Lecture Note

Semester- 6th

Subject – SWITCH GEAR AND PROTECTIVE DEVICES

Subject code- EET601

L-T-P – 5-0-0

Branch- Electrical engineering

Course outcomes

Co1: - acquire the knowledge of switchgear, busbar, shortcircuit, different types faults in a power system.

Co2: -calculation of symmetrical fault by acquiring the knowledge of percentage reactance, base KVA, short circuit KVA, location of reactors.

Co3: - acquire the knowledge of various types of fuses and circuit breakers, their design and constructional details, operation in normal and abnormal condition that could occur in power system.

Co4: -acquire knowledge of various conventional relays, their design and latest developments.

Co5: -identify different faults occur in alternator & explain protection of alternator. Describe protection of transformer, busbar, transmission line and feeders.

CO6: - explain various cause and mechanism of lightning discharge. Describe the various types of lightning arresters and surge absorber.

CO7: - describe the advantage of static relay, overcurrent relay & IDMT relay.

Program outcomes

1. **Basic and discipline specific knowledge**: apply knowledge of basic mathematics, science and engineering fundamentals and engineering specialization to solve the engineering problems.
2. **Problem analysis**: Identify and well-defined engineering problems using codified standard methods.
3. **Design / development of solutions**: design solutions for well defined technical problems and assist with the design of systems components or process to meet specified needs.
4. **Engineering tools, experimentation and testing**: apply modern engineering tools and appropriate technique to conduct standard test and measurements.
5. **Engineering practice for society, sustainability and environment**: appropriate technology in context of society, sustainability, environment and ethical practice
6. **Project management**: use engineering management principles individually, as a team member or a leader to manage projects an effectively communicate about well-defined engineering activities.
7. **Lifelong learning**: ability to analysis individual needs and engage in updating in the context of technological changes.

MAPPING BETWEEN CO AND PO

PO CO	1	2	3	4	5	6	7
1	✓			✓	✓		✓
2	✓	✓	✓			✓	✓
3	✓	✓	✓	✓			✓
4	✓	✓	✓	✓		✓	✓
5	✓			✓		✓	✓
6	✓				✓	✓	✓
7	✓				✓		✓

Chapter 1 INTRODUCTION TO SWITCHGEAR

Switchgear:

The apparatus used for switching, controlling and protecting the electrical circuits and equipment is known as **switchgear**.

The switchgear equipment is essentially concerned with switching and interrupting currents either under normal or abnormal operating conditions. The tumbler switch with ordinary fuse is the simplest form of switchgear and is used to control and protect lights and other equipment in homes, offices *etc*. For circuits of higher rating, a high-rupturing capacity (H.R.C.) fuse in conjuction with a switch may serve the purpose of controlling and protecting the circuit. However, such a switchgear cannot be used profitably on high voltage system (3·3 kV) for two reasons. Firstly, when a fuse blows, it takes sometime to replace it and consequently there is interruption of service to the customers. Secondly, the fuse cannot successfully interrupt large fault currents that result from the faults on high voltage system.

With the advancement of power system, lines and other equipments operate at high voltages and carry large currents. When a short circuit occurs on the system, heavy current flowing through the equipment may cause considerable damage. In order to interrupt such heavy fault currents, *automatic circuit breakers* (or simply circuit breakers) are used. A circuit breaker is a switchgear which can open or close an electrical circuit under both normal and abnormal conditions. Even in instances where a fuse is adequate, as regards to breaking capacity, a circuit breaker may be preferable. It is because a circuit breaker can close circuits, as well as break them without replacement and thus has wider range of use altogether than a fuse.

Essential features of switchgear:

The essential features of switchgear are :

(i) **Complete reliability.** With the continued trend of interconnection and the increasing capacity of generating stations, the need for a reliable switchgear has become of paramount importance. This is not surprising because switchgear is added to the power system to improve the reliability. When fault occurs on any part of the power system, the switchgear must operate to isolate the faulty section from the remainder circuit.

(ii) **Absolutely certain discrimination.** When fault occurs on any section of the power system, the switchgear must be able to discriminate between the faulty section and the healthy section. It should isolate the faulty section from the system without affecting the healthy section. This will ensure continuity of supply.

(iii) **Quick operation.** When fault occurs on any part of the power system, the switchgear must operate quickly so that no damage is done to generators, transformers and other equipment by the short-circuit currents. If fault is not cleared by switchgear quickly, it is likely to spread into healthy parts, thus endangering complete shut down of the system.

(iv) **Provision for manual control.** A switchgear must have provision for manual control. In case the electrical (or electronics) control fails, the necessary operation can be carried out through manual control.

(v) **Provision for instruments.** There must be provision for instruments which may be required. These may be in the form of ammeter or voltmeter on the unit itself or the necessary current and voltage transformers for connecting to the main switchboard or a separate instrument panel.

Switchgear equipment:

Switchgear covers a wide range of equipment concerned with switching and interrupting currents under both normal and abnormal conditions. It includes switches, fuses, circuit breakers, relays and other equipment. A brief account of these devices is given below. However, the reader may find the detailed discussion on them in the subsequent chapters.

1. **Switches.** A switch is a device which is used to open or close an electrical circuit in a convenient way. It can be used under full-load or no-load conditions *but* it cannot interrupt the fault currents. When the contacts of a switch are opened, an *arc is produced in the air between the contacts. This is particularly true for circuits of high voltage and large current capacity. The switches may be classified into (*i*) air switches (*ii*) oil switches. The contacts of the former are opened in air and that of the latter are opened in oil.

(i) *Air-break switch.* It is an air switch and is designed to open a circuit *under load*. In order to quench the arc that occurs on opening such a switch, special arcing horns are provided. Arcing horns are pieces of metals between which arc is formed during opening operation. As the switch opens, these horns are spread farther and farther apart. Consequently, the arc is lengthened, cooled and interrupted. Air-break switches are generally used outdoor for circuits of medium capacity such as lines supplying an industrial load from a main transmission line or feeder.

(ii) *Isolator or disconnecting switch.* It is essentially a knife switch and is designed to open a circuit under *no load*. Its main purpose is to isolate one portion of the circuit from the other and is not intended to be opened while current is flowing in the line. Such switches are generally used on both sides of circuit breakers in order that repairs and replacement of circuit breakers can be made without any danger. They should never be opened until the circuit breaker in the same circuit has been opened and should always be closed before the circuit breaker is closed.

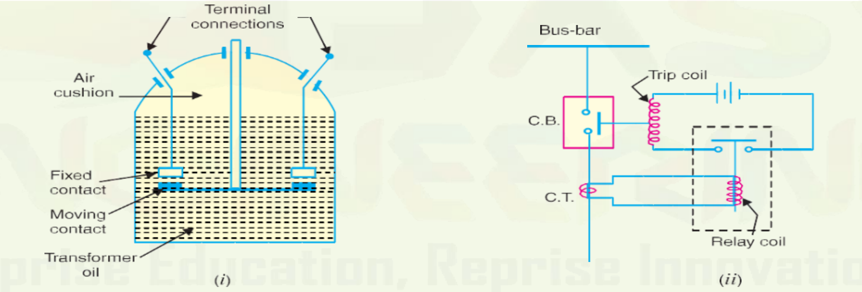
(iii) *Oil switches.* As the name implies, the contacts of such switches are opened under oil, usually transformer oil. The effect of oil is to cool and quench the arc that tends to form when the circuit is opened. These switches are used for circuits of high voltage and large current carrying capacities.

2. **Fuses.** A fuse is a short piece of wire or thin strip which melts when excessive current flows through it for sufficient time. It is inserted in series with the circuit to be protected. Under normal operating conditions, the fuse element it at a temperature below its melting point. Therefore, it carries the normal load current without overheating. However, when a short circuit or overload occurs, the current through the fuse element increases beyond its rated capacity. This raises the temperature and the 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. It is worthwhile to note that a fuse performs both detection and interruption functions.

3. **Circuit breakers.** A circuit breaker is an equipment which can open or close a circuit under all conditions *viz*. no load, full load and fault conditions. It is so designed that it can be operated manually (or by remote control) under normal conditions and automatically under fault conditions. For the latter operation, a relay circuit is used with a circuit breaker. Fig. 16.1 (*i*) shows the parts of

a typical oil circuit breaker whereas Fig. 16.1 (*ii*) shows its control by a relay circuit. The circuit breaker essentially consists of moving and fixed contacts enclosed in strong metal tank and immersed in oil, known as transformer oil.

Under normal operating conditions, the contacts remain closed and the circuit breaker carries the full-load current continuously. In this condition, the e.m.f. in the secondary winding of current transformer (C.T.) is insufficient to operate the trip coil of the breaker but the contacts can be opened (and hence the circuit can be opened) by manual or remote control. When a fault occurs, the resulting overcurrent in the C.T. primary winding increases the secondary e.m.f. This energises the trip coil of the breaker and moving contacts are pulled down, thus opening the contacts and hence the circuit. The arc produced during the opening operation is quenched by the oil. It is interesting to note that relay performs the function of detecting a fault whereas the circuit breaker does the actual circuit interruption.



(*i*) (*ii*)

Fig. 16.1

4. **Relays.** A relay is a device which detects the fault and supplies information to the breaker for circuit interruption. Fig. 16.1 (*ii*) shows a typical relay circuit. It can be divided into three parts *viz*.

   (i) The primary winding of a *current transformer (C.T.) which is connected in series with the circuit to be protected. The primary winding often consists of the main conductor itself.

   (ii) The second circuit is the secondary winding of C.T. connected to the relay operating coil.

   (iii) The third circuit is the tripping circuit which consists of a source of supply, trip coil of circuit breaker and the relay stationary contacts.

Under normal load conditions, the e.m.f. of the secondary winding of C.T. is small and the current flowing in the relay operating coil is insufficient to close the relay contacts. This keeps the trip coil of the circuit breaker unenergised. Consequently, the contacts of the circuit breaker remain closed and it carries the normal load current. When a fault occurs, a large current flows through the primary of C.T. This increases the secondary e.m.f. and hence the current through the relay operating coil. The relay contacts are closed and the trip coil of the circuit breaker is energised to open the contacts of the circuit breaker.

Busbar arrangement:

When a number of generators or feeders operating at the same voltage have to be directly connected electrically, bus-bars are used as the common electrical component. *Bus-bars are copper rods or thin walled tubes and operate at constant voltage. We shall discuss some important bus-bars arrangements used for power stations and sub-stations. All the diagrams refer to 3-phase arrangement but are shown in single-phase for simplicity.

(1) Single Bus-bar System. The single bus-bar system has the simplest design and is used for power stations. It is also used in small outdoor stations having relatively few outgoing or incoming feeders and lines. Fig. 16.2 shows the single bus-bar system for a typical power station. The generators, outgoing lines and transformers are connected to the bus-bar. Each generator and feeder is controlled by a circuit breaker. The isolators permit to isolate generators, feeders and circuit breakers from the bus-bar for maintenance. The chief advantages of this type of arrangement are low initial cost, less maintenance and simple operation.

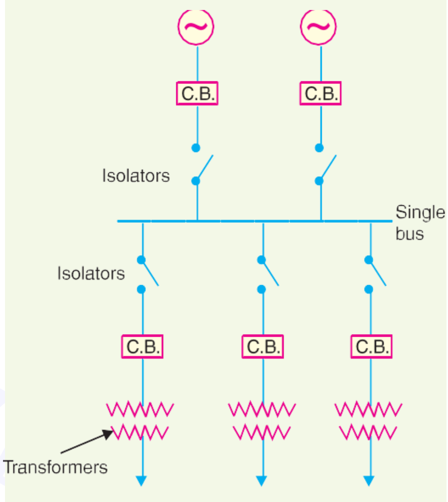


Fig. 16.2

Disadvantages: single busbar system has the following three disadvantages.

1. The busbar cannot be cleaned, repaired or tested without deenergizing the whole system.
2. If a fault occurs on the busbar itself, there is complete interruption of supply.
3. Any fault on the system is fed by all the generating capacity, resulting in very large fault currents.

(2) Single bus-bar system with Sectionalisation. In large generating stations where several units are installed, it is a common practice to sectionalise the bus so that fault on any section of the bus-bar will not cause complete shut down. This is illustrated in Fig. 16.3 which shows the bus-bar divided into two sections connected by a circuit breaker and isolators. Three principal advantages are claimed for this arrangement. Firstly, if a fault occurs on any section of the bus-bar, that section can be isolated without affecting the supply to other sections. Secondly, if a fault occurs on any feeder, the fault current is much **lower than with unsectionalised bus-bar. This permits the use of circuit breakers of lower capacity in the feeders. Thirdly, repairs and maintenance of any section of the bus-bar can be carried out by de-energising that section only, eliminating the possibility of complete shut-down.

It is worthwhile to keep in mind that a circuit breaker should be used as the sectionalising switch so that uncoupling of the bus-bars may be carried out safely during load transfer. Moreover, the circuit breaker itself should be provided with isolators on both sides so that its maintenance can be done while the bus-bars are alive.

(3) Duplicate bus-bar system. In large stations, it is important that breakdowns and maintenance should interfere as little as possible with continuity of supply. In order to achieve this objective, duplicate bus-bar system is used in important stations. Such a system consists of two bus-bars, a "main bus-bar'' and a "spare" bus-bar (see Fig. 16.4). Each generator and feeder may be connected to either bus-bar with the help of bus coupler which consists of a circuit breaker and isolators.

In the scheme shown in Fig. 16.4, service is interrupted during switch over from one bus to another. However, if it were desired to switch a circuit from one to another with- out interruption of service, there would have to be two circuit breakers per circuit. Such an arrangement will be too expensive.

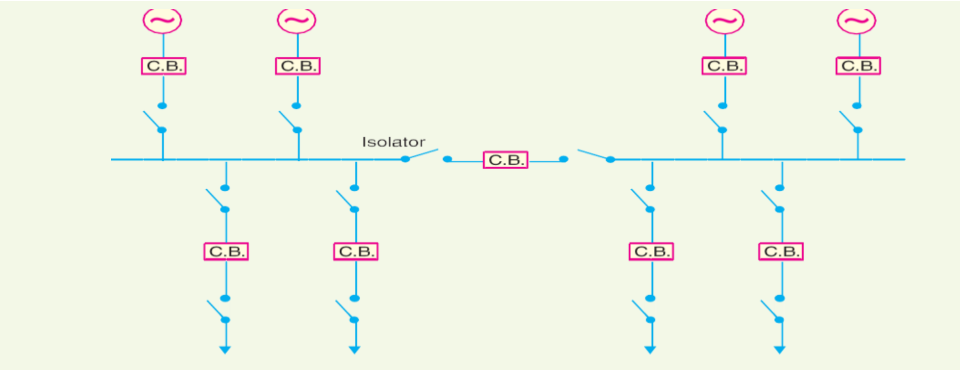


Fig. 16.3

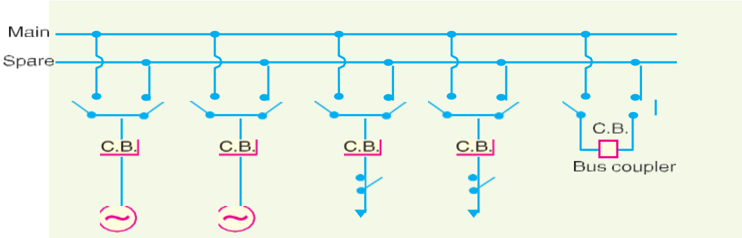


Fig. 16.4

Advantages

(i) If repair and maintenance it to be carried on the main bus, the supply need not be interrupted as the entire load can be transferred to the spare bus.

(ii) The testing of feeder circuit breakers can be done by putting them on spare bus-bar, thus keeping the main bus-bar undisturbed.

(iii) If a fault occurs on the bus-bar, the continuity of supply to the circuit can be maintained by transferring it to the other bus-bar.

Switchgear Accomodation:

The main components of a switchgear are circuit breakers, switches, bus-bars, instruments and instrument transformers. It is necessary to house the switchgear in power stations and sub-stations in such a way so as to safeguard personnel during operation and maintenance and to ensure that the effects of fault on any section of the gear are confined to a limited region. Depending upon the voltage to be handled, switchgear may be broadly classified into (*i*) outdoor type (*ii*) indoor type.

(i) *Outdoor type.* For voltages beyond 66 kV, switchgear equipment is installed outdoor. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers, transformers and others equipment become so great that it is not economical to install all such equipment indoor.

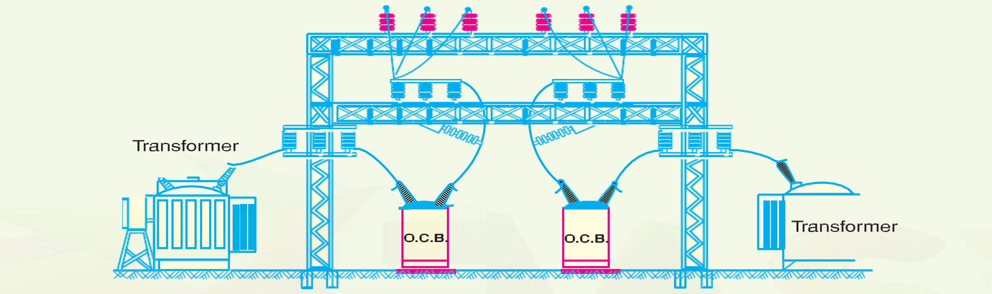


Fig. 16.5

Fig. 16.5 shows a typical outdoor sub-station with switchgear equipment. The circuit breakers, isolators, transformers and bus-bars occupy considerable space on account of large electrical clearance associated with high voltages.

(ii) *Indoor type.* For voltages below 66 kV, switchgear is generally installed indoor because of economic considerations. The indoor switchgear is generally of metal-clad type. In this type of construction, all live parts are completely enclosed in an earthed metal casing. The primary object of this practice is the definite localisation and restriction of any fault to its place of origin.

Short-Circuit:

Whenever a fault occurs on a network such that a large current flows in one or more phases, a **short-circuit** *is said to have occurred.*

When a short circuit occurs, a heavy current called short circuit current flows through the circuit. This can be beautifully illustrated by referring to Fig. 16.6 where a single phase generator of voltage V and internal impedance Z_i is supplying to a load Z. Under normal conditions, the current in the circuit is limited by *load impedance Z. However, if the load terminals get shorted due to any reason, the circuit impedance is reduced to a very low value ; being Z_i in this case. As Z_i is very small, therefore, a large current flows through the circuit. This is called short-circuit current. It is worthwhile to make a distinction between a **_short-circuit_ and an *overload*. When a short-circuit occurs, the voltage at fault point is reduced to zero and current of abnormally high magnitude flows through the network to the point of fault. On the other hand, an overload means that loads greater than the designed values have been imposed on the system. Under such conditions, the voltage at the overload point may be low, but not zero. The undervoltage conditions may extend for some distance beyond the overload point into the remainder of the system. The currents in the overloaded equipment are high but are substantially lower than that in the case of a short-circuit.

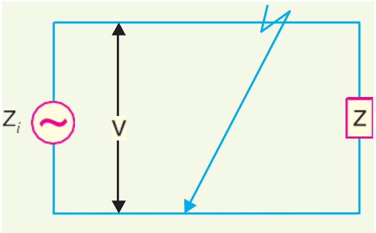


Fig. 16.6

Causes of short-circuit. A short circuit in the power system is the result of some kind of abnormal conditions in the system. It may be caused due to internal and/or external effects.

(i) *Internal effects* are caused by breakdown of equipment or transmission lines, from deterio- ration of insulation in a generator, transformer *etc*. Such troubles may be due to ageing of insulation, inadequate design or improper installation.

(ii) *External effects* causing short circuit include insulation failure due to lightning surges, over- loading of equipment causing excessive heating; mechanical damage by public *etc*.

Effects of short-circuit. When a short-circuit occurs, the current in the system increases to an abnormally high value while the system voltage decreases to a low value.

(i) The heavy current due to short-circuit causes excessive heating which may result in fire or explosion. Sometimes short-circuit takes the form of an arc and causes considerable damage to the system. For example, an arc on a transmission line not cleared quickly will burn the conductor severely causing it to break, resulting in a long time interruption of the line.

(ii) The low voltage created by the fault has a very harmful effect on the service rendered by the power system. If the voltage remains low for even a few seconds, the consumers' motors may be shut down and generators on the power system may become unstable.

Due to above deterimental effects of short-circuit, it is desirable and necessary to disconnect the faulty section and restore normal voltage and current conditions as quickly as possible.

Short-Circuit Currents:

Most of the failures on the power system lead to short-circuit fault and cause heavy current to flow in the system. The calculations of these short-circuit currents are important for the following reasons :

i. A short-circuit on the power system is cleared by a circuit breaker or a fuse. It is necessary, therefore, to know the maximum possible values of short-circuit current so that switchgear of suitable rating may be installed to interrupt them.

ii. The magnitude of short-circuit current determines the setting and sometimes the types and location of protective system.

iii. The magnitude of short-circuit current determines the size of the protective reactors which must be inserted in the system so that the circuit breaker is able to withstand the fault current.

iv. The calculation of short-circuit currents enables us to make proper selection of the associated apparatus (*e.g.* bus-bars, current transformers etc.) so that they can withstand the forces that arise due to the occurrence of short circuits.

Faults in a Power System:

A fault occurs when two or more conductors that normally operate with a potential difference come in contact with each other. These faults may be caused by sudden failure of a piece of equipment, accidental damage or short-circuit to overhead lines or by insulation failure resulting from lightning surges. Irrespective of the causes, the faults in a 3-phase system can be classified into two main categories *viz*.

v. Symmetrical faults ***(ii)*** Unsymmetrical faults

(i) **Symmetrical faults.** That fault which gives rise to symmetrical fault currents (*i.e.* equal faults currents with 120° displacement) is called a symmetrical fault. The most common example of symmetrical fault is when all the three conductors of a 3-phase line are brought together simultaneously into a short-circuit condition. The method of calculating fault currents for symmetrical faults is discussed in chapter 17.

(ii) **Unsymmetrical faults.** Those faults which give rise to unsymmetrical currents (*i.e.* unequal line currents with unequal displacement) are called unsymmetrical faults. The unsymmetrical faults may take one of the following forms :

(a) Single line-to-ground fault ***(b)*** Line-to-line fault ***(c)*** Double line-to-ground fault

The great majority of faults on the power system are of unsymmetrical nature; the most common type being a short-circuit from one line to ground. The calculations of such fault currents are made by "symmetrical components" method.

Chapter 2 FAULT CALCULATION

Symmetrical Faults on 3-Phase System:

That fault on the power system which gives rise to symmetrical fault currents (*i.e. equal fault currents in the lines with 120º displacement*) *is called a* **symmetrical fault.**

The symmetrical fault occurs when all the three conductors of a 3-phase line are brought together simultaneously into a short-circuit condition as shown in Fig. 17.1. This type of fault gives rise to symmetrical currents *i.e.* equal fault currents with 120º displacement. Thus referring to Fig. 17.1, fault currents I_R, I_Y and I_B will be equal in magnitude with 120° displacement among them. Because of balanced nature of fault, only one* phase need be considered in calculations since condition in the other two phases will also be similar. The following points may be particularly noted :

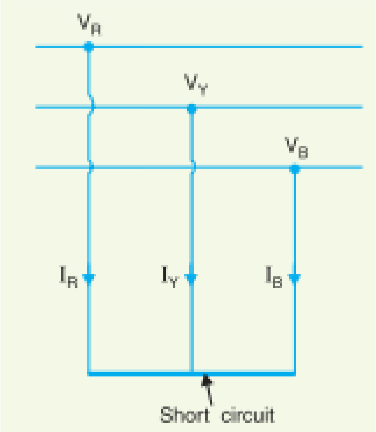


Fig. 17.1

- The symmetrical fault rarely occurs in practice as majority of the faults are of unsymmetrical nature. However, symmetrical fault calculations are being discussed in this chapter to enable the reader to understand the problems that short circuit conditions present to the power system.
- The symmetrical fault is the most severe and imposes more heavy duty on the circuit breaker.

Limitation of Fault Current:

When a short circuit occurs at any point in a system, the short-circuit current is limited by the impedance of the system upto the point of fault. Thus referring to Fig. 17.2, if a fault occurs on the feeder at point *F*, then the short circuit current from the generating station will have a value limited by the impedance of generator and transformer and the impedance of the line between the generator and the point of fault. This shows that the knowledge of the impedances of various equipment and circuits in the line of the system is very important for the determination of short-circuit currents.

In many situations, the impedances limiting the fault current are largely reactive, such as transformers, reactors and generators. Cables and lines are mostly resistive, but where the total reactance in calculations exceeds 3 times the resistance, the latter is usually neglected. The error introduced by this assumption will not exceed 5%.

Fig. 17.2

Percentage Reactance:

The reactance of generators, transformers, reactors *etc*. is usually expressed in *percentage reactance* to permit rapid short circuit calculations. The percentage reactance of a circuit is defined as under :

It is the percentage of the total phase-voltage dropped in the circuit when full-load current is flowing i.e.,

$$\%X = \frac{I\ X}{V} \times 100 \qquad \ldots(i)$$

where I = full-load current

V = phase voltage

X = reactance in ohms per

Alternatively, percentage reactance (%X) can also be expressed in terms* of kVA and kV as under :

$$\%X = \frac{(\text{kVA})\ X}{10\ (\text{kV})^2} \qquad \ldots(ii)$$

where X is the reactance in ohms.

If X is the only reactance element in the circuit, then short-circuit current is given by ;

$$I_{SC} = v/x$$

$$= I \times (100/\%X)$$

i.e. short circuit current is obtained by multiplying the full-load current by 100/% X

For instance, if the percentage reactance of an element is 20% and the full-load current is 50 A, then short-circuit current will be 50 × 100/20 = 250 A when only that element is in the circuit.

It may be worthwhile to mention here the advantage of using percentage reactance instead of ohmic reactance in short-circuit calculations. Percentage reactance values remain unchanged as they are referred through transformers, unlike ohmic reactances which become multiplied or divided by the square of transformation ratio. This makes the procedure simple and permits quick calculations.

Percentage Reactance and Base kVA:

It is clear from exp. (*ii*) above that percentage reactance of an equipment depends upon its kVA rating. Generally, the various equipments used in the power system have different kVA ratings. Therefore, it is necessary to find the percentage reactances of all the elements on a common kVA rating. This common kVA rating is known as *base kVA.* The value of this base kVA is quite unimportant and may be :

(i) equal to that of the largest plant

(ii) equal to the total plant capacity

(iii) any arbitrary value

The conversion can be effected by using the following relation :

$$\%\text{ age reactance at base kVA} = \frac{\text{Base kVA}}{\text{Rated kVA}} \times \%\text{ age reactance at rated kVA}$$

Thus, a 1000 kVA transformer with 5% reactance will have a reactance of 10% at 2000 kVA base.

Illustration. The fact that the value of base kVA does not affect the short circuit current needs illustration. Consider a 3-phase transmission line operating at 66 kV and connected through a 1000 kVA transformer with 5% reactance to a generating station bus-bar. The generator is of 2500 kVA with 10% reactance. The single line diagram of the system is shown in Fig. 17.3. Suppose a short-circuit fault between three phases occurs at the high voltage terminals of transformer. It will be shown that whatever value of base kVA we may choose, the value of short-circuit current will be the same.

(i) Suppose we choose 2500 kVA as the common base kVA. On this base value, the reactances of the various elements in the system will be :

Reactance of transformer at 2500 kVA base

$$= 5 \times 2500^{*}/1000 = 12{\cdot}5\%$$

Reactance of generator at 2500 kVA base

$$= 10 \times 2500/2500 = 10\%$$

Total percentage reactance on the common base kVA

$$\%X = 12{\cdot}5 + 10 = 22{\cdot}5\%$$

The full† load current corresponding to 2500 kVA base at 66 kV is given by ;

$$I = \frac{2500 \times 1000}{\sqrt{3} \times 66 \times 1000} = 21{\cdot}87 \text{ A}$$

$$\therefore \text{ Short-circuit current, } I_{SC} = I \times \frac{100}{\%X} = 21{\cdot}87 \times \frac{100}{22{\cdot}5} = \mathbf{97{\cdot}2\ A}$$

(*ii*) Now, suppose we choose 5000 kVA as the common base value.

Reactance of transformer at 5000 kVA base

$$= 5 \times 5000/1000 = 25\%$$

Reactance of generator at 5000 kVA base

$$= 10 \times 5000/2500 = 20\%$$

Total percentage reactance on the common base kVA

$$I = \frac{5000 \times 1000}{\sqrt{3} \times 66 \times 1000} = 43{\cdot}74 \text{ A}$$

$$\therefore \quad \text{Short-circuit current, } I_{SC} = I \times \frac{100}{\%X} = 43{\cdot}74 \times \frac{100}{45} = \mathbf{97{\cdot}2\,A}$$

which is the same as in the previous case.

From the above illustration, it is clear that whatever may be the value of base kVA, short-circuit current is the same. However, in the interest of simplicity, numerically convenient value for the base kVA should be chosen.

Short-Circuit KVA:

Although the potential at the point of fault is zero, it is a normal practice to express the short-circuit current in terms of short-circuit kVA based on the normal system voltage at the point of fault.

The product of normal system voltage and short-circuit current at the point of fault expressed in kVA is known as **short-circuit kVA**.

Let V = normal phase voltage in volts
I = full-load current in amperes at base kVA
$\%X$ = percentage reactance of the system on base kVA upto the fault point

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* $$\% \text{ reactance at base kVA} = \frac{\text{base kVA}}{\text{rated kVA}} \times \% \text{ reactance at rated kVA}$$

† Full-load current has to be found out for the base kVA selected.

Short-circuit current, I_{SC} =I(100/%X)

∴ Short-circuit kVA for 3-phase circuit

$$= \frac{3\,V\,I_{SC}}{1000}$$

$$= \frac{3\,V\,I}{1000} \times \frac{100}{\%X}$$

$$= \text{Base kVA} \times \frac{100}{\%X}$$

i.e. short-circuit kVA is obtained by multiplying the base kVA by 100/% X.

Reactor Control of Short-Circuit Currents:

With the fast expanding power system, the fault level (*i.e.* the power available to flow into a fault) is also rising. The circuit breakers connected in the power system must be capable of dealing with maximum possible short-circuit currents that can occur at their points of connection. Generally, the reactance of the system under fault conditions is low and fault currents may rise to a dangerously high value. If no steps are taken to limit the value of these short-circuit currents, not only will the duty required of circuit breakers be excessively heavy, but also damage to lines and other equipment will almost certainly occur.

In order to limit the short-circuit currents to a value which the circuit breakers can handle, additional reactances known as *reactors* are connected in series with the system at suitable points. A reactor is a coil of number of turns designed to have a large inductance as compared to its ohmic resistance. The forces on the turns of these reactors under short-circuit conditions are considerable and, therefore, the windings must be solidly braced. It may be added that due to very small resistance of reactors, there is very little change in the efficiency of the system.

Advantages

(iv) Reactors limit the flow of short-circuit current and thus protect the equipment from overheating as well as from failure due to destructive mechanical forces.

(v) Troubles are localised or isolated at the point where they originate without communicating their disturbing effects to other parts of the power system. This increases the chances of continuity of supply.

(vi) They permit the installation of circuit breakers of lower rating.

Location of Reactors:

Short circuit current limiting reactors may be connected ***(i)*** in series with each generator ***(ii)*** in series with each feeder and ***(iii)*** in bus-bars. No definite statement can be given as to which one of the above locations is preferable; each installation has its own particular demands which must be carefully considered before a choice of reactor location can be made.

(1) **Generator reactors.** When the reactors are connected in series with each generator, they are known as *generator reactors* (see Fig. 17.4). In this case, the reactor may be considered as a part of leak-

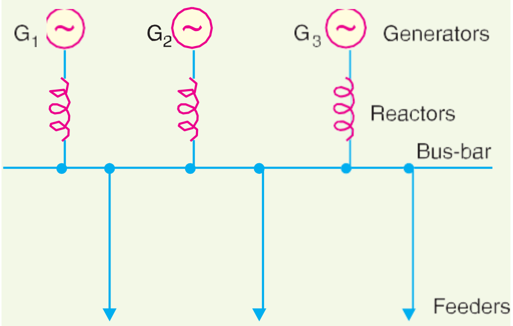


Fig. 17.4

-age reactance of the generator. Hence its effect is to protect the generator in the case of any short-circuit beyond the reactors.

Disadvantages

(i) There is a constant voltage drop and power loss in the reactors even during normal operation.

(ii) If a bus-bar or feeder fault occurs close to the bus-bar, the voltage at the bus-bar will be reduced to a low value, thereby causing the generators to fall out of step.

(iii) If a fault occurs on any feeder, the continuity of supply to other is likely to be affected.

Due to these disadvantages and also since modern power station generators have sufficiently large leakage reactance to protect them against short-circuit, it is not a common practice to use separate reactors for the generators.

(2) **Feeder reactors.** When the reactors are connected in series with each feeder, they are known as *feeder reactors* (see Fig. 17.5). Since most of the short-circuits occur on feeders, a large number of reactors are used for such circuits. Two principal advantages are claimed for feeder reactors. Firstly, if a fault occurs on any feeder, the voltage drop in its reactor will not affect the bus-bars voltage so that there is a little tendency for the generator to lose synchronism. Secondly, the fault on a feeder will not affect other feeders and consequently the effects of fault are localised.

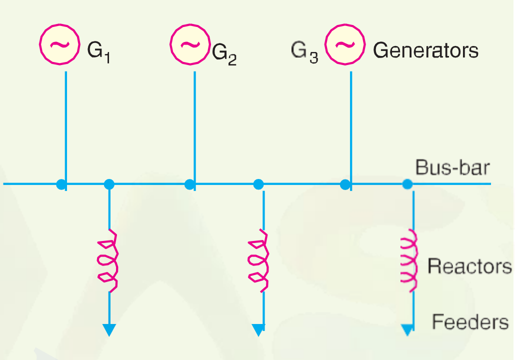


Fig. 17.5

Disadvantages

(i) There is a constant power loss and voltage drop in the reactors even during normal operation.

(ii) If a short-circuit occurs at the bus-bars, no protection is provided to the generators. However, this is of little importance because such faults are rare and modern generators have considerable leakage reactance to enable them to withstand short-circuit across their terminals.

(iii) If the number of generators is increased, the size of feeder reactors will have to be increased to keep the short-circuit currents within the ratings of the feeder circuit breakers.

(3) **Bus-bar reactors.** The above two methods of locating reactors suffer from the disadvantage that there is considerable voltage drop and power loss in the reactors even during normal operation. This disadvantage can be overcome by locating the reactors in the bus-bars. There are two methods for this purpose, namely ; Ring system and Tie-Bar system.

(i) *Ring system.* In this system, bus-bar is divided into sections and these sections are connected through reactors as shown in Fig. 17.6. Generally, one feeder is fed from one generator only. Under normal operating conditions, each generator will supply its own section of the load and very little power will be fed by other generators. This results in low power loss and voltage drop in the reactors. However, the principal advantage of the system is that if a fault occurs on any feeder, only one generator (to which the particular feeder is connected) mainly feeds the fault current while the current fed

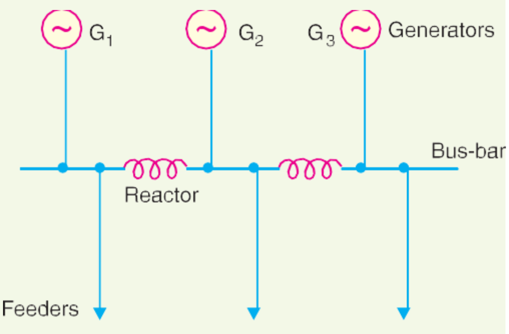


Fig. 17.6

from other generators is small due to the presence of reactors. Therefore, only that section of bus-bar is affected to which the feeder is connected, the other sections being able to continue in normal operation.

(ii) *Tie-Bar system.* Fig. 17.7 shows the tie-bar system. Comparing the ring system with tie-bar system, it is clear that in the tie-bar system, there are effectively two reactors in series between sections so that reactors must have approximately half the reactance of those used in a comparable ring system. Another advantage of tie-bar system is that additional generators may be connected to the system without requiring changes in the existing reactors. However, this system has the disadvantage that it requires an additional bus-bar *i.e.* the tie-bar.

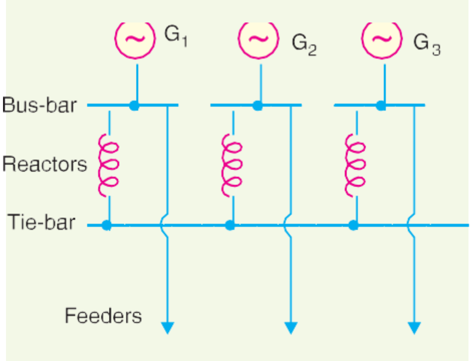


Fig. 17.7

Steps for Symmetrical Fault Calculations:

It has already been discussed that 3-phase short-circuit faults result in symmetrical fault currents *i.e.* fault currents in the three phases are equal in magnitude but displaced 120° electrical from one another. Therefore, problems involving such faults can be solved by considering one phase only as the same conditions prevail in the other two phases. The procedure for the solution of such faults involves the following steps :

(i) Draw a single line diagram of the complete network indicating the rating, voltage and percentage reactance of each element of the network.

(ii) Choose a numerically convenient value of base kVA and convert all percentage reactances to this base value.

(iii) Corresponding to the single line diagram of the network, draw the reactance diagram showing one phase of the system and the neutral. Indicate the % reactances on the base kVA in the reactance diagram. The transformer in the system should be represented by a reactance in series.

(iv) Find the total % reactance of the network upto the point of fault. Let it be X%.

(v) Find the full-load current corresponding to the selected base kVA and the normal system voltage at the fault point. Let it be I.

(vi) Then various short-circuit calculations are :

Short-circuit current, $I_{SC} = I \times \frac{100}{\%X}$

$$\text{Short-circuit kVA} = \text{Base kVA} \times \frac{100}{\%X}$$

Example 17.1. *Fig. 17.8 (i) shows the single line diagram of a 3-phase system. The percentage reactance of each alternator is based on its own capacity. Find the short-circuit current that will flow into a complete 3-phase short-circuit at F.*

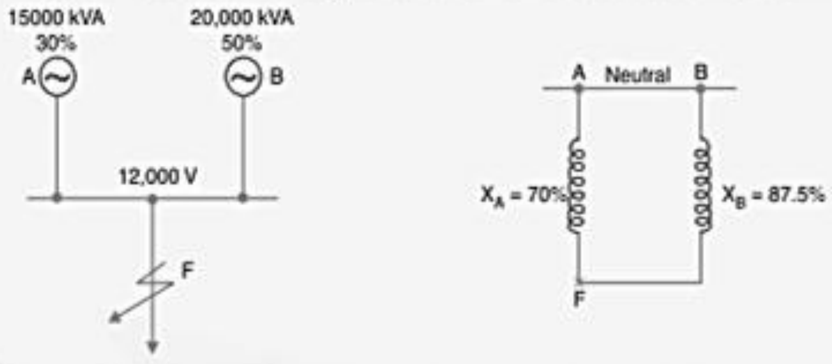
Solution. Let the base kVA be 35,000 kVA.

% Reactance of alternator A at the base kVA is

$$\% X_A = \frac{35{,}000}{15{,}000} \times 30 = 70\%$$

$$I = \frac{35{,}000 \times 10^3}{\sqrt{3} \times 12 \times 10^3} = 1684 \text{ A}$$

Fig. 17.8 (*ii*) shows the reactance* diagram of the network at the selected base kVA.



Single-line diagram
(*i*)

Reactance diagram at 35,000 kVA
(*ii*)

Fig. 17.8

Total % reactance from generator neutral up to fault point is

$$\%X = X_A \parallel X_B$$

$$= \frac{X_A X_B}{X_A + X_B} = \frac{70 \times 87{\cdot}5}{70 + 87{\cdot}5} = 38{\cdot}89\ \%$$

$\therefore$ Short-circuit current, $I_{SC} = I \times \frac{100}{\%X} = 1684 \times \frac{100}{38{\cdot}89} = 4330 \text{ A}$

Alternate method. The problem can also be solved by component short-circuit current method. Each alternator supplies short circuit current to the fault. The total current fed to the fault is the sum of the two.

Full-load current delivered by alternator A,

$$I_A = \frac{\text{Rated kVA of alternator } A}{\sqrt{3} \times \text{Bus} - \text{bar voltage}}$$

$$= \frac{15000 \times 10^3}{\sqrt{3} \times 12 \times 10^3} = 721{\cdot}7 \text{ A}$$

$\therefore$ Short-circuit current fed to fault by alternator A,

$$I_{SA} = I_A \times \frac{100}{\%\text{ Reactance}^{**}\text{of A}}$$

$$= 721{\cdot}7 \times (100/30) = 2405{\cdot}5 \text{ A}$$

Full-load line current delivered by alternator B,

$$I_B = \frac{20000 \times 10^3}{\sqrt{3} \times 12 \times 10^3} = 962{\cdot}28 \text{ A}$$

$\therefore$ Short-circuit current fed to fault by alternator B,

$$I_{SB} = 962{\cdot}28 \times 100/50 = 1924{\cdot}5 \text{ A}$$

$\therefore$ Total short-circuit current fed to fault,

$$I_{SC} = I_{SA} + I_{SB} = 2405{\cdot}5 + 1924{\cdot}5 = 4330 \text{ A}$$

Example 17.2. *A 3-phase, 20 MVA, 10 kV alternator has internal reactance of 5% and negligible resistance. Find the external reactance per phase to be connected in series with the alternator so that steady current on short-circuit does not exceed 8 times the full load current.*

Solution.

Full-load current, $$I = \frac{20\times10^6}{\sqrt{3}\times10\times10^3} = 1154{\cdot}7 \text{ A}$$

Voltage per phase, $$V = \frac{10\times10^3}{\sqrt{3}} = \frac{10{,}000}{\sqrt{3}} \text{ volts}$$

As the short-circuit current is to be 8 times the full-load current,

∴ Total percentage reactance required

$$= \frac{\text{Full-load current}}{\text{Short-circuit current}}\times 100$$

$$= \left(\frac{1}{8}\right)\times100 = 12{\cdot}5\ \%$$

∴ External percentage reactance required

$$= 12{\cdot}5 - 5 = 7{\cdot}5\%$$

Let $X\,\Omega$ be the per phase external reactance required.

Now, percentage reactance $$= \frac{I\,X}{V}\times100$$

or $$7{\cdot}5 = \frac{1154{\cdot}7X}{\frac{10{,}000}{\sqrt{3}}}\times100$$

∴ $$X = \frac{7{\cdot}5\times10000}{\sqrt{3}\times100\times1154{\cdot}7} = \mathbf{0{\cdot}375\,\Omega}$$

Example 17.3. *A 3-phase transmission line operating at 10 kV and having a resistance of 1Ω and reactance of 4 Ω is connected to the generating station bus-bars through 5 MVA step-up transformer having a reactance of 5%. The bus-bars are supplied by a 10 MVA alternator having 10% reactance. Calculate the short-circuit kVA fed to symmetrical fault between phases if it occurs*

(*i*) *at the load end of transmission line*

(*ii*) *at the high voltage terminals of the transformer*

Fig. 17.9

Solution. Fig. 17.9 shows the single line diagram of the network. Let 10,000 kVA be the base kVA.

% reactance of alternator on base kVA,

$$\% X_A = \frac{10{,}000}{10 \times 10^3} \times 10 = 10\%$$

% reactance of transformer on base kVA,

$$\% X_T = \frac{10{,}000}{5 \times 10^3} \times 5 = 10\%$$

The line impedance is given in ohms. It can be converted into percentage impedance by using exp. (*ii*) of Art. 17.3.

% reactance of transmission line is

$$\% X_L = \frac{(\text{kVA}) \times \text{reactance in } \Omega}{10\,(\text{kV})^2}$$

$$= \frac{10{,}000 \times 4}{10 \times (10)^2} = 40\%$$

% age resistance of transmission line,

$$\% R_L = \frac{10{,}000 \times 1}{10 \times (10)^2} = 10\%$$

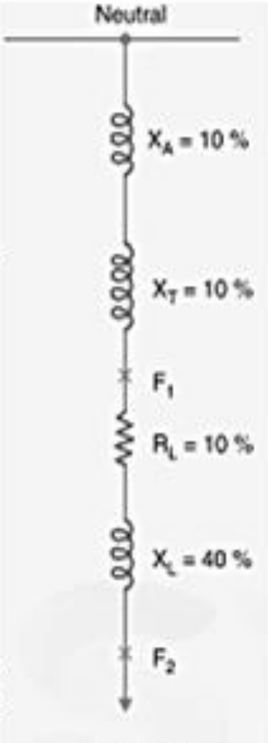


Fig. 17.10

(*i*) The reactance diagram of the network on the selected base kVA is shown in Fig. 17.10. For a fault at the end of a transmission line (point F_2),

$$\text{Total \% reactance} = \% X_A + \% X_T + \% X_L$$

$$= 10 + 10 + 40 = 60\%$$

$$\text{\% resistance} = 10\%$$

∴ % impedance from generator neutral upto fault point F_2

$$= \sqrt{(60)^2 + (10)^2} = 60{\cdot}83\%$$

$$\therefore \quad \text{Short-circuit kVA} = 10{,}000 \times 100/60{\cdot}83 = \mathbf{16{,}440\ kVA}$$

(*ii*) For a fault at the high voltage terminals of the transformer (point F_1),

Total % reactance from generator neutral upto fault point F_1

$$= \% X_A + \% X_T = 10 + 10 = 20\%$$

$$\therefore \quad \text{Short-circuit kVA} = 10{,}000 \times 100/20 = \mathbf{50{,}000\ kVA}$$

Example 17.4. *The plant capacity of a 3-phase generating station consists of two 10,000 kVA generators of reactance 12% each and one 5000 kVA generator of reactance 18%. The generators are connected to the station bus-bars from which load is taken through three 5000 kVA step-up transformers each having a reactance of 5%. Determine the maximum fault MVA which the circuit breakers on* (i) *low voltage side and* (ii) *high voltage side may have to deal with.*

Solution. Fig. 17.11 shows the single line diagram of the network. Let 10,000 kVA be the base kVA.

The percentage reactance of generators *A*, *B* and *C* and that of each transformer on the selected base kVA is

$$\% X_A = 12 \times 10{,}000/10{,}000 = 12\%$$

$$\% X_B = 12 \times 10{,}000/10{,}000 = 12\%$$

$$\% X_C = 18 \times 10{,}000/5{,}000 = 36\%$$

$$\% X_T = 5 \times 10{,}000/5{,}000 = 10\%$$

(*i*) When the fault occurs on the low voltage side of the transformer (point F_1 in Fig. 17.11), the reactance diagram at the selected base kVA will be as shown in Fig. 17.12. Obviously, the

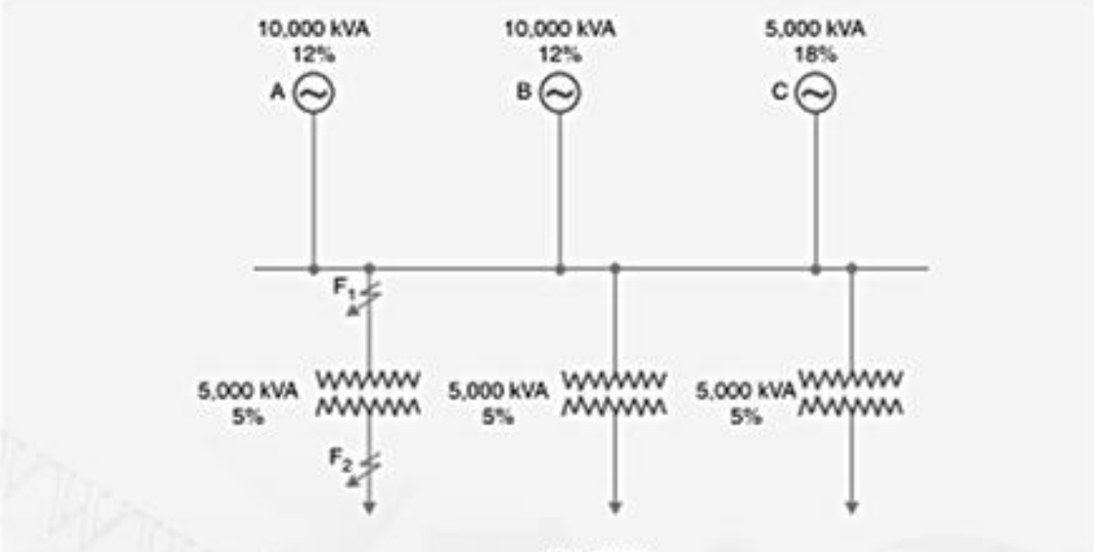


Fig. 17.11

total reactance upto the point of fault F_1 is the parallel combination of the reactances of the three alternators *i.e.*

Total % reactance form generator neutral upto fault point F_1

$$= \%X_A \,||\, \%X_B \,||\, \%X_C$$

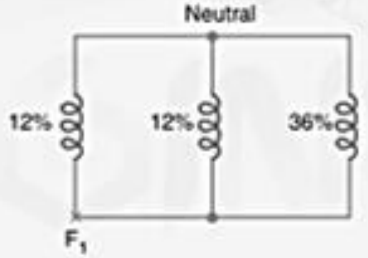


Fig. 17.12

Fig. 17.13

$$= 12\% \,||\, 12\% \,||\, 36\% = \frac{6 \times 36}{6 + 36} = 5{\cdot}14\%$$

$$\therefore \qquad \text{Fault MVA} = 10{,}000 \times \frac{100}{5{\cdot}14} \times \frac{1}{1000} = 194{\cdot}5$$

(*ii*) When the fault occurs on the high voltage side of the transformer (point F_2 in Fig. 17.11), the reactance diagram will be as shown in Fig. 17.13.

Total % reactance from generator neutral upto fault point F_2

$$= 5{\cdot}14 + 10 = 15{\cdot}14\%$$

$$\therefore \qquad \text{Fault MVA} = 10{,}000 \times \frac{100}{15{\cdot}14} \times \frac{1}{1000} = 66$$

It may be noted that circuit breakers of lower ratings will be required on the high voltage side of the transformers.

Example 17.5. *The section bus-bars A and B are linked by a bus-bar reactor rated at 5000 kVA with 10% reactance. On bus-bar A, there are two generators each of 10,000 kVA with 10% reactance and on B two generators each of 8000 kVA with 12% reactance. Find the steady MVA fed into a dead short circuit between all phases on B with bus-bar reactor in the circuit.*

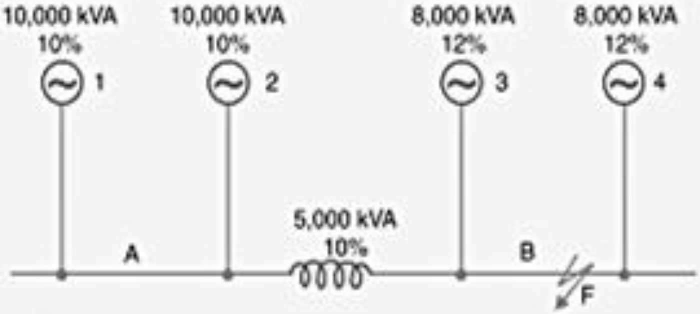


Fig. 17.14

Solution. Fig. 17.14 shows the single line diagram of the network.

Let 10,000 kVA be the base kVA.

% Reactance of generator 1 or 2 on the base kVA

$$= 10 \times 10{,}000/10{,}000 = 10\%$$

% Reactance of generator 3 or 4 on the base kVA

$$= 12 \times 10{,}000/8000 = 15\%$$

% Reactance of bus-bar reactor on the base kVA

$$= 10 \times 10{,}000/5000 = 20\%$$

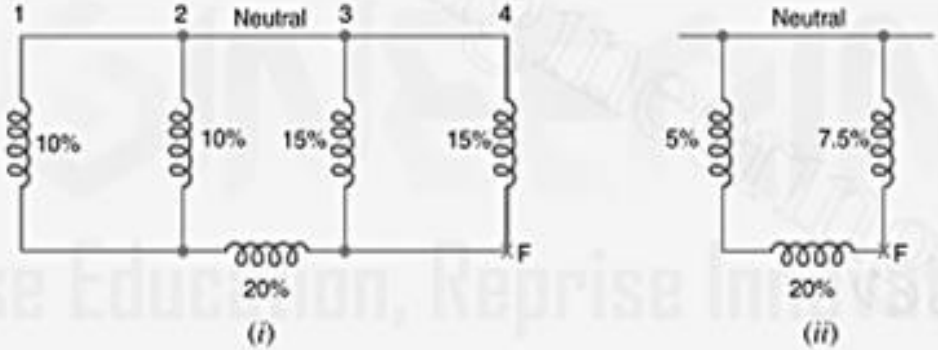


Fig. 17.15

When fault occurs on section *B* (point *F* in Fig. 17.14), the reactance diagram at the selected base kVA will be as shown in Fig. 17.15 (*i*). This series parallel circuit is further reduced to Fig. 17.15 (*ii*). Referring to Fig. 17.15 (*ii*), it is clear that reactance from generator neutral upto the fault point *F* is (5% + 20%) in parallel with 7·5% *i.e.*

Total % reactance from generator neutral upto fault point *F*

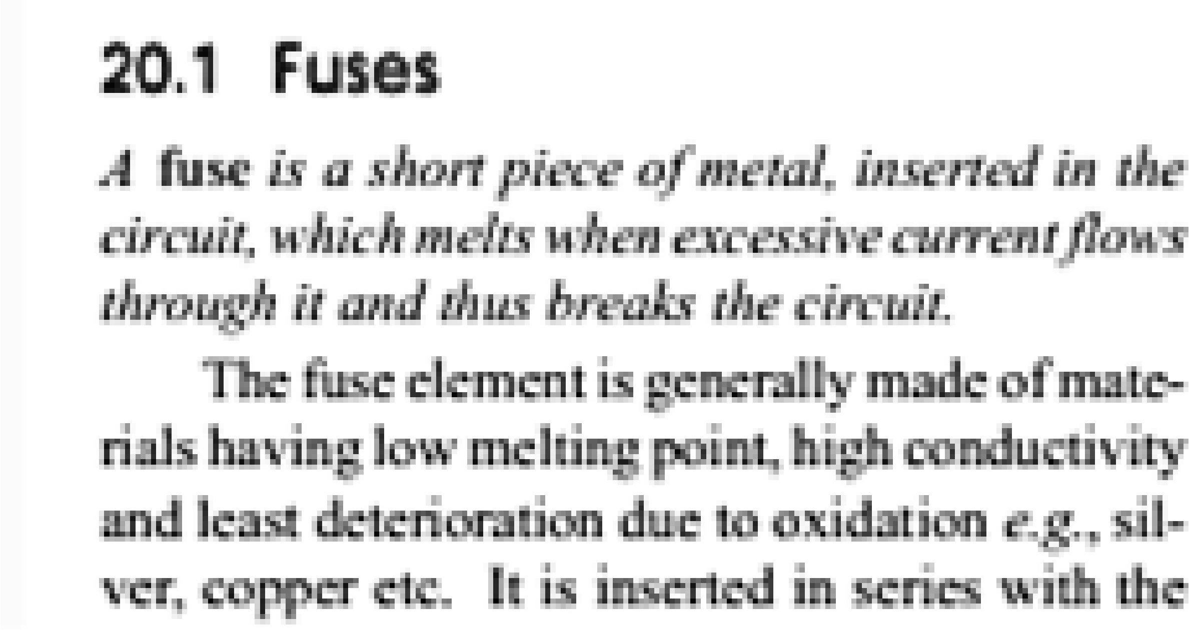
$$= (5\,\% + 20\%) \parallel 7{\cdot}5\%$$

$$= \frac{25 \times 7{\cdot}5}{25 + 7{\cdot}5} = 5{\cdot}77\%$$

$\therefore$ Fault kVA $= 10{,}000 \times 100/5{\cdot}77 = 1{,}73{,}310$

or Fault MVA $= 173{\cdot}31$

Chapter 3 Fuses



20.1 Fuses

A **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.

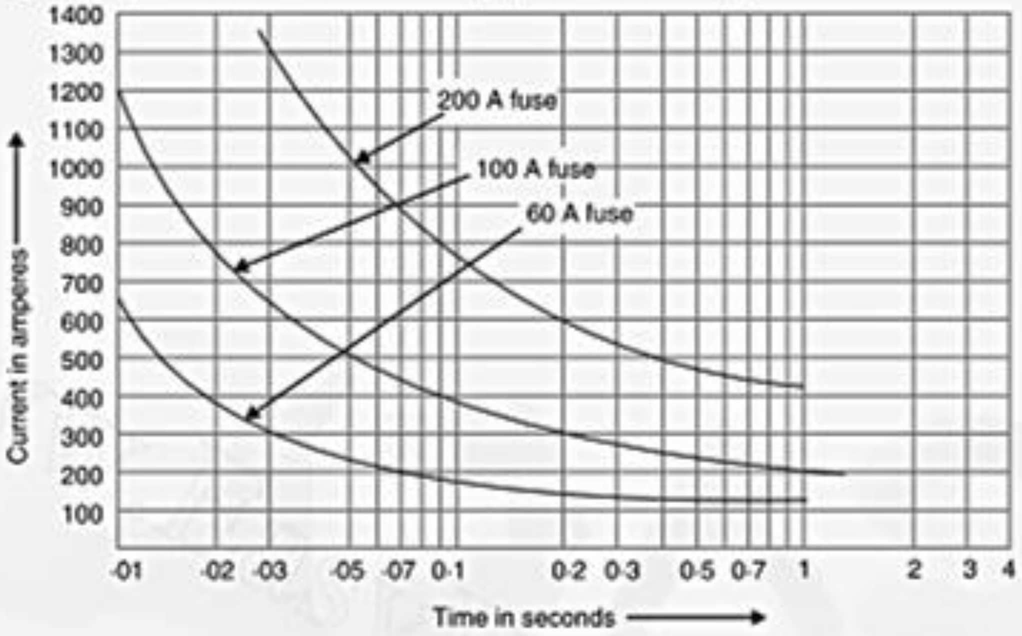


Fig. 20.1

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 shown in Fig. 20.1. 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.

20.2 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.

20.3 Fuse Element Materials

The most commonly used materials for fuse element are lead, tin, copper, zinc and silver. For small currents upto 10 A, 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.

20.4 Important Terms

The following terms are much used in the analysis of fuses :

(*i*) **Current rating of fuse element.** It is the current which the fuse element can normally carry without overheating or melting. It depends upon the temperature rise of the contacts of the fuse holder, fuse material and the surroundings of the fuse.

(*ii*) **Fusing current.** It is the minimum current at which the fuse element melts and thus disconnects the circuit protected by it. Obviously, its value will be more than the current rating of the fuse element.

For a round wire, the approximate relationship between fusing current I and diameter d of the wire is

$$I = k\,d^{3/2}$$

where k is a constant, called the *fuse constant*. Its value depends upon the metal of which the fuse element is made. Sir W.H. Preece found the value of k for different materials as given in the table below :

S. No.	Material	Value of k	
		d in cm	d in mm
1	Copper	2530	80
2	Aluminium	1873	59
3	Tin	405·5	12·8
4	Lead	340·6	10·8

The fusing current depends upon the various factors such as :

(*a*) material of fuse element

(*b*) length – the smaller the length, the greater the current because a short fuse can easily conduct away all the heat

(*c*) diameter

(*d*) size and location of terminals

(*e*) previous history

(*f*) type of enclosure used

(*iii*) **Fusing factor.** It is the ratio of minimum fusing current to the current rating of the fuse element *i.e.*

$$\text{Fusing factor} = \frac{\text{Minimum fusing current}}{\text{Current rating of fuse}}$$

Its value is always more than one. The smaller the fusing factor, the greater is the difficulty in avoiding deterioration due to overheating and oxidation at rated carrying current. For a semi-enclosed or rewirable fuse which employs copper wire as the fuse element, the fusing factor is usually 2. Lower values of fusing factor can be employed for enclosed type cartridge fuses using silver or bimetallic elements.

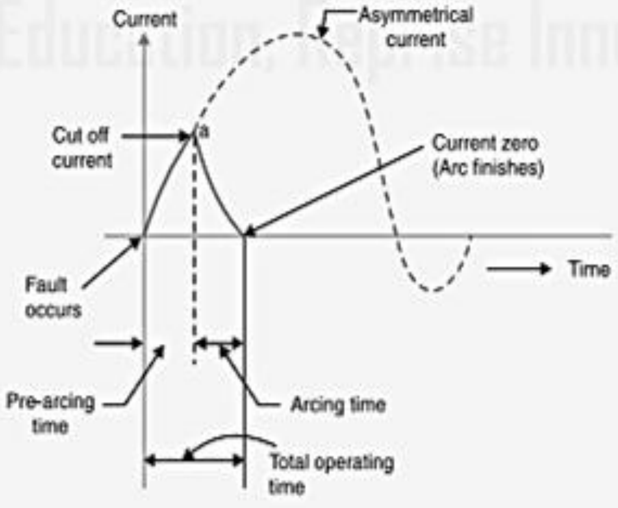


Fig. 20.2

(*iv*) **Prospective Current.** Fig. 20.2 shows how a.c. current is cut off by a fuse. The fault current would normally have a very large first loop, but it actually generates sufficient energy to melt the fuseable element well before the peak of this first loop is reached. The *r.m.s.* value of the first loop of fault current is known as prospective current. Therefore, prospective current can be defined as under:

It is the r.m.s. value of the first loop of the fault current obtained if the fuse is replaced by an ordinary conductor of negligible resistance.

(*v*) **Cut-off current.** It is the maximum value of fault current actually reached before the fuse melts.

On the occurrence of a fault, the fault current has a very large first loop due to a fair degree of asymmetry. The heat generated is sufficient to melt the fuse element well before the peak of first loop is reached (point '*a*' in Fig. 20.2). The current corresponding to point '*a*' is the cut off current. The cut off value depends upon :

(*a*) current rating of fuse
(*b*) value of prospective current
(*c*) asymmetry of short-circuit current

It may be mentioned here that outstanding feature of fuse action is the breaking of circuit *before* the fault current reaches its first peak. This gives the fuse a great advantage over a circuit breaker since the most severe thermal and electro-magnetic effects of short-circuit currents (which occur at the peak value of prospective current) are not experienced with fuses. Therefore, the circuits protected by fuses can be designed to withstand maximum current equal to the cut-off value. This consideration together with the relative cheapness of fuses allows much saving in cost.

(*vi*) **Pre-arcing time.** It is the time between the commencement of fault and the instant when cut off occurs.

When a fault occurs, the fault current rises rapidly and generates heat in the fuse element. As the fault current reaches the cut off value, the fuse element melts and an arc in initiated. The time from the start of the fault to the instant the arc is initiated is known as pre-arcing time. The pre-arcing time is generally small : a typical value being 0·001second

(*vii*) **Arcing time.** This is the time between the end of pre-arcing time and the instant when the arc is extinguished.

(*viii*) **Total operating time.** It is the sum of pre-arcing and arcing times.

It may be noted that operating time of a fuse is generally quite low (say 0·002 sec.) as compared to a circuit breaker (say 0·2 sec or so). This is an added advantage of a fuse over a circuit breaker. A fuse in series with a circuit breaker of low-breaking capacity is a useful and economical arrangement to provide adequate short-circuit protection. It is because the fuse will blow under fault conditions before the circuit breaker has the time to operate.

(*ix*) **Breaking capacity.** It is the r.m.s. value of a.c. component of maximum prospective current that a fuse can deal with at rated service voltage.

20.5 Types of Fuses

Fuse is the simplest current interrupting device for protection against excessive currents. Since the invention of first fuse by Edison, several improvements have been made and now-a-days, a variety of fuses are available. Some fuses also incorporate means for extinguishing the arc that appears when the fuse element melts. In general, fuses may be classified into :

(*i*) Low voltages fuses (*ii*) High voltage fuses

It is a usual practice to provide isolating switches in series with fuses where it is necessary to permit fuses to be replaced or rewired with safety. If such means of isolation are not available, the fuses must be so shielded as to protect the user against accidental contact with the live metal when the fuse carrier is being inserted or removed.

20.6 Low Voltage Fuses

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

1. **Semi-enclosed rewireable fuse.** Rewireable 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 re-inserted 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 rewireable 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.

2. **High-Rupturing capacity (H.R.C.) cartridge fuse.** The primary objection of low and uncertain breaking capacity of semi-enclosed rewireable fuses is overcome in H.R.C. cartridge fuse. Fig. 20.3 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.

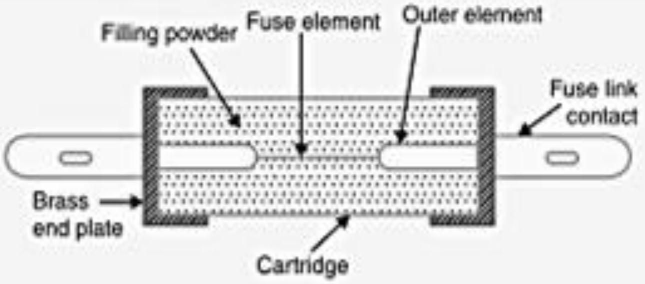


Fig. 20.3

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.

3. **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. 20.4 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.

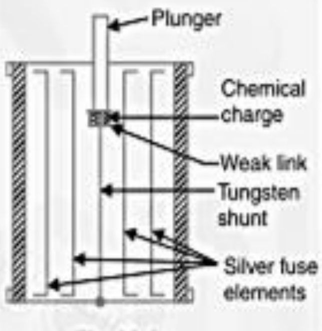


Fig. 20.4

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 short-circuit conditions.

HRC Fuse

20.7 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 about 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.

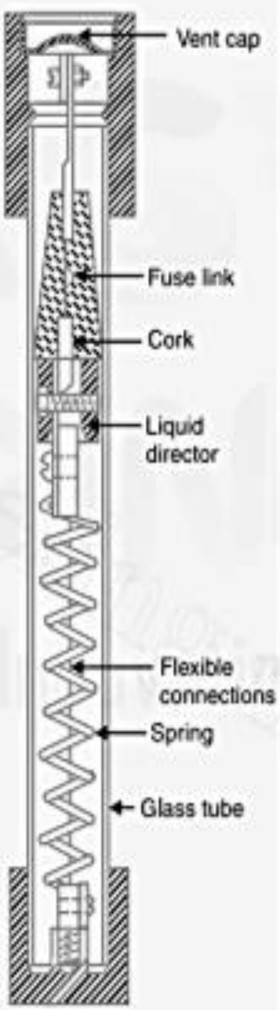


Fig. 20.5

(*iii*) **Metal clad fuses.** Metal clad oil-immersed fuses have been developed with the object of providing a substitute for the oil circuit breaker. Such fuses can be used for very high voltage circuits and operate most satisfactorily under short-circuit conditions approaching their rated capacity.

20.8 Current Carrying Capacity of Fuse Element

The current carrying capacity of a fuse element mainly depends on the metal used and the cross-sectional area but is affected also by the length, the state of surface and the surroundings of the fuse. When the fuse element attains steady temperature,

Heat produced per sec = Heat lost per second by convection, radiation and conduction

or $$I^2R = \text{Constant} \times \text{Effective surface area}$$

or $$I^2\left(\rho\frac{l}{a}\right) = \text{constant} \times d \times l$$

where d = diameter of fuse element

l = length of fuse element

$$\therefore \quad I^2\frac{\rho\, l}{(\pi/4)\,d^2} = \text{constant} \times d \times l$$

or $$I^2 = \text{constant} \times d^3$$

or $$I^2 \propto d^3 \qquad \ldots(i)$$

Expression (*i*) is known as ordinary *fuse law*.

Example 20.1. *A fuse wire of circular cross-section has a radius of 0·8 mm. The wire blows off at a current of 8A. Calculate the radius of the wire that will blow off at a current of 1A.*

Solution.

$$I^2 \propto r^3$$

$$\therefore \quad \left(\frac{I_2}{I_1}\right)^2 = \left(\frac{r_2}{r_1}\right)^3$$

or $$r_2 = r_1 \times \left(\frac{I_2}{I_1}\right)^{2/3} = 0{\cdot}8 \times \left(\frac{1}{8}\right)^{2/3} = 0{\cdot}2 \text{ mm}$$

20.9 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.	*Function*	It performs both detection and interruption functions.	It performs interruption function only. The detection of fault is made by relay system.
2.	*Operation*	Inherently completely automatic.	Requires elaborate equipment (*i.e.* relays) for automatic action.
3.	*Breaking capacity*	Small	Very large
4.	*Operating time*	Very small (0·002 sec or so)	Comparatively large (0·1 to 0·2 sec)
5.	*Replacement*	Requires replacement after every operation.	No replacement after operation.