CHAPTER-7
Underground Cables

Construction of Underground Cables:

Fig.shows the general Construction of Underground Cables. The various parts are :

Cores or Conductors:

A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. 11.1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

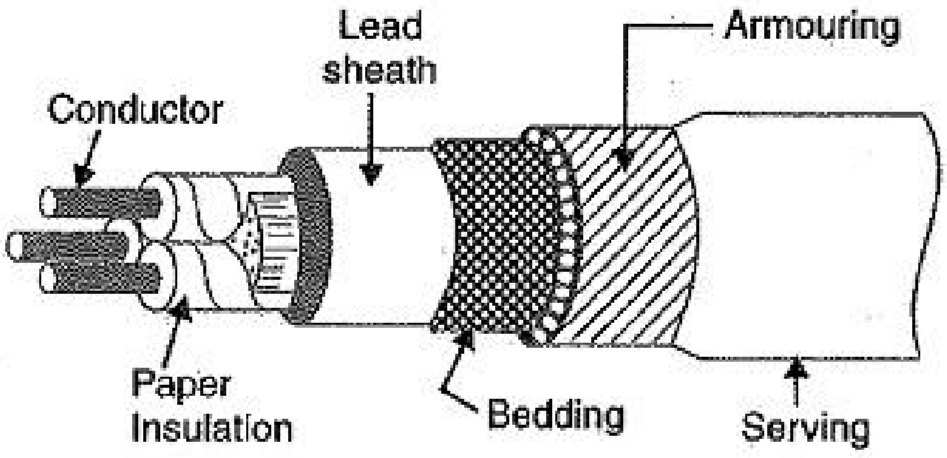


Fig. 11.1 Construction of a Cable

Insulation:

Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

Metallic sheath:

In order to protect the cable from moisture, Conductor gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig. 11.1

Bedding:

Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

Armouring:

Over the bedding, armouring is provided which consists of one or two layers of galvanised steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

Serving:

In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as **serving.**

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

Insulating Materials for Underground Cables:

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of Insulating Materials for Underground

Cables is of considerable importance. In general, the insulating materials used in cables should have the following properties :

- High insulation resistance to avoid leakage current.
- High dielectric strength to avoid electrical breakdown of the cable.
- High mechanical strength to withstand the mechanical handling of cables.
- Non-hygroscopic e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.
- Non-inflammable.
- Low cost so as to make the underground system a viable proposition.
- Unaffected by acids and alkalies to avoid any chemical action.

No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal of Insulating Materials for Underground Cables are rubber, vulcanised India rubber,impregnated paper, varnished cambric and polyvinyl chloride.

1.**Rubber:** Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/min and resistivity of insulation is $10^{17}\Omega$ cm. Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38°C), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2.**Vulcanised India Rubber (V.I.R.):** It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150°C. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

3.**Impregnated paper:** It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar.

Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lenghts are small and joints are required at a number of places, VIR cables will be cheaper and durable than paper insulated cables.

4.**Varnished cambric:** It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such Insulating Materials for Underground Cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/min and permittivity is 2.5 to 3.8.

5.**Polyvinyl chloride (PVC):** This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature.

Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme enviormental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

Classification of Underground Cables:

Classification of Underground Cables may be in two ways according to

1. **the type of insulating material used in their manufacture**
2. **the voltage for which they are manufactured.**

However, the latter method of Classification of Underground Cables is generally preferred, according to which cables can be divided into the following groups :

- **Low-tension (L.T.) cables – upto 1000 V**
- **High-tension (H.T.) cables – upto 11,000 V**
- **Super-tension (S.T.) cables – from 22 kV to 33 kV**
- **Extra high-tension (E.H.T.) cables – from 33 kV to 66 kV**
- **Extra super voltage cables – beyond 132 kV**

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be

1. **single-core**
2. **two-core**
3. **three-core**
4. **four-core etc.**

For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

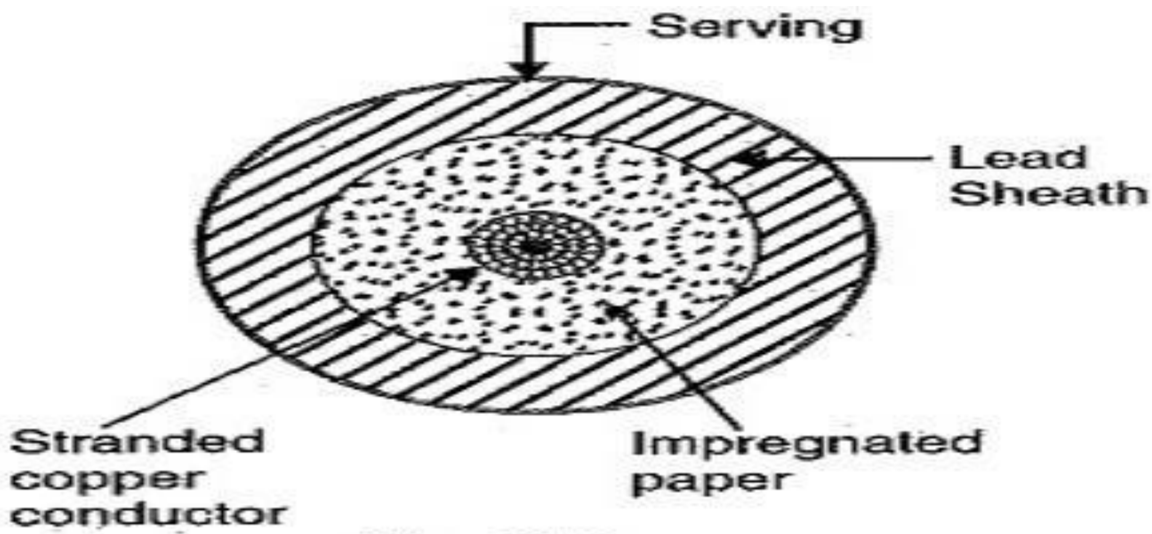


Fig. 11.2

Fig. 11.2 shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided.

Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

Three Phase Service Cable:

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages upto 66 kV, 3-core cable multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following types of cables are generally used for Three Phase Service Cable:

1. **Belted cables — upto 11 kV**
2. **Screened cables — from 22 kV to 66 kV**
3. **Pressure cables — beyond 66 kV**

1.**Belted cables:** These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Fig. 11.3 shows the constructional details of a 3-core, belted cable. The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of non-circular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).

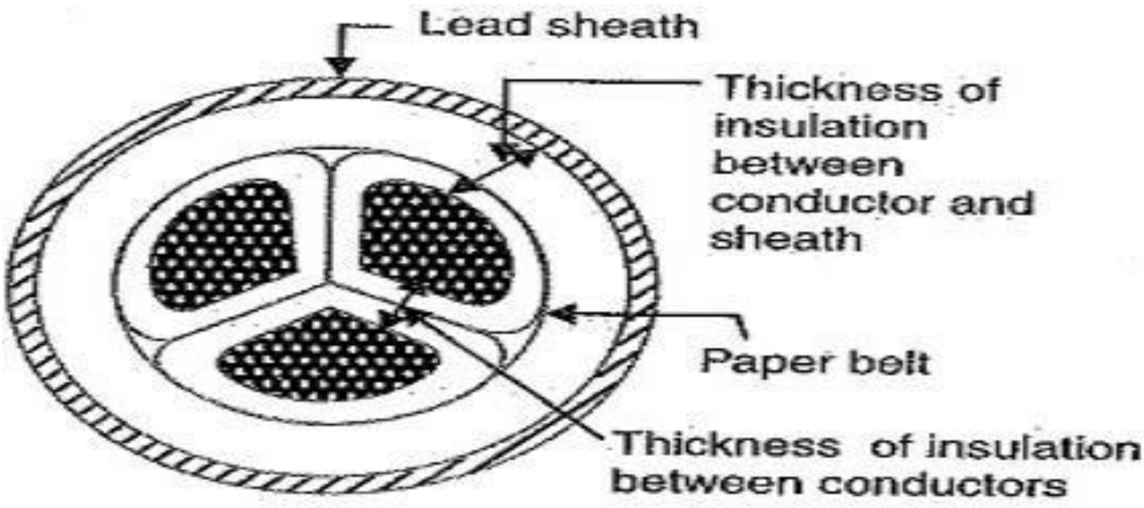
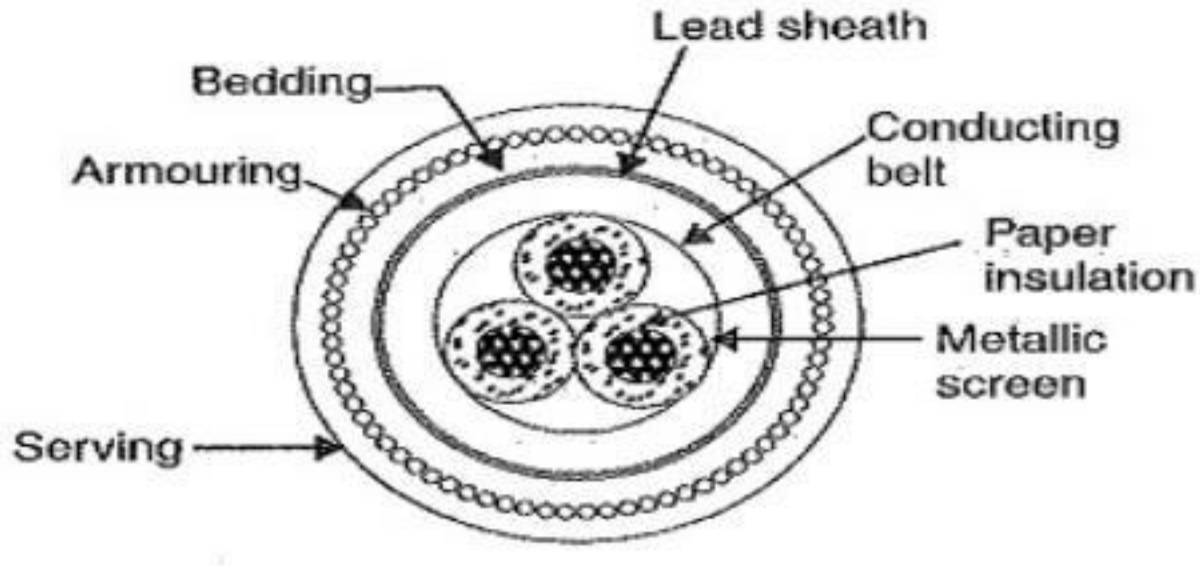


Fig. 11.3

The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the Three Phase Service Cable for these voltages are more or less radial i.e., across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

2.**Screened cables:** These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are H-type cables and S.L. type, cables.

(i) **H-type cables:** This type of Three Phase Service Cable was first designed by H. Hochstadter and hence the name. Fig. 1.1.4 shows the constructional details of a typical 3-core, H-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores. The Three Phase Service Cable has no insulating belt but lead sheath, bedding,armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at tearth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses.



rig. 11.4

Two principal advantages are claimed for H-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the Three Phase Service Cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

(ii) **S.L. type cables:** Fig. 11.5 shows the constructional details of a 3-core S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over H-type cables. Firstly, the separate sheaths minimize the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.

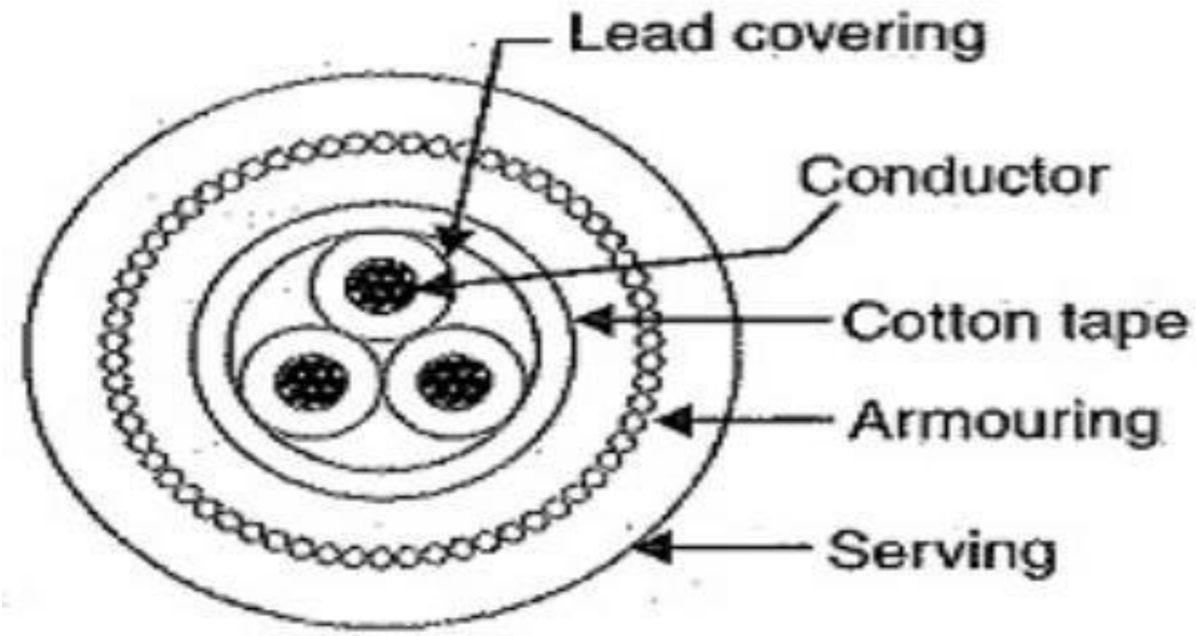


Fig. 11.5

Limitations of solid type cables: All the cables of above construction are referred, to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

(a) As a solid Three Phase Service Cable carries the load, its conductor temperature increases and the cable compound (i.e., insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(b) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.

(c) In practice, tvoids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound The breakdown strength of voids is considerably less than that of the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionisation causing permanent damage to the paper insulation.

3.**Pressure cables:** For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used.

(i) **Oil-filled cables:** In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the Three Phase Service Cable. Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers. Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 IN upto 230 kV. Oil-filled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels.

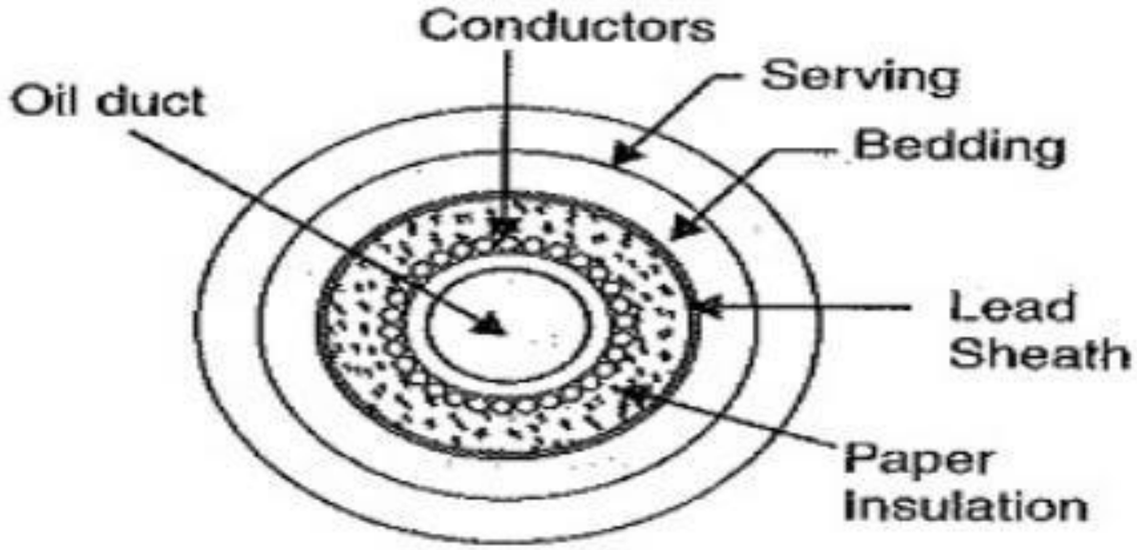


Fig. 11.6 Single-core conductor channel, oil-filled cable

Fig. 11.6 shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed Conductors that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The disadvantage of this type of cable is that the channel is at the middle of the Three Phase Service Cable and is at full voltage w.t: t. earth, so that a very complicated system of joints is necessary.

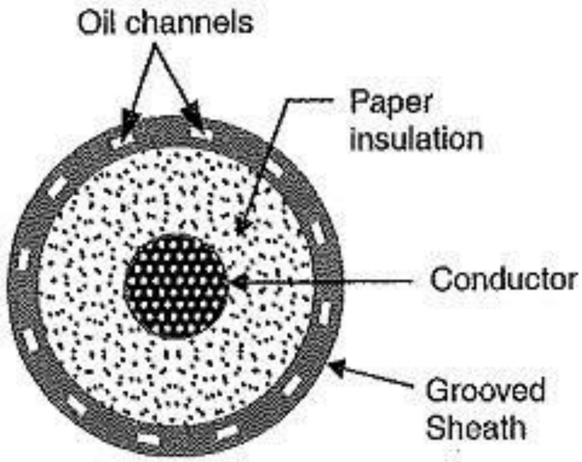


Fig. 11.7

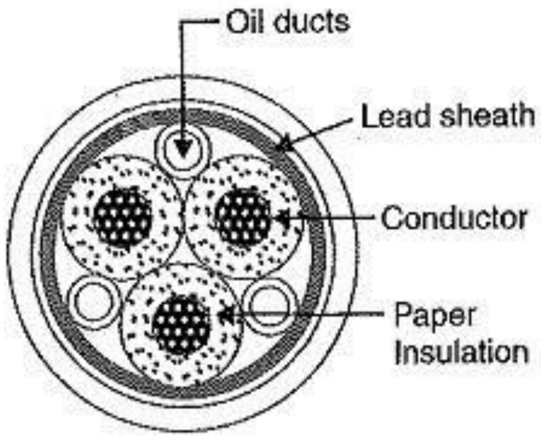


Fig. 11.8

Oil-filled cables

Fig. 11.7 shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown in Fig. 11.8, the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential.

The oil-filled cables have three principal advantages. Firstly, formation of voids and ionisation are avoided. Secondly, allowable temperature range and dielectric strength are increased. Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased. However, their major disadvantages are the high initial cost and complicated system of laying.

<u>(ii)</u> **<u>Gas pressure Cables:</u>** The voltage required to set up ionisation inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

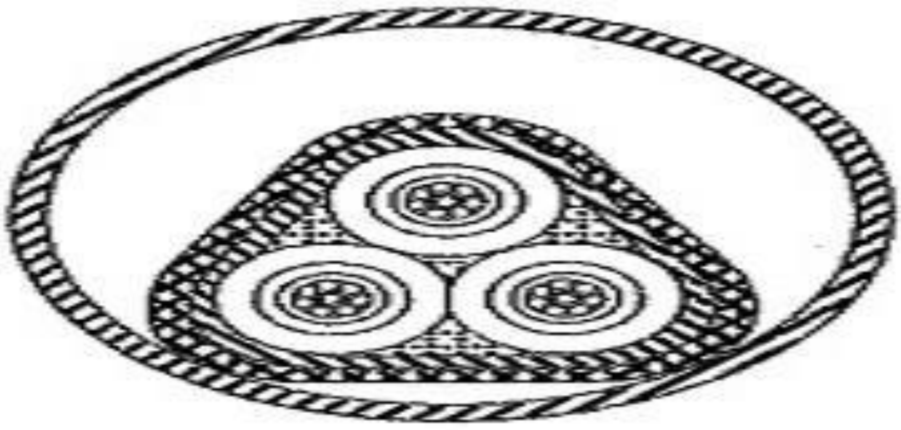


Fig. 11.9

Fig. 11.9 shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden. The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the Weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The Three Phase Service Cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and doses the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high.

Laying of Underground Cables:

The reliability of Laying of Underground Cables network depends to a considerable extent upon the proper laying and attachment of fittings i.e., cable end boxes, joints, branch connectors etc.

There are three main methods of Laying of Underground Cables viz.,

1. Direct laying,

2. Draw-in system and the
3. Solid system.

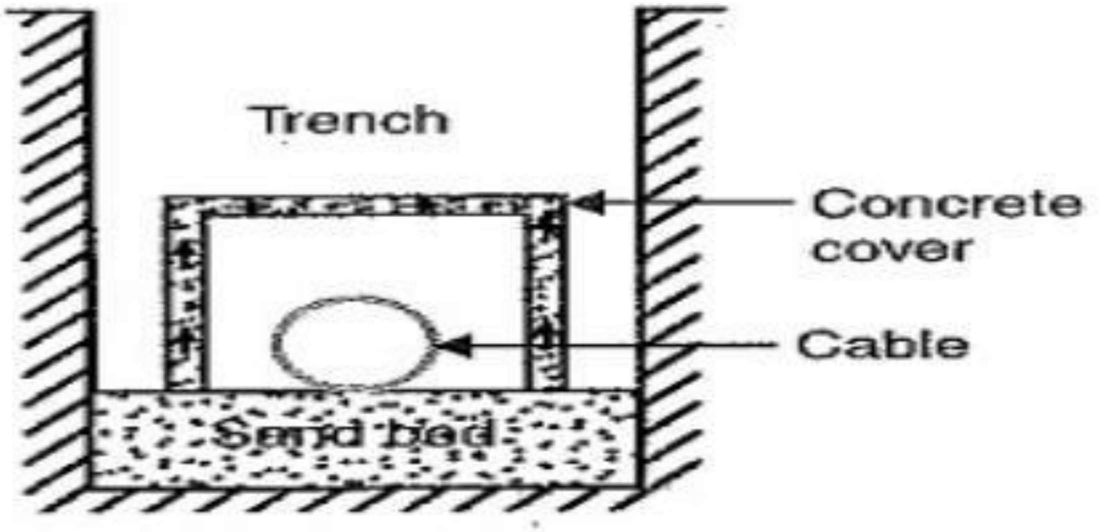


Fig. 11.10

1.**Direct laying:** This method of Laying of Underground Cables is simple and cheap and is much favoured in modern practice. In this method, a trench of about l .5 meters deep and 45 cm wide is dug. The trench is covered with a layer of fine sand (of about 10 cm thickness) and the cable is laid over this sand bed. The sand prevents the entry of moisture from the ground and thus protects the cable from decay. After the cable has been laid in the trench, it is covered with another layer of sand of about 10 cm thickness.

The trench is then covered with bricks and other materials in order to protect the cable from mechanical injury. When more than one cable is to be laid in the same trench, a horizontal or vertical inter-axial spacing of at least 30 cm is provided in order to reduce the effect of mutual heating and also to ensure that a fault occurring on one cable does not damage the adjacent cable. Cables to be laid in this way must have serving of bituminised paper and hessian tape so as to provide protection against concision and electorlysis.

Advantages

- It is a simple and less costly method.

- It gives the best conditions for dissipating the heat generated in the cables.
- It is a clean and safe method as the cable is invisible and free from external disturbances.

Disadvantages

- The extension of load is possible only by a completely new excavation which may cost as much as the original work.
- The alterations in the cable network cannot be made easily.
- The maintenance cost is very high.
- Localisation of fault is difficult.
- It cannot be used in congested areas where excavation is expensive and inconvenient.

This method of laying cables is used in open areas where excavation can be done conveniently and at low cost.

2. **Draw-in system:** In this method, conduit or duct of glazed stone or cast iron or concrete are laid in the ground with manholes at suitable positions along the cable route. The cables are then pulled into position from manholes. Fig. 11.11 shows section through four-way underground duct line. Three of the ducts carry transmission cables and the fourth duct carries relay protection connection, pilot wires. Care must be taken that where the duct line changes direction ; depths, dips and offsets be made with a very long radius or it will be difficult to pull a large cable between the manholes. The distance between the manholes should not be too long so as to simplify the pulling in of the cables. The cables to be laid in this way need not be armoured but must be provided with serving of hessian and jute in order to protect them when being pulled into the ducts.

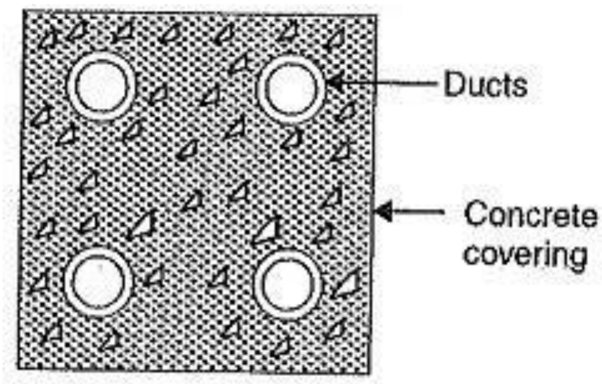


Fig. 11.11

Advantages

- Repairs, alterations or additions to the cable network can be made without opening the
- As the cables are not armoured, therefore, joints become simpler and maintenance cost is reduced considerably.
- There are very less chances of fault occurrence due to strong mechanical protection provided by the system.

Disadvantages

- The initial cost is very high.
- The current carrying capacity of the cables is reduced due to the close grouping of cables and unfavorable conditions for dissipation of heat.

This method of cable laying is suitable for congested areas where excavation is expensive and inconvenient, for once the conduits have been laid, repairs or alterations can be made without opening the ground. This method is generally used for short length cable routes such as in workshops, road crossings where frequent digging is costlier or impossible.

3.**Solid system:** In this method of laying, the cable is laid in open pipes or troughs dug out in earth along the cable mule. The troughing is of cast iron, stoneware, asphalt or treated wood. After the cable is laid in position, the troughing is filled with a bituminous or asphaltic compound and covered over. Cables laid in this manner an usually plain lead covered because troughing affords good mechanical protection.

Disadvantages

- It is more expensive than direct laid system.
- It requires skilled labour and favourable weather conditions.
- Due to poor heat dissipation facilities, the current carrying capacity of the cable is reduced.

In view of these disadvantages, this method of Laying of Underground Cables is rarely used now-adays.

Types of Cable Faults:

Cables are generally laid directly in the ground or in ducts in the underground distribution system. For this reason, there are little chances of faults in underground cables. However, if a fault does occur, it is difficult to locate and repair the fault because conductors are not visible.The following are the Types of Cable Faults most likely to occur in underground cables:

1. Open Circuit Fault
2. Short Circuit Fault
3. Earth Fault.

1.Open Circuit Fault:

When there is a break in the conductor of a cable, it is called **open circuit fault**. The open-circuit fault can be checked by a megger. For this purpose, the three conductors of the 3-core cable at the far end are shorted and earthed. Then resistance between each conductor and earth is measured by a megger. The megger will indicate zero resistance in the circuit of the conductor that is not broken. However, if the conductor is broken, the megger will indicate infinite resistance in its circuit.

2.Short Circuit Fault:

When two conductors of a multi-core cable come in electrical contact with each other due to insulation failure, it is called a **short circuit fault**. Again, we can seek the help of a megger to check this fault. For this purpose, the two terminals of the megger are connected to any two conductors. If the megger gives zero reading, it indicates short-circuit fault between these conductors.

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3.Earth Fault:

When the conductor of a cable comes in contact with earth, it is called **earth fault** or **ground fault**. To identify this fault, one terminal of the megger is connected to the conductor and the other terminal connected to earth. If the megger indicates zero reading, it means the conductor is earthed. The same procedure is repeated for other conductors of the cable.

Loop Tests in Underground Cables:

There are several methods for locating the faults in underground cables. However, two popular methods known as Loop Tests in Underground Cables are :

1. **Murray loop test**
2. **Varley loop test**

These simple tests can be used to locate the earth fault or short-circuit fault in underground cables provided that a sound cable tuns along the faulty cable. Both these tests employ the principle of Wheatstone bridge for fault location.

1.Murray Loop Test:

The Murray loop test is the most common and accurate method of locating earth fault or short-circuit fault in underground cables.

(i) **Earth fault:** Figure shows the circuit diagram for locating the earth fault by Murray loop test. Here AB is the sound cable and CD is the faulty cable; the earth fault occuring at point F. The far end D of the faulty cable is joined to the far end B of the sound cable through a low resistance link. Two variable resistances P and Q are joined to ends A and C (See Fig. 11.22) respectively and serve as the ratio arms of the Wheatstone bridge.

Let

R = resistance of the conductor loop upto the fault from the test end

X = resistance of the oth

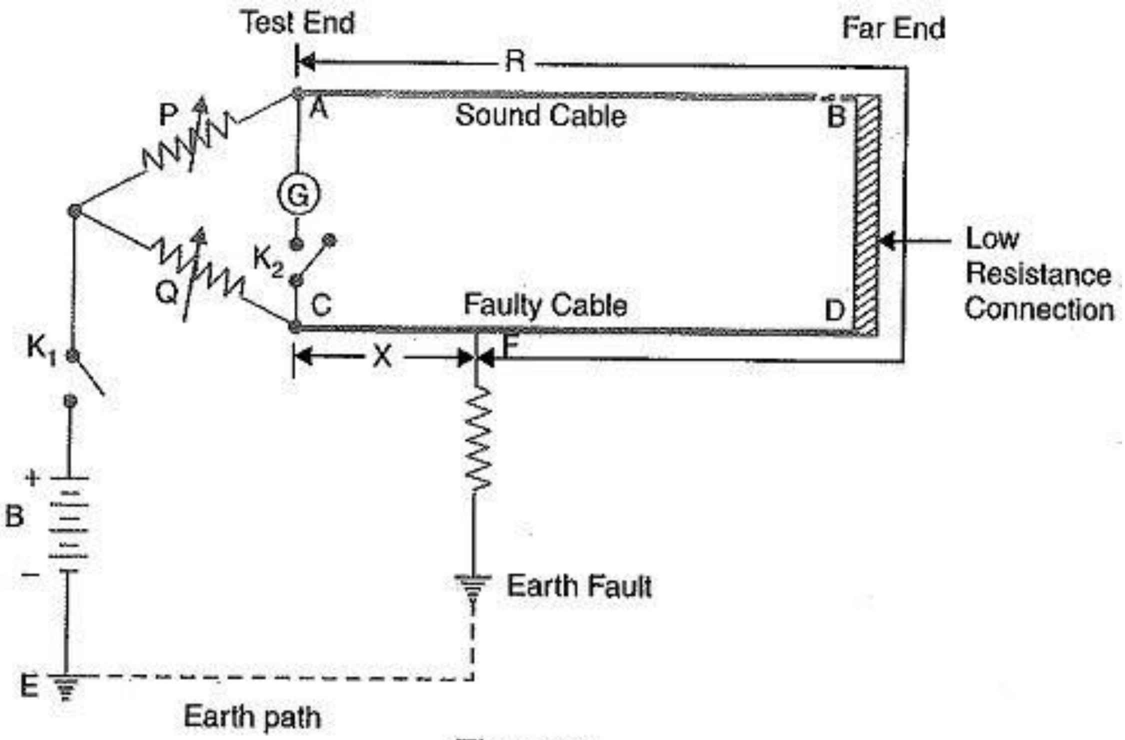


Fig. 11.22

er length of the loop

Note that P, Q, R and X are the four arms of the Wheatstone bridge. The resistances P and Q are varied till the galvanometer indicates zero deflection.

In the balanced position of the bridge, we have,

$$\frac{P}{Q} = \frac{R}{X}$$

$$\frac{P}{Q}+1 = \frac{R}{X}+1$$

$$\frac{P+Q}{Q} = \frac{R+X}{X}$$

If r is the resistance of each cable, then R + X = 2r.

$$\frac{P+Q}{Q} = \frac{2r}{X}$$

$$X = \frac{Q}{P+Q}\times 2r$$

If l is the length of each cable in metres, then resistance per metre length of cable = r / l.

Distance of fault point from test end is

$$d = \frac{X}{r/l} = \frac{Q}{P+Q}\times 2r\times\frac{l}{r} = \frac{Q}{P+Q}\times 2l$$

$$d = \frac{Q}{P+Q}\times(\text{loop length}) \quad \text{metres}$$

Thus the position of the fault is located. Note that resistance of the fault is in the battery circuit and not in the bridge circuit. Therefore, fault resistance does not affect the balancing of the bridge. However, if the fault resistance is high, the sensitivity of the bridge is reduced.

(ii) Short-circuit fault: Fig. 11.23 shows the circuit diagram for locating the short-circuit fault by Murray loop test. Again P, Q, R and X are the four arms of the bridge. Note that fault resistance is in the battery circuit and not in the bridge circuit. The bridge in balanced by adjusting the resistances P and Q. In the balanced position of the bridge :

$$\frac{P}{Q} = \frac{R}{X}$$

$$\frac{P+Q}{Q} = \frac{R+X}{X} = \frac{2r}{X}$$

$$X = \frac{Q}{P+Q} \times 2r$$

$$X = \frac{Q}{P+Q} \times (\text{loop length}) \text{ metres}$$

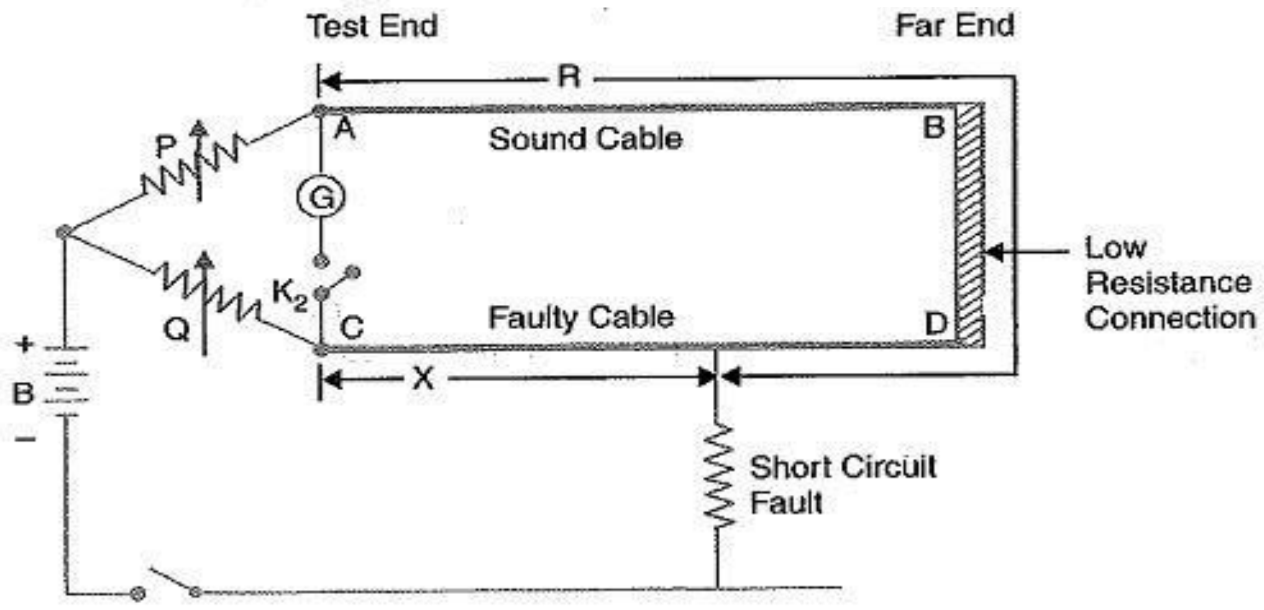


Fig. 11.23

Thus the position of the fault is located.

2.Varley Loop Test:

The Varley loop test is also used to locate earth fault or short-circuit fault in underground cables. This test also employs Wheatstone bridge principle. It differs from Murray loop test in that here the ratio arms P and Q are fixed resistances. Balance is obtained by adjusting the variable resistance connected to the test end of the faulty cable. The connection diagrams for locating the earth fault and short-circuit fault by Varley loop test are shown in Figs. 11.24 and 11.25 respectively.

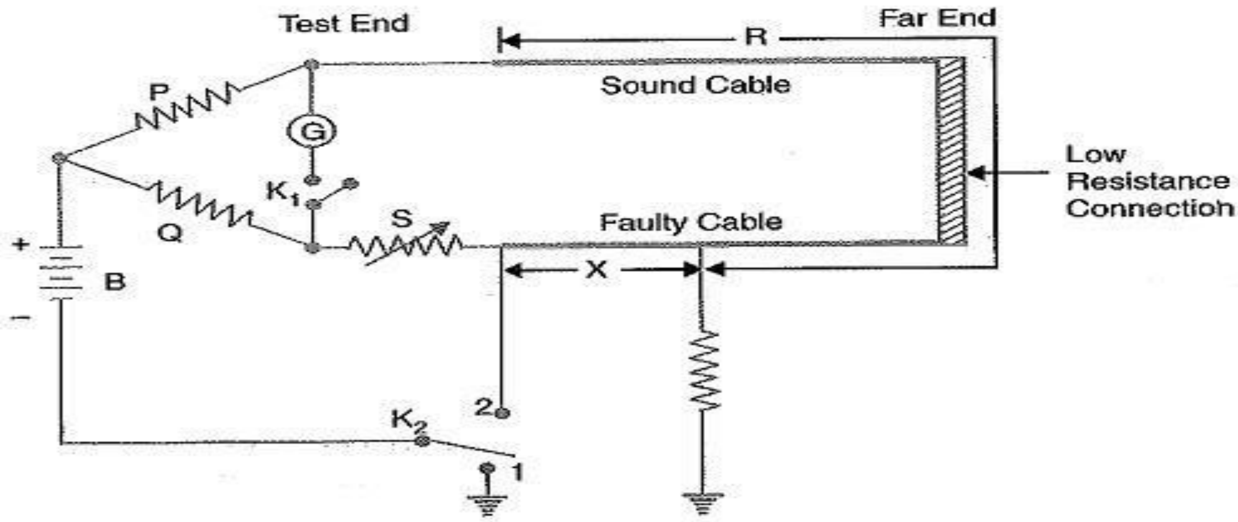
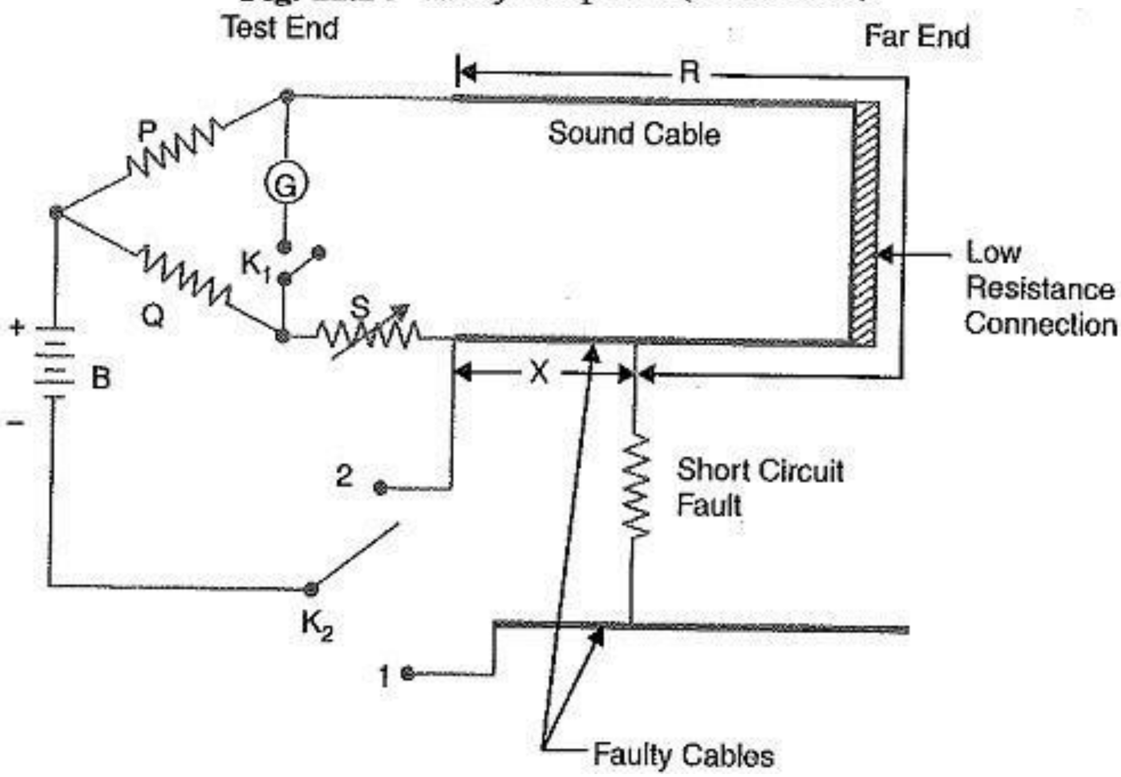


Fig. 11.24 Varley Loop Test (Earth Fault)



For earth fault or short-circuit fault, the key K_2 is first thrown to position 1. The variable resistance S is varied till the bridge is balanced for resistance value of S_1. Then,

$$\frac{P}{Q} = \frac{R}{X + S_1}$$

$$\frac{P+Q}{Q} = \frac{R + X + S_1}{X + S_1}$$

$$X = \frac{Q(R+X) - PS_1}{P+Q} \qquad \text{...}(i)$$

Now key K_2 is thrown to position 2 (for earth fault or short-circuit fault) and bridge is balanced with new value of resistance S_2. Then,

$$\frac{P}{Q} = \frac{R+X}{S_2}$$

$$(R+X)\,Q = PS_2 \qquad \text{...(ii)}$$

From eqs. (i) and (ii), we get,

$$X = \frac{P\,(S_2 - S_1)}{P+Q}$$

Since the values of P, Q, S_1 and S_2 are known, the value of X can be determined.

$$\text{Loop resistance} = R + X = \frac{P}{Q} S_2$$

If r is the resistance of the cable per metre length, then,

Distance of fault from the Loop Tests in Underground Cables end is

$$d = \frac{X}{r} \text{ metres}$$