17.5 COMPONENTS OF LT SWITCHGEAR

17.5.1. Fuses. Fuse is perhaps the simplest and cheapest device used for interrupting an electrical circuit under short circuit, or excessive overload, current magnitudes. As such, it is used for overload and/or short-circuit protection in high voltage (up to 66 kV) and low voltage (up to 400 V) installations/circuits. In high voltage circuits their use is confined to those applications where their performance characteristics are particularly suitable for current interruption.

The action of a fuse is based upon the heating effect of the electric current. In normal operating conditions, when the current flowing through the circuit is within safe limits, the heat developed in the fuse element carrying this current is readily dissipated into the surrounding air, and therefore, fuse element remains at a temperature below its melting point. However, when some fault, such as short circuit occurs or when load connected in a circuit exceeds its capacity, the current exceeds the limiting value, the heat generated due to this excessive current cannot be dissipated fast enough and the fusible element gets heated, melts and breaks the circuit. It thus protects a machine or apparatus or an installation from damage due to excessive current.

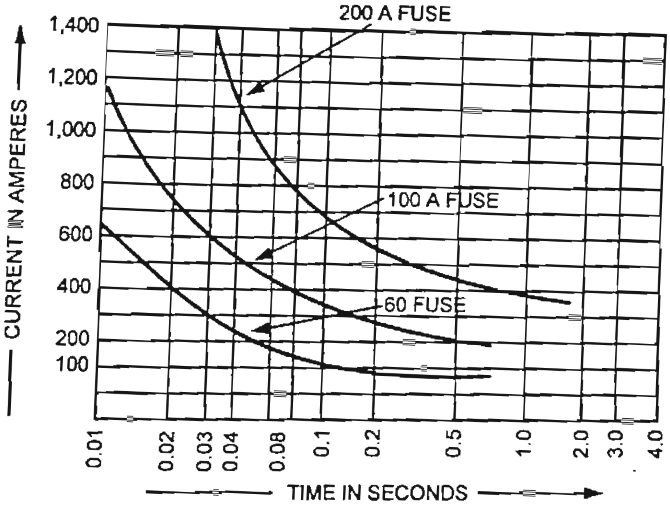


Fig. 17.19 *Time-Current Characteristic*

The time for blowing out of fuse depends upon the magnitude of the excessive current. Larger the current, the more rapidly the fuse will blow i.e., the fuse has inverse time-current characteristic, as shown in Fig. 17.19. Such a characteristic is desirable for protective gear.

Essentially, a fuse consists of a fusible element in the form of a metal conductor of specially selected small cross-sectional area, a case or cartridge to hold the fusible element, and in some cases, provided with a means to aid arc extinction. The part which actually melts and opens the circuit is known as the *fuse element.* It forms a series part of the circuit to be protected against short circuit or excessive overloads.

Fuses have following advantages and disadvantages.

Advantages

(*i*) It is the cheapest form of protection available.

(*ii*) It needs no maintenance.

(*iii*) Its operation is inherently completely automatic unlike a circuit breaker which requires an elaborate equipment for automatic action.

(*iv*) It interrupts enormous short circuit currents without noise, flame, gas or smoke.

(*v*) The minimum time of operation can be made much smaller than that with the circuit breakers.

(*vi*) The smaller sizes of fuse element impose a current limiting effect under short circuit conditions.

(*vii*) Its inverse time-current characteristic enables its use for overload protection.

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 considerable differences in the relative sizes of the fuses concerned.

(*iii*) The current-time characteristic of a fuse cannot always be correlated with that of the protected device.

The function of fuse wire is (*i*) to carry the normal working current safely without heating and (*ii*) to break the circuit when the current exceeds the limiting current.

Distribution circuits are protected from ground and short-circuit currents by fuses or circuit breakers so arranged as to disconnect the faulted equipment promptly from its source of supply. Fuses are used almost exclusively for the protection of cables in low-voltage light and power circuits and for transformers of rating not exceeding 200 kVA, in primary distribution systems. Circuit breakers are employed for larger amounts of power and in cases where the operation of the overload device is so frequent as to make the use of fuses impractical.

Necessity of Fuse in an Electric Circuit. If no fuse or other similar device is provided in the circuit then a dangerous situation would be created on developing of faults such as overload, short circuit or earth faults.

In case of overload, short circuit and heavy earth faults a heavy current will continue to flow through the consuming apparatus, current carrying cables or wires and other current carrying equipment. Due to continuous flow of heavy current through the cables or wires, apparatus etc., these will get heated up and so get damaged. The fire may also break out.

In case of earth leakage fault, (*i.e.* on the body of the electrical apparatus becoming alive), the body of the electrical apparatus will continue to be alive and at much higher potential above that of the earth. In such circumstances any person coming in contact with the metal body of the apparatus is liable to get an electric shock, even if it is earthed.

The main function of a fuse is to blow out under a fault and isolate the faulty section from the live side. If the fuse is provided on neutral wire, in place of live wire, then in abnormal conditions though the fuse will blow out but the lamp or other apparatus still remains connected to the live wire and in case of leakage some trouble will arise and cause a considerable damage. In case the earth fault takes on the neutral wire between lamp and fuse provided in it, the fuse will blow out because the neutral wire is slightly at a higher potential with respect to earth and so the fault current flows through the neutral wire and fuse melts itself. The current will flow through the live wire, lamp, neutral wire and earth fault, even after the fuse has blown out and this may cause serious damage to the wiring, the apparatus connected or building itself.

If fuses of same capacity are provided on the phase wire and neutral, then in case of short-circuit fault, one of them will blow out first. If the fuse on neutral wire blows out first, the fuse in phase line remains intact and faulty apparatus still remains connected to the live. If some person comes in contact with the faulty apparatus, he is liable to get electric shock. In case the installation is connected to 3-phase 4-wire supply system, and fuses are provided on both live and neutral wire and fuse on neutral wire blows out then voltage of each phase to neutral will become considerably different, which is not desirable. *Hence the fuse is provided only in phase or live pole, never on neutral pole.*

17.5.2. Fuse Units. A fuse unit essentially consists of the metal fuse element or link, a set of contacts between which it is fixed and a body to support and isolate them. Many types of fuses also have some means for extinguishing the arc which appears when the fuse element melts.

The various types of fuse units, most commonly available are :

1. Round type fuse unit.
2. Kit-kat type fuse unit.
3. Cartridge type fuse unit
4. HRC (High rupturing capacity) fuse units and
5. Semiconductor fuse units

1. Round Type Fuse Unit. This type of fuse unit consists of a porcelain or bakelite box and two separated wire terminals for holding the fuse wire between them. This type of fuse is not in common use on account of its following disadvantages :

1. One of the terminals remain always energised and, therefore, for replacement of fuse either the worker will have to touch the live mains or open the main switch.

2. Appreciable arcing takes place at the instant of blowing off fuse and thus damage the terminals. After two or three arcing the fuse unit becomes unusable.

2. Rewirable or Kit-Kat Type Fuses. The most commonly used fuse in 'house wiring' and small current circuits is the semi-enclosed or rewirable fuse (also sometimes known as kit-kat type fuse). It consists of a *porcelain base* carrying the fixed contacts to which the incoming and outgoing live or phase wires are connected and a *porcelain fuse carrier* holding the fuse element, consisting of one or more strands of fuse wire, stretched between its terminals. The fuse carrier is a separate part and can be taken out or inserted in the base without risk, even without opening the main switch. If fuse holder or carrier gets damaged during use, it may be replaced without replacing the complete unit.

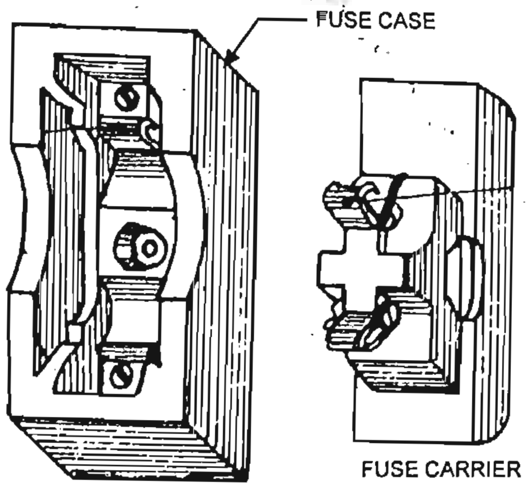


Fig. 17.20 *Rewirable or Kit-Kat Type Fuses*

The fuse wire may be of lead, tinned copper, aluminium or an alloy of tin-lead. The actual fusing current will be about twice the rated current. When two or more fuse wires are used, the wires should be kept apart and a derating factor of 0.7 to 0.8 should be used to arrive at the total fuse rating.

The specifications for rewirable fuses are covered by IS : 2086-1963. Standard ratings are 6, 16, 32, 63 and 100 A. A fuse wire of any rating not exceeding the rating of the fuse may be used in it *i.e.* a 80 A fuse wire can be used in a 100 A fuse, but not in the 63 A fuse.

On occurrence of fault, the fuse element blows off and the circuit is interrupted. The fuse carrier is pulled out, the blown out fuse element is replaced by new one and the supply is restored by re-inserting the fuse carrier in the base.

Though such fuses have the advantages of easy removal or replacement without any danger of coming into contact with a live part and negligible replacement cost but they suffer from the following disadvantages:

(*a*) ***Unreliable Operation.*** The operation of the rewirable fuses is unreliable because of the following factors:

(*i*) There is a possibility of renewal by the fuse wire of wrong size.

(*ii*) The fuse wire deteriorates, over a period, due to oxidation through the continuous heating up of the element. After a relatively short period the current causes the metal to deteriorate and the fuse operates at a lower current than originally rated.

(*iii*) A fuse with normal rated capacity of say 60 A would fuse at nearly 120 amperes. Should that amount of current damage the apparatus in the circuit, obviously the size of the fuse wire must be smaller but, as its rated capacity will also be lower, the same dependence could not be placed upon it.

(*iv*) The protective capacity is uncertain *i.e.* no dependence can be placed upon the wire to interrupt the circuit when a given current flows. For instance although theoretically a No.17 SWG wire should interrupt a circuit when a current of 135 A is flowing, the circuit may be interrupted when a lower current flows or in other circumstances when only a much higher current flows.

(*v*) Accurate calibration of the fuse wire is impossible, as a longer fuse operates earlier than one of shorter length.

Single phasing of three-phase induction motors is a common occurrence where rewirable type fuses are employed in motor circuits.

(*b*) ***Lack of Discrimination.*** Due to unreliable operation, discrimination cannot be always ensured. However, it will be possible to achieve some measure of discrimination by using a fuse which has twice the rating of the next fuse ahead of it in series. For example, a fuse of 80 A will discriminate with a fuse of 40 A, but not with a fuse of 55 A.

(c) ***Small Time Lag.*** Due to the small time lag, such fuses can blow with large transient currents which are encountered during the starting of motors and switching-on operation of transformers, capacitors, fluorescent lights etc., unless fuses of sufficiently high rating are used.

(d) ***Low Rupturing Capacity.*** Rewirable fuses have limited breaking or rupturing capacity. For example, according to IS : 2086-1963 the rewirable fuse of 16 A normal current have a breaking current of 2 kA and those up to 200 A normal current have a breaking current of 4 k A.

(e) ***No Current-Limiting Feature.***

(f) ***Slow Speed of Operation.*** No special means are employed to extinguish the arc that blows after the fuse melts. Thus arcing time is more in such fuses.

3. Cartridge Type Fuse. This is a totally enclosed type fuse unit. It essentially consists of an insulating container of bulb or tube shape and sealed at its ends with metallic cap known as *cartridge* enclosing the fuse element and filled up with powder or granular material known as filler. There are various types of materials used as filler like sand, calcium carbonate, quartz etc. There is sometimes a blow out device in the side of the tube to indicate when the fuse is blown. On overloads or short circuits, the fusible element is heated to a high temperature causing it to vaporize. The powder in the fuse cartridge cools and condenses the vapour and quenches the arc thereby interrupting the flow of current.

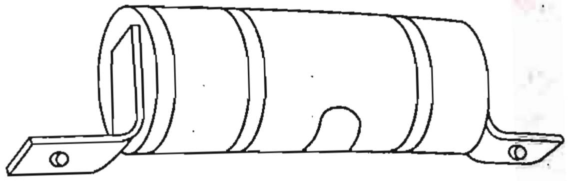


Fig. 17.21 *Cartridge Fuse*

Since it is totally enclosed it will not be possible to rewire and, therefore, the whole unit will have to be replaced, once it blows out. It provides complete security against fire risk, as it is a totally enclosed unit. The filling powder provides good insulating path and helps to extinguish the arc at the time of blowing up of fuse. This type of fuse is available up to 660 V and the current rating up to 800 A.

4. High Rupturing Capacity (HRC) Fuses. With a very heavy generating capacities of the modern power stations, extremely heavy currents would flow into the fault and the fuse clearing the fault would be required to withstand extremely high stresses in this process. A rewirable fuse may not be useful in this case and, therefore, high rupturing capacity fuses commonly known as HRC fuses, designed and developed after intensive research for use in medium and high voltage installations, are used for such duties. Their rupturing capacity is as high as 500 MVA up to 66 kV and above. The main advantages of HRC fuses are:

(i) They are cheaper as compared with other types of circuit interrupters of same breaking capacity.
(ii) No maintenance is required.
(iii) The operation is quick and sure.
(iv) They do not deteriorate with time.
(v) They have inverse time-current characteristic.
(vi) They are capable of clearing high as well as low currents.
(vii) They are quite reliable and can be selected for proper discrimination.

HRC fuses suffer from the following disadvantages :

(i) They are required to be replaced after each operation.
(ii) Interlocking is not possible.
(iii) They lack relays in complete discrimination.

Since the advantages outweigh the disadvantages to a very large extent, HRC fuses are extensively used.

(a) *Cartridge Type HRC Fuse.* The high rupturing capacity cartridge fuse is most popular. In its simplest form an HRC cartridge fuse consists of a heat resisting ceramic body having metal end-caps to which are welded fusible silver (or bimetallic) current-carrying elements. The complete space within the body surrounding the elements is filled with a powder which acts as an arc extinguishing agent.

The process of fusing comprises the following operations :

1. Pre-arcing operation *i.e.* melting of silver elements.
2. Arcing operation *i.e.* vaporisation of the elements.

3. Fusion of silver vapours and the filling powder, and
4. Extinction of arc under fusion process.

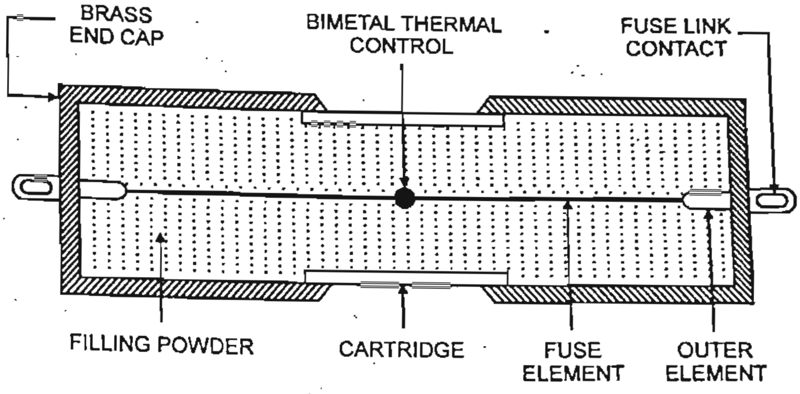


Fig. 17.22 *HRC Cartridge Fuse*

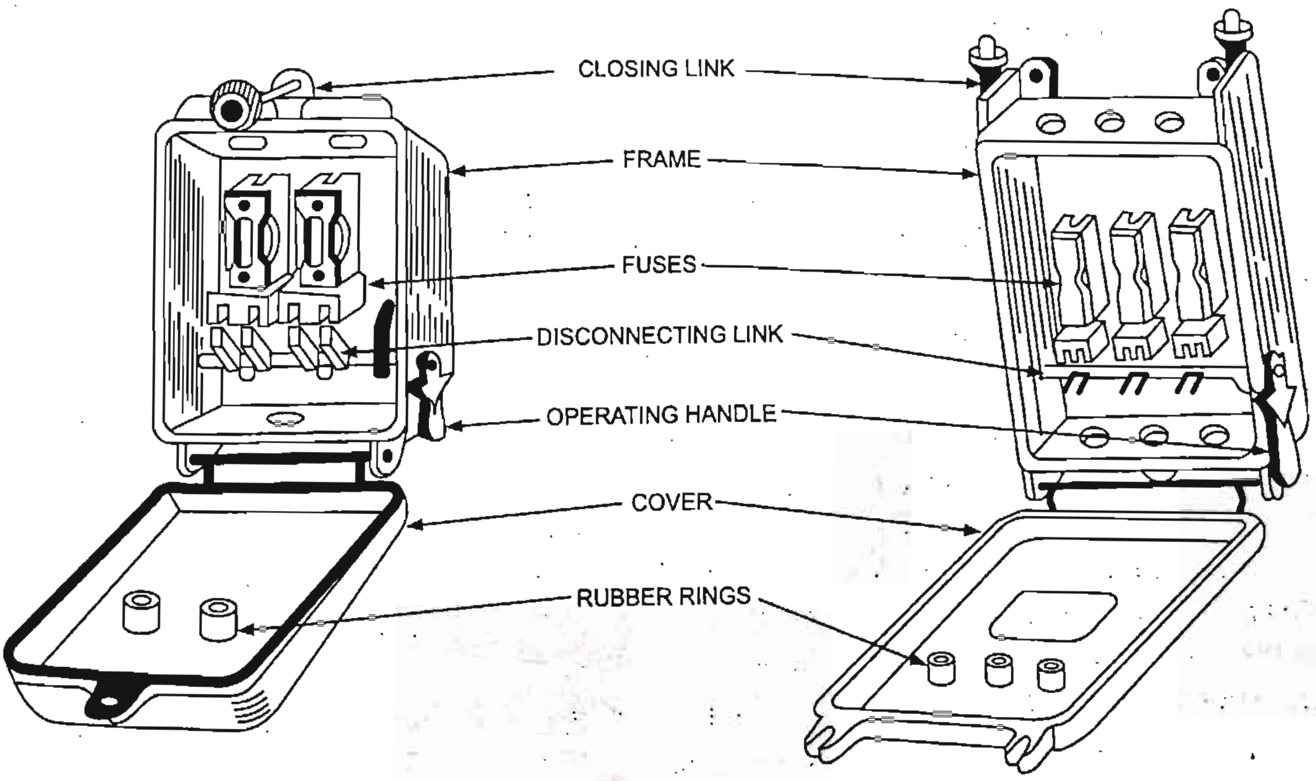
On the occurrence of a fault, short-circuit current flows through the fuse element and element is thus heated up to its melting point. When the melting process is completed, an arc is formed. The chemical reaction between silver vapour and filling powder tends to establish high resistance. The high resistance acts as an insulator because the fault current decreases along with the high pressure created within the fuse by the fault (excessive) current. Thereafter a transient voltage is created at the instant of fault current interruption on account of sudden release of energy.

The physical phenomena associated with the process of fusing include a sudden rise of temperature and the generation of a high internal pressure.

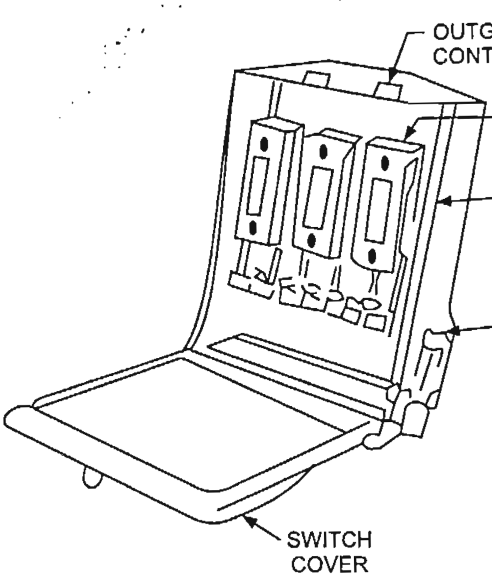
(*b*) *Tetra Chloride Type HRC Fuse.* It essentially consists of a glass tube filled with carbon tetrachloride solution and sealed at both ends with brass caps. Inside the tube a high resistance fuse wire is sealed at one end of the glass tube and the other end of the fuse wire is held by a strong phosphor bronze spiral spring fixed to the other end of the glass tube. A flexible copper wire is also similarly held between the spring and the other end of cap in parallel with the high resistance wire. On short circuit or overload, the high resistance fuse wire melts and spring pulls back the flexible copper wire. The arc produced is extinguished by carbon tetrachloride vapour.

5. ***Semiconductor Fuses.*** These are very fast acting fuses for protection of thyristor and other electronic circuits.

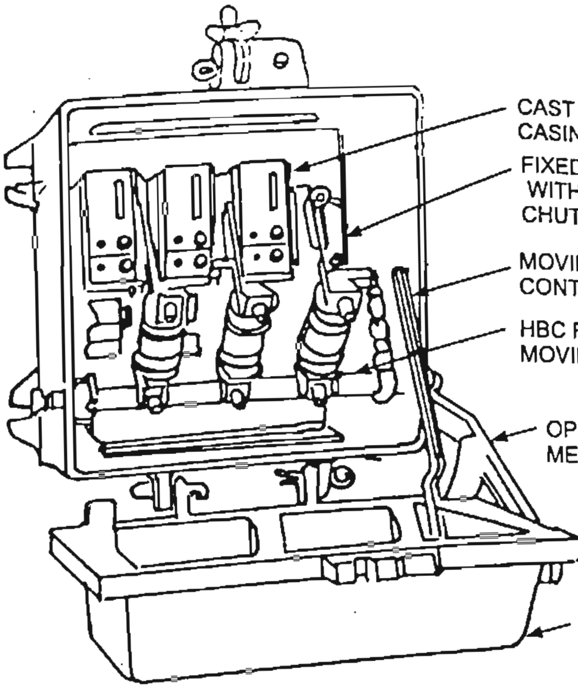
17.5.3. Switch Fuse Units. As per Indian Electricity Rule 50 a suitable linked switch (a switch operating simultaneously on phase or line and neutral wires) is to be provided immediately after the meter board. This rule also stipulates that a suitable cutout must be provided just after the linked switch to protect the circuit against excessive current. The linked main switch and fuse unit may be provided as one unit or as separate units.



(*a*) *DPIC Switch* (*b*) *TPIC Switch*



(c)



(d)

Fig. 17.23 *Switches and Switch Fuses*

Switch fuse is a combined unit and is known as an iron *clad switch*, being made of iron. It may be double pole for controlling single phase two-wire circuits or triple pole for controlling three-phase, 3-wire circuits or triple pole with neutral link for controlling 3-phase, 4-wire circuits. The respective switches are known as double pole iron clad (DPIC); *triple pole iron clad* (TPIC) and *triple pole with neutral link iron clad* (TPNIC) switches. These switches are shown in Figs. 17.23 and 17.24.

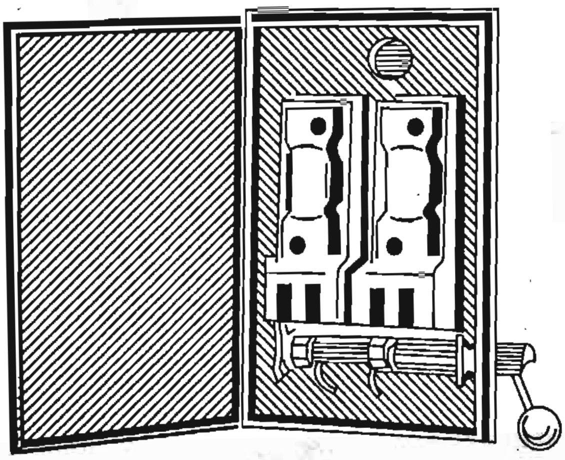
Since no fuse is to be provided in neutral (IE Rule 32), in DPIC switch fuses, where provision is made for fuses in both the wires, one fuse carrier is furnished with fuse element and the other with a thick copper wire.

The specifications of IC switch fuse units are given below as samples :

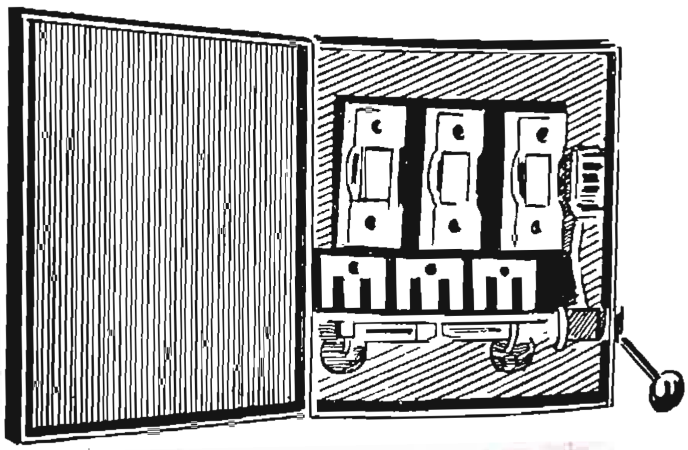
1. For Two-Wire DC Circuits or Single Phase AC Circuits. 240 V, 16 A, DPIC switch fuse of any make approved by IS.

2. For Three-Wire DC Circuits. 500 V, 32 A (63/100/150 or higher amperes), IS approved TPIC switch fuse.

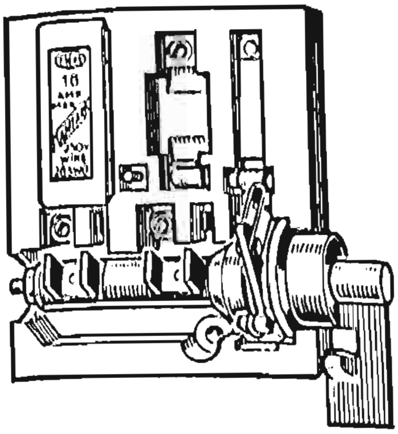
3. For Three-Phase Balanced Load Circuits. 415 V, 32 A (63/100/150 or higher amperes), IS approved TPIC switch fuse.



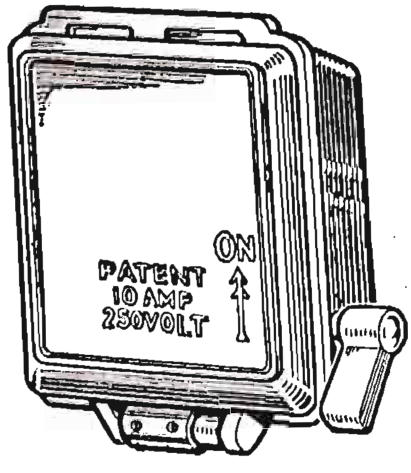
(a) Double Pole Iron Clad Switch



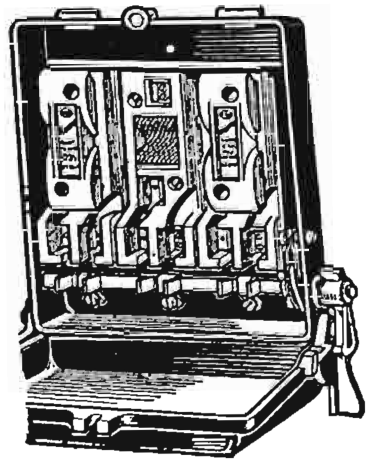
(b) Triple Pole, Iron Clad Switch



(c) 16-Amp. All insulated Main Switch



(d) All insulated Switch With Moulded Cover and Base For Circuits Up to 16 Amperes Capacity



(e) Three-Phase Iron Clad Main Switch For Power Use

Fig. 17.24

17.5.4. Miniature Circuit Breaker (MCB). Is a device that provides definite protection to the wiring installations and sophisticated equipment against overcurrents and short-circuit faults. The outer and interior views of an MCB are shown in Fig. 17.25. Thermal operation (overload protection) is achieved with a bimetallic strip, which deflects when heated by any overcurrents flowing through it. In doing so, releases the latch mechanism and causes the contacts to open. Inverse time-current characteristics result, *i.e.* greater the overload or excessive current, shorter the time required to operate the MCB. On the occurrence of a short circuit, the rising current energizes the solenoid, operating the plunger to strike the trip lever causing immediate release of the latch mechanism. Rapidity of the magnetic solenoid operation causes instantaneous opening of contacts.

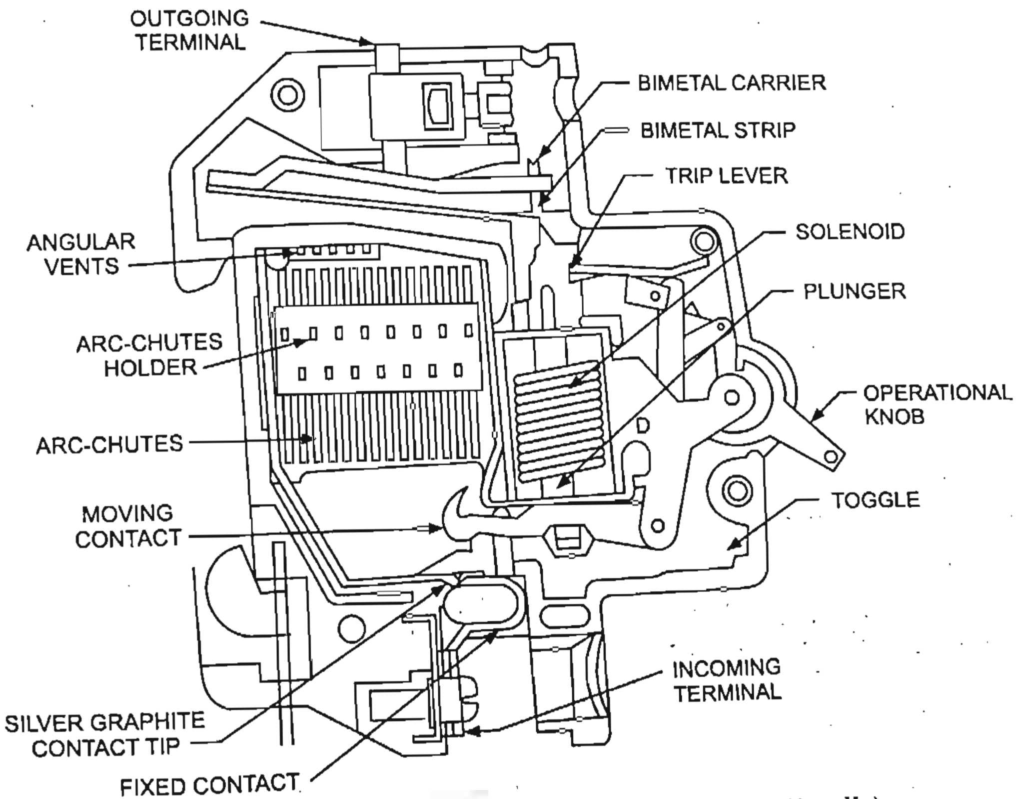


Fig. 17.25 *Miniature Circuit Breaker (Courtesy Havells)*

Miniature circuit breakers are available with different current ratings of 0.5, 1, 2, 2.5, 3, 4, 5, 6, 7.5, 10, 16, 20, 25, 32, 35, 40, 63, 100, 125, 160 A and voltage ratings of 240/415 V ac and up to 220 V dc. Operating time is very short (less than 5 ms). So they are very suitable for the protection of important and sophisticated equipment, such as air-conditioners, refrigerators, computers etc.

17.5.5. Earth-Leakage Circuit Breaker (ELCB). It is a device that provides protection against earth leakage. These are of two types viz, the current operated type and the voltage operated type.

Current operated earth-leakage circuit breaker is used when the product of the operating current in amperes and the earth-loop impedance in ohms does not exceed 40. Where such a circuit breaker is used, the consumer's earthing terminal is connected to a suitable earth electrode. A current-operated earth leakage applied to a 3-ϕ, 3-wire circuit is shown in Fig. 17.26. In normal conditions when there is no earth leakage the algebraic sum of the currents in the three coils of the current transformers (CTs) is zero, and no current flows through the trip coil. In case of any earth leakage, the currents are unbalanced and the trip coil is energized and thus the circuit breaker is tripped.

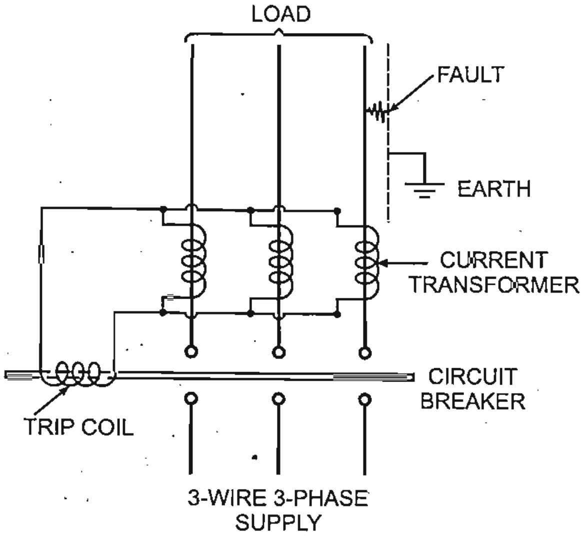


Fig. 17.26 *Current-Operated Earth-Leakage Trip*

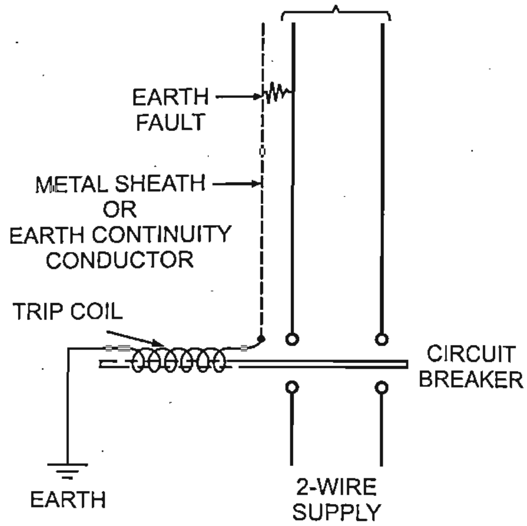


Fig. 17.27 *Voltage-Operated Earth-Leakage Trip*

Voltage-operated earth leakage circuit breaker is suitable for use when the earth-loop impedance exceeds the values applicable to fuses or excess-current circuit breaker or to current-operated earth-leakage circuit breaker. Such an earth-leakage trip in a 2-wire circuit is shown in Fig. 17.27. When the voltage between the earth continuity conductor (ECC) and earth electrode rises to a sufficient value, the trip coil will carry the required current to trip the circuit breaker. With such a circuit breaker the earthing lead between the trip-coil and the earth electrode must be insulated; in addition, the earth electrode must be placed outside the resistance area of any other parallel earths which may exist.

In both the above types of ELCB the tripping operation may be tested by means of a finger-operated test button which passes a predetermined current from the line wire through a high resistance to trip the coil and thus to earth. This test operation should be performed regularly.

Both types of earth-leakage circuit breakers are arranged to work manually and may take the place of the linked switch and fuses, or the excess-current circuit breaker.

17.5.6. Molded Case Circuit Breaker (MCCB). A *molded case circuit breaker*, abbreviated *MCCB*, is a type of electrical protection device that can be used for a wide range of voltages, and frequencies of both 50 Hz and 60 Hz. The main distinctions between molded-case and miniature circuit breaker are that the MCCB can have current ratings of up to 2,500 amperes, and its trip settings are normally adjustable. An additional difference is that MCCBs tend to be much larger than MCBs. As with most types of circuit breakers, an MCCB has three main functions:

- ***Protection against overload:*** Currents above the rated value that last longer than what is normal for the application.

- ***Protection against electrical faults:*** During a fault such as a short circuit or line fault, there are extremely high currents that must be interrupted immediately.
- ***Switching a circuit on and off:*** This is a less common function of circuit breakers, but they can be used for that purpose if there isn't an adequate manual switch.

The wide range of current ratings available from molded-case circuit breakers allows them to be used in a wide variety of applications. MCCBs are available with current ratings that range from low values such as 15 amperes, to industrial ratings such as 2,500 amperes. This allows them to be used in both low-power and high-power applications.

Operating Mechanism. At its core, the protection mechanism employed by MCCBs is based on the same physical principles used by all types of thermal-magnetic circuit breakers.

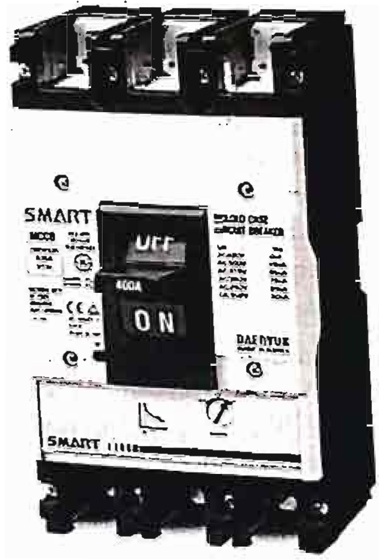


Fig. 17.28 *Molded Case Circuit Breaker (MCCB)*

- Overload protection is accomplished by means of a thermal mechanism. MCCBs have a bimetallic contact what expands and contracts in response to changes in temperature. Under normal operating conditions, the contact allows electric current through the MCCB. However, as soon as the current exceeds the adjusted trip value, the contact will start to heat and expand until the circuit is interrupted. The thermal protection against overload is designed with a time delay to allow short duration overcurrent, which is a normal part of operation for many devices. However, any overcurrent conditions that last more than what is normally expected represent an overload, and the MCCB is tripped to protect the equipment and personnel.
- On the other hand, fault protection is accomplished with electromagnetic induction, and the response is instant. Fault currents should be interrupted immediately, no matter if their duration is short or long. Whenever a fault occurs, the extremely high current induces a magnetic field in a solenoid coil located inside the breaker – this magnetic induction trips a contact and current is interrupted. As a complement to the magnetic protection mechanism, MCCBs have internal arc dissipation measures to facilitate interruption.

As with all types of circuit breakers, the MCCB includes a disconnection switch which is used to trip the breaker manually. It is used whenever the electric supply must be disconnected to carry out field work such as maintenance of equipment upgrades.

17.6 ELECTRIC SHOCK (EFFECTS OF ELECTRIC CURRENTS ON HUMAN BODY)

Bruner (1967) states that the threshold of perception of electric shock is about 1 mA. At this level a tingling sensation is felt by the subject when there is a contact with an electrified object through intact skin. With the increase in magnitude of ac, the sensation of tingling gives way to contraction of muscles. The muscular contractions increase as the current is increased and finally a value of current is reached at which the subject cannot release his grip on the current carrying conductor. The maximum current at which the subject is still capable of releasing a conductor by using muscles directly stimulated by the current is called "*let go current*". The value of this current is significant because an individual can withstand, without serious after effects, repeated exposures to his 'let go current' for at least the time required for him to release the conductor. Also, currents slightly in excess of 'let go current' would not permit the individual to release his grip from the conductor supplying current.

Based on the experiments conducted on males and females, it is generally accepted that the safe 'let go current' could be taken approximately 9 mA and 6 mA for men and women respectively.

At current levels higher than the 'let go current' the subject loses ability to control his own muscle actions and he is unable to release his grip on the electrical conductor. Such currents are very painful and hard to bear. This type of accident is called 'hold-on-type' accident, and is caused by currents in the range 20-100 mA. These currents may also cause physical injury due to powerful contraction of the skeletal muscles. However, the heart and respiratory function usually continue because of uniform spread of current through the trunk of the body.

If current contacts contact skin and passed through the trunk, at about 100 mA and above, there is a likelihood of pulling the heart into ventricular fibrillation. In this condition, the rhythmic action of the heart ceases, pumping action stops and the pulse disappears. Ventricular fibrillation is a serious cardiac emergency because once it starts, it practically never stops spontaneously. It proves *fatal* unless corrected within minutes, since the brain begins to die 2 to 4 minutes after it is robbed of its supply of oxygenated blood.

At very high currents of the order of 6 A and above, there is a danger of temporary respiratory paralysis and also of serious burns. However, if the shock duration is of only a very few seconds, there is a possibility of heart reverting to the normal rhythmic action.

The threshold of perception depends largely on the current density in the body tissues. It may vary widely depending upon the size of the current contact. At very small point contact, it is probable that even 0.3 mA current may be felt whereas a current in excess of perhaps 1 mA may not produce sensation if the contacts are somewhat larger. Similarly, depending on the size of contact, the threshold of pain may also be considerably above 1 mA, probably 10 mA if the contacts are large enough.

Besides the magnitude of current, the current duration and the relationship of current flow resistance are also important. Duration of less than 10 ms typically does not produce fibrillation whereas duration of 0.1 s or longer does. It has been found experimentally that the safe value of current in amperes (rms) which a human body can tolerate is given as

$$I = \frac{0.165}{\sqrt{t}} \text{ for } t < 3 \text{ s and } I = 9 \text{ m A for } t > 3 \text{ s.}$$

where t is the time duration in seconds of the flow of current.

The tolerable currents mentioned above are for power-frequency currents. It has been found that human body can tolerate about 5 times higher direct current. At high frequencies (3-10 kHz) still higher currents are tolerable.

17.7 EARTHING AND ITS IMPORTANCE

Earthing means connections of the neutral point of a supply system or the non-current carrying parts of electrical apparatus, such as metallic framework, metallic covering of cables, earth terminal of socket outlet, stay wires etc., to the general mass of earth in such a manner that at all times an immediate discharge of electrical energy takes place without danger.

Earthing is provided

1. to ensure that no current carrying conductor rises to a potential with respect to general mass of earth than its designed insulation,
2. to avoid electric shock to the human beings, and
3. to avoid risk of fire due to earth leakage current through unwanted path.

In an electric installation, if a metallic part of an electric appliance comes in direct contact with a bare or live wire (that may be due to failure of insulation or otherwise) the metal being a good conductor of electricity is charged and static charge on it will accumulate. Now if any person comes in contact with this charged metallic part, he will get a severe shock. But if the metallic parts of the appliances are earthed, the charge will be transferred to the earth immediately, as the metallic part comes in direct contact with a bare or live wire or breakdown occurs. And as the discharge takes place to earth, the impedance of path of the current is low, a large amount of current flows to earth, the instant, the current exceeds the limiting value, the fuse provided in the circuit will blow off and cut off the appliance from supply. Thus earthing of metallic parts of electrical equipment and appliances provides safety.

17.8 METHODS OF EARTHING

The various methods of earthing are :

1. Strip or Wire Earthing. In this system of earthing, strip electrodes of cross section not less than 25 mm × 1.6 mm if of copper and 25 mm × 4 mm if of galvanised iron or steel are buried in horizontal trenches of minimum depth 0.5 metre. If round conductors are used, their cross-sectional area shall not be smaller than 3.0 mm^2 if of copper and 6 mm^2 if of galvanised iron or steel. The length of buried conductor shall be sufficient to give the required earth resistance. It shall, however, be not less than 15 metres. The electrodes shall be as widely distributed as possible, preferably in a single straight or circular trench or in a number of trenches radiating from a point. If conditions require use of more than one strip, they shall be laid either in parallel trenches or in radial trenches.

This type of earthing is used at places which have rocky soil earth bed because at such places excavation work of plate earthing is difficult.

2. Rod Earthing. In this system of earthing, 12.5 mm diameter solid rods of copper or 16 mm diameter solid rods of galvanised iron or steel or hollow section 25 mm GI pipes of length not less than 2.5 metres are driven vertically into the earth either manually or by pneumatic hammer. In order to increase the embedded length of electrodes under the ground, which is sometimes necessary to reduce the earth resistance to desired value, more than one rod sections are hammered one above the other.

This system of earthing is suitable for areas which are sandy in character. This system of earthing is very cheap as no excavation work is involved.

3. Pipe Earthing. This is the most common and best system of earthing as compared to other systems suitable for the same earth and moisture conditions.

In this method of earthing, a galvanised steel and perforated pipe of approved length and diameter is placed upright in a permanently wet soil, as shown in Fig. 17.29.

The size of the pipe depends upon the current to be carried and type of soil. Usually the pipe used for this purpose is of diameter 40 mm and 2.5 metres in length for ordinary soil or of greater length in case of dry and rocky soil. The depth at which the pipe must be buried depends upon the moisture of the ground. The pipe is placed at a depth of 3.75 metres (minimum). The pipe is provided with a tapered casting at the lower end in order to facilitate the driving. The pipe at the bottom is surrounded by broken pieces of coke or charcoal for a distance of about 15 cm around the pipe. Generally alternate layers of coke and salt are used to increase the effective area of the earth and to decrease the earth resistance respectively. Another pipe of 19 mm diameter and minimum length 1.25 metres is connected at the top of GI pipe through reducing socket.

In our country in summer season the moisture in the soil decreases which causes increase in earth resistance. So a cement concrete work, as shown in Fig. 17.29, is done in order to keep the water arrangement accessible, and in summer to have an effective earth, 3 or 4 buckets of water are put through the funnel connected to 19 mm diameter pipe, which is further connected to GI pipe.

The earth wire (either GI wire or GI strip of sufficient cross section to carry faulty current safely) is carried in a GI pipe of diameter 12 mm at a depth of about 60 cm from the ground.

Care should be taken that earth wire is well protected from mechanical injury, when it is carried over from one machine to another.

4. Plate Earthing. This is another common system of earthing. In plate earthing an earthing plate eithe of copper of dimensions 60 cm × 60 cm × 3 mm or of galvanised iron of dimensions 60 cm × 60 cm × 6 mm i buried into the ground with its face vertical at a depth of not less than 3 metres from ground level. The eart late is embedded in alternate layers of coke and salt for a minimum thickness of 15 cm. The earth wire (GI wi for GI plate earthing and copper wire for copper plate earthing) is securely bolted to an earth plate with tl help of a bolt, nut and washer made of material of that of earth plate (made of copper in case of copper pla earthing and of galvanised iron in case of GI plate earthing).

Fields of Application. As this system of wiring provides protection against fire, mechanical damage and dampness so this is the only approved system of wiring for:

(*i*) places where considerable dust or fluff is present such as in textile mills, sawmills, flour mills etc.

(*ii*) damp situations.

(*iii*) in workshops for lighting and motor wirings.

(*iv*) places, where there is possibility of fire hazards such as in oil mills, varnish factories etc.

(*v*) places, where important documents are kept such as a record room.

(*vi*) residential and public buildings where appearance is the prime thing.

The recessed type conduit wiring is preferred for residential and public buildings.

PVC conduit wiring system (particularly concealed) is cheaper in cost and takes less time but does not provide protection against fire. Insurance requirements stipulate metallic conduit wiring and PVC wiring only for offices.

17.4 TYPES OF WIRES AND CABLES

The wires employed for internal wiring of buildings may be divided into different groups according to (*i*) conductor used (*ii*) number of cores used (*iii*) voltage grading and (*iv*) type of insulation used.

According to the conductor material used in cables, these may be divided into two classes known as *copper conductor cables* and *aluminium conductor cables.*

According to the number of cores, the cable consists of, the cables may be divided into classes known as *single core* cables; *twin core* cables; *three core cables;* two core with ECC (earth continuity conductor) cables etc.

According to voltage grading the cables may be divided into two classes : (*i*) 250/440 volt cables and (*ii*) 650/1,100 volt cables.

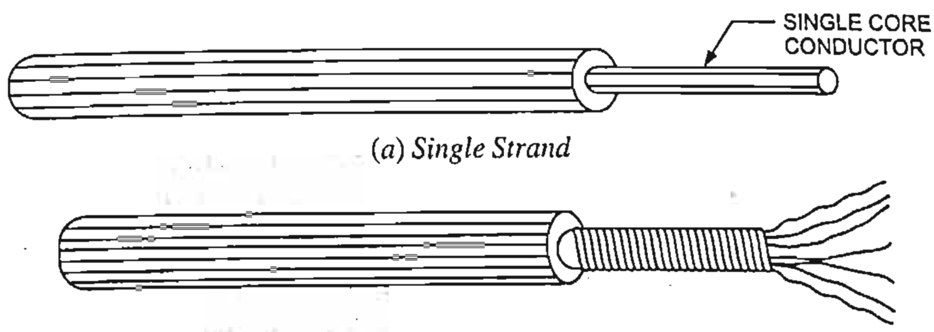
According to type of insulation the cables are of the following types :

1. Vulcanized Indian Rubber (VIR) insulated cables.
2. Tough rubber sheathed (TRS) or cab tyre sheathed (CTS) cables.
3. Lead sheathed cables.
4. Polyvinyl chloride (PVC) cables.
5. Weatherproof cables.
6. Flexible cords and cables.
7. XLPE cables.
8. Multi-strand cables.

1. Vulcanized Indian Rubber (VIR) Cables. VIR, cables are available in 240/415 volt as well as in 650/1,100 volt grades.

VIR cable consists of either tinned copper conductor covered with a layer of vulcanized Indian rubber insulation. Over the rubber insulation cotton tape sheathed covering is provided with moisture resistant compound bitumen wax or some other insulating material for making the cables moisture proof. The thickness of rubber insulation depends upon the voltage grade for which the cable is required.

The copper conductor is tinned to provide protection against corrosion due to presence of traces of sulphur, zinc oxide and other mineral ingredients in the VIR.



(*a*) *Single Strand*

(*b*) *Seven Strand*

Fig. 17.15 *Single Core VIR Cables*

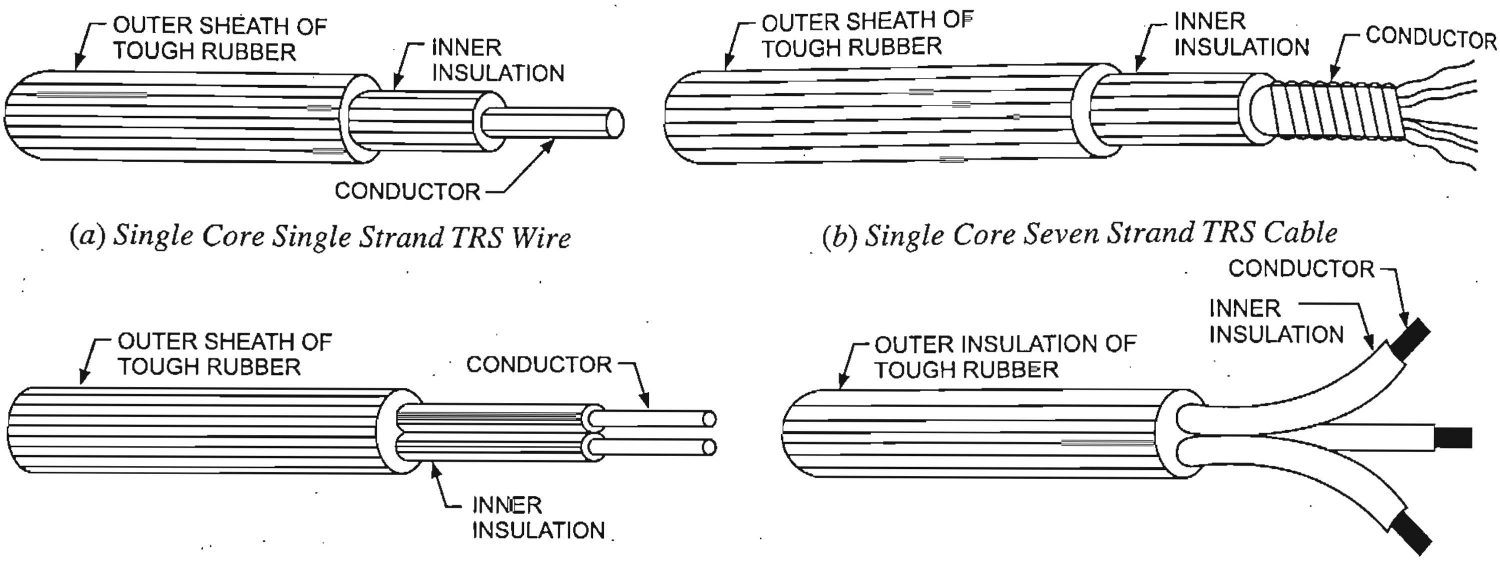
A single core single strand VIR wire may be employed but larger cables have to be stranded.

Single core single strand VIR wire and single core seven strand VIR cables are shown in Figs. 17.15(*a*) and 17.15(*b*) respectively.

2. Tough Rubber Sheathed (TRS) or Cab Tyre Sheathed (CTS) Cables. These cables are available in 250/440 volt and 650/1,100 volt grades and used in CTS (or TRS) wiring. TRS cable is nothing but a vulcanized rubber insulated conductor with an outer protective covering of tough rubber, which provides additional insulation and protection against wear and tear. These cables are waterproof, hence can be used in wet conditions. These cables are available as single core, circular twin core, circular three core, flat three core, twin or three core with an earth continuity conductor (ECC). The cores are insulated from each other and covered with a common sheathing. Different types of TRS cables are shown in Fig. 17.16.

In wiring of 3 pin plugs separate earth wire may be used as it is cheaper in cost and easier in installation.

These cables are cheaper in cost and lighter in weight than lead alloy sheathed cables and have the properties similar to those of lead sheathed cables and thus provide cheaper substitute to lead sheathed cables.



(*a*) *Single Core Single Strand TRS Wire*

(*b*) *Single Core Seven Strand TRS Cable*

(*c*) *Twin Core Single Strand TRS Cable For Indoor Service*

(*d*) *Three Core Single Strand TRS Cable For Indoor Service*

Fig. 17.16

3. Lead Sheathed Cables. These cables are available in 240/415 volt grade. The lead sheathed cable is a vulcanized rubber insulated conductor covered with a continuous sheath of lead. The lead sheath provides very good protection against the absorption of moisture and sufficient protection against mechanical injury and so can be used without casing or conduit system. It is available as a single core, flat twin core, flat three core and flat twin or three core with an earth continuity conductor. Two-core lead sheathed cable is shown in Fig. 17.17.

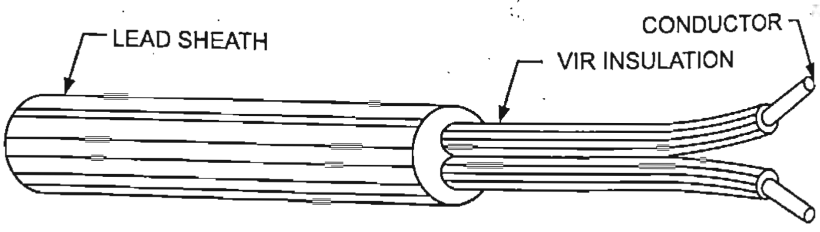


Fig. 17.17 *2-Core Lead Sheathed Cable*

4. Polyvinyl Chloride (PVC) Insulated Cables. These cables are available in 250/440 volt and 650/1,100 volt grades and are used in casing-capping, batten and conduit wiring system. In this type of cable conductor is insulated with PVC insulation. Since PVC is harder than rubber, PVC cable does not require cotton taping and braiding over it for mechanical and moisture protection.

PVC insulation is preferred over VIR insulation because of the following reasons:

(*i*) PVC insulation has better insulating qualities.

(*ii*) PVC insulation provides better flexibility.

(iii) PVC insulation has no chemical effect on metal of the wire.
(iv) Thin layer of PVC insulation will provide the desired insulation level.
(v) PVC coated wire gives smaller diameter of cable and, therefore, more number of wires can be accommodated in the conduit of a given size in comparison to VIR or CTS wires.

PVC cables are most widely used for internal wiring these days. Though the insulation resistance of PVC is lower than that of VIR but its effect is negligible for low and medium voltages, below 600 V.

5. Weather Proof Cables. These cables are used for outdoor wiring and for power supply or industrial supply. These cables are either PVC insulated or vulcanized rubber insulated conductors being suitably taped (only in case of vulcanized rubber insulated cable) braided and then compounded with weather resisting material. These cables are available in 240/415 volt and 650/1,100 volt grades. These cables are not affected by heat or sun or rain. Weather proof cable is shown in Fig. 17.18.

Although TRS cables can be used for outdoor purposes but due to their higher cost, weather proof cables are generally used for outdoor services.

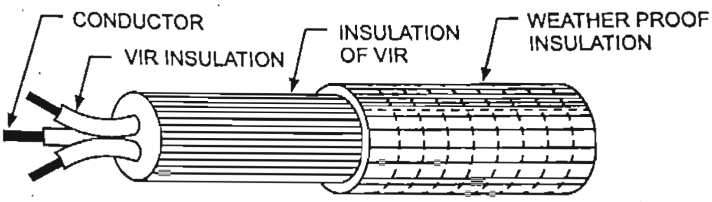


Fig. 17.18 *3-Core Weather Proof Cable*

6. Flexible Cords and Cables. The flexible cords consist of wires silk/cotton/plastic covered. Plastic cover is popular as it is available in different pleasing colours. Flexible cords have tinned copper conductors. Flexibility and strength is obtained by using conductors having larger number of strands. These wires or cables are used as connecting wires for such purposes as from ceiling rose to lamp holder, socket outlet to portable apparatus such as radios, fans, lamps, heaters etc. The flexibility of such wires facilitates in handling the appliances and prevents the wires from breakage. These must not be used in fixed wiring.

The flexible cords used for household appliances are available in various sizes and with various thicknesses of coating as very thin/thin/medium/thick/very thick/extra thick etc.

7. XLPE Cables. PVC and XLPE cables are built of insulation made of polymers. Polymers are substances consisting of long macromolecules built up of small molecules or groups of molecules as repeated units. These are divided into homopolymers and copolymers. Homopolymers are built by reactions of identical monomers. Copolymers are built up of at least two different kinds of monomers.

The mechanical properties of the polymers e.g. tensile strength, elongation elasticity and resistance against cold depend upon chemical structure. Their resistance against external chemical influences, acids, bases or oils together with their electrical and thermal characteristics are the decisive factors for the usefulness of cables insulated and sheathed with these materials.

Advantages of PVC Cables Over Other Types of Cables

1. Non-hygroscopic insulation almost unaffected by moisture.
2. Non-migration of compound allowing vertical installation.
3. Complete protection against most forms of electrolytic/chemical corrosion.
4. Tough/Resilient sheath with excellent fire resisting qualities.
5. Good ageing characteristics.
6. Not affected by vibrations.

Advantages of XLPE Cables Over Both PVC and All Other Types of Cables

1. Higher current rating.
2. Higher short-circuit current rating.
3. Longer service life.
4. Can withstand 130°C (maximum) for short time and is favourable to endure short-circuit stresses.
5. It is less sensitive to the setting of network protection.
6. Because of thermosetting process taking place through cross-linking, crack resistance is increased.

7. Due to chemical cross-linking internal stresses are reduced. Consequently material is less sensitive, during manufacture, to the setting of the cooling gradient.
8. The thermal resistivity of cross-linked material is favourably low, compared to thermoplastic material.
9. Low dielectric loss (a significant advantage).
10. Excellent mechanical features of the insulation improves the protection against external effects.
11. The resistance of XLPE to acids, alkalies is outstanding and often compensates adverse environmental influences.

Presently XLPE cables are used extensively for high tension and low tension work. Even for distribution work at 3-phase 415 V industry is using XLPE cables.

8. Multi-Strand Cables. Multi-strand cables have got the following advantages with respect to the single solid conductor and hence preferred.

(*i*) The multi-strand cables are more flexible and durable and, therefore, can be handled conveniently.
(*ii*) The surface area of multi-strand cable is more as compared to the surface area of equivalent single solid conductor, so heat radiating capacity, being proportional to the surface area, is more.
(*iii*) Skin effect is better as the conductors are tubular, specially in case of high frequency.

The number of strands in stranded cable must be 3, 7, 19, 37, 61, 91 and so on in order to obtain a circular contour. The section of a 3-strand cable at right angle to its length is three circles touching one another, the centres of which are the corners of an equilateral triangle. All other have a centrally disposed conductor with all the other around it. Thus a 7-strand cable has one central wire with 6 wires surrounding it; the 19-strand cable has another 12 wires surrounding the 7-strands; the 37-strand cable has another 18 wires surrounding the 19-strands and so on. It is seen that each layer of wires has always 6 more wires in it than the layer beneath it.

The various conductors are spiralled round the central conductor and when there is more than one layer, alternate layers are spiralled in opposite directions. This to is prevent "bird-aging" when the conductor is bent.

Since the length of each spiralled conductor is greater than the central strand and the current flows along the various conductors, resistance is increased and so we should be particular in the designation of the x-section.

The nominal cross section is the area of the x-section of one conductor in a plane perpendicular to its length, multiplied by the number of conductors. The actual cross section is the area of the oblique cross section due to the cutting of the stranded cable by a plane perpendicular to the core of the cable, multiplied by the number of conductors. The equivalent x-section, *defined as the cross section of a solid conductor of the same length as the cable and having the same resistance at the same temperature,* is taken less than nominal cross section because of increase in resistance due to spiralling. Loss in lay *i.e.* the additional length due to spiralling is taken approximately 2% by the cable manufacturers and this percentage has been added in giving the equivalent x-sectional area. Actual cross section is 2 per cent more instead of 2 per cent less. In calculating weight of the conductor the 2 per cent loss in the lay has to be added.

The size of a cable is given in various manners, explained below.

The size of the cable can be given by a designation giving number of strands and gauge number of each strand. For example, a cable having 3 strands each of gauge 20 SWG may be referred as 3/20. In the system of specifying the size of cables, numerator indicates the number of strands employed and denominator indicates the gauge number of each strand.

The size of cables, may also be given in terms of number of strands and diameter of each strand in mm. For example a cable having 19 strands, each strand of diameter 1.12 mm may be referred as 19/1.12 mm.

The cable size is often denoted in terms of total cross-sectional area of the core instead of number and diameter of strands. As 19/1.12 mm cable has a cross section of 19.35 mm^2 so this cable is often referred to as a 19.35 mm^2 cable.

Batteries

Inside this Chapter

18.1 INTRODUCTION

As the world increasingly comes to rely on electrical and electronic systems for its daily functions, both vital and mundane, we are ever more dependent on batteries. As electrical and electronic systems become smaller and more efficient, batteries provide the key to portability. And, even with stationary systems, batteries are becoming increasingly important to provide memory backup or keep essential functions operational when the main power is not available.

Not only has the world become more dependent on batteries in general, it has also come to appreciate the economy and reliability of rechargeable batteries. It is only due to rechargeable batteries that travellers can now work at their laptop computer throughout a transcontinental airline flight and then recharge their batteries overnight using only a few rupees worth of electricity. At home, rechargeable appliances kept on their chargers are always fully charged and ready for use. Rechargeable flashlights provide the security of knowing they will respond when needed–eliminating the mystery of when the last time the batteries were charged and guessing at how much they have been used since then.

Now, improvements in battery technology are opening many new applications for batteries. The rapid development of markets such as portable electronics and cordless appliances and power tools have relied heavily on today's improved batteries. In a diversity of applications, creative use of batteries is translating directly into improved sales and increased profits. But, creative use of batteries is aided greatly by knowing how batteries operate.

Interest in new and improved batteries remains strong today. The demand for versatile, clean, high-power energy sources grows as electronics becomes an increasingly essential part of both consumer and industrial products. To date, the results of the battery industry's development efforts have been most evident in the dramatic improvements in existing battery types. However, the newly developed batteries, such as nickel-hydrogen cells, silver-zinc batteries, nickel-metal hydride batteries, using different materials and technology are, exhibiting the greatest application in commercial products.

18.1.1. Primary vs Secondary Batteries. Batteries are either primary or secondary. Primary batteries can be used only once because the chemical reactions that supply the current are irreversible. Secondary batteries, sometimes called *storage batteries* or *accumulators*, can be used, recharged and reused. In these batteries, the chemical reactions that provide current from the battery are readily reversed when current is supplied to the battery. The process of inducing or storing energy in an accumulator is called the *charging*, and the process of giving out energy in the form of an electric current, the *discharging*. Accumulators or storage batteries owe their name "secondary" due to the fact that they can supply electrical energy only after they have been charged.

Primary batteries are the most common batteries available today because of their low cost and simplicity in use. Carbon-zinc dry cells and alkaline cells dominate portable consumer battery applications where currents are low and usage is sporadic. Other primary batteries, such as those using mercury or lithium-based chemistries, may be used in applications when high energy densities, small sizes, or long shelf life are especially important. In general, primary batteries have dominated two areas: consumer products where the initial cost of battery is very important and electronic products (such as watches, hearing aids and pacemakers) where drains are low or recharging is not feasible.

Secondary batteries, which are rechargeable, have traditionally been most widely used in industrial and automotive applications. Here users are willing to trade higher initial cost and additional handling and care requirements for high current delivery and the economies of a rechargeable product. Only two rechargeable battery chemistries, lead acid and nickel-cadmium, have, to-date, achieved significant commercial success. The recently introduced nickel-metal hydride couple currently shows promise of supplementing nickel-cadmium cells in many commercial applications.

Recently, the battery market has changed significantly with consumers indicating that, for many products, they are willing to pay the initial premium necessary to have the long-term benefits of rechargeable batteries. Wet (flooded) versions of rechargeable batteries had achieved only limited penetration of the consumer and portable markets. Development of sealed high-performance forms of both lead-acid and nickel-cadmium batteries has allowed secondary batteries to make substantial inroads into traditional primary battery markets such as consumer products.

Recent improvements in secondary battery technology have improved performance and reduced costs. These improvements have spurred sustained growth in applications, both consumer and industrial, relying on rechargeable battery power.

18.2 LEAD-ACID BATTERIES

Classification. Lead-acid batteries, according to service rendered by them, are classified into automotive, motive-power and stationary batteries.

Lead-acid automotive batteries are used to supply power for starting, lighting and ignition of IC engines employed to propel auto-vehicles (motor cycles, motor cars, buses, trucks etc.). Normally these batteries consist of 6 cells, connected in series, with capacity of the order of 100 ampere-hours and provide power at 12 V.

Nowadays maintenance free (MF) batteries are available for this purpose. Such batteries are constructed of such material that no gassing occurs during charging, the electrolyte is either absorbed within the microporous separators and the plates or immobilized with suitable gelling agents and addition of water is not required throughout their normal service life of 2–5 years.

Automotive batteries are charged from ac supply (or alternator) through a full-wave bridge rectifier employing semiconductor diodes. The alternator output voltage is controlled by the transistorised voltage controller (not by cut-out) to meet the requirements of batteries under charge. The batteries are charged at constant voltage.

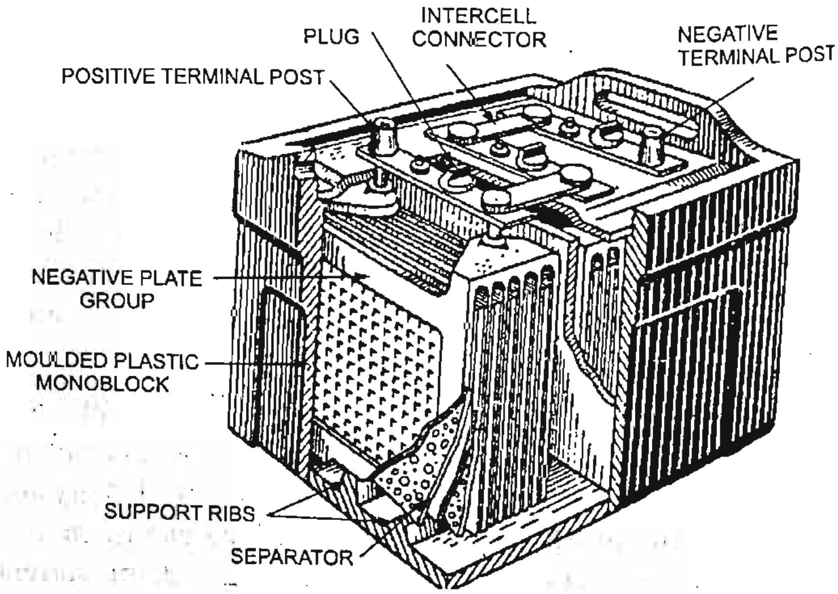


Fig. 18.1 *Exploded View of Exide HSP Classic Motive Power Battery*

Lead-acid motive-power batteries are of better quality in comparison to automotive batteries and provide constant output voltage, high volumetric capacity, good resistance to vibration and a long service life (1,000–1,500 cycles). Such batteries are capable to withstand prolonged and deep discharges and deep recharges on a daily basis. These batteries supply power at voltage ranging from 12 V to 240 V.

These batteries find applications in industrial trucks and commercial vehicles of various types plying on roads, mining, airport tractors, aircraft service vehicles, electric cars and in robotics and guide vehicles.

Lead-acid stationary batteries, in the standby applications, are used to supply power to essential services or to provide alarms or emergency lighting, in case of breakdown of main power supply. In recent years, there is a tremendous increase in standby applications due to increase in demand for uninterruptable power systems (UPS) and tremendous growth in new telecommunication networks. Banks of sealed lead-acid standby batteries are employed these days in telecommunication systems and for UPS applications.

Advanced lead-acid batteries (100 MWh capacity) have been recently developed for use in electric power generating stations to store energy during off-hours and supply the stored energy during peak-load hours.

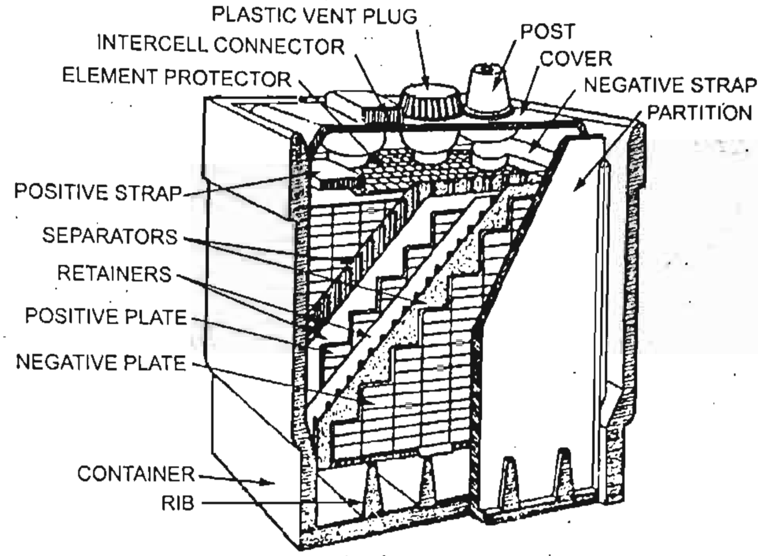


Fig. 18.2 *Lead Acid Battery*

18.2.1. Construction. Various parts of a lead-acid battery are shown in Fig. 18.2.

18.2.2. Active Materials. The materials, in a cell (or battery), taking active participation in chemical reaction (absorption or evolution of electrical energy) during charging or discharging are called the *active materials* of the cell.

The active materials of a lead-acid battery are

1. **Lead peroxide** (PbO_2) dark chocolate brown in colour. It forms the positive active material.
2. **Sponge lead** (Pb) grey in colour. It forms the negative active material.
3. **Dilute sulphuric acid** (H_2SO_4) is used as electrolyte. The electrolyte of a fully charged battery contains about 31% sulphuric acid by weight and 21% by volume for specific gravity of 1.23 at 70 °C. This is the recommended value for the tropical climate. Slightly higher values can be used in winter, if desired. The acid should be made from sulphur and not from pyrites, as the latter is liable to contain injurious substances.

The mixture should be made by pouring the acid slowly into the water, *never the reverse*.

18.2.3. Chemical Reactions.

1. Chemical Reaction During Discharging. When the cell is fully charged anode is of lead peroxide (PbO_2) and cathode is of sponge metallic lead (Pb). When the electrodes are connected through a resistance, the cell discharges and electrons flow in a direction opposite to that during charging. Now sulphuric acid molecules again break up into ($2H^+$) and (SO_4^{--}) ions. Each hydrogen ion now moves to the anode and reaching the anode receives one electron from the anode (coming from cathode through external circuit) and becomes hydrogen atom. Since it is directly in contact with anode of PbO_2, so it attacks and forms lead sulphate ($PbSO_4$), whitish in colour and water according to chemical equation

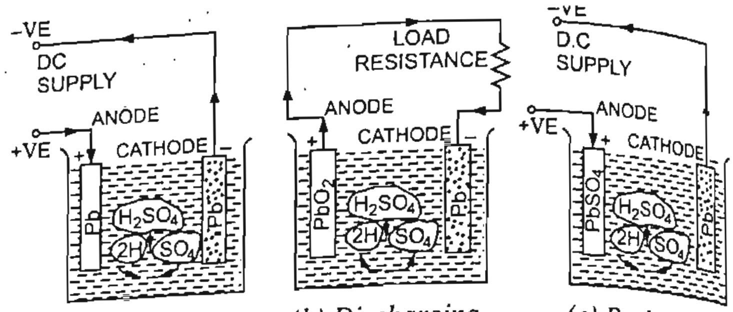
$$PbO_2 + 2H = PbO + H_2O$$

$$PbO + H_2SO_4 = PbSO_4 + H_2O$$

$$PbO_2 + H_2SO_4 + 2H = PbSO_4 + 2H_2O$$

Each sulphate ion (SO_4^{--}) moves towards the cathode and reaching there gives up two electrons (moving to the anode through external circuit) becomes radical SO_4, attacks the metallic lead cathode and forms lead sulphate, whitish in colour according to chemical equation $Pb + SO_4 = PbSO_4$.

Thus, during discharging (*i*) both of the electrodes are converted into lead sulphate, whitish in colour (*ii*) terminal potential of the cell falls (*iii*) density of the electrolyte decreases due to formation of water during chemical action and (*iv*) chemical energy stored is converted into electrical energy and is supplied to an external circuit.



(*a*) *Charging* (*b*) *Discharging* (*c*) *Recharging*

Fig. 18.3 *Charging and Discharging of Lead Acid Cells*

Chemical Action During Recharging. When the cell gets discharged as explained above both of the electrodes are converted into lead sulphate ($PbSO_4$), whitish in colour. On recharging of the cell, the anode and cathode are connected to the positive and negative terminals, of the dc supply mains respectively. The molecules of sulphuric acid (H_2SO_4) in solution again breaks up into ($2H^+$) and (SO_4^{--}) ions. Hydrogen ions ($2H^+$) being positively charged move to the cathode, receives two electrons from there (coming from anode through external circuit), form hydrogen atom and react with lead sulphate cathode forming lead and sulphuric acid according to chemical equation,

$$PbSO_4 + 2H = H_2SO_4 + Pb$$

SO_4^{--} ion moves to the anode, gives up its two additional electrons, (moving to the cathode through external circuit) becomes radical SO_4, reacts with lead sulphate anode and forms lead peroxide (PbO_2) and sulphuric acid according to chemical equation

$$PbSO_4 + 2H_2O + \dot{S}O_4 = PbO_2 + 2H_2SO_4$$

Hence, during recharging

(*i*) Lead sulphate anode gets converted into lead peroxide (PbO_2) dark chocolate brown in colour.
(*ii*) Lead sulphate cathode gets converted into lead, grey in colour.
(*iii*) Terminal potential of the cell increases.
(*iv*) Density (concentration) of the electrolyte (H_2SO_4) increases (due to formation of H_2SO_4 during chemical reaction).
(*v*) Electrical energy received from the external source is stored in the form of chemical energy.

The charging and discharging of cell can be represented by a single reversible equation given below:

$$\underset{\text{Positive plate}}{PbO_2} + 2H_2SO_4 + \underset{\text{Negative plate}}{Pb} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} \underset{\text{Positive plate}}{PbSO_4} + 2H_2O + \underset{\text{Negative plate}}{PbSO_4} + \text{Electrical energy}$$

The equation should be read from left to right for discharge and from right to left for recharge.

18.2.4. Charging and Discharging Curves. Typical charge and discharge curves (variations in terminal voltage) of a lead-acid accumulator are shown in Fig. 18.4. When the cell is charged, the voltage of the cell increases from 1.8 V to 2.2 V during first two hours, then increases very slowly, rather remains almost constant for sufficient time and finally rises to 2.5 to 2.7 V.

When a charged storage cell has just been disconnected from a charging source, its terminal voltage falls rapidly to 2.2 V. On discharge, the voltage of the cell drops to 2.0 V in the beginning; remains constant for sufficient time and falls to 1.8 V finally, as illustrated in Fig. 18.4.

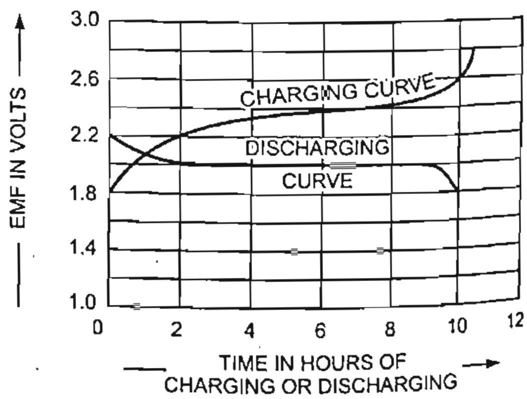


Fig. 18.4 *Typical Charge and Discharge Curves For Lead-Acid Accumulator*

Caution. The cell should never be allowed to discharge beyond 1.75 V otherwise lead sulphate will be formed on the electrodes which is hard, insoluble and increases the internal resistance of the cell. The conversion of active material into lead sulphate is termed *sulphatization.*

18.2.5. Charging Indications. Full charging of lead-acid accumulator (or cells) can be judged from the following indications:

1. ***Gassing.*** When the cell is fully charged, the hydrogen and oxygen gases are liberated at the cathode and anode respectively, so liberation of gases (hydrogen and oxygen), known as *gassing*, on the electrodes indicates that the cells are fully charged.

2. ***Colour.*** When the cell is fully charged, the lead sulphate anode gets converted into lead per oxide (PbO_2) dark chocolate brown in colour and lead sulphate cathode gets converted into lead (Pb), grey in colour. It is considered one of the best tests for ascertaining the condition of a battery.

3. ***Voltage.*** When the cell is fully charged its terminal potential will be approximately 2.6 volts.

4. ***Specific Gravity of The Electrolyte.*** When the cell is fully charged, the specific gravity of the electrolyte will be approximately 1.21. When the cell is fully discharged its value falls to 1.17.

Cells are considered to be fully charged once three successive hourly readings of cell voltage and electrolyte gravity are found to be constant. However, the minimum total ampere-hours input, as mentioned by the manufacturers, must be provided to the cells even if the voltages and specific gravities are observed to be constant before that.

18.2.6. Electrical Characteristics. There are three important characteristics of an accumulator (or storage battery) namely, (*i*) voltage (*ii*) capacity and (*iii*) efficiency.

(*i*) *Voltage.* Average emf of cell is approximately 2.0 volts. The value of emf of a cell does not remain constant but varies with the change in specific gravity of electrolyte, temperature and the length of time since it was last charged.

The emf of the cell increases with the increase in specific gravity of the electrolyte and vice versa but increase in specific gravity of the electrolyte also causes increase in internal resistance of the cell, therefore, its value should not go beyond 1.22. Best results are obtained with the electrolyte of specific gravity 1.21.

The emf of the cell, though not much, but slightly increases with the increase in temperature.

The terminal voltage of a battery is higher during charge than that during discharge due to the following reasons.

The internal voltage developed by chemical action, depends on the strength of electrolyte and increases slightly as the acid becomes stronger and the concentration of electrolyte increases due to formation of H_2SO_4 during charging and decreases due to formation of water during discharging. Moreover, since acid is formed in the pores of active material during charging and water is formed during discharging, and since it takes time for the acid or water to diffuse out, it follows that the strength of the electrolyte that is in actual contact with the active material is considerably greater during charging than the average strength of the electrolyte (acid) while during discharging it is considerably lesser than the average. Therefore, emf of the cell is greater during charging than that during discharging.

The terminal voltage of a battery is equal to $E + Ir$ while charging and to $E - Ir$ while discharging where I is the charging or discharging current and r is the internal resistance of the cell.

(*ii*) *Capacity (Backup).* The ability of an accumulator to last and provide current is called the rated output or the capacity/backup. While the voltage of the cell is determined by its chemistry, the capacity of the cell is infinitely variable.

The capacity of a cell is essentially the number of electrons that can be obtained from it. Since the current is the number of electrons per unit time, cell capacity is the integration of current supplied by the cell over time. The capacity of the cell is, therefore, expressed in *ampere-hours* (A-h) and is equal to the product of the specified discharge current in amperes multiplied by the number of hours before the cell discharges to the specified extent. Thus, a rated output (or capacity) of 10 ampere-hours means that one ampere current can be drawn for 10 hours, or half an ampere current for 20 hours.

Thus, the capacity of a battery may be defined as the useful quantity of electricity that can be drawn from a battery at the specified discharge rate before it falls to the specified value of voltage which is equal to 1.75 V multiplied by the number of cells. The capacity of battery depends upon several factors, principal among which are area of plate surface; quantity, arrangement and porosity of the active material used in the manufacture of the plates; quantity and specific gravity of the electrolyte used; and the porosity of the separators. Rate of discharge and temperature also play important role.

The capacity of the cell increases with the increase in *plate surface area*. A rough rule for estimating the capacity of a battery is the surface area of positive plates in mm^2 multiplied by the number of such plates and divided by 1,000. For example, the capacity of a battery having 5 positive plates each of dimensions of 100 mm and 50 mm, will be $(100 \times 50 \times 5)/1{,}000$ *i.e.* 25 Ah.

Since electricity is produced by chemical action taking place within the cells, the capacity of the battery depends directly upon the *kind and amount of active material used*. Theoretically, roughly 4 grams of metallic lead on either element is required to be reduced to sponge lead or to lead peroxide to produce one ampere-hour of electricity. In practice, from four to six times this amount is required. The reason for this is that it is impossible to reduce all the active material, to bring every particle in contact with the electrolyte, or to cause every part to be penetrated by the current. Experiment shows that from 15 to 22 grams of sponge lead, and from 16 to 24 grams of metallic lead converted into PbO_2, are required on their respective elements to produce a discharge of one ampere-hour at ordinary commercial rates.

The capacity of the cell depends on the *concentration* or the *specific gravity* of the electrolyte as it affects the internal resistance and vigourisity of chemical reaction taking place in a cell. It increases with the increase in specific gravity of the electrolyte.

At a particular temperature, the capacity of the cell depends on its rate of discharging. For instance, a 100 ampere-hour battery capable of giving a continuous discharge of 10 A for 10 hours should theoretically give a discharge of 20 A continuously for 5 hours or 50 A for 2 hours or 100 A for one hour, but in reality, the *ampere-hour capacity decreases with the increase in discharging rate.* With the increase in the rate of discharge, voltage of the cell falls more rapidly due to internal resistance of the cell, the chemical reactions become brisk and so weaken the plates and reduce the capacity of the cell. If the cell is discharged too rapidly it may break the plates, and in case of pasted plates, a very sudden discharge will dislodge the paste.

The capacities of chloride tubular stationary lead-acid cells at various rates of discharge, expressed as a percentage of the ampere-hours available at the 10 hour rate, are given in Fig. 18.5.

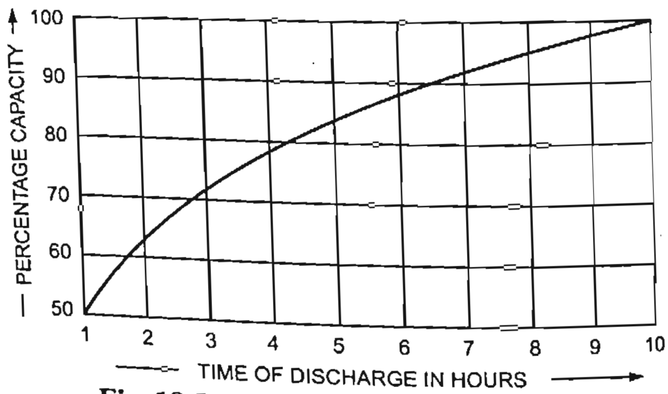


Fig. 18.5 *Courtesy Chloride India Ltd.*

The capacity of a battery increases with the increase in temperature (Fig. 18.6) because at high temperature, the chemical reactions taking place within the cell become more vigorous, the acid resistance is reduced and diffusion of electrolyte is improved. However, at high temperature, the paste gets rapidly converted into lead sulphate which is always accompanied by expansion of paste particularly at positive plates causing in buckling and cracking of the grid. At high temperature the antimony-lead alloy grid, terminal posts and wooden separators are also attacked by the acid. So, it will not be advisable to operate lead-acid batteries beyond temperature of 40 °C. With the fall in temperature, the chemical reactions become slow, cell internal resistance increases and diffusion of electrolyte becomes poor. Consequently, the

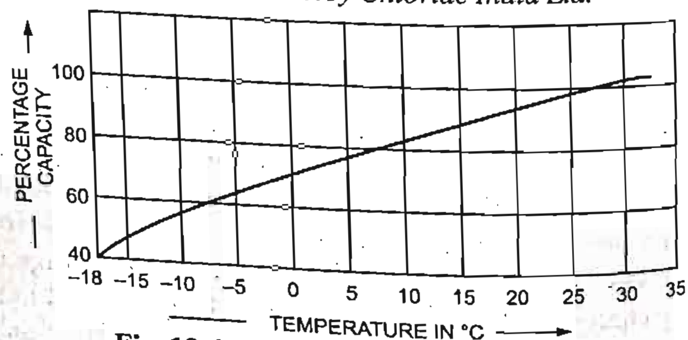


Fig. 18.6 *Courtesy Chloride India Ltd.*

capacity of the cell decreases with the fall in temperature till at freezing point (–35°C at specific gravity of 1.22 of electrolyte) the capacity is reduced to zero even though the battery otherwise be fully charged.

(*iii*) *Efficiency.* The efficiency of the cell can be given in two ways, enumerated and explained below.

1. *The Quantity or Ampere-Hour (A-H) Efficiency.* Since variations in terminal potential of the cell during charge and discharge are not taken into account while working out this efficiency and terminal potential of the cell during charge is higher than that during discharge, therefore, quantity efficiency is always higher than energy efficiency, in which variations of terminal potential of the cell are taken into account.

As generally efficiency is defined as the ratio of output to the input, similarly quantity efficiency or ampere-hour efficiency is defined as the ratio of ampere-hours of discharge and ampere-hours of charge.

$$i.e.\ \text{Ampere-hour efficiency}, \eta_{AH} = \frac{\text{Ampere-hours of discharge}}{\text{Ampere-hours of charge}} \times 100 = \frac{I_d \times T_d}{I_c \times T_c} \times 100$$

The quantity efficiency of the lead acid cell varies from 90 to 95%. It would be 100 per cent if it were not for the gassing on charge, which represents a non-reversible chemical reaction. If the charging is discontinued each time as soon as the gassing becomes appreciable, the ampere-hour efficiency will be nearly 100 per cent but ampere-hour capacity will be reduced and it is advisable to give the battery a full charge from time to time in order to avoid deterioration of the otherwise unused lead sulphate. The quantity efficiency also decreases due to self discharge of the plates caused by local reactions and because of current leakage caused by faulty insulation between the cells and the battery.

2. *Energy or Watt-hour Efficiency.* Energy efficiency is defined as the ratio of energy delivered in watt-hours by the cell during discharge and the energy drawn in watt-hours during charge.

$$i.e.\ \text{Energy or watt-hour efficiency}, \eta_{W-H} = \frac{\text{Output in watt-hours}}{\text{Input in watt-hours}} \times 100$$

$$= \frac{\text{Current delivered} \times \text{time of discharge} \times \text{average pd during discharge}}{\text{Current drawn} \times \text{time of charge} \times \text{average pd during charge}} \times 100$$

$$= \frac{I_d \times T_d \times V_d}{I_c \times T_c \times V_c} \times 100 = \frac{I_d\, T_d}{I_c\, T_c} \times 100 \times \frac{V_d}{V_c} = \eta_{A-H} \times \frac{V_d}{V_c}$$

Operation at low rate of charge and discharge and at reduced ampere-hour capacity both tend to raise the watt-hour efficiency. Actual watt-hour or energy efficiency obtained in practice ranges from about 75 to 85 per cent.

18.2.7. Battery Ratings. The standards adopted, both by industry and government organisations, are given below:

1. *Ampere-hour Capacity Rating.* The ampere-hour rating of a battery is usually determined from its ability to deliver current continuously for 20 hours at 27°C. A battery that can deliver 5 amperes steadily for 20 hours then its rating will be 100 Ah.

2. *Reserve Capacity.* The reserve capacity of a battery is indicated in terms of minutes, a battery is capable of tolerating a drain of 25 A without dropping terminal voltage below 10.5 V (1.75 volts per cell). Higher this rating, better the battery is.

3. *Cold Rating.* The cold rating of a battery indicates the number of minutes a battery can deliver 300 A at –18 °C (0°F). This is applicable in relation to craft which ply in freezing weather.

4. *Cold Cranking Power Rating.* This rating is applicable to all 12 V batteries irrespective of their size. The battery is discharged at –18°C till its terminal voltage falls to 7.2 V. The output current is measured for 30 s. Higher the output, better the battery is.

18.2.8. Uses of Lead-Acid Batteries. The storage batteries are employed for a great variety and range of purposes such as to supply current for electric vehicles and gas engine ignition, and in telephone exchanges, railway trains, mines, laboratories, hospitals, broadcasting stations, telecommunication systems, emergency lightings, UPS systems, solar photovoltaic systems, power generating stations and distribution work as standby unit.

The storage batteries are employed in central power stations for (*i*) supplying the whole load during light load periods (*ii*) supplying peak load during the peak load hours (*iii*) local lighting for odd time of breakdown (*iv*) regulation of load and voltage (*v*) compensating feeder drop and as a preventive against shut down.

A very important use of storage batteries is in the providing of standby power for various electrical systems. In some electrical systems, storage batteries are connected in parallel with the generator and load. When the generator is in operation the batteries draw enough current to keep them fully charged. In case of shut down/breakdown of supply from the generator, the batteries supply the load.

Railway-car lighting systems are supplied from axle-driven generators when the train is running, with batteries supplying the system when the speed of the train is low or the train is stopped.

Automobile electrical systems are similar to the above mentioned system in that the generator, and the load are connected in parallel, the battery supplying power for starting and lighting when the generator is not in operation.

Hospitals and other places, where a continuous source of power supply is absolutely essential, often use storage batteries as an emergency (or standby) supply.

Applications in which storage batteries supply the normal current are in industrial truck or mine-locomotive propulsion portable lighting equipment, portable radios and other applications in which continuous supply from a generator is impracticable.

18.2.9. Elementary Calculations for Energy Consumption

Example 18.1. A battery has taken a charging current of 5.2 A for 24 hours at a voltage of 2.25 V, while discharging it gave a current of 4.5 A for 24 hours at an average voltage of 1.85 V. Calculate the quantity efficiency and the energy efficiency of the battery.

Solution:

Charging current, $I_c = 5.2$ A

Charging mean voltage, $V_c = 2.25$ V

Charging period, $T_c = 24$ hours

Discharging current, $I_d = 4.5$ A

Discharging mean voltage, $V_d = 1.85$ V

Discharging period, $T_d = 24$ hours

$$\text{Quantity efficiency, } \eta_{AH} = \frac{I_d\, T_d}{I_c\, T_c} \times 100 = \frac{4.5 \times 24}{5.2 \times 24} \times 100 = 86.54\% \text{ Ans.}$$

$$\text{Energy efficiency, } \eta_{WH} = \frac{I_d\, T_d}{I_c\, T_c} \times \frac{V_d}{V_c} \times 100 = \frac{4.5 \times 24}{5.2 \times 24} \times \frac{1.85}{2.25} \times 100 = 71.15\% \text{ Ans.}$$

Example 18.2. An alkaline cell is discharged at a steady current of 4 A for 12 hours, the average terminal voltage being 1.2 V. To restore it to original state of voltage, a steady current of 3 A for 20 hours is required, the average terminal voltage being 1.44 V. Calculate the ampere-hour and watt-hour efficiencies in this particular case.

Solution:

Charging current, $I_c = 3$ A

Charging average voltage, $V_c = 1.44$ V

Charging period, $T_c = 20$ hours

Discharging current, $I_d = 4$ A

Discharging average voltage, $V_d = 1.2$ V

Discharging period, $T_d = 12$ hours

$$\text{Ampere-hour efficiency, } \eta_{AH} = \frac{I_d\, T_d}{I_c\, T_c} \times 100 = \frac{4 \times 12}{3 \times 20} \times 100 = 80\ \% \text{ Ans.}$$

$$\text{Watt-hour efficiency, } \eta_{WH} = \eta_{AH} \times \frac{V_d}{V_c} = 80 \times \frac{1.2}{1.44} = 66.7\ \% \text{ Ans.}$$