however, will be only on that portion of the line right under the cloud and the portions of the line away from it will be positively charged as shown in Fig. The induced positive charge leaks slowly to earth *via* the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the wire is isolated as it cannot flow quickly to earth over the insulators. The result is that negative charge rushes along the line in both directions in the form of travelling waves. It may be worthwhile to mention here that majority of the surges in a transmission line are caused by indirect lightning strokes



Harmful Effects of Lightning

A direct or indirect lightning stroke on a transmission line produces a steep-fronted voltage wave on the line. The voltage of this wave may rise from zero to peak value (perhaps 2000 kV) in about $1\ \mu\text{s}$ and decay to half the peak value in about $5\ \mu\text{s}$. Such a steep-fronted voltage wave will initiate travelling waves along the line in both directions with the velocity dependent upon the L and C parameters of the line.

- (i) The travelling waves produced due to lightning surges will shatter the insulators and may even wreck poles.
- (ii) If the travelling waves produced due to lightning hit the windings of a transformer or generator, it may cause considerable damage. The inductance of the windings opposes any sudden passage of electric charge through it. Therefore, the electric charges “pile up” against the transformer (or generator). This induces such an excessive pressure between the windings that insulation may breakdown, resulting in the production of arc. While the normal voltage between the turns is never enough to *start* an arc, once the insulation has broken down and an arc has been started by a momentary overvoltage, the line voltage is usually sufficient to *maintain* the arc long enough to severely damage the machine.
- (iii) If the arc is initiated in any part of the power system by the lightning stroke, this arc will set up very disturbing oscillations in the line. This may damage other equipment connected to the line.

5.8 Protection against Lightning

Transients or surges on the power system may originate from switching and from other causes but the most important and dangerous surges are those caused by lightning. The lightning surges may cause serious damage to the expensive equipment in the power system (*e.g.* generators, transformers etc.) either by direct strokes on the equipment or by strokes on the transmission lines that reach the equipment as travelling waves. It is necessary to provide protection against both kinds of surges. The most commonly used devices for protection against lightning surges are :

- (i) Earthing screen
- (ii) Overhead ground wires
- (iii) Lightning arresters or surge diverters

Earthing screen provides protection to power stations and sub-stations against direct strokes whereas overhead ground wires protect the transmission lines against direct lightning strokes. However, lightning arresters or surge diverters protect the station apparatus against both direct strokes and the strokes that come into the apparatus as travelling waves. We shall briefly discuss these methods of protection.

Protection of Stations and Sub – Stations from Direct Strokes

The power stations and sub-stations generally house expensive equipment. These stations can be protected against direct lightning strokes by providing earthing screen. It consists of a network of copper conductors (generally called shield or screen) mounted all over the electrical equipment in the sub-station or power station. The shield is properly connected to earth on atleast two points through a low impedance. On the occurrence of direct stroke on the station, screen provides a low resistance path by which lightning surges are conducted to ground. In this way, station equipment is protected against damage. The limitation of this method is that it does not provide protection against the travelling waves which may reach the equipment in the station

Power stations are usually indoor while substations may be indoor or outdoor. For protection of a structure from direct strokes there are three requirements which are to be fulfilled. These requirements are interception, conduction and dissipation.

These requirements involve:

- (i) An object in good electrical connection with the earth so that the leader stroke may get attracted,
- (ii) A low impedance path joining this object to earth so that the discharge follows it in preference to any other path,
- (iii) A low resistance connection with the earth body.

For 1, the upper portion of a metal structure may be employed. Alternatively a separate metallic system, often called the shield, either mounted on the structure or near to and above it may be provided. A particular shield configuration in the form of masts or overhead ground wires is considered to provide good shielding.

For 2, the requirements are:

- (i) Low resistance (i.e., adequate conductivity and cross- section, properly bounded joints, free from possible corrosion),
- (ii) Low reactance (i.e., absence of sharp bends, or loops and short conductors),
- (iii) And sufficient clearance from any other conducting objects that might provide separate uncontrolled path to ground.

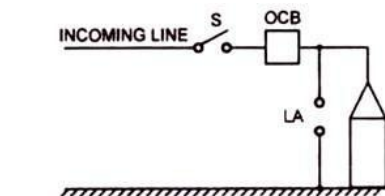
Outdoor substations have much of equipment carried on metal gantries and the interconnection of the upper portion of these will screen the apparatus. Usually, there is suitable grounding provided.

Shielding of the station and the incoming lines (about 0.8 km out from the station) to restrict the severity of the waves that can enter the station through the lines is a desirable supplement, particularly in the case of hv lines (66 kV and above) to the lightning arrester located in the station [below Fig. (b)].

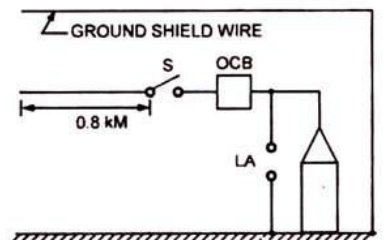
Where overhead ground wires cannot be provided on the incoming lines due to existing structure/construction, additional protection of the station equipment against direct lightning strokes can be provided by equipping each

line with protector tubes at the entrance to the structure of the station and at each tower for a distance of about 0.8 km out from the station, as illustrated in below Fig. c). However, shielding of the power station/substation is the only way of eliminating direct strokes to the station itself.

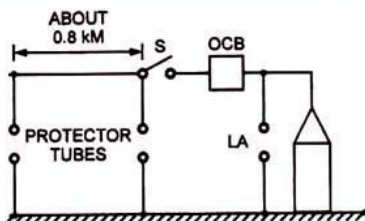
If sufficient supports are available for overhead groundwires, these may be run over the station in such a way that the station and all equipments will lie in the protected zone. Ground wire should be strong so that entire station is covered, including any apparatus outside the main structure as shown.



(a) Lightning Arrester at Station With No Direct Stroke Shielding



(b) Lightning Arrester At Station With Shielding Against Direct Lightning Strokes



(c) Lightning Arrester At Station With Protector Tube Extending Out 0.8 KM Station Protection Schemes

Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires:

The two methods of protecting overhead transmission lines against lightning strokes are:

(i) Overhead ground wires and (ii) Expulsion protector tubes.

(i) Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires:

A ground wire is a form of lightning protection employing a conductor or conductors, well-grounded at regular intervals, preferably at each support (pole or tower), and attached from support to support above the transmission line conductors.

No doubt the ground wire can be run below the line but running of ground wire above the line is considered better as it provides more effective shield. The ground wire shields the phase or line conductors by attracting itself the lightning strokes which, in the absence of ground wire, would strike the line conductors.

The elevation at which the ground wire is strong is likewise determined by calculation and selected so that the line conductors come within the zone of protection of the respective ground wire. For reliable protection the protective angle α is taken equal to 20-30 degrees. This is the angle between the vertical line through the ground wire axis and the line passing from the ground wire axis to the outermost line or phase conductor.

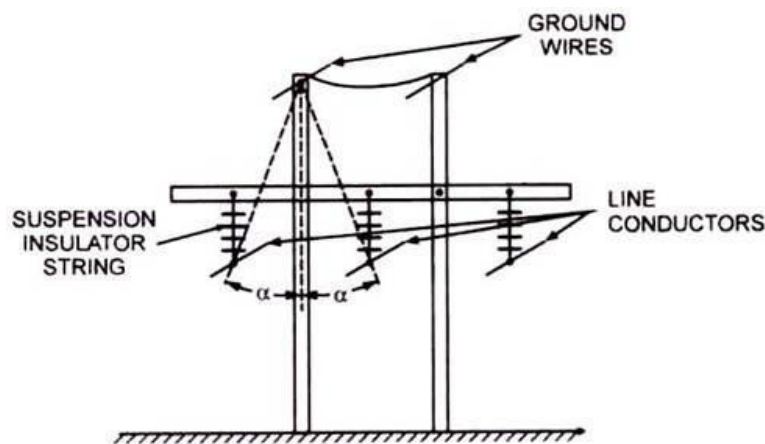


Fig. Arrangement of Ground Wires on a Transmission Line For Direct Stroke Lightning Protection

Coupling Factor:

The entire ground wire voltage does not show up across the line insulators as a voltage of the same polarity as the ground wire is also induced in the line conductors. The ratio of the induced voltage on the line to the potential of ground wire is called the coupling factor, i.e.,

$$\text{Coupling factor, } K = \frac{\text{Voltage induced in the line conductors}}{\text{Potential of ground wire}} = \frac{V_{Ll}}{V_g}$$

The voltage across the line conductor and earth is the product of coupling factor and ground wire potential.

Consider an arrangement of line conductors and ground wire, as illustrated in Fig. When the ground wire is struck by a lightning stroke at point A, currents flow as indicated in the figure. Currents I_1 and I_2 flow in opposite directions from point A. Again at point B, the current subdivides and let I_4 flow, through earth connecting wire, to the ground.

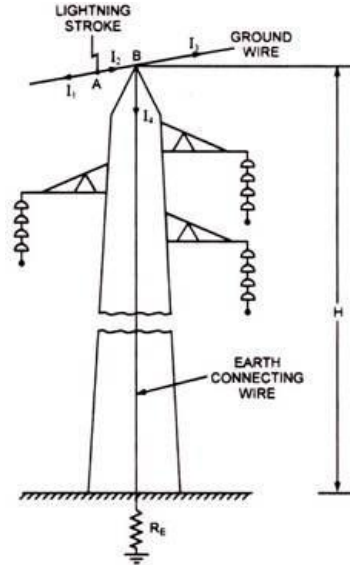


Fig. 9.12. Arrangement of Conductors and Earth Representing Lightning Current

Suppose the ground resistance R_E is high. The currents in the down lead and into the earth (I_4) causes a voltage drop in the ground connection, thereby raising the potential of ground (or shield) wire above true earth potential.

Let this be V_g –

$$\text{So } V_g = I_4 R_E$$

Potential between the line conductor and earth,

$$V_l = K V_g$$

Where k is the coupling factor and is given as –

$$K = \frac{\log_e \frac{h}{h_1}}{\log_e \frac{2H}{r}}$$

where h is the distance from phase conductor to ground wire, h_1 is the distance between conductor image and ground, H is the height of ground wire above ground and r is the radius of ground wire.

In the absence of corona the electrostatic and electromagnetic coupling factors are equal.

In case of corona, electrostatic coupling increases while the electromagnetic coupling remains unaffected.

The electromagnetic coupling factor is determined as above using the actual diameter of the ground wire while the electrostatic coupling factor is determined by using the increased diameter of the ground wire due to corona as follows –

$$K_{fs} = \frac{\log_e \frac{h}{h_1}}{\log_e \frac{2H}{r_1}}$$

where r_1 is the increased radius of ground wire and K_{fs} is the electrostatic coupling factor,

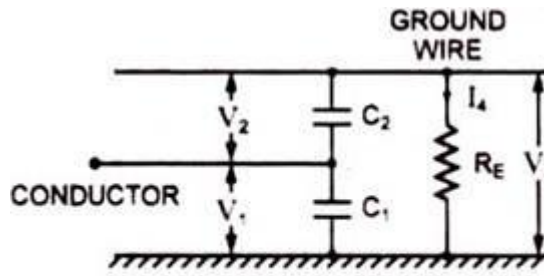


Fig. 9.13. Equivalent Electrical Circuit

The resultant coupling factor,

$$K_{fr} = \sqrt{K_{fs} K_{fm}}$$

where kf_m is the electromagnetic coupling factor.

Above Figure 9.13 represents the equivalent electrical circuit corresponding to arrangement shown in above Fig. 9.12. C_1 and C_2 are the capacitances between conductor and earth and between ground wire and conductor respectively. Let V_1 and V_2 be the potential drops across these capacitances. Also from the equivalent electrical circuit diagram shown in above Fig, we have –

$$V_2 = V_g - V_1$$

$$V_2 = V_g - V_1 = V_g - K V_g = V_g (1 - K) = I_4 R_E (1 - K)$$

i.e., the potential difference between the ground wire and the line, V_2 may be high. If the clearance between the down lead and the line conductor is not sufficient or if the support is metallic and the insulator is small, a flashover will be caused from the ground wire to the line conductor.

This is just as bad as a direct hit on the line conductor with flashover from it to ground because either may cause a short circuit. Sometimes, special measures such as counterpoise rods (horizontal rods buried in ground) may be necessary to obtain reasonable ground resistance (about 5 – 10 Ω) and sometimes it may be necessary to offset the down leads so that adequate clearances are obtained.

Besides taking the brunt of a direct stroke, the ground wire reduces the voltage electrostatically or electromagnetically induced in the conductors by the discharge of a neighbouring cloud. For example, referring to below Fig, if C_1 is the capacitance of cloud to the line and C_2 the capacitance of the line to ground.

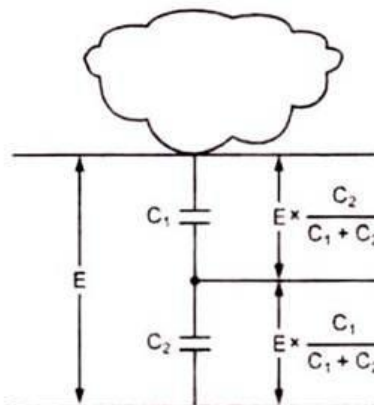


Fig. 9.14. Reduction in Induced Voltage Due To Ground Wire

$$\frac{C_1}{C_1 + C_2}$$

The induced voltage on the line is $\frac{C_1}{C_1 + C_2}$ times the cloud voltage. The presence of the ground wire above the line causes a considerable increase in C_2 and therefore, a reduction of the induced voltage on the line.

The induced voltage could be very much reduced by an array of ground wires but this is too expensive to install in practice. Peak has made a laboratory study of the protective effect of ground wires and has found that a single ground wire reduces the induced lightning voltage to one-half of that without ground wire; for two ground wires the reduction is one-third, while for three ground wires it is to one-fourth. These results were obtained under the favourable conditions of good earths and low impedance for the earth connections.

The ground wire also affords an additional protective effect by causing an attenuation of any travelling waves that are set up in the lines by acting as a short-circuited secondary of the line conductors. For this reason its resistance should not be too large. Ground wire is usually made of steel, which has a high permeability and thus possesses a resistance which increases with frequency.

The objections to the ground wire are the additional cost, and the possibility of the wire breaking and falling across the line conductors, thus causing a direct short circuit. Failure due to the latter cause, however, is rare, as substantial galvanized stranded steel conductors are usually employed. Indeed, such a steel conductor joining the tops of the towers generally adds greatly to the mechanical strength and stability of the line, particularly if the line is of the flexible type.

Ground wires are extensively used for direct-stroke protection of transmission lines for voltages of 110 kV and upward (up to 500 kV). Ground wires are usually strung on all vital transmission lines and on all sections of transmission lines running through regions subject to frequent lightning storms.

The selection of size, number and arrangement of ground wires is of great importance in line design. The selection of size of ground wire is based on the consideration of mechanical strength rather than electrical considerations.

In practice, one ground wire is generally used, which allows the intensity of over-voltages to be considerably reduced, and lessens the work demanded from the lightning arresters connected to the system. In exposed situations, or lines subject to severe lightning disturbances, it would probably be good practice to install one or two additional wires. In case of horizontal spacing of conductors on the tower, two ground wires are run on the top portion of the tower.

On wood-pole transmission lines within the working voltage range of 33 to 110 kV, ground wires are provided only at the approaches to the power station and system substations. No special means of lightning protection is provided on the remaining sections of such lines as advantage can be taken of the insulation provided by the wood-pole supports. By installing the ground wires on the substation approaches of the lines the latter will be guarded against the possibility of lightning strokes close to the substations.

(ii) Protection of Overhead Transmission Lines from Direct Lightning Strokes by Protector Tube:

Even after reduction in the induced voltage by using a ground wire, there still exist over-voltages in the system which must be removed by using additional protective devices such as lightning arrester that bypasses the surges to the ground. Another device that is quite common in use is the protector tube.

Expulsion protector tube consists of a backlisted fibre tube containing two built-in electrodes between which an internal gap is provided. An outer electrode or arcing horn, made from steel wire 5 or 6 mm in dia is attached to the bolt at the upper end of the protector tube (below Fig 9.15) to provide an external spark gap between it and a line conductor.

The internal gap can be adjusted by turning the tube about the bolt which secures the tube to the bracket. The external gap is adjusted to templates made from wire 3 or 4 mm in diameter.

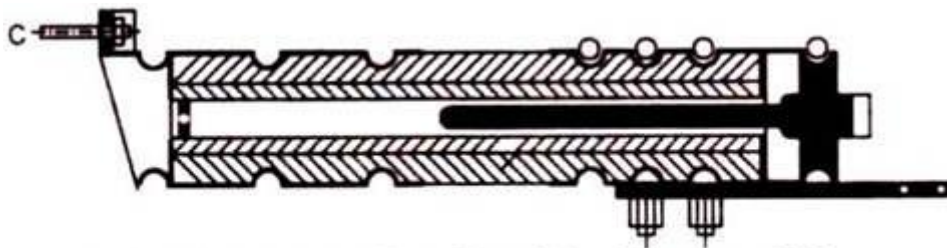


Fig. 9.15. Power Line Expulsion Protector Tube

On a transmission tower one tube is often mounted below each line so that the upper electrode is connected to an arc-shaped horn located at the proper distance below the line, thus forming a series gap G_2 with it [below Fig. 9.16(a)], The lower electrode is solidly grounded.

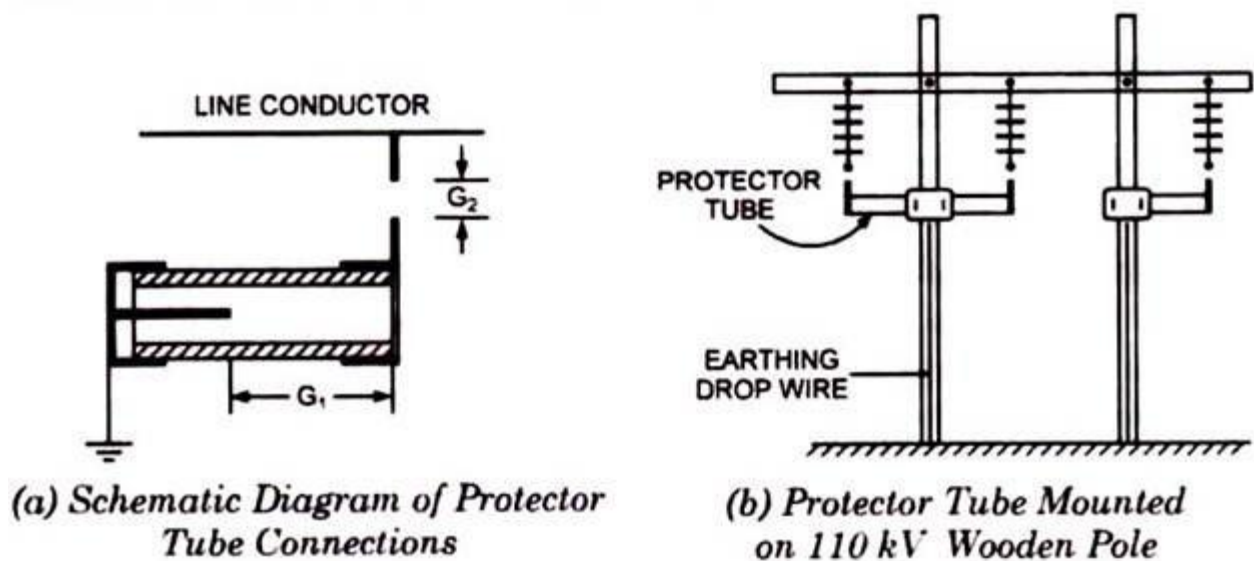


Fig. 9.16. Expulsion Protector Tube

When a surge of sufficient voltage travels along the phase conductor and reaches the point where the expulsion tube is mounted, both of the series air gaps (internal air gap G_1 and external air gap G_2) breakdown and drain the surge current to ground through the tube and its earthing conductor; thereby reducing the crest value of surge voltage.

On breakdown of the tube gaps on two or three phases, or on one phase of solidly-grounded neutral circuits, the operating voltage simultaneously initiates a flow of short circuit or power current. This current must flow through the tubes and set up arcs between their spark gaps.

The high temperature of the arc across the gap in the tubes then produces a large amount of gases due to decomposition of some of the tube material. These gases flash out of the tube under pressures reaching from 100 to 500 atm and intensely deionize the arc. The latter is thus extinguished and the circuit insulation returned to its normal value with respect to earth.

Arc extinction duration will be only one or two half-periods. This interval is too short for the protective relays of the line to come into action, the circuit breaker remains closed and the line remains in operation. Immediately after the gases have been expelled and the arc suppressed, every tube is ready for a new operation.

The purpose of external air gap G_2 is to isolate the expulsion tube from the line conductor. Failure to provide the external gap would otherwise place the tube at the operating potential of the conductor and cause flow of

leakage currents over the tube surface and to eventual carbonizing of the tube material and final destruction of the tube.

3. Protection of Electrical Equipment from Travelling Waves:

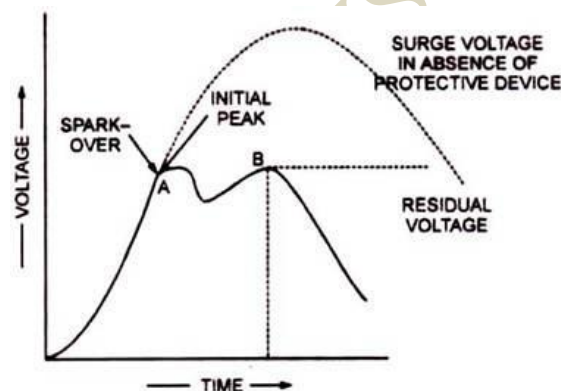
The ground wire or earthing screen used for the protection of overhead lines and power stations and substations not only provides an adequate protection against lightning but also reduces the over-voltages induced electrostatically or electromagnetically, but such shielding is inadequate in providing protection against travelling waves which may reach the terminal equipment and cause damage to it.

The damages that may be caused by travelling waves are:

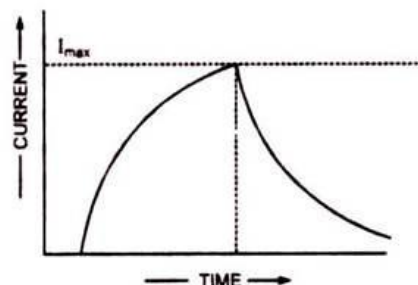
- The high peak or crest voltage of the surge may cause flashover in the internal winding thereby spoil the winding insulation.
- The steep wave front of the surge may cause internal flashover between inter-turns of the transformer.
- The high peak voltage of the surge may cause external flashover, between the terminals of the electrical equipment which may result in damage to insulators.
- The steep wave front resulting into resonance and high voltages may cause internal or external flashover of an un-predicable nature causing building up of the oscillation in the electrical apparatus.

Thus it is absolutely necessary to provide some protective device at the power stations or substations to prevent transformers and other equipment from being subjected to travelling surges reaching there. The most common devices used for protection of equipment at the substations against travelling waves are lightning arresters or surge diverters.

A surge diverter is a device that is connected between line and earth, i.e., in parallel with the equipment to be protected at the substation.



(a) Voltage Characteristic



(b) Current Characteristic
Voltage and Current Characteristics of
Surge Diverters

Fig. 9.17

When a travelling wave reaches the diverter, it sparks-over at a certain prefixed voltage as illustrated by point A in the figure, and provides a conducting path of relatively low impedance between the line and ground.

The surge impedance of the line restricts the amplitude of current flowing to ground. This is necessary in order to protect the insulation of the equipment. Fig. 9.17 shows the shape of voltage and of current at the diverter terminals.

It should, however, be noted that the surge diverter should provide a path of low impedance only when the travelling surge reaches the surge diverter, neither before it nor after it.

An ideal surge diverter should have the following characteristics:

- i. It should not draw any current during normal operating conditions, i.e., its spark over voltage must be above the normal or abnormal power frequency that may occur in the system.
- ii. Any abnormal transient voltage above the breakdown value must cause it to breakdown as quickly as possible so that it may provide a conducting path to ground.
- iii. When the breakdown have taken place, it should be capable of carrying the resulting discharge current without getting damaged itself and without the voltage across it exceeding the breakdown value.
- iv. The power frequency current following the breakdown must be interrupted as soon as the transient voltage has fallen below the breakdown value.

There are many types of surge diverters which are used to protect the power system.

The choice of lightning arrester depends upon the following factors:

- (i) Voltage of the line.
- (ii) Frequency of the lightning.
- (iii) Cost.
- (iv) Weather conditions.
- (v) Reliability.

Types of Lightning Arresters

There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle viz. providing low resistance path for the surges to the ground. We shall discuss the following types of lightning arresters :

1. Rod gap arrester 2. Horn gap arrester 3. Multigap arrester 4. Expulsion type lightning arrester 5. Valve type lightning arrester

Expulsion type arrester. This type of arrester is also called 'protector tube' and is commonly used on system operating at voltages upto 33 kV. Below Fig. (i) shows the essential parts of an expulsion type lightning arrester. It essentially consists of a rod gap A A' in series with a second gap enclosed within the fibre tube. The gap in the fibre tube is formed by two electrodes. The upper electrode is connected to rod gap and the lower electrode to the earth. One expulsion arrester is placed under each line conductor. Fig. (ii) shows the installation of expulsion arrester on an overhead line. On the occurrence of an overvoltage on the line, the series gap A A' is spanned and an arc is struck between the electrodes in the tube. The heat of the arc vaporises some of the fibre of tube walls, resulting in the production of a neutral gas*. In an extremely short time, the gas builds up high pressure and is expelled through the lower electrode which is hollow. As the gas leaves the tube violently, it carries away ionised air around the arc. This de-ionising effect is generally so strong that arc goes out at a current zero and will not be re-established.

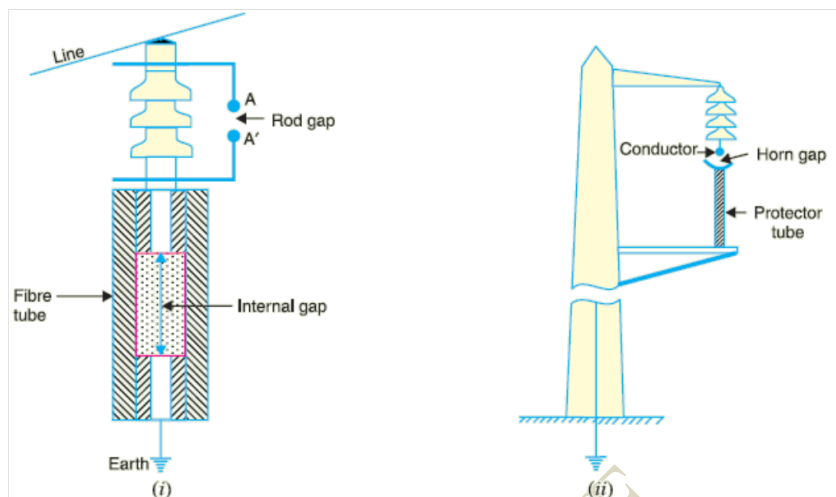
Advantages

- (i) They are not very expensive.
- (ii) They are improved form of rod gap arresters as they block the flow of power frequency follow currents.
- (iii) They can be easily installed.

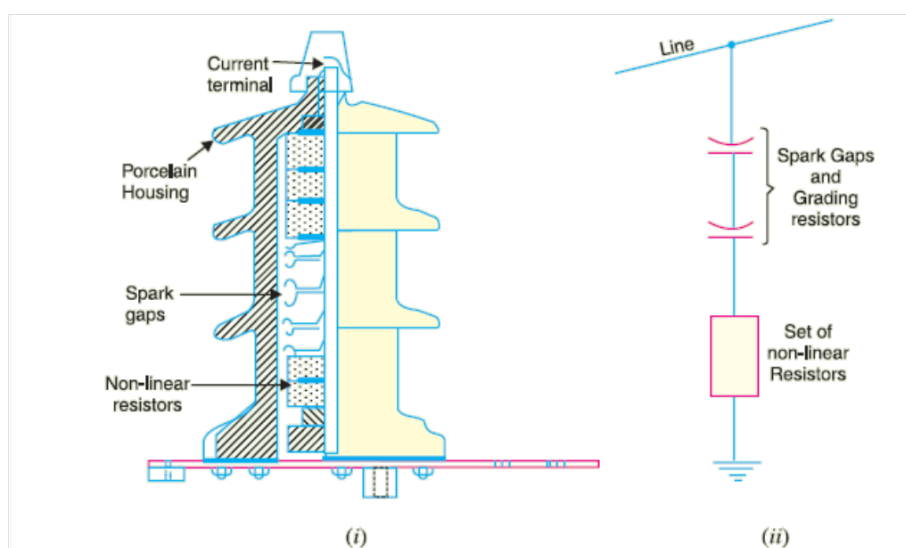
Limitations

- (i) An expulsion type arrester can perform only limited number of operations as during each operation some of the fibre material is used up.

- (ii) This type of arrester cannot be mounted in an enclosed equipment due to the discharge of gases during operation.
- (iii) Due to the poor volt/amp characteristic of the arrester, it is not suitable for the protection of expensive equipment



Valve type arrester. Valve type arresters incorporate non-linear resistors and are extensively used on systems operating at high voltages. Fig. 24.13 (i) shows the various parts of a valve type arrester. It consists of two assemblies (i) series spark gaps and (ii) non-linear resistor discs (made of material such as thyrite or metrosil) in series. The non-linear elements are connected in series with the spark gaps. Both the assemblies are accommodated in tight porcelain container. (i) The spark gap is a multiple assembly consisting of a number of identical spark gaps in series. Each gap consists of two electrodes with a fixed gap spacing. The voltage distribution across the gaps is linearised by means of additional resistance elements (called grading resistors) across the gaps. The spacing of the series gaps is such that it will withstand the normal circuit voltage. However, an overvoltage will cause the gap to breakdown, causing the surge current to ground via the non-linear resistors. (ii) The non-linear resistor discs are made of an inorganic compound such as Thyrite or Metrosil. These discs are connected in series. The non-linear resistors have the property of offering a high resistance to current flow when normal system voltage is applied, but a low resistance to the flow of high-surge currents. In other words, the resistance of these non-linear elements decreases with the increase in current through them and *vice-versa*.



Working. Under normal conditions, the normal system voltage is insufficient to cause the breakdown of air gap assembly. On the occurrence of an overvoltage, the breakdown of the series spark gap takes place and the surge current is conducted to earth via the non-linear resistors. Since the magnitude of surge current is very large, the non-linear elements will offer a very low resistance to the passage of surge. The result is that the surge will rapidly go to earth instead of being sent back over the line. When the surge is over, the non-linear resistors assume high resistance to stop the flow of current.

Advantages

- (i) They provide very effective protection (especially for transformers and cables) against surges.
- (ii) They operate very rapidly taking less than a second.
- (iii) The *impulse ratio is practically unity.

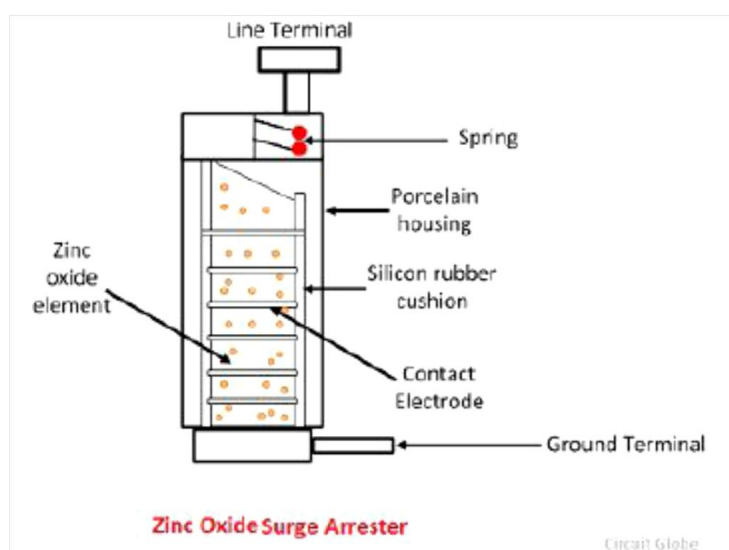
Limitations

- (i) They **may fail to check the surges of very steep wave front from reaching the terminal apparatus. This calls for additional steps to check steep-fronted waves.
- (ii) Their performance is adversely affected by the entry of moisture into the enclosure. This necessitates effective sealing of the enclosure at all times.

Applications. According to their application, the valve type arresters are classified as (i) station type and (ii) line type. The station type arresters are generally used for the protection of important equipment in power stations operating on voltages upto 220 kV or higher. The line type arresters are also used for stations handling voltages upto 66 kV.

Metal Oxide Lightning Arrester

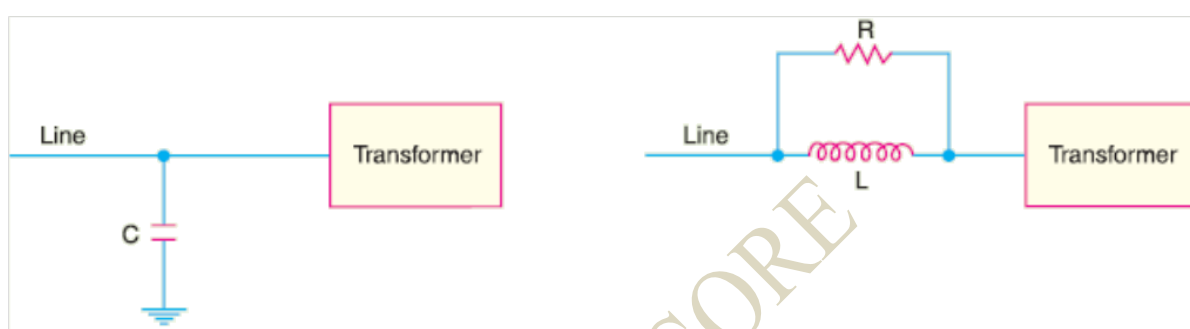
Such Types of diverter are also known as gapless surge diverters, or Zinc oxide diverter. The base material used for manufacturing metal oxide resistor is zinc oxide. It is a semiconducting N-type material. The material is doped by adding some fine power of insulating oxides. The powder is treated with some processes and then it is compressed into a disc-shaped. The disc is then enclosed in a porcelain housing filled with nitrogen gas or SF₆. This arrester consists a potential barrier at the boundaries of each disc of ZNO. This potential barrier controls the flow of current. At normal operating condition, the potential barrier does not allow the current to flow. When an overvoltage occurs, the barrier collapse and sharp transition from insulating to conducting take place. The current start flowing and the surge is diverted to ground



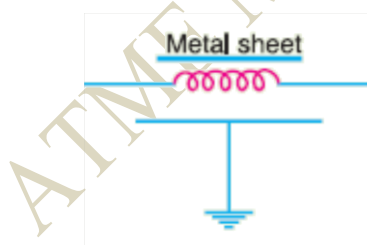
Surge Absorber

The travelling waves set up on the transmission lines by the surges may reach the terminals apparatus and cause damage to it. The amount of damage caused not only depends upon the amplitude of the surge but also upon the steepness of its wave front. The steeper the wave front of the surge, the more the damage caused to the equipment. In order to reduce the steepness of the wave front of a surge, we generally use surge absorber. A **surge absorber** is a protective device which reduces the steepness of wave front of a surge by absorbing surge energy. Although both surge diverter and surge absorber eliminate the surge, the manner in which it is done is different in the two devices. The surge diverter diverts the surge to earth but the surge absorber absorbs the surge energy. A few cases of surge absorption are discussed below :

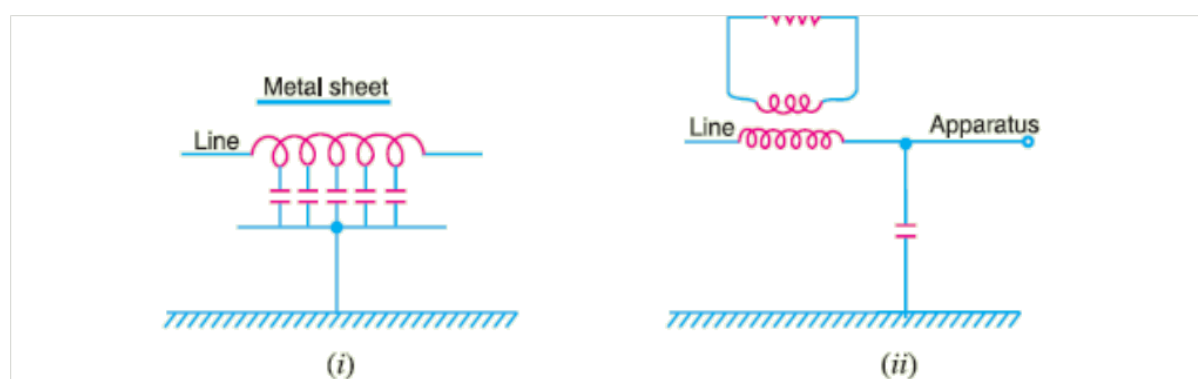
(i) A condenser connected between the line and earth can act as a surge absorber. Below Fig. shows how a capacitor acts as surge absorber to protect the transformer winding. Since the reactance of a condenser is inversely proportional to frequency, it will be low at high frequency and high at low frequency. Since the surges are of high frequency, the capacitor



(ii) Another type of surge absorber consists of a parallel combination of choke and resistance connected in series with the line as shown in below Fig.. The choke offers high reactance to surge frequencies ($X_L = 2\pi f L$). The surges are, therefore, forced to flow through the resistance R where they are dissipated.



(iii) Below Fig. shows the another type of surge absorber. It is called Ferranti surge absorber. It consists of an air cored inductor connected in series with the line. The inductor is surrounded by but insulated from an earthed metallic sheet called dissipator. This arrangement is equivalent to a transformer with short-circuited secondary. The inductor forms the primary whereas the dissipator forms the short-circuited secondary. The energy of the surge is used up in the form of heat generated in the dissipator due to transformer action. This type of surge absorber is mainly used, Fig. (i) shows the schematic diagram of 66 kV Ferranti surge absorber while Fig. (ii) shows its equivalent circuit



5.9 Insulation Coordination

Insulation Coordination is the process of determining the proper insulation levels of various components in a power system as well as their arrangements. It is the selection of an insulation structure that will withstand voltage stresses to which the system, or equipment will be subjected to, together with the proper surge arrester. The process is determined from the known characteristics of voltage surges and the characteristics of surge arresters.

Some common terms that must be known when performing an Insulation Coordination Study.

1. Basic Impulse Insulation Level (BIL)

This is the reference insulation level expressed as an impulse crest (or peak) voltage with a standard wave not longer than a **1.2 x 50 microsecond** wave.

A **1.2 x 50 microsecond** wave means that the impulse takes 1.2 microseconds to reach the peak and then decays to 50% of the peak in 50 microseconds.

2. Withstand Voltage

This is the BIL level that can repeatedly be applied to an equipment without flashover, disruptive charge or other electrical failure under test conditions.

3. Chopped Wave Insulation Level

This is determined by using impulse waves that are of the same shape as that of the BIL waveform, with the exception that the wave is chopped after 3 microseconds. Generally, it is assumed that the Chopped Wave Level is 1.15 times the BIL level for oil filled equipment such as transformers. However, for dry type equipment, it is assumed that the Chopped Wave Level is equal to the BIL level.

4. Critical Flashover Voltage

This is the peak voltage for a 50% probability of flashover or disruptive charge.

5. Impulses Ratio

This is normally used for Flashover or puncture of insulation. It is the ratio of the impulse peak voltage to the value of the 60 Hz voltage that causes flashover or puncture. Or, it is the ratio of breakdown voltage at surge frequency to breakdown voltage at normal system frequency (60 Hz).

5.10 Basic Insulation Level Definition

When lightning impulse over voltage appears in the system, it is discharged through surge protecting devices before the equipments of the system gets damaged. Hence, the insulation of such equipment must be designed to withstand a certain minimum voltage before the lightning impulse over voltage gets discharged through surge protecting devices. Therefore, operating voltage level of surge protecting devices must be lower than the said minimum voltage withstanding level of the equipment. This minimum voltage rating is defined as BIL or basic insulation level of electrical equipment.

It is needless to say, that the voltage withstanding capacity of all equipments of an electrical substation or an electrical transmission system must be decided as per its operating system voltage. To ensure the stability of the system, during over voltage phenomenon, the breakdown or flash-over strength of all equipments connected to the system, should exceed a selected level. There may be different kind of over voltage stresses appeared on the system. These over voltages may differ in characteristics such as amplitude, duration, waveform and frequency etc. In the view of economy, an electrical power system must be designed for a basic insulation level or BIL depending upon the different characteristics of all possible over voltages appear on the system. Moreover there are different over voltage protecting devices installed in the system, which safely protect the system against different over voltage phenomenon. Due to these protecting devices the abnormal over voltages disappear from the system as fast as possible

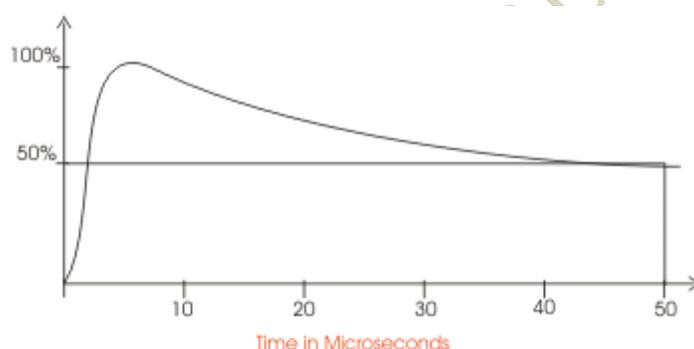
Hence, this is unnecessary to design a system whose insulation can withstand all types of over voltages for all duration of time. For example, a lightning impulse voltage appears on the system for a period of microsecond range and this is cleared from the system by lightning arrester as rapidly as possible. The insulation of an electrical equipment must be so designed that it should not be damaged before the lighting impulse voltage is cleared by lightning arrester. The basic insulation level or BIL of an electrical equipment determines the

principle dielectric qualities of the apparatus and is expressed for impulse tested apparatus by peak value of the 1/50 microsecond full wave withstand voltage

The amount of insulation provided on any piece of apparatus and particularly the transformers constitutes quite an appreciable part of the cost. The standardizing bodies have had in mind to fix the basic insulation level or BIL as low as is commensurate with safety. The lightning impulse voltage is fully natural phenomena and hence it is highly uncertain in nature. So it is impossible to predict the shape and size of lightning surge. After studying and working lots on the nature of lightning surges, the standardizing bodies have decided and introduces a basic shape of impulse wave which is used for high voltage impulse testing purpose of electrical equipments. Although this created impulse voltage does not have any direct relation with natural lightning surges. Before going through details of basic insulation level of an electrical system, let's try to understand basic shape of standard impulse voltage

Impulse Voltage

As per American Standard the impulse wave shape is 1.5/40 microsecond. As per Indian Standard this is 1.2/50 microsecond. This representation of the wave has a special significance. Such as 1.2/50 microsecond impulse wave represents a unidirectional wave which rises to its peak value from zero in 1.2 microseconds and then falls to 50% of peak value in 50 microseconds. The represented wave shape is shown below,



The breakdown or flash-over voltage of the electrical equipment with this wave shape are required to be equal or higher than the basic insulation level fixed and the spark over voltage and discharge voltage of the protecting devices like lightning arresters, are definitely required to be lower than these values so that during lightning surges, the discharge occurs through the lightning arresters not through the equipment itself. There must be sufficient margin between the lightning arrestor and insulation level of the equipments.

Basic Insulation Level Table

Nominal System Voltage	Indian Standards BIL	British Standards BIL
11 KV	75 KV	-
33 KV	170 KV	200 KV
66 KV	325 KV	450 KV
132 KV	550/650 KV	650/750 KV
220 KV	900/1050 KV	900/1050 KV

Modern Trends in Power System Protection:

Gas insulated substations (GIS) have been used in power systems over the last three decades because of their high reliability, easy maintenance, small ground space requirement etc. In India also, a few GIS units are under various stages of installation. The basic insulation level (BIL) required for a gas insulated substation (GIS) is different from that of the conventional substation because of certain unique properties of the former. Gas insulated bus has a surge impedance (70Ω) more than that of the conventional oil filled cables, but much less than that of an over head line ($300\Omega - 400\Omega$). Further, the average bus run for a compact GIS is much less than that for the conventional station. In addition, the GIS is totally enclosed and therefore is free from any atmospheric contamination. Hence, in general the GIS permit lower BIL rating than the conventional one. However the life of GIS is affected by several factors such as: conductive particles, particle discharges and contamination (decomposition products, moisture, etc.). Conductive particles inside the enclosure are known to reduce the breakdown level of Gas insulated systems. Partial discharges can develop from conductive particles, contamination, and defects during the manufacturing process, etc.

The GIS require less number of lightning arresters than a conventional one. This is mainly because of its compactness. The basic consideration for insulation coordination is V-T characteristic. The V-T characteristic of SF₆ is considerably flat compared to that of air. Air can withstand to very high voltages for very short time. However, as the duration of voltage increases, the withstand voltage falls off considerably. On the other hand, SF₆ exhibits a flat characteristic, thus the ratio of basic lightning impulse level is close to unity for GIS, whereas for the conventional substations this ratio varies between 0.6 and 0.86. Although GIS has been in operation for several years, a lot of problems encountered in practice need further understanding. Some of the problems studied are:

- a. Switching operations generate very fast transient overvoltages (VFTOS)
- b. VFTOS may cause secondary breakdowns inside a GIS and Transient Enclosure Voltages (TEV) outside the GIS
- c. Prolonged arcing may produce corrosive / toxic by products. Support spacers can be weak points when arc by products and metallic particles are present
- e. From the reliability point of view, partial discharge detection is important. The methods of detection are of acoustic system and electric systems etc. These methods lack quality control.

5.10 GAS INSULATED SUBSTATIONS

SF₆ gas insulated high voltage switchgear has been in commercial operation for more than 30 years. Continuous technological and design improvements of all the components during the course of the time are characterized by appreciable savings in area and volume occupied by the substation. Gas insulated substations are in service up to the highest voltage of 800 kV, meeting almost all the requirements in urban, industrial as well as rural areas. In the initial stages, the new SF₆ gas insulated substations were almost exclusively used where space limitations, site restrictions or exponential ambient conditions made it difficult to use conventional air insulated substations. However, over the last 30 years, GIS at voltage up to 800 kV in various station configurations and with various performance requirements, have been installed in increasing numbers worldwide. The modular of design of GIS offers a high degree of flexibility to meet layout requirements of both substations, as well as power station switchgear, making efficient use of available space. GIS technology has reached a stage of application and a wide range of GIS equipment up to highest voltage of 800 kV is available with many unique features. They are:

1. Wide spread application of aluminum enclosure materials for standardized component models for all voltage ranges
2. The light weight enclosures have good conductivity, low eddy-current losses and a high resistance to corrosion
3. Easy handling, as well as reduced stresses on foundation and support structure are additional features
4. Standard arrangements can be easily modified and extended with good co-ordination between the manufacturer and the user.
5. A gas- tight barrier insulator in switchgear serve for the separation of gas compartments and prevents neighbouring switchgear parts from being affected during maintenance.

The Gas insulated substation comprises the following components:

- 1 Circuit breaker
- 2 Disconnect switch
- 3 Earthing switch
- 4 Current transformer
- 5 Voltage transformer
- 6 Bus bar & connectors
- 7 Power transformer
- 8 Surge arrester
- 9 Cable termination
- 10 SF6 / air or SF6 / oil bushing

Advantages of GIS over the conventional open air substation

The application of GIS during the last fifteen years has been very rapid. The rapid growth in GIS application is due to the following special advantages:

1. Area and volume saving in construction for over or underground applications. Therefore they offer saving in land area and construction costs.
2. Insensitivity to external influences because of grounded metal enclosures.
3. Greatly improved safety and reliability due to earthed metal housing of all high voltage parts and much higher intrinsic strength of SF6 gas as insulation.
4. Short on site erection times, based on large factory assembled and tested shipping units
5. Fulfillment of aesthetic requirements with indoor applications
6. High service reliability due to non-exposure of the use of high voltage parts to atmosphere influences
7. Reduction in radio interference with the use of earthed metal enclosures
8. Use as mobile substations for transportation to load centers on standard tracks. These substations can be located closer to load centers thereby reducing transmission losses and expenditure in the distribution network.
9. More optimal life cycle costs because of lesser maintenance, down time and repair costs.
10. It is not necessary that high voltage or extra high voltage switchgear has to be installed out doors

Disadvantages of GIS

Although GIS has been in operation for several years, a lot of problems encountered in practice need fuller understanding. Some of the problems being studied are:

1. Switching operation generate Very Fast Transients Over Voltages (VFTOS).
2. VFTOS may cause secondary breakdown inside a GIS and Transient Enclosure Voltages (TEV) outside the GIS.
3. Field non-uniformities reduce withstanding levels of a GIS.
4. Prolonged arcing may produce corrosive/toxic by-products.
5. Support spacers can be weak points when arc by-products and metallic particles are present

Course outcomes:

Interpret the construction and operating principle of different types of fuses and to give the definitions of different terminologies related to a fuse and Discuss protection against Overvoltages and Gas Insulated Substation