SWAMI VIVEKANANDA SCHOOL OF ENGINEERING & TECHNOLOGY

MADANPUR,BBSR

LECTURE NOTES

ON

ELECTRICAL EQUIPMENT IN MINES

YEAR & SEMESTER:2ND YEAR & 4TH SEMESTER

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ELECTRICAL EQUIPMENT IN MINES
LECTURE NOTE

SESSION-20022

BRANCH- MINING ENGINEERING

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1. Introduction to Cables used in Mines:

Electricity is used for many purposes at many places in any mine, both underground and at the surface. The electrical power required is obtained either from a generating station at the colliery or, more usually, from the local electricity supply, through a substation.
It is a known fact that cables used underground at collieries have to withstand unfavorable conditions, being exposed to falls of roof, dampness and other potential causes of damage.
Mining cables must therefore be robustly made to withstand the rough use they receive. Further, constant maintenance is required to ensure their safety and reliability. In fact, reliable and robust cables are most essential for efficient coal production.
Moreover, these mining cables should conform to the earthing regulations, namely, that the conductance of the earthing conductor should be at least 50 per cent of that of one of the power conductors.

2. Distribution Cables:

In the mines, for the main high and medium voltage distribution lines, PVC/XLP insulated cables with metric dimensions are now used. Previous to the introduction of metric cable size, the same cables in inch sizes were used. In fact, the inch or imperial size cables are still in use. Also, before the PVC insulated cables were used, the most commonly used cable was the paper-insulated lead sheathed type.

Considerable amounts of this type of cable are still in use. Cables having from two to four core or conductors are available. For three phase a.c. distribution, three core cables are normally used, one core for each phase of the supply system.

The make-up of the cores is as follows:

(a) Plain copper wires-stranded conductor.

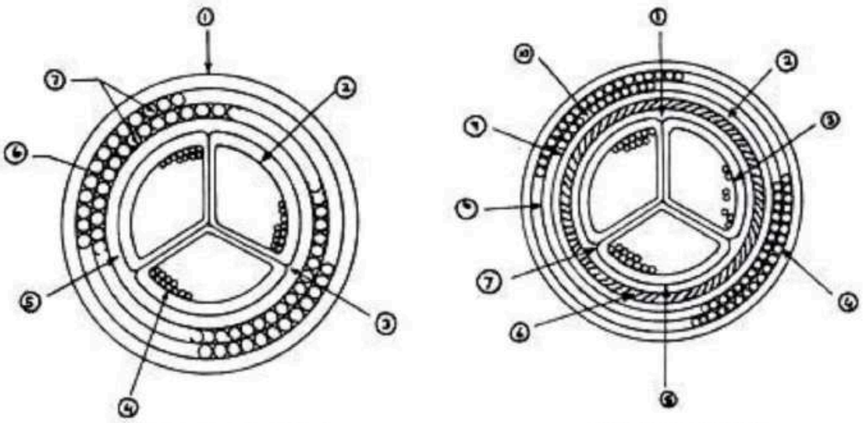
(b) Pre-formed solid aluminium rod – Solid conductor.

(c) Plain Aluminium wires – Stranded conductor.

The cross section of a conductor is made of a sector of a circle. The individual cores are insulated by a covering of coloured PVC insulating compound, the colours of the three power cores being red, yellow and blue. When four core cables are used, the fourth core is the neutral and coloured with black insulating compound.
The conductors of the cable are laid up together in a spiral. Any gaps between them may be filled out with worming to give a uniform circular section. The assembled conductors are usually bound together with a layer of tape.

The laid up cable is covered by a bedding, i.e. sheath of extruded PVC to prevent moisture from getting in. Cables available can be of single-armoured or double-armoured type. Each layer of armour consists of galvanized steel wires laid spirally along the cable.

With double armoured cable, a seperator of compounded fibrous tape separates the two layers of armour, and the galvanized wires are spiralled in opposite directions. The armoring forms the earth conductor of the cable, and so it is important from earthing point of view.



(a) P. V. C. Insulated Cable

(1) Extruded P. V. C. outer Sheath
(2) Extruded P.V. C. conductor insulation
(3) Binding Tape and worming
(4) Conductor (or Core), may be stranded copper stranded Aluminium or Solid Aluminium.
(5) Extruded P.V.C. Bedding
(6) Separator between Layers of Armour.
(7) Stranded wire Armour.

(b) Paper Insulated Cable

(1) Impregnated Paper-Tape Binding
(2) Compounded Bedding
(3) Stranded Core Conductor.
(4) Extruded PVC Outer Sheath
(5) Impregnated Paper-Tape Conductor insulation.
(6) Lead Sheath.
(7) Paper or Jute worming
(8) Separator Between Layers of Armour
(9) Inner Armour
(10) Outer Armour

Fig. 15.1(a) & (b)

Paper Insulated Cable:

The conductors of paper insulated cables are covered with layers of paper tape. They are then laid up with paper or jute worming and bound in more paper tape. The laid up cable is impregnated with a non-draining insulating compound.

This is then enclosed in an extruded lead sheath which is covered with a layer of compounded fibrous tape. This type of cable may have a single or double armour over the lead sheath, the armour being covered overall by an extruded PVC sheath.

3. Installation of Cables:

Several methods of installation are used at the surface of the mine. The method of installation of course depends upon conditions in a particular colliery.

The methods generally are:

(a) Suspension:

Suspended from a centenary wire or wall hooks. Raw hides or lead braided cable suspenders are usually used for this purpose.

(b) Cleats:

Cleat fixing is most commonly used where the cable is required to run along the side of a building.

(c) Duct:

A duct is made by digging a trench and lining it with bricks or concrete, the cable is fastened to the wall of the duct by brackets or cleats.

(d) Wall Brackets:

The cable rests in brackets bolted to the wall. This type of installation is normally used when the cable runs along a wall inside a building.

(e) Trench:

The cable trench should be of adequate depth taking account of the operating voltage of the cable, and the site conditions. The cable should be laid in a bed of sand in the trench- bottom, and then covered with sand. Interlocking cable tiles should then be bedded on to the sand so as to provide a continuous cover over the length of buried cable.

The cable tiles should then be covered with earth free from stones, foreign objects etc. then the trench is backfilled. Finally cable trench **"Marker Posts"** should be erected to identify the cable trench route.

(f) Shaft Installation:

The normal method of securing a cable vertically in the shaft is to clamp it at regular intervals by means of wooden cleats. Wooden cleats are obtainable in lengths from 2 ft. to 6 ft. The choice of cleat of course depends upon the load it has to carry.

Boring the Cleat:

Cleats are bored individually to suit the cable being installed thereby ensuring that they obtain a very firm grip. The method of boring the cleat is to clamp the two halves together with a 6.35 mm (1/4 inch) board sandwiched between them.

A hole is then drilled through the cleat to the same diameter as the cable over the outer wire armour i.e. omitting the overall serving. When the boring is complete, the board is removed so that the cleat has a 6.35 mm. nip on the cable when tightened correctly.

Single Point Suspension:

An alternative method of installation in a shaft is to suspend the cable from a single point at the top of the shaft. A suspension cone is used. At the point from which it is to be suspended the cable is provided with quadruple armouring.

The cable in-fact is suspended by two layers of armouring doubled over and fitted into the cone. When the cone is assembled the cavity at the top is filled with compound. The suspension core is fastened to the top of the shaft by heavy chains. This method is only suitable for comparatively shallow shafts and is a method not frequently adopted.

Lowering the Cable:

Normal method of lowering the cable into the shaft is to install the drum in a cage and to lay out the cable as the cage is lowered. The cable is anchored at the shaft top and cleared as the cage gradually descends. If the drum is too large to go into the cage, a platform is sometimes built underneath to accommodate the cable drum and the men would accompany it.

An alternative method of lowering the cable is to lash it to a wire rope so that the cable can be controlled from the top of the shaft. The cable is usually lashed to the rope at approximately ten foot intervals. When the cable has been lowered, a number of lashings at the top are cut, and this part of the cable is secured by cleats.

Work then proceeds down the cable. At each step sufficient lashings are cut to enable a cleat to be installed. The cleat is then secured before more lashings are cut.

Installation Underground:

Close to the pit bottom, cleats on brackets may be used to secure cables to walls, but in roadways and gates, the usual method of installation is to suspend the cables from bars or arches. Rawhide or lead braid suspenders, such as those with catenary wires, are commonly used underground. Canvas or mild steel suspenders are also in use.

The cable is suspended as high as possible over the roadway so the chance of it being damaged by activity below is minimised. The cable suspenders are usually designed to break in the event of a serious fall of roof, so that the cable will come down with the roof. In this way, the risk of damage to the cables is minimised.

The cable must not be drawn tight at any point. Slackness is necessary throughout its length to accommodate roof movements.

4. Cable Junctions:

The length of cable which can be taken underground in one piece is limited by either:
(1) The size of cable drum which can be lowered down the shaft and transported in bye or

(2) The amount of cable which can be coiled and which is necessary to take the electricity supply from the pit bottom, and therefore, have to consist of lengths of cable joined together by means of cable coupler or junction (joint) box. Both methods result in a satisfactory joint when filled with compound.

Cable Couplers:
A cable coupler is in two identical halves, one half fitted to the end of each of the cables to be joined. Each half of the coupler has a contact tube for each cable conductor. When the cables are in place the two halves of the cable are brought together, and contact pins are inserted into the contact tubes to complete the connections. The halves are then bolted together to make a flameproof joint as shown in Fig. 15.2.

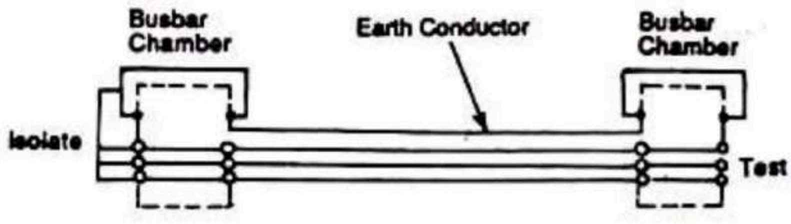


Fig. 15.2.

If it becomes necessary to part the cable again, the two halves of the coupler are unbolted and drawn apart. However all the work of assembling the coupler halves to the cables is done at the surface. Each cable is taken underground with the couplers attached.

Junction Box:
When a junction box is used, each conductor of the cable is joined to the corresponding conductor of the other cable by means of an individual ferrule or connector. When the junction is complete, the box is filled with compound. Once the junction box has been filled, it is difficult to part cables again, as their operation involves melting the compound and draining it from the box in order to free the connectors. All the work of assembling a junction box has to be done underground at or very near the place where it is to be installed and as such, junction boxes are now less commonly used than cable couplers.

Connecting a Cable to a Cable Coupler:

A typical sequence of operations for making up a cable coupler is as follows:

(1) Preparing the Cables:
The length of serving, armouring, bedding and conductor insulation which are removed from the end of the cable depend upon the maker of coupler and can be found from the maker's instructions. Before armour is removed, the armour clamp is passed along the cable. When removing the armour, do not cut right through with a hack-saw, as it will then be difficult to avoid damaging the bedding.

The correct procedure is to cut part of the way through the strands and then to break them off by bending them to and fro. When the cable has been cut back, the exposed armouring must be cleaned until it is bright, and if the cable has a lead sheath, this also must be cleaned thoroughly.

(2) Fitting the Cable Gland:
The ends of the armoring's are expanded so that the inner core gland, complete with gland bolts, can be inserted beneath it. If there are two layers of armouring an inter armour core is inserted between the two layers. The armour clamp, (which was put on before cutting the armour) is drawn forward over the expanded armour and on both gland bolts, the bolts are then tightened to secure the armour in the gland. If the cable has a lead sheath the gland should be packed with lead wool in accordance with the manufacturer's instruction.

(3) Fitting the contact tubes and interior insulator moulding:
The insulation of the individual conductors is now cut back to the prescribed length. The insulator steel support pillars are fitted to the inner core gland and the interior-insulator moulding complete with contact tubes is offered up to the support pillars, and this enables the core lengths to be checked.

If correct, the contact tubes can now be fitted to the cable cores in the case of aluminium conductor cores these may be soldered (specially in inert gas) or crimped by the compression tool in accordance with the manufacturers' instructions.

In the case of copper conductor cores, these may be soldered or fixed by grub screws. After fixing the cores in the contact tubes the interior insulator moulding must be fitted to the tubes and secured to the support pillars.

(4) Fitting the Coupler Body:
The coupler body may now be fitted over the interior insulator and, to be bolted in position, check the F.L.P. gap to ensure that it is flameproof.

(5) Filling the Coupler Case:
The filler and vent plugs are removed, and insulating compound is poured in. With PVC cables, hot filling compound (with a temperature not exceeding 135°C) or a cold pouring compound is used in order to avoid melting the cable insulation. The compound may contract as it sets and needs to be topped up. When the compound has set, the plugs are replaced.

(6) Insulation Test:
When a coupler has been assembled and the compound has set hard, insulation resistance between each pair of conductors, and between each conductor and the coupler case, is tested with a suitable tester, like Megger or Metro-ohm.

(7) Continuity Test:
When both ends of the cable have been prepared, the continuity of each conductor through the cable is tested with a continuity tester, to ensure that the internal connections are secured and adequate.

It is particularly important to test continuity between the cases of two couplers to ensure that the earth conductor conform with earthing regulations, namely that the conductivity of the earth conductor is at least 50 per cent of that of a power conductor.

If the earth conductor is provided by the cable armouring, then earth continuity will depend upon how securely the armouring has been clamped by the cable gland. It is important, when testing such a cable, to measure earth continuity between the cases of the cable couplers so that the electrical connections between the armour glands and the armouring are tested correctly.

(8) Storage:
When a coupler has been tested it is wrapped tightly in hessians or plastic sheets, and the cable-end is lashed to a staple on the drum. It is good practice to bolt a blanking plate over the end of the coupler to protect the flange of the flameproof point. While the cable is in storage it should be kept as dry as possible to prevent moisture from getting into the insulation.

Making up a Junction Box:

The sequence of operations for making up a junction box is as follows:

(1) Mounting the Box:
If conditions permit, the box is first bolted in the position in which it is to be installed i.e. on a brick pillar, or in an inset. If the position is hard to reach, the box may be made below or alongside its final position and lilted into place when complete.

(2) Preparing the Cable:

The method of preparing the cables is similar to that for a cable coupler.

(3) Clamping the Cable:
The armour clamps and .glands are similar to those used with cable coupler. It is usual to bolt down the clamps before beginning work on the internal connections.

(4) Making Electrical Connections:
The insulation of the individual conductors is cut back to the required dimensions, and the remaining insulations strengthened by wrapping insulation tape around them. The ends of the conductors are shaped to a circular section, if

necessary. The ferrule or connections are now fitted to the ends of the conductors, and their grub screws are tightened. The entire joint is then bound with insulation tape.

(5) Setting the Joints:
In some types of boxes, the connection are bolted to wooden or porcelain bases. In other types, the ferrules are unsupported, but the cable conductors are held apart by insulating spreaders. Some makers require that connections should be staggered inside the box. The requirement will be anticipated by the dimensions given for the individual conductors when the cable is prepared.

(6) Insulation Test:
Before the box is closed, the insulation resistance between each pair of conductors and between each conductor and the box must be tested with a suitable insulation resistance tester. A similar test from the unconnected end of one of the cables is required after the box has been filled.

(7) Covering the Box:
The cover is now bolted on. The joints between the cover and the body of the box should be tested with a feeler gauge to ensure that they are flameproof. If an earth board is provided, ensure that it is fitted securely and with good electrical contacts.

(8) Filling with Compound:
The filling plugs and the vent plugs are removed and the box filled with compound. As the compound sets and contracts, it may be necessary to top it up. When the box has been filled, the plugs are replaced. If the junction box is underground, or in a shaft, the compound cannot be heated near the actual site of the box.

If hot pouring compound is to be used, it must be heated on the surface and carried in an insulated bracket to the place where it is to be filled. The minimum pouring temperature for many compounds is around 150°C. If the junction box is far away underground, and needs a long journey to reach it, then it may not be possible to keep the compound hot long enough to be poured in the junction box when at last it is reached.

In such cases, and where it is impracticable to use hot compound, it is advisable that the box be filled with a cold pouring compound. In fact a cold pouring compound is made by mixing a hardener into a bituminous oil. As soon as the two constituents are mixed, the compound take up to 24 hours to set hard.

The compound can, of course, be mixed underground besides the box. In most practical cases this type of cold pouring compound has been found very much useful. To fill with cold pouring compound, at first pour the bituminous oil into a clean container and then add the hardener to it. The mixture must be stirred vigorously until the two constituents are thoroughly blended, so that no sediment remains.

The compound should be poured into the box without delay, and the filling plugs be replaced. As soon as the joint has been filled, any amount of the mixture left in the bucket should be cleaned as compounds left cannot be removed once they are allowed to set.

Installing Cable Couplers and Junction Boxes:
Junction boxes used underground, are usually mounted on brick pillars, or in insets cut into the side of a roadway. Cables are usually attached to the wall by cleats near where they enter the junction boxes. Plenty of slack is left, so that in the event of a roof fall which brings down the cable, as little strain as possible is placed directly upon the box.

Cable couplers, and sometimes junction boxes are suspended from the roof by cradles. If there is a roof fall, the coupler or box comes down with the cable. Cable joints are rarely made in shafts, but when they are, the box is usually placed in an inset in the side of the shaft. Some types of junction boxes are designed to be bolted vertically to the side of the shaft.

5. Types of Flexible Cables in Mines:

Flexible cables used in the electrical system of a mine fall into two main categories – trailing cables and pliable wire armour cables.

(1) Trailing Cables:

The majority of modern trailing cables have five cores—three power cores for the three phase a.c. supply, a fourth core for the pilot and a fifth core for the earth. Cores are always insulated with a synthetic insulation such as C.S.P. (Chloro Sulphonated Polyethylene) or E.P.R. (Ethylene Propylene Rubber). Some cores have an insulation of E.P.R. which is then covered with a layer of C.S.P. (two layers of insulation).

The earth core in some types of trailing cable is not insulated but laid up bare in the centre of the cable. The synthetic compound C.S.P. is a harder insulating compound than rubber, it is more resistant to penetration by broken core or screen wires. It has a low insulation resistance and high capacitance with consequential long charging time when measuring the insulation resistance.

The insulated cores are laid up in a variety of ways dependent upon the type of cable.

In some, the cores are laid up in a spiral about a center cradle, the spiral is fairly tight particularly in the case of drill cables so that the cable can flex easily without imposing stresses on the individual cores. In others, either the pilot, or the earth core runs in the center cradle with the other cores laid up around it.

Screening:

The majority of modern trailing cables are of the individually screened type where the screens are earthed. The screening provides electrical protection for the cables should it is accidentally damaged and penetrated by a metallic object; the object will first make contact with the earthed screen before touching the live core.

Therefore, the possibility of a short circuit between live cores etc. is greatly reduced, as the earth leakage protection will detect an earth fault and trip the controlling gate-end box before the short circuit is made.

There are two types of individually screened trailing cables:

(1) The copper / nylon braided screen and

(ii) The conductive rubber screen.

Trailing cables having conductive rubber screens must only be used on a system having sensitive earth leakage which limits the earth fault current to 750 m.a. on power cables and 125 m.a. on drill cables, Trailing cables are sheathed over all around in P.C.P. (Poly-chloroprene).

(2) Pliable Wire Armoured Cables:

These cables consist of three or four cores with synthetic insulation on the cores. The core insulation being usually C. S. P. or E.P.R. (or C.S.P. over E.P.R.) for cables operating on system voltage up to 1,100 voltage. For cables operating on systems in excess of 1,100 volts and up to 6,600 volts, the core insulation is butyl or E.P.R.

The cores are laid up round a center, they are then enclosed in an inner sheath of P.C.P. The armour in-fact consists of a layer of flexible galvanized steel strands laid up in a spiral over the inner sheath, the cable is covered overall by a sheath of P.C.P.

Screening:
Copper / Nylon braided screening is provided around each individual power core. In a similar manner and for similar reasons to those previously mentioned earth cores are not screened for trailing cables.

Plug and Sockets:
Trailing cables are normally connected to equipment by means of a plug which mates with a corresponding socket on the equipment. Plugs and sockets are of two kinds, i.e. bolted and restrained types. Bolted plugs and sockets have matching flanges which mate when the plug is fully inserted in the socket, the flanges are then bolted together by studs which screw into the socket flange.

Restrained plugs and sockets are pulled and held together by an extractor screw. The socket extractor screw has a latch (cam) which engages in a flat on the plug body by screening the screw in the plug, and is pulled into the socket and held in situ. When properly assembled, both bolted and restrained types form flameproof junctions. Here again the flameproof path and gaps must be checked.

Plugs and sockets with different current and voltage ratings are in use, the ratings used depending upon the loading of the equipment to which the cable is connected as also with reference to the system voltage. The 150 amp. restrained plug and socket is the one most commonly used on voltage up to 660 volts.

A dual voltage versions of the 150 amp restrained plug and socket has been designed and recently made available. This is suitable for operation on 600 /1100 volt systems and in addition, it has been updated to 200 amps. To differentiate between 660 volt and 1,100 volt, the 1100 volts mode has its insulators and contact tubes turned through 180°. The 660 volt mode is fully interchangeable with the 150 amp 660 volts range.

However, the 30 amp 660 volt bolted type plug and socket is provided for the small h.p. equipment, the plugs and sockets of different manufacturers are designed to plug into each other. Also in existence are earlier types 1,100 volt plugs and sockets of 50 amp and 150 amp.

These older types are not interchangeable with the types noted above, also they do not interchange with other manufacturer's products. In present day's design inter changeability is a most vital point to consider.

Colour Code:
This is another important feature of electrical engineering. The standard colour code for cable core identification has changed due to metrication. For comparison, the following table gives the new metric colour code along with the old imperial colour code. This is important considering the fact that old codes are still in use and those shall remain in use for years to come.

	Imperical	Metric
Power Cores	Red, White & Blue	Brown,
Pilot Cores	Black	Blue
Earth Cores	Green	Green / Yellow

Installation:
Wherever possible, pliable armoured and trailing cables are suspended from roof bars or arches. Where they have to run along the floor, they should be laid to one side where they will be out of the way of passing traffic and exposed to the minimum risk of damage.

At road heads, cables must be protected by steel channels or pipes. Trailing cables running down the face must be placed where they will not foul machinery, jacks and roof supports, and where they are least likely to suffer damage from work in progress, falls of roof or any other cause.

Many conveyors are fitted with an armoured channel to receive cables and where such a conveyor is in use, it is a must to ensure that the cable is properly protected by the channel. If the coalface machine is fitted with a cable handling device, ensure that the cable engages with it correctly. Cables are made in standard length and, for this reason, a cable may be longer than the run for which it is to be used.

The spare length of cable should be taken up by making it in a figure of eight. Do not ever make a circular coil, as this will introduce twists, which could lead to the conductors being strained, or the armouring ' 'bird-caging". The coils provide a reserve of cable which can be laid out if the run is to be lengthened e.g. between the in-bye substation and the gate-end panels when the face moves forward.

In fact electrical engineers in mines will always have to be alert to consider the factors to avoid any delay, and thus to prevent any loss of production, and above all to avoid any accident.

Fault Finding:

Fault in cables are usually detected because of their effect upon the equipment they serve. A Fault is likely to trip out a contactor or circuit breaker through the earth fault protection or the overload protection. The type of fault can be confirmed and the conductor or conductors affected, can be discovered by caring out the insulation and conductance tests.

After the type of fault has been known there remain the problem of finding where along the length of the cable has the fault occurred. To find the fault by inspected is laborious, and a fault could be passed unnoticed, unless a very thorough and detailed examination is made. One of the following tests is, therefore, used to find the approximate position of the fault before visual examination begins.

These tests are most frequently performed in the workshop. If a trailing or pliable armored cable becomes defective, it is replaced by a sound cable and brought to the surface for repair. If a fault should develop on a main distribution line, it may be necessary to perform a test with the cable in position, so that the fault can be repaired on the spot, or only a small section of the cable renewed.

The tests are of particular value when a fault occurs in a buried cable at the surface.

Earth Fault Test:

This test is used to locate a fault between a conductor and the screen or armouring. Several forms of the test are in use, the simplest is the Murray loop test, which uses the principle of Wheatstone bridge. The equipment required and the connection to be made is shown in Fig. 15.3.

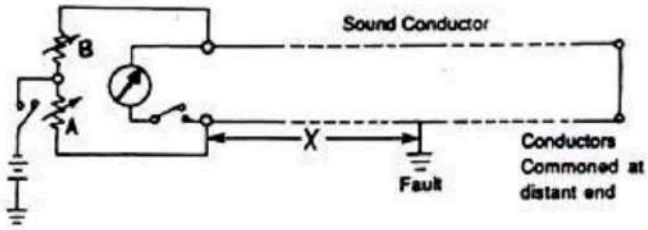


Fig. 15.3.

Note:

A and B are two variable resistances (or parts of a resistance box).

The earth fault test is described below:
1. Isolate both ends of the cable and discharge to earth.
2. At one end of the cable, connect the faulty conductor to a sound conductor of equal cross-sectional area.
3. At the other end of the cable, connect the test equipment as a shown in Fig. 15.3.
4. Switch on the supply and adjust the resistance A & B until the galvanometer reads zero.
5. The values of the resistances A & B when the galvanometer is at zero -are used to find the fault i.e. the distance (X) to the fault = A /A+B × twice the length of the cable.

Short circuit test:
This test is used to find a short circuit between two conductors of a cable. One of the faulty conductors is earthed, and the fault is located by Murray loop test, using the other faulty conductor and the sound conductor, as shown in Fig. 15.4., where we see A & B are two variable resistances (or parts of a resistance box).

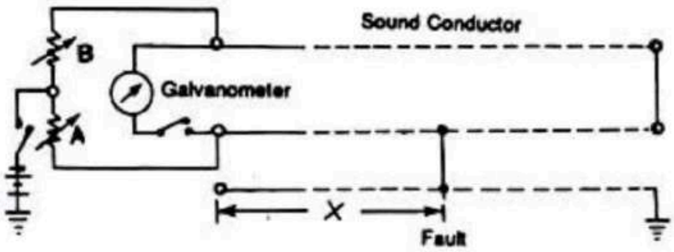


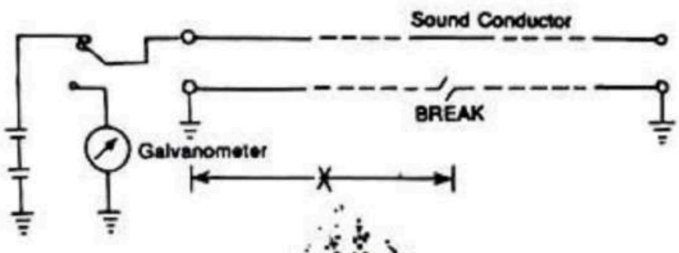
Fig. 15.4.

The Galvanometer is balanced at zero by adjusting the resistance.

Open Circuit Test:
This test is used to find a break in one of the cable conductors. The principle of the test is to compare the capacitance of one part of the faulty conductor, with the capacitance of the whole of a sound conductor.

The methods is as follows:
1. Isolate both ends of the cable and discharge to earth.

2. At one end of the cable, connect the test equipment as shown in Fig. 15.5. The sound conductor to be used must have the same cross sectional area as the broken conductor.



3. Earth both ends of the broken conductor and all the conductors in the cable, except the sound conductor to which the supply is to be connected.
4. Switch the supply on to the sound conductor and allow the conductor to become fully charged.
5. Immediately connect the charged conductor to the galvanometer and note the time taken for the conductor to discharge. The discharge time is measured from the moment when the switch is connected to the moment when the galvanometer pointer returns to zero.

6. Disconnect the test equipment from the sound conductor, and earth the conductor.
7. Remove the earth connection from the test end of the broken conductor, and connect the test equipment to the conductor.
8. Charge the broken conductor, and find the discharge time.
9. The distance (X) to the fault
= Discharge time for broken conductor x length of cable. / Discharge time for sound conductor.

System Earth:
All the earth system for the various sections of the colliery are, in fact, connected into a single system, which ends somewhere on the surface, where it is connected to the general body of the earth by one or more earth plate connections.

The safety of the whole electrical system depends upon efficient earthing at the point, and the earth plate connections must therefore be tested from time to time. The test can be carried out with an earth tester (e.g. the Megger), or by fall-of-potential method using the equipment as shown in Fig. 15.6 which explains in detail the method of testing called Earth Plate Test.

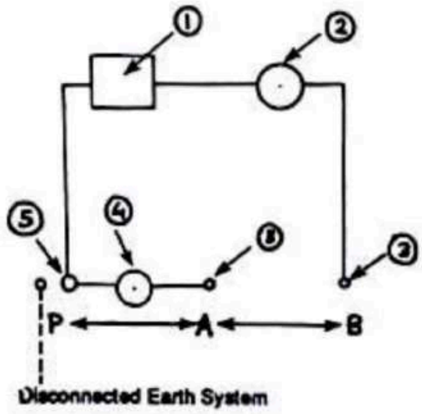


Fig. 15.6.

Earth Plate Test:

This is a very important test; the method of testing is as follows:
1. Disconnect the earth plate to be tested from the electrical system.

Ensure that the electrical system is still connected to earth by other plates. If there is only one earth plate, the test can be carried out only when the electrical system is shut down.

2. Insert the two earthing spikes into the ground, placing one about twice as far from the earth plate as the other. Suitable distances would be: PA 12 m, PB 24 m. A large distance is required to ensure that each electrode is well outside the resistance area of the earth plate under test. Ensure that each spike makes a good connection to earth.

3. Connect the equipment as shown in Fig. 15.6. Correct connections for an earth tester are supplied with the instrument.

4. Switch on the test supply and note the readings on the two instruments. The reading on the voltmeter, divided by the reading on the ammeter gives a value in ohm for the resistance of the earth plate connection to earth. The resistance can be read directly from an earth tester.

5. Switch off the supply and move spike B about 6 m. closer to the earth plate, e.g. PA 12 m, PB 18 m.

6. Switch on the supply and again find the earth plate resistance.

7. Switch on the supply and move spike B to a position about 6 m. further from the earth plate than its original position, e.g. PA 12 m, PB 30 m.

8. Switch on the supply and again find the earth plate resistance.

9. If the three values obtained in steps 4, 6 and 8 lie within about 0.25 ohm of one another, find the average of the three values and accept this as the resistance of the earth plate connection to earth.

If the three values now show a greater variation it is probable that the test spikes were not located outside the resistance area of the earth plate. It will be necessary to repeat the entire test to find three readings which do not differ by more than 0.25 ohm. Start with test spikes further apart than before.

A final value of 1 ohm or less indicates a good earth connection. The maximum value which may be accepted is 2 ohms.

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.

Advantages (i) It is the cheapest form of protection available. (ii) It requires no maintenance. (iii) Its operation is inherently completely automatic unlike a circuit breaker which requires an elaborate equipment for automatic action. (iv) It can break heavy short-circuit currents without noise or smoke. (v) The smaller sizes of fuse element impose a current limiting effect under short-circuit conditions. (vi) The inverse time-current characteristic of a fuse makes it suitable for overcurrent protection. (vii) The minimum time of operation can be made much shorter than with the circuit breakers. Disadvantages (i) Considerable time is lost in rewiring or replacing a fuse after operation. (ii) On heavy short-circuits, *discrimination between fuses in series cannot be obtained unless there is sufficient difference in the sizes of the fuses concerned. (iii) The current-time characteristic of a fuse cannot always be co-related with that of the protected apparatus.

Desirable Characteristics of Fuse Element The function of a fuse is to carry the normal current without overheating but when the current exceeds its normal value, it rapidly heats up to melting point and disconnects the circuit protected by it. In order that it may perform this function satisfactorily, the fuse element should have the following desirable characteristics : (i) low melting point e.g., tin, lead. (ii) high conductivity e.g., silver, copper. (iii) free from deterioration due to oxidation e.g., silver. (iv) low cost e.g., lead, tin, copper. The above discussion reveals that no material possesses all the characteristics. For instance, lead has low melting point but it has high specific resistance and is liable to oxidation. Similarly, copper has high conductivity and low cost but oxidises rapidly. Therefore, a compromise is made in the selection of material for a fuse. 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.

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

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 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 reinserted in the base to restore the supply. This type of fuse has two advantages. Firstly, the detachable fuse carrier permits the replacement of fuse element without any danger of coming in contact with live parts. Secondly, the cost of replacement is negligible. Disadvantages (i) There is a possibility of renewal by the fuse wire of wrong size or by improper material. (ii) This type of fuse has a low-breaking capacity and hence cannot be used in circuits of high fault level. (iii) The fuse element is subjected to deterioration due to oxidation through the continuous heating up of the element. Therefore, after some time, the current rating of the fuse is decreased i.e., the fuse operates at a lower current than originally rated. (iv) The protective capacity of such a fuse is uncertain as it is affected by the ambient conditions. (v) Accurate calibration of the fuse wire is not possible because fusing current very much depends upon the length of the fuse element. Semi-enclosed 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 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. When a fault occurs, the silver fuse elements are the first to be blown out and then current is transferred to the tungsten wire. The weak link in series with the tungsten wire gets fused and causes the chemical charge to be detonated. This forces the plunger outward to operate the circuit breaker. The travel of the plunger is so set that it is not ejected from the fuse body under fault conditions. Advantages. H.R.C. fuse with a tripping device has the following advantages over a H.R.C. fuse without tripping device : (i) In case of a single phase fault on a three-phase system, the plunger operates the tripping mechanism of circuit breaker to open all the three phases and thus prevents "single phasing". (ii) The effects of full short circuit current need not be considered in the choice of circuit breaker. This permits the use of a relatively inexpensive circuit breaker. (iii) The fuse-tripped circuit breaker is generally capable of dealing with fairly small fault currents itself. This avoids the necessity for replacing the fuse except after highest currents for which it is intended. Low voltage H.R.C. fuses may be built with a breaking capacity of 16,000 A to 30,000 A at 440V. They are extensively used on low-voltage distribution system against over-load and shortcircuit conditions. High 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. (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

20.9 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.

Circuit Breakers

Introduction

During the operation of power system, it is often desirable and necessary to switch on or off the various circuits (*e.g.*, trans-

mission lines, distributors, generating plants etc.) under both normal and abnormal conditions. In earlier days, this function used to be performed by a switch and a fuse placed in series with the circuit. However, such a means of control pre-sents two disadvantages. Firstly, when a fuse blows out, it takes quite sometime to replace it and restore supply to the customers. Secondly, a fuse cannot successfully interrupt heavy fault cur-rents that result from faults on modern high-volt-age and large capacity circuits. Due to these dis-advantages, the use of switches and fuses is lim-ited to low-voltage and small capacity circuits where frequent operations are not expected *e.g.*, for switching and protection of distribution trans-formers, lighting circuits, branch circuits of dis-tribution lines etc.

Circuit Breakers

A circuit breaker is a piece of equipment which can

(i) make or break a circuit either manually or by remote control under normal conditions

(ii) break a circuit *automatically* under fault conditions

(iii) make a circuit either manually or by remote control under fault conditions

Thus a circuit breaker incorporates manual (or remote control) as well as automatic control for switching functions. The latter control employs relays and operates only under fault conditions. The mechanism of opening of the circuit breaker under fault conditions has already been briefed in chap-ter 16.

Operating principle. A circuit breaker essentially consists of fixed and moving contacts, called electrodes. Under normal operating conditions, these contacts remain closed and will not open auto-matically until and unless the system becomes faulty. Of course, the contacts can be opened manually or by remote control whenever desired. When a fault occurs on any part of the system, the trip coils of the circuit breaker get energised and the moving contacts are pulled apart by some mechanism, thus opening the circuit.

When the contacts of a circuit breaker are separated under fault conditions, an arc is struck between them. The current is thus able to continue until the discharge ceases. The production of arc not only delays the current interruption process but it also generates enormous heat which may cause damage to the system or to the circuit breaker itself. Therefore, the main problem in a circuit breaker is to extinguish the arc within the shortest possible time so that heat generated by it may not reach a dangerous value.

Arc Phenomenon

When a short-circuit occurs, a heavy current flows through the contacts of the *circuit breaker before they are opened by the protective system. At the instant when the contacts begin to separate, the contact area decreases rapidly and large fault current causes increased current density and hence rise in temperature. The heat produced in the medium between contacts (usually the medium is oil or air) is sufficient to ionise the air or vapourise and ionise the oil. The ionised air or vapour acts as conduc-tor and an arc is struck between the contacts. The p.d. between the contacts is quite small and is just sufficient to maintain the arc. The arc provides a low resistance path and consequently the current in the circuit remains uninterrupted so long as the arc persists.

During the arcing period, the current flowing between the contacts depends upon the arc resis-tance. The greater the arc resistance, the smaller the current that flows between the contacts. The arc resistance depends upon the following factors :

(i) *Degree of ionisation*— the arc resistance increases with the decrease in the number of ionised particles between the contacts.

(ii) *Length of the arc*— the arc resistance increases with the length of the arc *i.e.,* separation of contacts.

(iii) *Cross-section of arc*— the arc resistance increases with the decrease in area of X-section of the arc.

Principles of Arc Extinction

Before discussing the methods of arc extinction, it is necessary to examine the factors responsible for the maintenance of arc between the contacts. These are :

(i) p.d. between the contacts

(ii) ionised particles between contacts

Taking these in turn,

(i) When the contacts have a small separation, the p.d. between them is sufficient to maintain the arc. One way to extinguish the arc is to separate the contacts to such a distance that p.d. becomes inadequate to maintain the arc. However, this method is impracticable in high voltage system where a separation of many metres may be required.

(ii) The ionised particles between the contacts tend to maintain the arc. If the arc path is deionised, the arc extinction will be facilitated. This may be achieved by cooling the arc or by bodily removing the ionised particles from the space between the contacts.

Methods of Arc Extinction

There are two methods of extinguishing the arc in circuit breakers *viz.*

High resistance method.**2.** Low resistance or current zero method

High resistance method. In this method, arc resistance is made to increase with time so that current is reduced to a value insufficient to maintain the arc. Consequently, the current is interrupted or the arc is extinguished. The principal disadvantage of this method is that enormous energy is dissipated in the arc. Therefore, it is employed only in d.c. circuit breakers and low-capacity a.c. circuit breakers.

The resistance of the arc may be increased by :

(i) *Lengthening the arc.* The resistance of the arc is directly proportional to its length. The length of the arc can be increased by increasing the gap between contacts.

(ii) *Cooling the arc.* Cooling helps in the deionisation of the medium between the contacts. This increases the arc resistance. Efficient cooling may be obtained by a gas blast directed along the arc.

(iii) *Reducing X-section of the arc.* If the area of X-section of the arc is reduced, the voltage necessary to maintain the arc is increased. In other words, the resistance of the arc path is increased. The cross-section of the arc can be reduced by letting the arc pass through a narrow opening or by having smaller area of contacts.

(iv) *Splitting the arc.* The resistance of the arc can be increased by splitting the arc into a number of smaller arcs in series. Each one of these arcs experiences the effect of lengthen-ing and cooling. The arc may be split by introducing some conducting plates between the contacts.

Low resistance or Current zero method. This method is employed for arc extinction in a.c. circuits only. In this method, arc resistance is kept low until current is zero where the arc extinguishes naturally and is prevented from restriking inspite of the rising voltage across the contacts. All modern high power a.c. circuit breakers employ this method for arc extinction.

In an a.c. system, current drops to zero after every half-cycle. At every current zero, the arc extinguishes for a brief moment. Now the medium between the contacts contains ions and electrons so that it has small dielectric strength and can be easily broken down by the rising contact voltage known as *restriking voltage.* If such a breakdown does occur, the arc will persist for another half-cycle. If immediately after current zero, the dielectric strength of the medium between contacts is built up more rapidly than the voltage across the contacts, the arc fails to restrike and the current will

be interrupted. The rapid increase of dielectric strength of the medium near current zero can be achieved by :

(a) causing the ionised particles in the space between contacts to recombine into neutral molecules.

(b) sweeping the ionised particles away and replacing them by un-ionised particles

Therefore, the real problem in a.c. arc interruption is to rapidly deionise the medium between contacts as soon as the current becomes zero so that the rising contact voltage or restriking voltage cannot breakdown the space between contacts. The de-ionisation of the medium can be achieved by:

(i) *lengthening of the gap.* The dielectric strength of the medium is proportional to the length of the gap between contacts. Therefore, by opening the contacts rapidly, higher dielectric strength of the medium can be achieved.

(ii) *high pressure.* If the pressure in the vicinity of the arc is increased, the density of the particles constituting the discharge also increases. The increased density of particles causes higher rate of de-ionisation and consequently the dielectric strength of the medium between contacts is increased.

(iii) *cooling.* Natural combination of ionised particles takes place more rapidly if they are al-lowed to cool. Therefore, dielectric strength of the medium between the contacts can be increased by cooling the arc.

(iv) *blast effect.* If the ionised particles between the contacts are swept away and replaced by un-ionised particles, the dielectric strength of the medium can be increased considerably. This may be achieved by a gas blast directed along the discharge or by forcing oil into the contact space.

19.5 Important Terms

The following are the important terms much used in the circuit breaker analysis :

(i) Arc Voltage. *It is the voltage that appears across the contacts of the circuit breaker during the arcing period.*

As soon as the contacts of the circuit breaker separate, an arc is formed. The voltage that appears across the contacts during arcing period is called the arc voltage. Its value is low except for the *period the fault current is at or near zero current point. At current zero, the arc voltage rises rapidly to peak value and this peak voltage tends to maintain the current flow in the form of arc.

(ii) Restriking voltage. *It is the transient voltage that appears across the contacts at or near current zero during arcing period.*

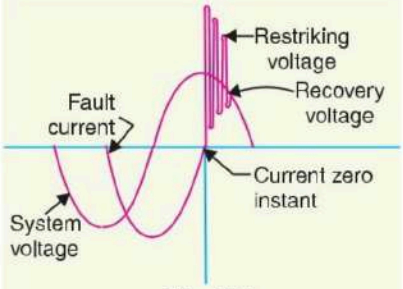


Fig. 19.1

At current zero, a high-frequency transient voltage appears across the contacts and is caused by the rapid distribution of energy between the magnetic and electric fields associated with the plant and transmission lines of the system. This transient voltage is known as restriking voltage (Fig. 19.1). The current interruption in the circuit depends upon this voltage. If the restriking voltage rises more rapidly than the dielectric strength of the medium between the contacts, the arc will persist for another half-cycle. On the other hand, if the dielectric strength of the medium builds up more rapidly than the restriking voltage, the arc fails to restrike and the current will be interrupted.

(iii) Recovery voltage. *It is the normal frequency (50 Hz) r.m.s. voltage that appears across the contacts of the circuit breaker after final arc extinction. It is approximately equal to the system voltage.*

When contacts of circuit breaker are opened, current drops to zero after every half cycle. At some current zero, the contacts are separated sufficiently apart and dielectric strength of the medium between the contacts attains a high value due to the removal of ionised particles. At such an instant, the medium between the contacts is strong enough to prevent the breakdown by the restriking voltage. Consequently, the final arc extinction takes place and circuit current is interrupted. Immediately after final current interruption, the voltage that appears across the contacts has a transient part (See Fig. 19.1). However, these transient oscillations subside rapidly due to the damping effect of system resistance and normal circuit voltage appears across the contacts. The voltage across the contacts is of normal frequency and is known as recovery voltage.

19.6 Classification of Circuit Breakers

There are several ways of classifying the circuit breakers. However, the most general way of classification is on the basis of medium used for arc extinction. The medium used for arc extinction is usually oil, air, sulphur hexafluoride (SF_6) or vacuum. Accordingly, circuit breakers may be classi-fied into :

(i) *Oil circuit breakers* which employ some insulating oil (*e.g.*, transformer oil) for arc extinction.

(ii) *Air-blast circuit breakers* in which high pressure air-blast is used for extinguishing the arc.

(iii) *Sulphur hexafluroide circuit breakers* in which sulphur hexafluoride (SF_6) gas is used for arc extinction.

(iv) *Vacuum circuit breakers* in which vacuum is used for arc extinction.

Each type of circuit breaker has its own advantages and disadvantages. In the following sections, we shall discuss the construction and working of these circuit breakers with special emphasis on the way the arc extinction is facilitated.

19.7 Oil Circuit Breakers

In such circuit breakers, some insulating oil (*e.g.,* trans-former oil) is used as an arc quenching medium. The con-tacts are opened under oil and an arc is struck between them. The heat of the arc evaporates the surrounding oil and dissociates it into a substantial volume of gaseous *hy-drogen at high pressure. The hydrogen gas occupies a volume about one thousand times that of the oil decom-posed. The oil is, therefore, pushed away from the arc and an expanding hydrogen gas bubble surrounds the arc re-gion and adjacent portions of the contacts (See Fig. 19.2). The arc extinction is facilitated mainly by two processes. Firstly, the hydrogen gas has high heat conductivity and

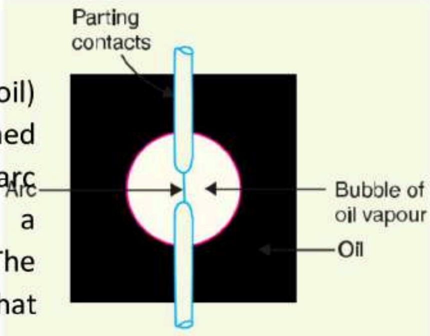


Fig. 19.2

cools the arc, thus aiding the de-ionisation of the medium between the contacts. Secondly, the gas sets up turbulence in the oil and forces it into the space between contacts, thus eliminating the arcing products from the arc path. The result is that arc is extinguished and circuit current †interrupted.

Advantages. The advantages of oil as an arc quenching medium are :

(i) It absorbs the arc energy to decompose the oil into gases which have excellent cooling properties.

(ii) It acts as an insulator and permits smaller clearance between live conductors and earthed components.

(iii) The surrounding oil presents cooling surface in close proximity to the arc. **Disadvantages.** The disadvantages of oil as an arc quenching medium are : ***(i)*** It is inflammable and there is a risk of a fire.

(ii) It may form an explosive mixture with air

(iii) The arcing products (*e.g.,* carbon) remain in the oil and its quality deteriorates with succes-sive operations. This necessitates periodic checking and replacement of oil.

Plain Break Oil Circuit Breakers

A plain-break oil circuit breaker involves the simple process of separating the contacts under the whole of the oil in the tank. There is no special system for arc control other than the increase in length caused by the separation of contacts. The arc extinction occurs when a certain critical gap between the contacts is reached.

The plain-break oil circuit breaker is the earliest type from which all other circuit breakers have developed. It has a very simple construction. It consists of fixed and moving contacts enclosed in a strong weather-tight earthed tank containing oil upto

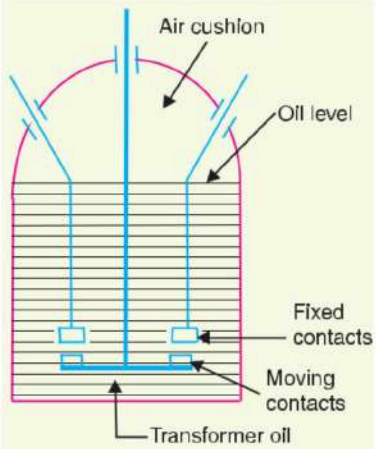


Fig. 19.3

a certain level and an air cushion above the oil level. The air cushion provides sufficient room to allow for the reception of the

arc gases without the generation of unsafe pressure in the dome of the circuit breaker. It also absorbs the mechanical shock of the upward oil movement. Fig. 19.3 shows a *double break plain oil circuit breaker. It is called a double break because it provides two breaks in series.

Under normal operating conditions, the fixed and moving contacts remain closed and the breaker carries the normal circuit current. When a fault occurs, the moving contacts are pulled down by the protective system and an arc is struck which vapourises the oil mainly into hydrogen gas. The arc extinction is facilitated by the following processes :

(i) The hydrogen gas bubble generated around the arc cools the arc column and aids the de-ionisation of the medium between the contacts.

(ii) The gas sets up turbulence in the oil and helps in eliminating the arcing products from the arc path.

(iii) As the arc lengthens due to the separating contacts, the dielectric strength of the medium is increased.

The result of these actions is that at some critical gap length, the arc is extinguished and the circuit current is interrupted.

Disadvantages

(i) There is no special control over the arc other than the increase in length by separating the moving contacts. Therefore, for successful interruption, long arc length is necessary.

(ii) These breakers have long and inconsistent arcing times.

(iii) These breakers do not permit high speed interruption.

Due to these disadvantages, plain-break oil circuit breakers are used only for low-voltage applications where high breaking-capacities are not important. It is a usual practice to use such breakers for low capacity installations for voltages not exceeding †11 kV.

Arc Control Oil Circuit Breakers

In case of plain-break oil circuit breaker discussed above, there is very little artificial control over the arc. Therefore, comparatively long arc length is essential in order that turbulence in the oil caused by the gas may assist in quenching it. However, it is necessary and desirable that final arc extinction should occur while the contact gap is still short. For this purpose, some arc control is incorporated and the breakers are then called arc control circuit breakers. There are two types of such breakers, namely :

(i) *Self-blast oil circuit breakers*— in which arc control is provided by internal means *i.e.* the arc itself is employed for its own extinction efficiently.

(ii) *Forced-blast oil circuit breakers*— in which arc control is provided by mechanical means external to the circuit breaker.

(*i*) Self-blast oil circuit breakers. In this type of circuit breaker, the gases produced during arcing are confined to a small volume by the use of an insulating rigid pressure chamber or pot surrounding the contacts. Since the space available for the arc gases is restricted by the chamber, a very high pressure is developed to force the oil and gas through or around the arc to extinguish it. The magnitude of pressure developed depends upon the value of fault current to be interrupted. As the pressure is generated by the arc itself, therefore, such breakers are some-times called self-generated pressure oil circuit breakers.

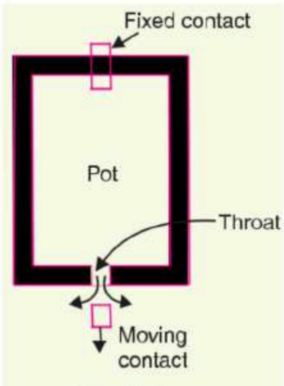


Fig. 19.4

The pressure chamber is relatively cheap to make and gives reduced final arc extinction gap length and arcing time as against the plain-break oil circuit breaker. Several designs of pressure chambers (sometimes called explosion pots) have been developed and a few of them are described below :

(a) Plain explosion pot. It is a rigid cylinder of insulating material and encloses the fixed and moving contacts (See Fig. 19.4). The moving contact is a cylindrical rod passing through a restricted opening (called throat) at the bottom. When a fault occurs, the contacts get separated and an arc is struck between them. The heat of the arc decomposes oil into a gas at very high pressure in the pot. This high pressure forces the oil and gas through and round the arc to extinguish it. If the final arc extinction does not take place while the moving contact is still within the pot, it occurs immediately after the moving contact leaves the pot. It is because emergence of the moving contact from the pot is followed by a violent rush of gas and oil through the throat producing rapid extinction.

The principal limitation of this type of pot is that it cannot be used for very low or for very high fault currents. With low fault currents, the pressure developed is small, thereby increasing the arcing time. On the other hand, with high fault currents, the gas is produced so rapidly that explosion pot is liable to burst due to high pressure. For this reason, plain explosion pot operates well on moderate short-circuit currents only where the rate of gas evolution is moderate.

(b) Cross jet explosion pot. This type of pot is just a modification of plain explosion pot and is illustrated in Fig. 19.5. It is made of insulating material and has channels on one side which act as arc splitters. The arc splitters help in increasing the arc length, thus facilitating arc extinction. When a fault occurs, the moving contact of the circuit breaker begins to separate. As the moving contact is withdrawn, the arc is initially struck in the top of the pot. The gas generated by the arc exerts pressure on the oil in the back passage. When the moving contact uncovers the arc splitter ducts, fresh oil is forced **across* the arc path. The arc is, therefore, driven sideways into the "arc splitters" which increase the arc length, causing arc extinction.

The cross-jet explosion pot is quite efficient for interrupting heavy fault currents. However, for low fault currents, the gas pressure is †small and consequently the pot does not give a satisfactory operation.

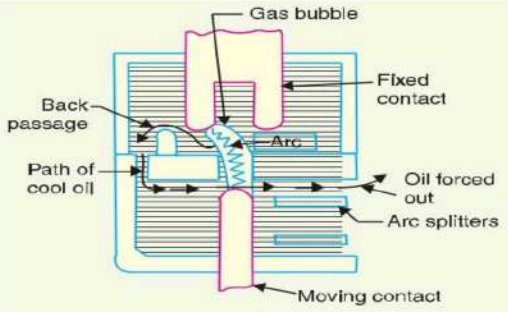


Fig. 19.5

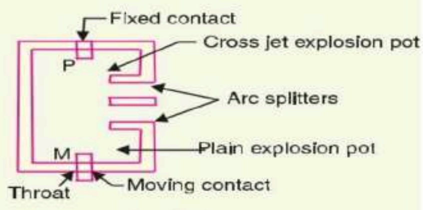


Fig. 19.6

Low Oll Circuit Breakers

In the bulk oil circuit breakers discussed so far, the oil has to perform two functions. Firstly, it acts as an arc quenching medium and secondly, it insulates the live parts from earth. It has been found that only a small percentage of oil is actually used for arc extinction while the major part is utilised for insulation purposes. For this reason, the quantity of oil in bulk oil circuit breakers reaches a very high figure as the system voltage increases. This not only increases the expenses, tank size and weight of the breaker but it also increases the fire risk and maintenance problems.

The fact that only a small percentage of oil (about 10% of total) in the bulk oil circuit breaker is actually used for arc extinction leads to the question as to why the remainder of the oil, that is not immediately surrounding the device, should not be omitted with consequent saving in bulk, weight and fire risk. This led to the development of low-oil circuit breaker. A low oil circuit breaker employs solid materials for insulation purposes and uses a small quantity of oil which is just sufficient for arc extinction. As regards quenching the arc, the oil behaves identically in bulk as well as low oil circuit breaker. By using suitable arc control devices, the arc extinction can be further facilitated in a low oil circuit breaker.

Construction. Fig 19.7 shows the cross section of a single phase low oil circuit breaker. There are two compartments separated from each other but both filled with oil. The upper chamber is the circuit breaking chamber while the lower one is the supporting chamber. The two chambers are separated by a partition and oil from one chamber is prevented from mixing with the other chamber. This arrangement permits two advantages. Firstly, the circuit breaking chamber requires a small volume of oil which is just enough for arc extinction. Secondly, the amount of oil to be replaced is reduced as the oil in the supporting chamber does not get contaminated by the arc.

(i) *Supporting chamber.* It is a porcelain chamber mounted on a metal chamber. It is filled with oil which is physically separated from the oil in the circuit breaking compartment. The oil inside the supporting chamber and the annular space formed between the porcelain insulation and bakelised paper is employed for insulation purposes only.

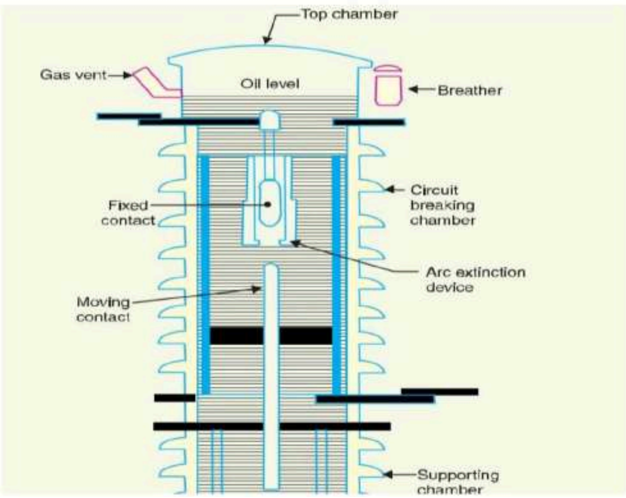
(ii) *Circuit-breaking chamber.* It is a porcelain enclosure mounted on the top of the supporting compartment. It is filled with oil and has the following parts :

(a) upper and lower fixed contacts

(b) moving contact

(c) turbulator

The moving contact is hollow and includes a cylinder which moves down over a fixed piston. The turbulator is an arc control device and has both axial and radial vents. The axial venting ensures the interruption of low currents whereas radial venting helps in the interruption of heavy currents.



Air-Blast Circuit Breakers

These breakers employ a high pressure *air-blast as an arc quenching medium. The contacts are opened in a flow of air-blast established by the opening of blast valve. The air-blast cools the arc and sweeps away the arcing products to the atomsphere. This rapidly increases the dielectric strength of the medium between contacts and prevents from re-establishing the arc. Consequently, the arc is extinguished and flow of current is interrupted.

Advantages. An air-blast circuit breaker has the following advantages over an oil circuit breaker:

(i) The risk of fire is eliminated.

(ii) The arcing products are completely removed by the blast whereas the oil deteriorates with successive operations; the expense of regular oil replacement is avoided.

(iii) The growth of dielectric strength is so rapid that final contact gap needed for arc extinction is very small. This reduces the size of the device.

(iv) The arcing time is very small due to the rapid build up of dielectric strength between con-tacts. Therefore, the arc energy is only a fraction of that in oil circuit breakers, thus resulting in less burning of contacts.

(v) Due to lesser arc energy, air-blast circuit breakers are very suitable for conditions where frequent operation is required.

(vi) The energy supplied for arc extinction is obtained from high pressure air and is independent of the current to be interrupted.

Disadvantages. The use of air as the arc quenching medium offers the following disadvantges :

(i) The air has relatively inferior arc extinguishing properties.

(ii) The air-blast circuit breakers are very sensitive to the variations in the rate of rise of restrik-ing voltage.

(iii) Considerable maintenance is required for the compressor plant which supplies the air-blast. The air blast circuit breakers are finding wide applications in high voltage installations. Major-

ity of the circuit breakers for voltages beyond 110 kV are of this type.

Sulphur Hexaflouride (SF_6) Circuit Breakers

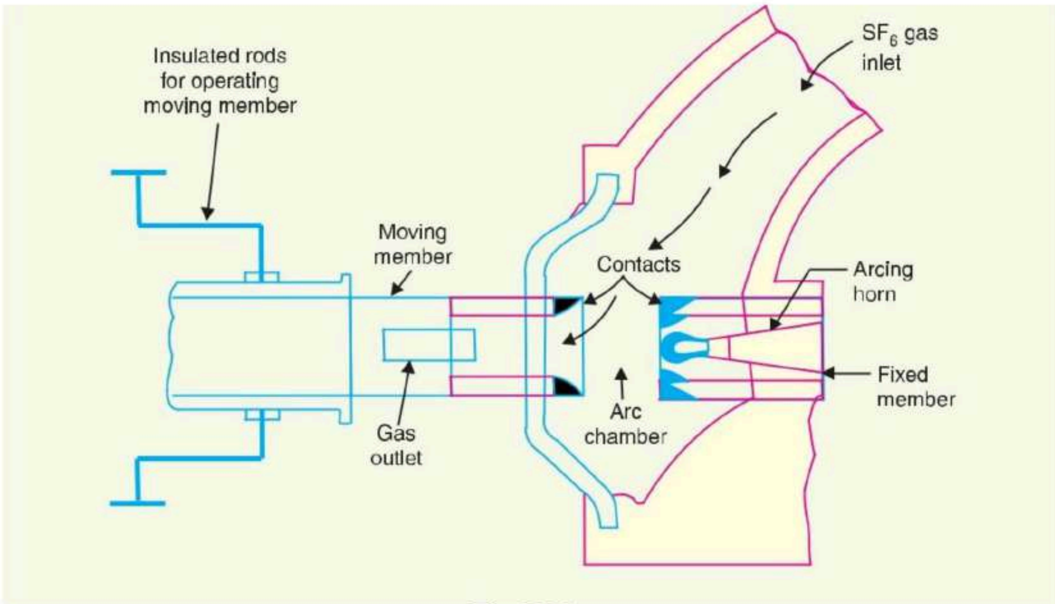
In such circuit breakers, sulphur hexaflouride (SF_6) gas is used as the arc quenching medium. The SF_6 is an electro-negative gas and has a strong tendency to absorb free electrons. The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them. The conducting free electrons in the arc are rapidly captured by the gas to form relatively immobile negative ions. This loss of conducting electrons in the arc quickly builds up enough insulation strength

to extinguish the arc. The SF_6 circuit breakers have been found to be very effective for high power and high voltage service.

Construction. Fig. 19.11 shows the parts of a typical SF_6 circuit breaker. It consists of fixed and moving contacts enclosed in a chamber (called arc interruption chamber) containing SF_6 gas. This chamber is connected to SF_6 gas reservior. When the contacts of breaker are opened, the valve mechanism permits a high pressure SF_6 gas from the reservoir to flow towards the arc interruption chamber. The fixed contact is a hollow cylindrical current carrying contact fitted with an arc horn. The moving contact is also a hollow cylinder with rectangular holes in the sides to permit the SF_6 gas to let out through these holes after flowing along and across the arc. The tips of fixed contact, moving contact and arcing horn are coated with copper-tungsten arc resistant material.

Since SF_6 gas is costly, it is reconditioned and reclaimed by suitable auxiliary sytem after each operation of the breaker.

Working. In the closed position of the breaker, the contacts remain surrounded by SF_6 gas at a pressure of about 2·8 kg/cm^2. When the breaker operates, the moving contact is pulled apart and an arc is struck between the contacts. The movement of the moving contact is synchronised with the opening of a valve which permits SF_6 gas at 14 kg/cm^2 pressure from the reservoir to the arc interrup-tion chamber. The high pressure flow of SF_6 rapidly absorbs the free electrons in the arc path to form immobile negative ions which are ineffective as charge carriers. The result is that the medium be-tween the contacts quickly builds up high dielectric strength and causes the extinction of the arc. After the breaker operation (*i.e.,* after arc extinction), the valve is closed by the action of a set of springs.



Advantages. Due to the superior arc quenching properties of SF_6 gas, the SF_6 circuit breakers have many advantages over oil or air circuit breakers. Some of them are listed below :

(i) Due to the superior arc quenching property of SF_6, such circuit breakers have very short arcing time.

(ii) Since the dielectric strength of SF_6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.

(iii) The SF_6 circuit breaker gives noiselss operation due to its closed gas circuit and no exhaust to atmosphere unlike the air blast circuit breaker.

(iv) The closed gas enclosure keeps the interior dry so that there is no moisture problem.

(v) There is no risk of fire in such breakers because SF_6 gas is non-inflammable.

(vi) There are no carbon deposits so that tracking and insulation problems are eliminated.

(vii) The SF_6 breakers have low maintenance cost, light foundation requirements and minimum auxiliary equipment.

(viii) Since SF_6 breakers are totally enclosed and sealed from atmosphere, they are particularly suitable where explosion hazard exists *e.g.,* coal mines.

Disadvantages

(i) SF_6 breakers are costly due to the high cost of SF_6.

(ii) Since SF_6 gas has to be reconditioned after every operation of the breaker, additional equip-ment is requried for this purpose.

Applications. A typical SF_6 circuit breaker consists of interrupter units each capable of dealing with currents upto 60 kA and voltages in the range of 50—80 kV. A number of units are connected in series according to the system voltage. SF_6 circuit breakers have been developed for voltages 115 kV to 230 kV, power ratings 10 MVA to 20 MVA and interrupting time less than 3 cycles.

D.C. Motors

D. C. motors are seldom used in ordinary applications because all electric supply companies furnish alternating current However, for special applications such as in steel mills, mines and electric trains, it is advantageous to convert alternating current into direct current in order to use d.c. motors. The reason is that speed/torque characteristics of d.c. motors are much more superior to that of a.c.motors.

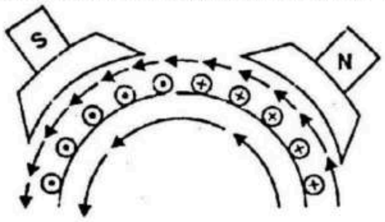
D.C. Motor Principle

A machine that converts d.c. power into mechanical power is known as a d.c. motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by;

F = BIl newtons

Working of D.C. Motor

Consider a part of a multipolar d.c. motor as shown in Fig. (4.1). When the terminals of the motor are connected to an external source of d.c. supply: (i) the field magnets are excited developing alternate N and S poles; (ii) the armature conductors carry ^currents. All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.



Back or Counter E.M.F.

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator The induced e.m.f. acts in opposite direction to the applied voltage V(Lenz's law) and in known as back or counter e.m.f. Eb. The back e.m.f. Eb(= P f ZN/60 A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.

Significance of Back E.M.F.

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load. Armature current, Ia= V-E_B/R_A (i) When the motor is running on no load, small torque is required to overcome the friction and windage losses. Therefore, the armature current Ia is small and the back e.m.f. is nearly equal to the applied voltage.

(ii) If the motor is suddenly loaded, the first effect is to cause the armature toslow down. Therefore, the speed at which the armature conductors move through the field is reduced and hence the back e.m.f. Eb falls. The decreased back e.m.f. allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.

(iii) If the load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque
required by the load.

Types of D.C. Motors

Like generators, there are three types of d.c. motors characterized by the connections of field winding in relation to the armature viz.:

(i) **Shunt-wound motor** in which the field winding is connected in parallel with the armature [See Fig. 4.4]. The current through the shunt field winding is not the same as the armature current. Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current.

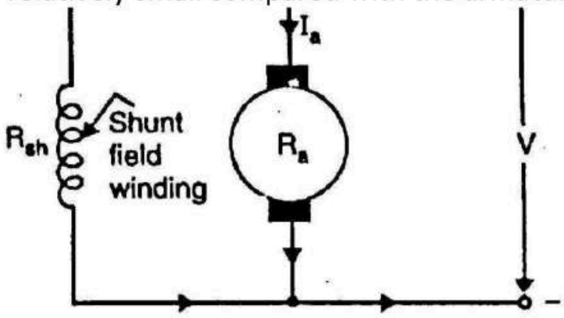


Fig. (4.4)

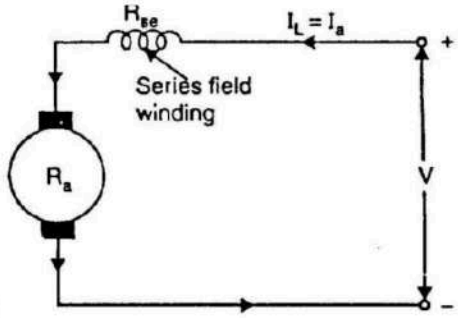


Fig. (4.5)

(ii) **Series-wound motor** in which the field winding is connected in series with the armature [See Fig. 4.5]. Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same m.m.f. Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

(iii) **Compound-wound motor** which has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections (like generators). When the shunt field winding is directly connected across the armature terminals [See Fig. 4.6], it is called short-shunt connection.

Speed Control of D.C. Motors

The speed of a d.c. motor is given by:

$$N \propto \frac{E_b}{\phi}$$

or $$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.}$$

where $R = R_a$ for shunt motor

$= R_a + R_{se}$. for series motor

From exp. (i), it is clear that there are three main methods of controlling the speed of a d.c. motor, namely:

(i) By varying the flux per pole (ϕ). This is known as flux control method.

(ii) By varying the resistance in the armature circuit. This is known as armature control method.

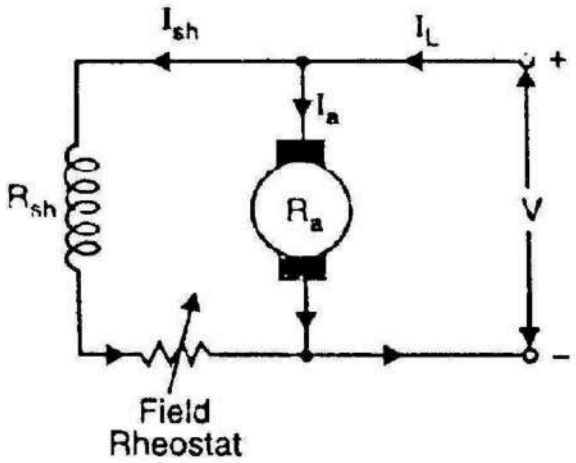
(iii) By varying the applied voltage V. This is known as voltage control method.

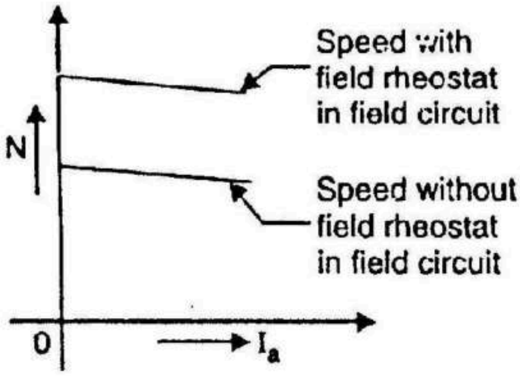
Speed Control of D.C. Shunt Motors

The speed of a shunt motor can be changed by (i) flux control method (ii) armature control method (iii) voltage control method. The first method (i.e. flux control method) is frequently used because it is simple and inexpensive.

1. Flux control method

It is based on the fact that by varying the flux f, the motor speed (N µ 1/f) can be changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding as shown in Fig. (5.1).





The shunt field rheostat reduces the shunt field current Ish and hence the flux f. Therefore, we can only raise the speed of the motor above the normal speed (See Fig. 5.2). Generally, this method permits to increase the speed in the ratio 3:1. Wider speed ranges tend to produce instability and poor commutation.

Advantages

(i) This is an easy and convenient method.

(ii) It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of Ish.

(iii) The speed control exercised by this method is independent of load on the machine.

Disadvantages

(i) Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below Rsh—the shunt field winding resistance.

Armature control method

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This

is done by inserting a variable resistance RC (known as controller resistance) in series with the armature as shown in Fig. (5.3).

Fig. (5.3) Fig. (5.4)

N µ V - Ia (Ra + RC)

where RC = controller resistance

Due to voltage drop in the controller resistance, the back e.m.f. (Eb) is decreased. Since N µ Eb, the speed of the motor is reduced. The highest speed obtainable is lhat corresponding to RC = 0 i.e., normal speed. Hence, this method can only provide speeds below the normal speed (See Fig. 5.4).

Disadvantages

(i) A large amount of power is wasted in the controller resistance since it carries full armature current Ia.

(ii) The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.

(iii) The output and efficiency of the motor are reduced.

(iv) This method results in poor speed regulation.

Due to above disadvantages, this method is seldom used to control tie speed of shunt motors.

Note. The armature control method is a very common method for the speed control of d.c. series motors. The disadvantage of poor speed regulation is not important in a series motor which is used only where varying speed service is required.

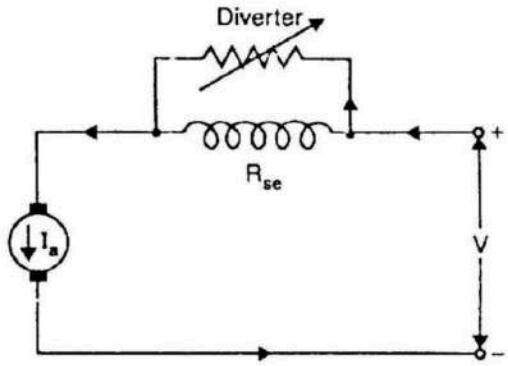
Speed Control of D.C. Series Motors

The speed control of d.c. series motors can be obtained by (i) flux control method (ii) armature-resistance control method. The latter method is mostly used.

1. Flux control method

In this method, the flux produced by the series motor is varied and hence the speed. The variation of flux can be achieved in the following ways:

(i) **Field divertcrs.** In this method, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in Fig. (5.6). Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed (??N ??1/?). The lowest speed obtainable is that corresponding to zero current in the diverter (i.e., diverter is open). Obviously, the lowest speed obtainable is the normal speed of the motor. Consequently, this method can only provide speeds above the normal speed. The series field diverter method is often employed in traction work.



(ii) **Armature diverter.** In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature as shown in Fig. (5.7). The diverter shunts some of the line current, thus reducing the armature current. Now for a given load, if Ia is decreased, the flux ??must increase (??T ???Ia). Since N ??1/? the motor speed is decreased. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

(iii) **Tapped field control.** In this method, the flux is reduced (and hence speed is increased) by decreasing the number of turns of the series field winding as shown in Fig. (5.8). The switch S can short circuit any part of the field

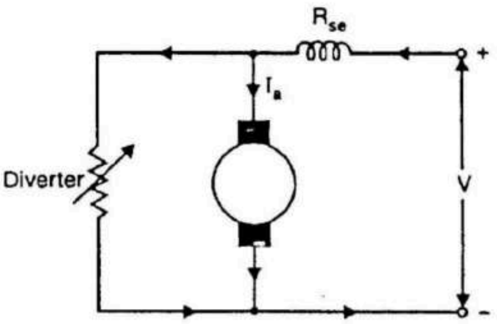


Fig. (5.7)

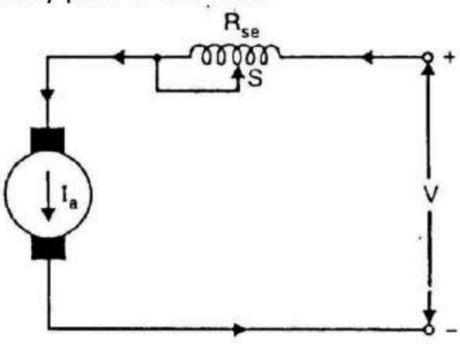


Fig. (5.8)

winding, thus decreasing the flux and raising the speed. With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out, speeds higher than normal speed are achieved.

Electric Braking

Sometimes it is desirable to stop a d.c. motor quickly. This may be necessary in case of emergency or to save time if the motor is being used for frequently repeated operations. The motor and its load may be brought to rest by using either (i) mechanical (friction) braking or (ii) electric braking. In mechanical braking, the motor is stopped due to the friction between the moving parts of the motor and the brake shoe i.e. kinetic energy of the motor is dissipated as heat. Mechanical braking has several disadvantages including non-smooth stop and greater stopping time.

In electric braking, the kinetic energy of the moving parts (i.e., motor) is converted into electrical energy which is dissipated in a resistance as heat or alternativley, it is returned to the supply source (Regenerative braking). For d.c. shunt as well as series motors, the following three methods of electric braking are used:

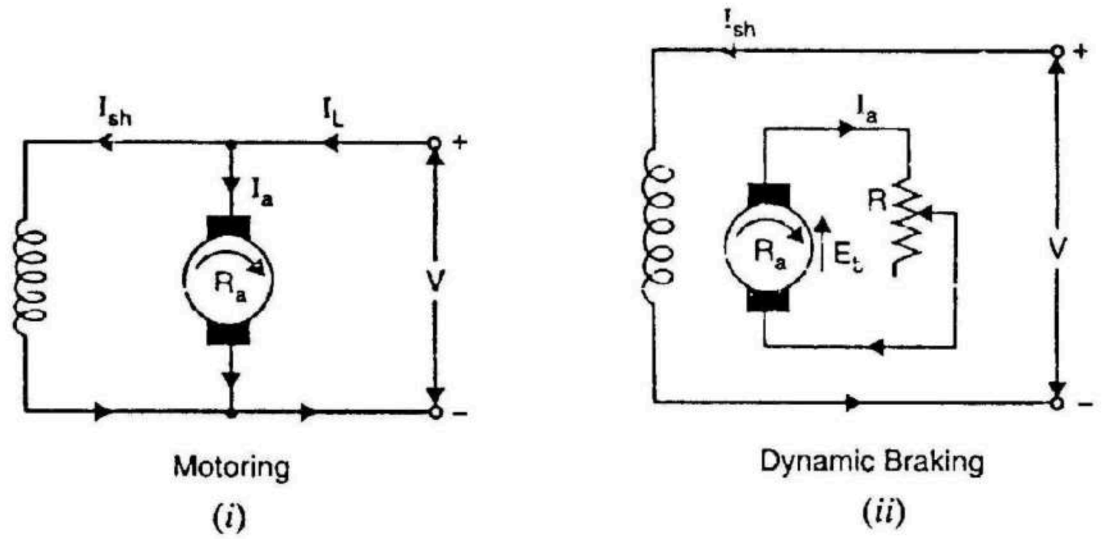
(i) Rheostatic or Dynamic braking

(ii) Plugging

Regenerative braking

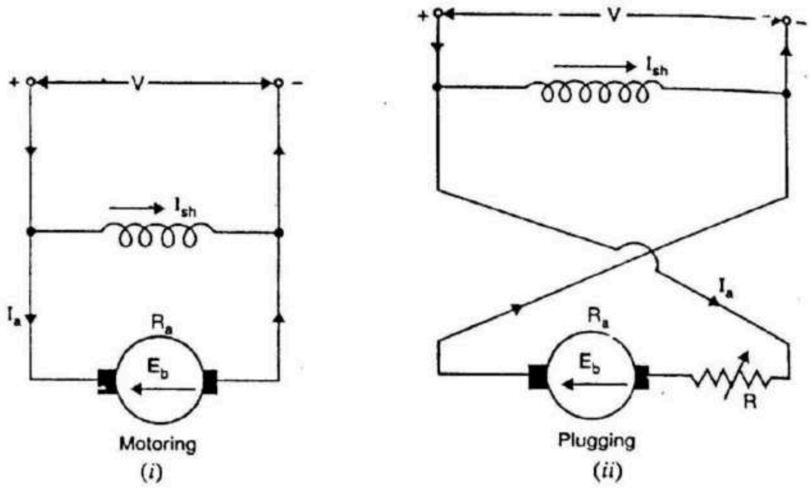
(i) Rheostatic or Dynamic braking

In this method, the armature of the running motor is disconnected from the supply and is connected across a variable resistance R. However, the field winding is left connected to the supply. The armature, while slowing down, rotates in a strong magnetic field and, therefore, operates as a generator, sending a large current through resistance R. This causes the energy possessed by the rotating armature to be dissipated quickly as heat in the resistance. As a result, the motor is brought to standstill quickly. Fig. (5.13) (i) shows dynamic braking of a shunt motor. The braking torque can be controlled by varying the resistance R. If the value of R is decreased as the motor speed decreases, the braking torque may be maintained at a high value. At a low value of speed, the braking torque becomes small and the final stopping of the motor is due to friction. This type of braking is used extensively in connection with the control of elevators and hoists and in other applications in which motors must be started, stopped and reversed frequently.



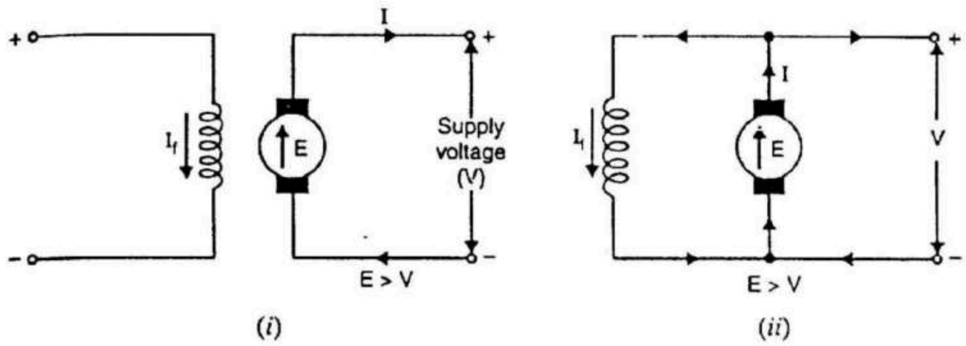
Plugging

In this method, connections to the armature are reversed so that motor tends to rotate in the opposite direction, thus providing the necessary braking effect. When the motor comes to rest, the supply must be cut off otherwise the motor will start rotating in the opposite direction.



Regenerative braking

In the regenerative braking, the motor is run as a generator. As a result, the kinetic energy of the motor is converted into electrical energy and returned to the supply. Fig. (5.15) shows two methods of regenerative braking for a shunt motor.



Necessity of D.C. Motor Starter

At starting, when the motor is stationary, there is no back e.m.f. in the armature. Consequently, if the motor is directly switched on to the mains, the armature will draw a heavy current (Ia = V/Ra) because of small armature resistance. As an example, 5 H.P., 220 V shunt motor has a full-load current of 20 A and an armature resistance of about 0.5 If this motor is directly switched on to supply, it would take an armature current of 220/0.5 = 440 A which is 22 times the full-load current. This high starting current may result in:

(i) burning of armature due to excessive heating effect,

(ii) damaging the commutator and brushes due to heavy sparking,
(iii) excessive voltage drop in the line to which the motor is connected. The result is that the operation of other appliances connected to the line may be impaired and in particular cases, they may refuse to work

Types of D.C. Motor Starters

The stalling operation of a d.c. motor consists in the insertion of external resistance into the armature circuit to limit the starting current taken by the motor and the removal of this resistance in steps as the motor accelerates. When the motor attains the normal speed, this resistance is totally cut out of the armature circuit. It is very important and desirable to provide the starter with protective devices to enable the starter arm to return to OFF position
(i) when the supply fails, thus preventing the armature being directly across the mains when this voltage is restored. For this purpose, we use no-volt release coil.
(ii) when the motor becomes overloaded or develops a fault causing the motor to take an excessive current. For this purpose, we use overload release coil.

Three-Point Starter

This type of starter is widely used for starting shunt and compound motors.

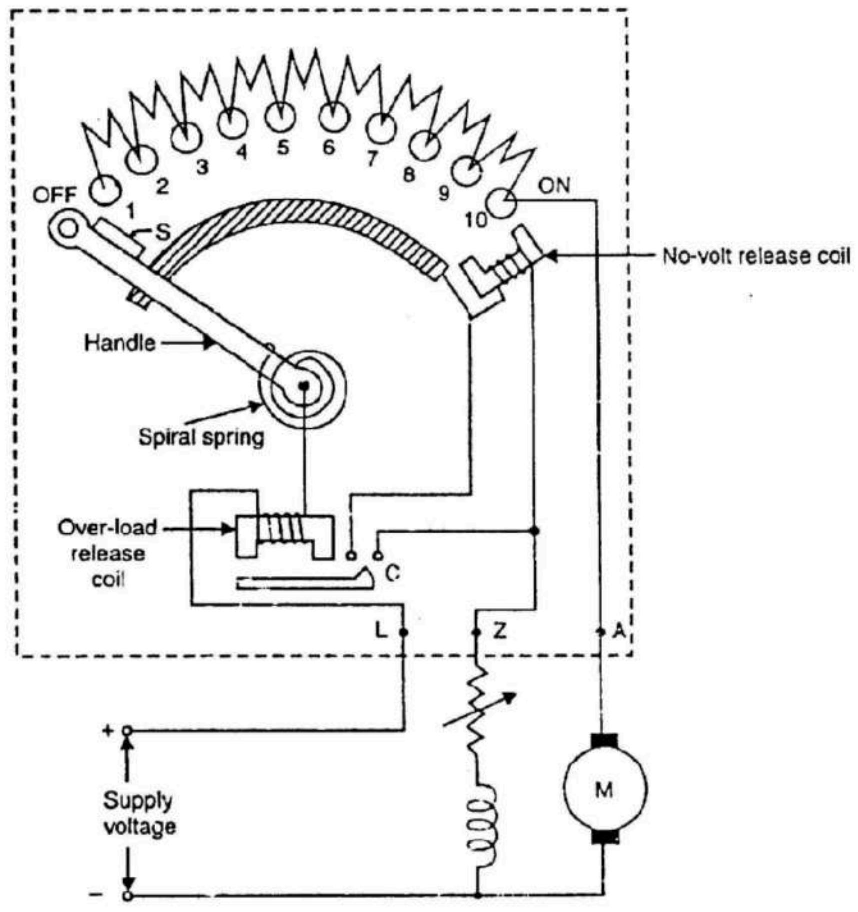
Schematic diagram

Fig. (5.16) shows the schematic diagram of a three-point starter for a shunt motor with protective devices. It is so called because it has three terminals L, Z and A. The starter consists of starting resistance divided into several sections and connected in series with the armature. The tapping points of the starting resistance are brought out to a number of studs. The three terminals L, Z and A of the starter are connected respectively to the positive line terminal, shunt field terminal and armature terminal. The other terminals of the armature and shunt field windings are connected to the negative terminal of the supply. The no-volt release coil is connected in the shunt field circuit. One end of the handle is connected to the terminal L through the over-load release coil. The other end of the handle moves against a spiral spring and makes contact with each stud during starting operation, cutting out more and more starting resistance as it passes over each stud in clockwise direction.

Operation

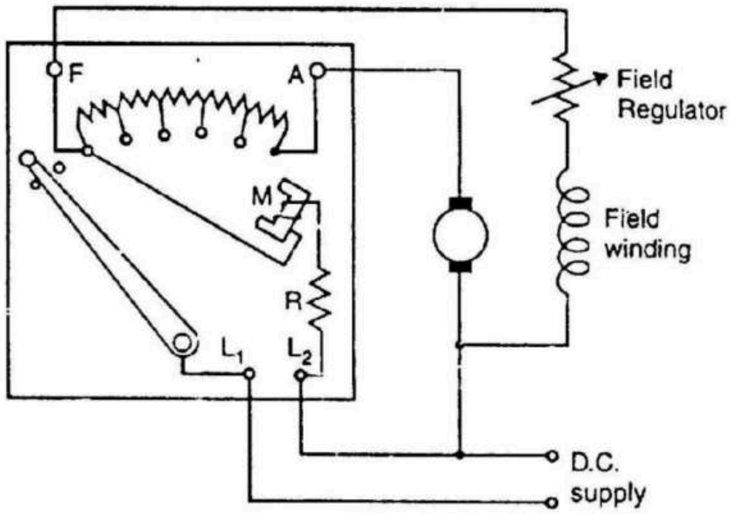
(i) To start with, the d.c. supply is switched on with handle in the OFF position.
(ii) The handle is now moved clockwise to the first stud. As soon as it comes in contact with the first stud, the shunt field winding is directly connected across the supply, while the whole starting resistance is inserted in series

with the armature circuit.
(iii) As the handle is gradually moved over to the final stud, the starting resistance is cut out of the armature circuit in steps. The handle is now held magnetically by the no-volt release coil which is energized by shunt field current.
(iv) If the supply voltage is suddenly interrupted or if the field excitation is accidentally cut, the no-volt release coil is demagnetized and the handle goes back to the OFF position under the pull of the spring. If no-volt release coil were not used, then in case of failure of supply, the handle would remain on the final stud. If then supply is restored, the motor will be directly connected across the supply, resulting in an excessive armature current.
(v) If the motor is over-loaded (or a fault occurs), it will draw excessive current from the supply. This current will increase the ampere-turns of the over-load release coil and pull the armature C, thus short-circuiting the no-volt release coil. The no-volt coil is demagnetized and the handle is pulled to the OFF position by the spring. Thus, the motor is automatically disconnected from the supply.



Four-Point Starter

In a four-point starter, the no-volt release coil is connected directly across the supply line through a protective resistance R. Fig. (5.17) shows the schematic diagram of a 4-point starter for a shunt motor (over-load release coil omitted for clarity of the figure). Now the no-volt release coil circuit is independent of the shunt field circuit. Therefore, proper speed control can be exercised without affecting the operation of novolt release coil.Note that the only difference between a three-point starter and a four-point starter is the manner in which no-volt release coil is connected. However, the working of the two starters is the same. It may be noted that the threepoint starter also provides protection against an openfield circuit. This protection is not provided by the four-point starter.



What is a Transformer?

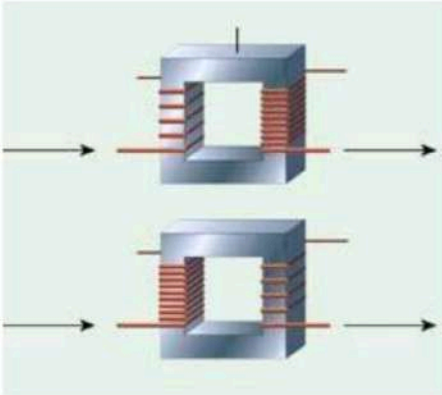
A transformer is a static piece of equipment used either for raising or lowering the voltage of an AC supply with a corresponding decrease or increase in current.

Working Principle of a Transformer

A transformer is a static (or stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as shown in Fig. 32.1. The two coils possess high mutual inductance. If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f. (according to Faraday's Laws of Electromagnetic Induction e = MdI/dt). If the second coil circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil. The first coil, in which electric energy is fed from the a.c. supply mains, is called primary winding and the other from which energy is drawn out, is called secondary winding. In brief, a transformer is a device that

1. transfers electric power from one circuit to another
2. it does so without a change of frequency
3. it accomplishes this by electromagnetic induction and

4. where the two electric circuits are in mutual inductive influence of each other.



Transformer Construction

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and the steel core. Other necessary parts are : some suitable container for assembled core and windings ; a suitable medium for insulating the core and its windings from its container ; suitable bushings (either of porcelain, oil-filled or capacitor-type) for insulating and bringing out the terminals of windings from the tank.In all types of transformers, the core is constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-gap included. The steel used is of high silicon content, sometimes heat treated to produce a high permeability and a low hysteresis loss at the usual operating flux densities. The eddy current loss is minimised by laminating the core, the laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface. The thickness of laminations varies from 0.35 mm for a frequency of 50 Hz to 0.5 mm for a frequency of 25 Hz. The core laminations (in the form of strips) are joined as shown in Fig. 32.2. It is seen that the joints in the alternate layers are staggered in order to avoid the presence of narrow gaps right through the cross-section of the core. Such staggered joints are said to be 'imbricated'.

Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core. The two types are known as (i) core-type and (ii) shelltype. Another recent development is spiral-core or wound-core type, the trade name being spirakore transformer.
In the so-called core type transformers, the windings surround a considerable part of the core whereas in shell-type transformers, the core surrounds a considerable portion of the windings as shown schematically in Fig. 32.3 (a) and (b) respectively.

Concept of Ideal Transformer-

A transformer is said to be ideal if it satisfies following properties:
i) It has no losses. ii) Its windings have zero resistance. iii) Leakage flux is zero i.e. 100 % flux produced by primary links with the secondary. iv) Permeabitity of core is so high that negilgiblc current is required to establish the flux in it

E.M.F. Equation of a Transformer

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

Φ_m = Maximum flux in core in webers

$= B_m \times A$

f = Frequency of a.c. input in Hz

As shown in Fig. 32.14, flux increases from its zero value to maximum value Φ_m in one quarter of the cycle *i.e.* in $1/4f$ second.

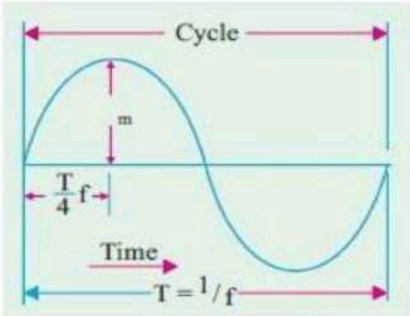


Fig. 32.14

$\therefore$ Average rate of change of flux $= \dfrac{\Phi_m}{1/4f}$

$$= 4f\Phi_m \text{ Wb/s or volt}$$

Now, rate of change of flux per turn means induced e.m.f. in volts.

$$\therefore \quad \text{Average e.m.f/turn} = 4f\Phi_m \text{ volt}$$

If flux Φ varies *sinusoidally*, then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form factor.

$$\text{Form factor} = \frac{\text{r.m.s. value}}{\text{average value}} = 1.11$$

$$\therefore \quad \text{r.m.s. value of e.m.f/turn} = 1.11 \times 4f\Phi_m = 4.44 f\Phi_m \text{ volt}$$

Now, r.m.s. value of the induced e.m.f. in the whole of primary winding

$$= (\text{induced e.m.f/turn}) \times \text{No. of primary turns}$$

$$E_1 = 4.44 f N_1 \Phi_m = 4.44 f N_1 B_m A \qquad \text{...(i)}$$

Voltage Transformation Ratio (K)

From equations (*i*) and (*ii*), we get

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

This constant K is known as voltage transformation ratio.

(*i*) If $N_2 > N_1$ *i.e.* $K > 1$, then transformer is called *step-up* transformer.

(*ii*) If $N_2 < N_1$ *i.e.* $K < 1$, then transformer is known as *step-down* transformer.

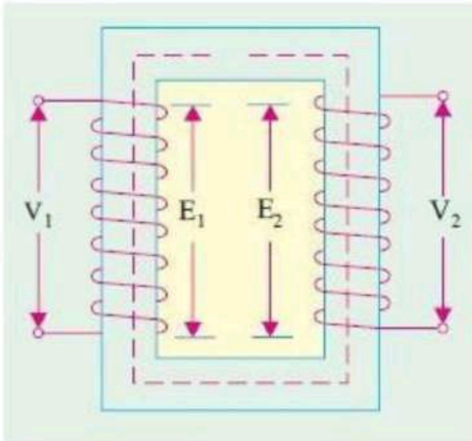


Fig. 32.15

Again, for an *ideal* transformer, input VA = output VA.

$$V_1 I_1 = V_2 I_2 \text{ or } \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

Hence, currents are in the inverse ratio of the (voltage) transformation ratio.

<u>Practical Transformer on No Load</u>

Transformer on No-load

In the above discussion, we assumed an ideal transformer *i.e.* one in which there were no core losses and copper losses. But practical conditions require that certain modifications be made in the foregoing theory. When an *actual* transformer is put on load, there is iron loss in the core and copper loss in the windings (both primary and secondary) and these losses are not entirely negligible.

Even when the transformer is on no-load, the primary input current is not wholly reactive. The primary input current under no-load conditions has to supply (*i*) iron losses in the core *i.e.* hysteresis loss and eddy current loss and (*ii*) a very small amount of copper loss in primary (there being no Cu loss in secondary as it is open). Hence, the no-load primary input current I_0 is not at 90° behind V_1 but lags it by an angle $\phi_0 <$ 90°. No-load input power

$$W_0 = V_1 I_0 \cos \phi_0$$

where $\cos \phi_0$ is primary power factor under no-load conditions. No-load condition of an actual transformer is shown vectorially in Fig. 32.16.

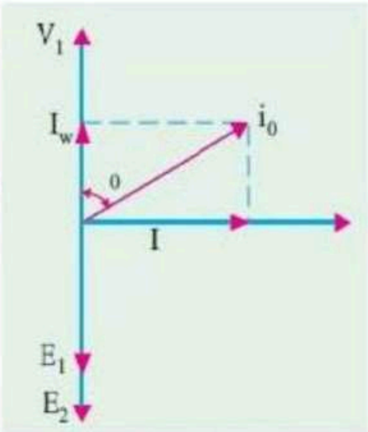


Fig. 32.16

As seen from Fig. 32.16, primary current I_0 has two components :

(*i*) One in phase with V_1. This is known as *active* or *working* or *iron* loss component I_w because it mainly supplies the iron loss plus small quantity of primary Cu loss.

$$I_w = I_0 \cos \phi_0$$

(*ii*) The other component is in quadrature with V_1 and is known as *magnetising* component I_μ because its function is to sustain the alternating flux in the core. It is wattless.

$$I_\mu = I_0 \sin \phi_0$$

Obviously, I_0 is the vector sum of I_w and I_μ, hence $I_0 = (I_\mu^2 + I_\omega^2)$.

The following points should be noted carefully :

1. The no-load primary current I_0 is very small as compared to the full-load primary current. It is about 1 per cent of the full-load current.

2. Owing to the fact that the permeability of the core varies with the instantaneous value of the exciting current, the wave of the exciting or magnetising current is not truly sinusoidal. As such it should not be represented by a vector because only sinusoidally varying quantities are represented by rotating vectors. But, in practice, it makes no appreciable difference.

3. As I_0 is very small, the no-load primary Cu loss is negligibly small which means *that no-load primary input is practically equal to the iron loss in the transformer.*

4. As it is principally the core-loss which is responsible for shift in the current vector, angle ϕ_0 is known as *hysteresis angle of advance.*

Practical Transformer - A practical transformer differs from the ideal transformer in many respects. The practical transformer has (i) iron losses (ii) winding resistances and (iii) magnetic leakage, giving rise to leakage reactance. (i) Iron losses. Since the iron core is subjected to alternating flux, there occurs eddy current and hysteresis loss in it. (ii) Winding resistances. Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R1 and secondary resistance R2 act in series with the respective windings as shown below:

(iii) Leakage reactance. Both primary and secondary currents produce flux. The flux Φ which links both the windings is the useful flux However, primary current would produce some flux Φ which would not link the secondary winding and is called mutual flux

Testing, Efficiency, and Voltage Regulation Voltage Regulation of Transformer –

The voltage regulation of a transformer is the arithmetic difference (not phasor difference) between the no-load secondary voltage (0V2) and the secondary voltage V2 on load expressed as percentage of no-load voltage i.e

Voltage regulation= 0V2- V2/0V2*100

Losses in a Transformer- The power losses in a transformer are of two types, namely;

1. Core or Iron losses 2. Copper losses

A- Core or Iron losses (P_i)

These consist of ***hysteresis and eddy current losses*** and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test (see next sections).

$$\text{Hysteresis loss, } = k_h\ f\ B_m^{1.6} \quad \text{watts/m}^3$$
$$\text{Eddy current loss, } = k_e\ f^2\ B_m^2 t^2 \quad \text{watts/m}^3$$

Both hysteresis and eddy current losses depend upon

- Maximum flux density B_m in the core and
- Supply frequency f.

B- Copper losses (P_c)

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test

Total copper Cu losses:

$$P_C = I_1^2 R_1 + I_2^2 R_2$$
$$= I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

Hence, total losses in a transformer are:

$$\text{Total losses in a transformer} = P_I + P_C$$
$$= \text{Constant losses} + \text{Variable losses}$$

Electric motors are an integral part of mining and mineral processing and, more recently, several trends have been taking place above and below ground. Historically, the mining business used a lot of DC motors. Steadily those motors are being replaced with AC motors, especially in underground coal mining applications. Likewise drive systems are evolving from fixed to variable speed. Similar to AC motors taking over DC motors, the mining business is seeing a move from induction motors to synchronous motors on the surface.

In addition to better control, AC motors are also easier to maintain than DC motors. Many of the OEMs for underground coal mining equipment are converting DC systems to AC systems with variable frequency drives (VFDs). DC motors require a lot of maintenance, especially with brushes, commutators, etc. A lot of those issues will disappear when an AC motor is placed in the same application.

1. Induction Motors in Mines:

In mines, induction motors are mostly used in a flameproof enclosure. Besides the enclosure, performance of the induction motors is the same as that of the other motors, as per the particular design. We know from our experience and knowledge that, among the induction motors, the squirrel cage-types are the most simple of all electric motors.

Induction Motors consists of two parts only. One is the stator, a stationary winding which is connected to the supply, and the other is a rotor-a rotating winding which rotates within the stator and drives the load.

The squirrel cage motors can be designed to operate from single or three phase supplies. A three phase Induction motor will start under load as soon as the supply is switched on. Starters are used only if it is necessary to reduce the starting current.

Because of their simplicity, squirrel cage motors are widely used in mines and also in other industries. They are used underground to drive drills, coal cutters; loaders, conveyors and haulages, and they may also be found to be used extensively in pumps, auxiliary fans and small compressors.

Condition for Maximum Efficiency

Output power = $V_2 I_2 \cos\phi_2$

If R_{02} is the total resistance of the transformer referred to secondary, then,

$$\text{Total Cu loss, } P_C = I_2^2 R_{02}$$

$$\text{Total losses} = P_i + P_C$$

$$\text{Transformer } \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}}$$

$$= \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + P_i / I_2 + I_2 R_{02}}$$

For a load of given pf, efficiency depends upon load current I_2. Hence, the efficiency to be maximum ***the denominator should be minimum*** i.e.

$$\frac{d}{dI_2}(V_2 \cos\phi_2 + P_i / I_2 + I_2 R_{02}) = 0$$

$$\text{or} \qquad 0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

$$\text{or} \qquad P_i = I_2^2 R_{02}$$

i.e., Iron losses = Copper losses

Hence efficiency of a transformer will be maximum when copper losses are equal to constant or iron losses.

From above, the load current I2 corresponding to maximum efficiency is:

$$I_2 = \sqrt{\frac{P_i}{R_{02}}}$$