13

Earthing and Screening

13.1 PURPOSE OF EARTHING

There are three main reasons why it is necessary to earth, or to ground, electrical equipment:-

- To prevent electric shock to human operators, maintenance personnel and persons in the vicinity of electrical equipment.
- To minimise damage to equipment when excessive current passes between the conductors and the casing or frame during an internal fault condition.
- To provide a point of zero reference potential in the power system for the conductors.

13.1.1 Electric Shock

Electric shock occurs when two factors exist:-

- Two points in an electrical circuit that have unequal potentials are in contact with the human body.
- The difference in these two potentials exceeds a lower threshold value.

At the threshold limit slight perception of pain or 'tingling' near to the points of contact will occur. A continuous alternating current at a power system frequency, e.g. 50 or 60 Hz, of approximately 1 mA will cause this slight reaction. Increasing the current causes a greater intensity of reaction. At approximately 12 mA the muscles become very difficult to control, i.e. almost unable to 'let go' of the contact. Between approximately 20 mA and 50 mA the current tends to cause difficulty in breathing, but not to an irreversible extent. A continuous current above 50 mA and up to 100 mA will tend to cause ventricular fibrillation and may lead to heart failure and death.

Some of the early detailed work on this subject was published in 1936 by Ferris, King, Spence and Williams. Much work has been published by Dalziel and his co-authors from about 1941 and 1972, see Reference 1, Chapter 20 'Bibliography' for details. In this reference [B26] and [B29] showed that the current threshold withstand versus time duration characteristic has an 'I-squared-t' form, as follows:-

$$\sqrt{t_n} = \frac{K_h}{I_h} \tag{13.1}$$

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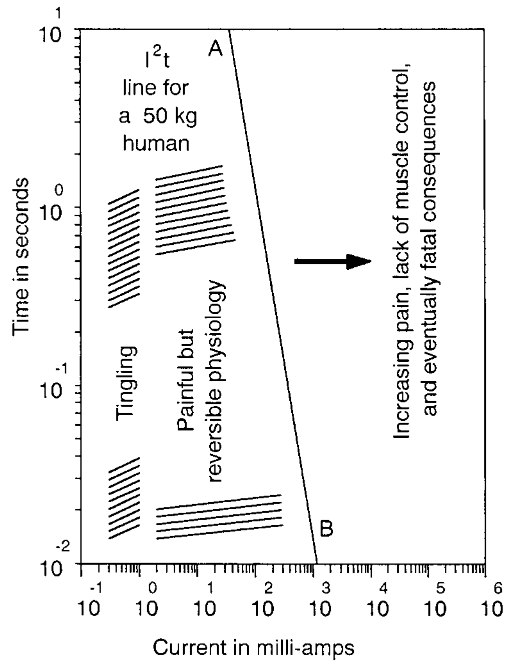

Figure 13.1 Intensity of electric shock for human beings.

Where K_h = 0.116 for a human body weighing 50 kg.
I_h = non-fibrillating current tolerable by a human body, in amperes.
t_n = non-fibrillating time duration of tolerance, in seconds.

Figure 13.1 shows the form of the characteristic as the line A-B, and the approximate regions of increasing danger. IEC60479 part 1 shows a similar figure with its Figure 14 providing numerical data.

In a practical situation the value of t_n will be equal to the fault current clearance time of the device protecting the circuit. The current I_h may be assumed to be limited by the resistance of the human body as it makes contact with two different potentials. In Reference 2 Ryder recommended in 1949 that a resistance of 500 ohms could be used to represent the resistance between both hands. In more recent times the IEEE80, in its Chapter 5 uses 1000 ohms generally in relation to the design of substation grounding grid and rod systems. The assumption used by Ryder was that the hands were thoroughly wet, which is still a reasonable assumption. The IEC60479 (1994 edition), part 1, clause 2.6 also uses 500 ohms as the appropriate value for hand-to-hand and hand-to-foot when the contact area is large, and notes that it does not vary significantly with the contact area unless it is very small, i.e. a few square millimetres. Ryder also recommends a limiting current that a human should be subjected to without fatal consequences as 100 mA, at a power frequency of 50 to 60 Hz. IEC60479, part 1, and Reference 3 describe the impedances of different parts of the human body and how they form a complete electrical circuit.

It is on the basis of a body resistance of 500 ohms and a current of 100 mA that the hand-to-hand maximum voltage limit of 50 volts (root-mean-square alternating voltage) has been established and used in the international literature, e.g. IEC60364. The corresponding hand-to-hand direct voltage is usually taken as 110 volts. If a resistance of 1000 ohms is used as a standard value then from equation (13.1) the threshold voltage E_{shock} will be:-

$$E_{\text{shock}} = 1000 \times \frac{0.116}{\sqrt{t_s}} \quad \text{volts} \tag{13.2}$$

Where t_s is the time duration of the shock in seconds. This voltage can be withstood by 99.5% of human bodies weighing 50 kg.

13.1.2 Damage to Equipment

Occasionally an electrical fault will occur inside a piece of equipment such as a switchboard or motor that causes a conductor to touch the casing or frame. In most power systems this type of fault would cause a much larger than normal current to flow in the conductors. This current would flow through the casing or frame and in so doing would usually cause serious damage to the conductors, their insulation and casing metalwork due to sparking or arcing. The damage will usually increase with time and can only be minimised by a careful design of the electrical protective relaying schemes that detect the fault current, see Chapters 11 and 12.

13.1.3 Zero Reference Potential

Most power systems comprise several different three-phase voltage levels, e.g. 11,000 V, 6600 V and 440 V. They are isolated from one another by the use of transformers. Each isolated sub-section is invariably 'earthed' or 'grounded' at one or more points. (The term 'earthed' will be used hereinafter.) The purpose of this is to ensure that the voltage difference between any conductor and its casing cannot rise above a predetermined amount. The voltage difference can increase due to several causes.

Static charge builds up across the insulation and causes the conductor potential to rise. This is more of a problem with high voltage equipment because the dielectric properties of the insulation are more pure. The insulation resistance is extremely high and does not discharge the accumulated charge.

If a fault occurs between the primary and the secondary windings of a transformer, the lower voltage winding may experience a high voltage being impressed upon it.

If a three-phase sub-system is unearthed and a line-to-casing fault occurs, then the two 'healthy' lines will have their voltage-to-casing raised by a factor of $\sqrt{3}$. Normally the insulation of machines and cables can withstand this increase for a long period of time without harm. It is good practice to specify that the insulation systems of transformers, motors, generators and cables should be able to withstand an overvoltage of this type continuously.

13.2 SITE LOCATIONS

The environment in which the power system is located will have an impact on how the methods of earthing equipment are applied. The environments can be broadly grouped as:-

- Steel structures.
- Land-based plants.
- Concrete and brick-built structures.

13.2.1 Steel Structures

Some processing plants are constructed predominantly from steel, e.g. ships, offshore platforms, drilling vessels, compact refineries and chemical plants. In these plants the superstructures and processing equipment are generally made of steel beams, steel plating, steel flooring, steel vessels and pipe-work. These items are either welded or bolted together, and by so doing they tend to form a continuous electrical circuit as far as the passage of 'earth' currents are concerned. In some situations where bolting is used it is necessary to provide additional copper bonding conductors across the bolted surfaces, e.g. piping flanges, cable racking, machinery footings. It is essential to maintain a low impedance continuous circuit, in order to minimise the risk of electric shock when fault currents pass in the steelwork.

In certain parts of a power system it can be seen that very large earth currents can flow in adjacent steel-work, e.g. generator frames, high power switchboards. These locations are often provided with a specially designed sub-system of interconnected copper busbars and common reference earth points. The principle behind this sub-system is to provide what is in effect a set of very low impedance conductors in parallel with the steelwork. The sub-system has the effect of forcing the earth currents to pass in well-defined routes, in which the interconnecting conductors are situated. This occurs because the impedance of each 'copper route' is designed to be much lower than the 'steel route'. In general it is extremely difficult to calculate the impedance between any two points in a typical steelwork electric circuit because of its three-dimensional nature. Even calculating the low frequency impedance of a simple steel plate or 'H' section beam to the passage of alternating current is difficult due to the creation of eddy currents, skin effect and local magnetic saturation of the steel. The impedance would be a complicated function of the current magnitude. Consequently the calculation of the sizes of earthing busbars and their interconnectors is based on assuming that all the current flows in the copper and none in the parallel steel. This leads to a conservative and safe result.

The method of calculating the cross-sectional area of busbars, interconnectors and bonding conductors is given in 9.4.3.5.

13.2.2 Land-Based Plants

Processing plants located on land frequently have the benefit of space, wherein the plant is subdivided into discrete units. Each unit occupies a separate plot of land. Hence the plant is horizontally distributed as opposed to an offshore platform in which the plant is both vertically and horizontally distributed.

Each discrete unit is usually supplied with power from one or two main circuits, called feeders, from a central high voltage source, e.g. local captive generators, supply authority overhead line intake. The high voltage supply is used in two forms. Firstly to supply a few large consumers such as large gas compressors, oil transporting pumps or large cooling water pumps. Secondly it is transformed down to a lower voltage for all the small process motors, heaters, utilities, lighting and small power.

This two-fold situation requires the earthing to be dealt with in two distinct ways, one for the high voltage feeders and one for the low voltage distributors. With a land-based plant the high voltage feeders may be routed over reasonably long distances, i.e. 0.5 km to 2.0 km, at voltages between 3000 V and 13,800 V (longer distances may require voltages up to 66,000 V).

13.2.2.1 High voltage feeders

Long distances make it impractical to route earthing interconnectors to carry the full earth current for the high voltage feeders. In such situations advantage is taken of the conductivity of the surrounding soil, sand, clay or rocks (the material hereinafter called the 'ground'). The notation adopted is that a power system is 'earthed' in some manner to the 'ground'. Nearly all 'grounds' have some moisture content at some depth, even rocky ground, and thereby provides a satisfactory low impedance circuit over a long distance. It can be shown mathematically that if for example two separate earthing rods are driven into the ground and that they are separated by a distance much greater than their depth, then by assuming that the physical structure of the ground is uniform it is found that the potential difference over most of the horizontal distance is negligible. Most of the potential difference caused by the fault current occurs close to the vertical rods, as shown in Reference 2, Chapter XI. It declines approximately as an inverse function of the distance from the rod. In such circumstances the potential gradient across most of the surface of the ground between the rods is very small and is not sufficient to cause an electric shock to a person standing anywhere along a direct route between the rods. Some precautions need to be taken near to the rods for high voltage and high power situations, e.g. erection of a fence at a suitable radius from each rod.

It is common practice to earth a high voltage system through a high impedance, usually a resistance bank, so that the maximum earth current is limited to between 20 A and 200 A. If the line voltage of the star winding exceeds approximately 15 kV then an earthing transformer may be used, in which the earthing impedance is connected to the lower voltage secondary winding. This enables the design of the earthing impedance to be more robust, with thicker conductors. When this is done the risk of electric shock is negligible, even close to the rods. The deliberate limitation of the prospective earth current is also implemented in order to minimise the physical damage that could occur in the source equipment, e.g. supply transformer windings, generator windings, or even in the consumer equipment such as motor windings and switchboards. The reduction of current magnitude will reduce the mechanical forces in windings by a quadratic factor, and will also greatly reduce burning or arcing damage in the laminations of iron cores of machines. For further discussion on the choice of the current magnitude that should be used, see References 4 to 8.

13.2.2.2 Low voltage local consumers

The local power system at a processing unit usually derives its source of voltage from one or two local power transformers, e.g. 11,000 V/440 V step-down ratio. Each of these transformers usually has a star-connected low voltage winding to provide a four-wire supply. The star point is usually connected directly to a ground rod or grid, and a neutral connection is brought to the switchgear. An earthing impedance is not generally used. However, there are some exceptions that will be described later. Such a connection is described as a 'solidly earthed system'. This type is preferred because in systems where the neutral is used for single-phase loads it is necessary to have the neutral potential maintained as close to the 'zero' earth potential as possible. This minimises the risk of electric shock, and ensures that the upstream earth fault protection devices clear the fault current very quickly. In most plants where both high and low voltages are present, it is generally the case that the operating personnel have more direct physical contact with low voltage equipment than with high voltage equipment. Extra measures are taken with low voltage systems to further reduce the risk of electric shock. Often the high voltage equipment such as switchboards and neutral earthing resistors (NERs) are located in rooms that are only accessible by specially qualified operating staff, who are trained in high voltage switching practices and procedures. For safety reasons high voltage switchgear is often operated nowadays by remote control, i.e. from a central control room.

The local processing equipment will be similar to that described in sub-section 13.2.1, and therefore the earthing practices will be similar, for example the use of copper interconnected busbars and bonding conductors. However, if the plant is mounted on concrete foundations then extra earthing rods will usually be needed at each foundation site. All reinforcing steelwork in concrete should be earthed to busbars or through their own rods.

13.2.3 Concrete and Brick-Built Structures

Concrete buildings such as offices and storehouses contain reinforcing steel rods and bars inside the concrete columns, walls, floors and ceilings. Steel beams are used to carry the structural loads of the building, and these beams are either encased in concrete or exposed. Brick-built structures also use steel beams in a similar manner. In all cases the unseen steel should be bonded to the earthing system. This is carried out at the footings and foundations, either by using local earth rods or an interconnecting cable to a nearby point in the earth system.

All electrical equipment and appliances inside the building must be earthed, including metal luminairs, socket outlets, MCB and MCCB panels, cooking appliances and the like. Earthing is achieved by routing separate earthing conductors to each appliance, from a central earth point that is usually at the main power intake at the building. References 9 and 10 give full details of earthing practices for buildings.

It has become standard practice in recent years to use sensitive earth leakage current detectors in circuit breakers to further protect against electric shock. The current sensitivity can be chosen from a range of standard current values, e.g. 30, 100, 500 and 1000 mA. The 30 mA sensitivity is used at individual consumer sub-circuits, e.g. feeders to domestic and small power socket outlets, feeders to luminairs. The higher sensitivities are used in the upstream circuit breakers so that protection discrimination is achieved.

13.3 DESIGN OF EARTHING SYSTEMS

This section covers the design of high voltage and low voltage earthing systems and highlights some difficulties that can be experienced in practical installations. The concepts and practical requirements of References 9 and 10 will be discussed.

13.3.1 High Voltage Systems

A plant requiring more than about 1000 kW of power will normally receive a supply at a high voltage, drilling rigs are often an exception because they tend to use captive diesel engine driven generators. The primary source of high voltage power will be generators or supply authority transformers. The supply authority voltage could range from typically 3000 V to 132,000 V depending upon the total and future power demands of the plant, and to some extent the distance from the ‘point of connection’ to the central grid or power station. The supply of power would be transmitted through overhead lines or cables. The authority would take care of the earthing requirements for the supply, in a manner similar to that described later.

High voltage supplies within a plant are invariably arranged as three-phase star-connected systems. The star point of the transformer secondary winding or the generator stator winding is

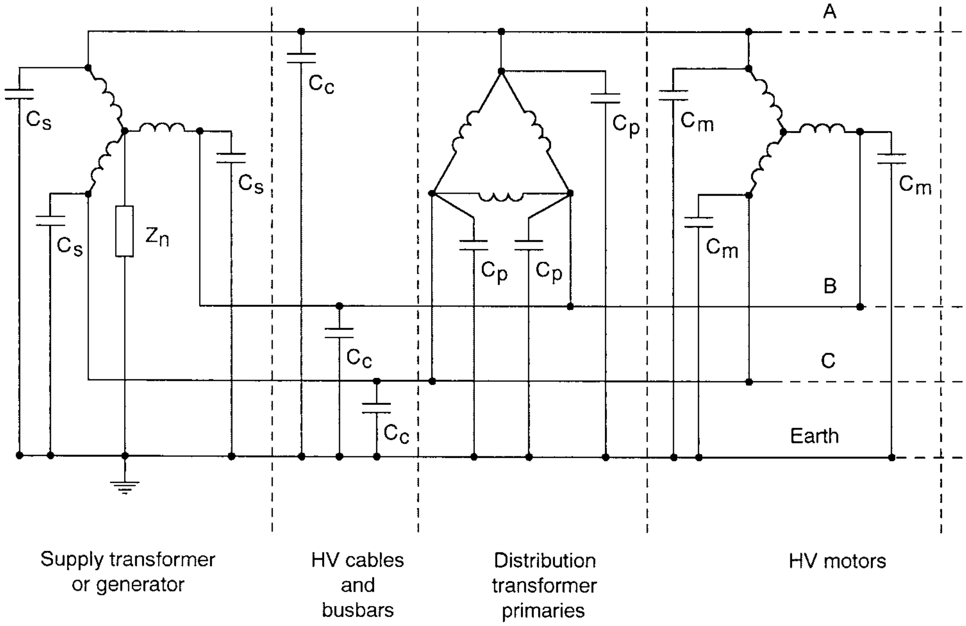

Figure 13.2 Earthing circuit of leakage capacitance in a high voltage system.

earthed locally through an impedance. This impedance is large enough to reduce the prospective earth current to a much lower level than would be the case if solid earthing were to be used. It has become the practice over the last 20 years or so to restrict the current to between 20 A and 200 A, as explained in 13.2.2. The lowest current is recommended but there is a restriction on the minimum value that can be reliably used. This restriction is due to the total capacitive charging, or shunt, current caused by all the insulation systems in the high voltage network. All the components in the network will have an amount of capacitive charging current, e.g. cables, motors, transformers, generators, switchboard busbars. Cables are the main source of charging current. Each component can be represented by a single capacitor connected between each phase and the earthed neutral reference or the ground plane, see Figure 13.2.

All the capacitors in each phase can be considered as being connected in parallel, and so the total charging current can be reasonably easy to calculate. An industrial standard practice is to choose the impedance Z_n to be less than one-third of the reactance of the total parallel capacitance in one phase of the system to earth. The impedance Z_n is usually chosen to be a resistance R_n for oil industry networks, see Reference 6. Reference 11, Chapters 14 and 19, and Reference 12 gives discussions on the various types of neutral earthing methods where the capacitive reactance between the lines and ground are involved. The possibility of overvoltages occurring when a fault is cleared, and the power dissipation from NERs are discussed. Reference 9 recommends References 13 and 14 for further reading on this subject.

13.3.2 Low Voltage Three-Phase Systems

A low voltage in this context is the lowest three-phase voltage that is commonly used for plant motors, heaters and general utilities, e.g. 380 V, 400 V, 415 V, 440 V and for drilling systems

600 V. In general there are two approaches used for earthing low voltage three-phase networks in the oil industry:-

- Solidly earthed star points.
- High impedance earth points.

Most power systems use the solidly earthed star points. High impedance earthing may be preferred for ships, occasionally for offshore platforms, and frequently for emergency and uninterruptible supplies in all locations.

a) Solidly earthed star points.

   A low voltage secondary winding of a transformer, or a generator winding, has a star point solidly earthed, i.e. no intermediate impedance. Most solidly earthed systems are designed for four-wire operation and so the neutral conductor of the associated switchgear is also connected to the star point. There are several alternative methods used to make the earth connection to the ground for transformers and generators, and the choice depends upon various factors:-

   - The distance between the windings and the switchgear.
   - Whether the transformer or generator is located outdoors or indoors.
   - The type of connection between the windings and the switchgear, e.g. cables, bus-ducting.
   - The ground material, e.g. soil, steel decking.
   - Whether a circuit breaker is used at the incoming side of the switchgear.
   - Whether there are one, two or more feeders to the switchgear.
   - The design of the earth fault relay protection scheme for the winding.
   - Whether earthing connections and neutral busbars need to be isolated during maintenance, e.g. as may be required when two transformers feed a common switchboard.
   - Whether three-pole or four-pole circuit breakers are used in the switchgear.
   - Whether the system supplies consumers in a hazardous area.

   See also sub-section 13.3.3 for a description of the IEC standardised earthing circuits for low and high voltage systems.

b) High impedance earthed star points.

   It is possible to design three-wire and four-wire systems that do not need to be solidly earthed. Instead a high impedance is inserted between the star point connection and earth, as shown in Figure 13.3. Alternatively an artificial star point is created and again a high resistance is connected to earth as shown in Figure 13.4.

The high impedance is usually a resistance chosen to limit the earth current to about 20 mA. A current detector is used in conjunction with the resistance to raise an alarm if a line-to-earth fault occurs. A zig-zag transformer, or reactor, is sometimes used with three-wire supplies such as used in drilling rigs and emergency systems. It is specially designed and internally connected to create a very low zero sequence impedance to earth currents. Therefore, the current is limited only by the resistance of the neutral earthing resistor. Some special purpose earth current alarm systems are available that inject a small DC current into the three-phase system, which is used to identify the actual location of the fault.

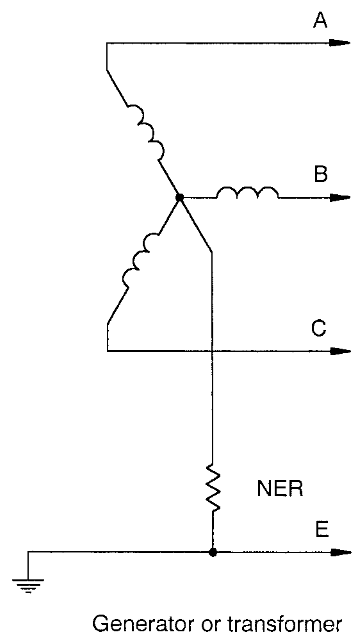

Figure 13.3 Earthing a high voltage system by using a neutral earthing resistor.

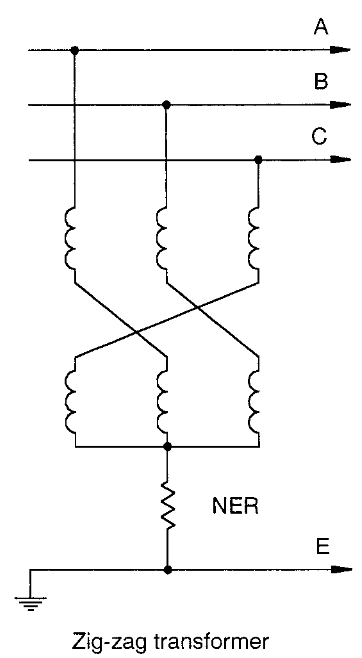

Figure 13.4 Earthing a high voltage system by using a zig-zag transformer and a neutral earthing resistor.

The main advantage of using a high impedance is that the system will function satisfactorily if only one line is faulted to earth. This is highly beneficial for emergency and essential services such as process shut-down supplies, computer supplies, fire protection systems, telecommunications and public address systems. These consumers must be maintained whenever possible. The earth fault would be detected and the operating staff alerted. The staff would then be in a position to decide whether or not to defer the shutting down of the supply to a later more convenient time. The single fault cannot develop into an explosive or damaging state because the current is far too small. A solidly earthed system does not have this benefit.

Reference 9 recommends Reference 15 for further reading on this subject.

13.3.3 IEC Types of Earthing Systems

The international standards IEC60364, part 4, and Reference 10 use a set of diagrams to clarify five basic methods of earthing and providing the neutral where it is required. Three of these methods are most commonly applied to oil industry installations. The five methods are abbreviated TNC, TNS, TNCS, TT and IT, and are shown in Figures 13.5 to 13.9. The three common ones are TN, TT and IT. The first letter is T or I. The second letter is N or T.

- The first letter denotes the source of power from a star-connected winding. T denotes that the star point of the source is solidly connected to earth, which is usually at a location very near to the winding. I denotes that the star point and the winding are isolated from earth by their design and

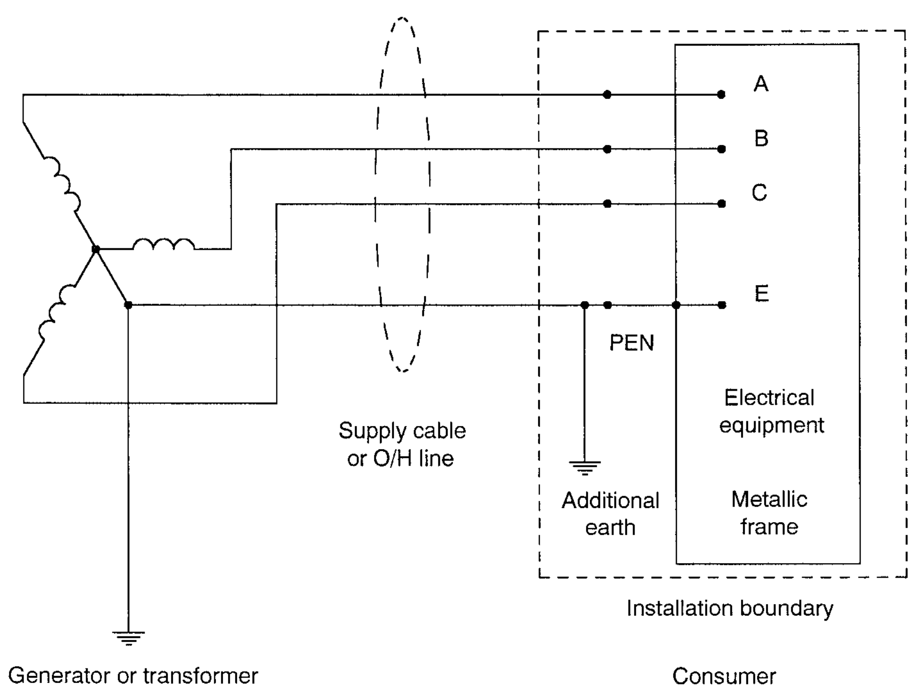

Figure 13.5 IEC earthing system type TNC.

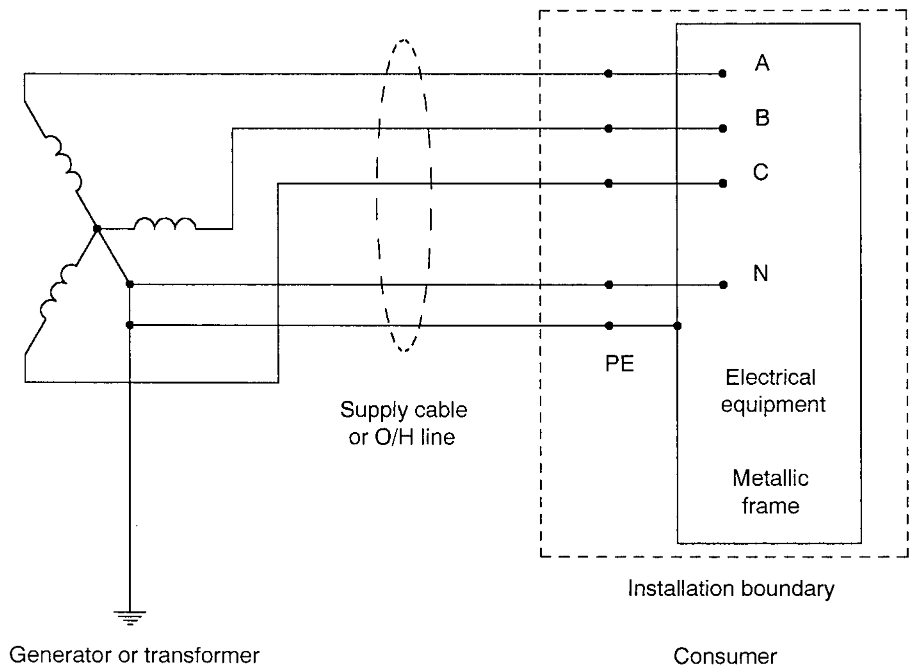

Figure 13.6 IEC earthing system type TNS.

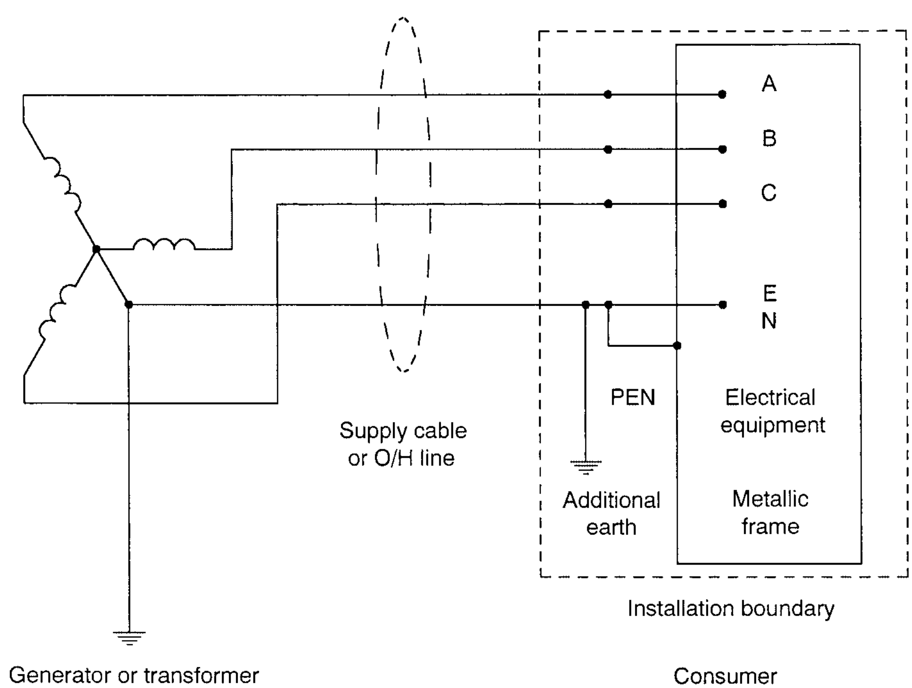

Figure 13.7 IEC earthing system type TNCS.

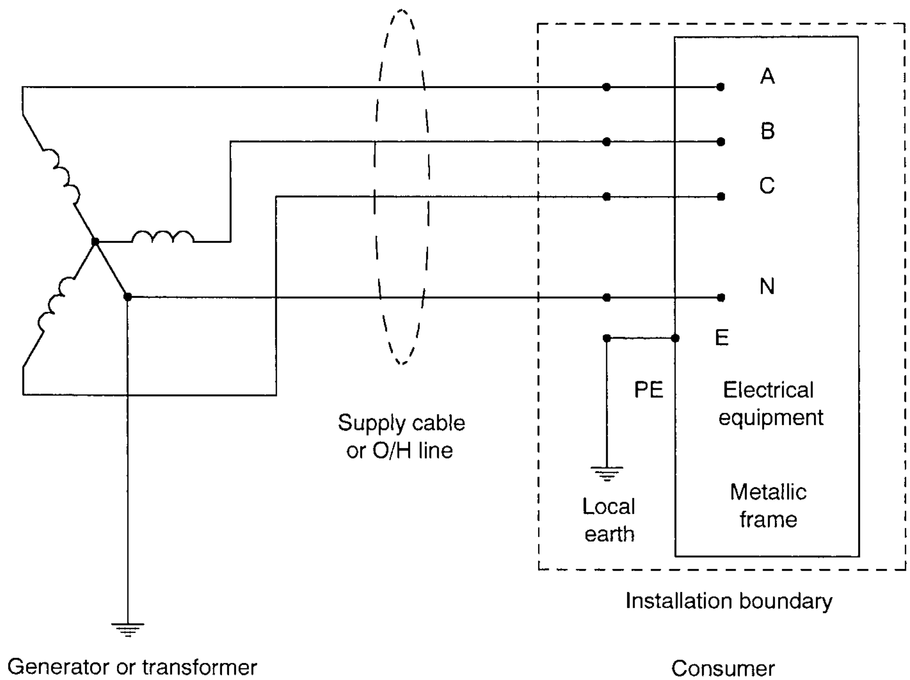

Figure 13.8 IEC earthing system type TT.

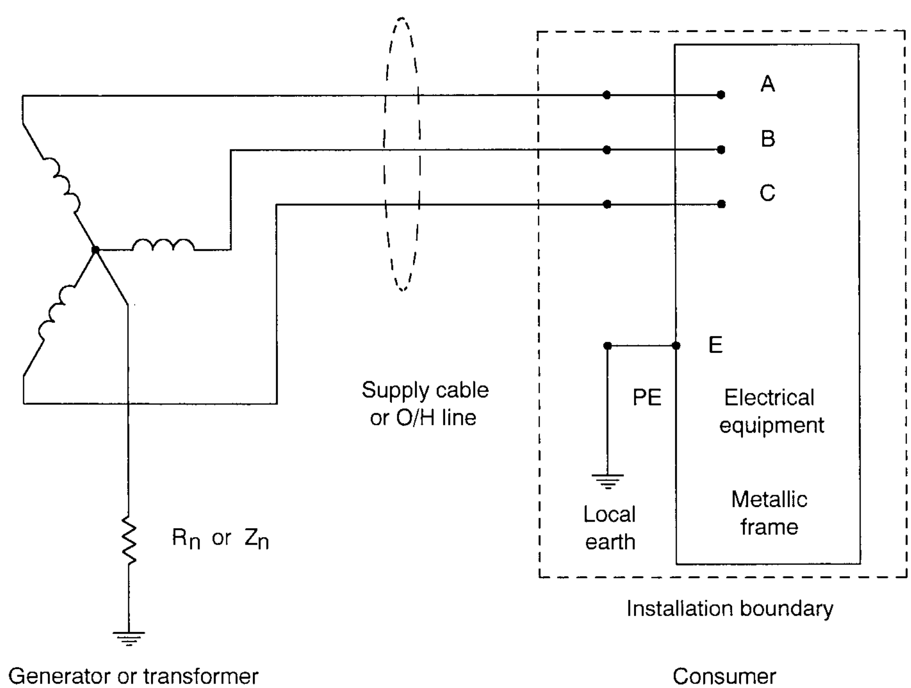

Figure 13.9 IEC earthing system type IT.

construction, but it is accessible by a proper terminal. The star point is usually connected to an inductive impedance or resistance. Capacitive impedance is not used.

- The second letter denotes the consumer. The consuming equipment needs to be earthed. There are two basic methods that can be used to earth frames, cubicles, panels and the like. The letters are T and N. The letter N is sub-divided into other letters, S and C, thus giving NS and NC and the composite NCS. T denotes that the consumer is solidly earthed independently of the source earthing method. N denotes that a low impedance conductor is taken from the earth connection at the source and routed directly to the consumer for the specific purpose of earthing the consuming equipment. S denotes that the neutral conductor routed from the source is separate from the protective earthing conductor, which is also routed from the source. This means that five conductors need to be routed for a three-phase consumer. C denotes that the neutral conductor and the protective earthing conductor are one and the same conductor. This means that four conductors need to be routed for a three-phase consumer.

Oil industry installations can generally be described in terms of the two-letter code as follows:-

- Land-based installations.

  The high voltage network is IT.

  The low voltage network is TT (or TNC or TNS) for four-wire systems.

  (A motor feeder could be regarded as a TT system with neutral not present.)
- Offshore and marine installations.

  The high voltage network is IT.

  The low voltage network is TT due to the abundance of interconnected steelwork.

  (A motor feeder could be regarded as a TT system with neutral not present.)

13.3.3.1 Influence of hazardous area classification

Where a site is classified as being Zone 1 or Zone 2, with regard to explosion ignition of flammable gases and vapours, it is necessary to take special precautions when installing live conductors. In some situations these conductors may be bare having no sheathing or insulation provided. It should not be possible to make intentional or accidental contact with bare live conductors, because a spark may occur. The energy of a spark that is needed to ignite an explosive mixture of air and gas is surprisingly small, see IEC60079 parts 11 and 15.

The term 'live conductors' in this context means any conductor that can carry current in the steady state, or in the transient state such as when a line-to-ground fault occurs. Therefore all forms of earthing conductors can be included. An important aspect in the design of earthing systems for hazardous areas is to maintain an 'equi-potential' conducting system within the area. In this sense 'equi-potential' means as far as is practically and economically possible. Only a few millivolts of difference should occur in the event of fault currents flowing in the conductor system. This is usually achieved by adequately sizing and positioning the earthing busbars, bonding cables, terminal systems and connections for a prospectively high I-squared-t duty, see Chapter 9. This aspect came to the attention of engineers in 1989 when several serious accidents that occurred offshore were reported, which resulted in Safety Notices being issued by the Department of Energy in the UK, see for example References 16 and 17 in particular, and Reference 18 as further reading of an allied subject. Investigations were carried out in the UK by the leading manufacturers of large motors, and recommendations were subsequently made.

IEC60079, part 14, clause 6.2 draws attention to the methods of earthing the neutrals, and to the use of neutral conductors and protective earthing conductors. The three methods, TN, TT and IT, discussed above and the use of 'Safety Extra Low Voltage' (SELV) and 'Protective Extra Low Voltage' (PELV) systems and equipment as defined in IEC60364 (or identically in Reference 10), part 4, chapter 41, require the following features when hazardous areas are being considered.

- Type TN earthing.

  The type TNS method should be used, TNC and TNCS are not recommended. The neutral conductor and the protective earth conductor shall only be connected together at the star point of the source. A transition from TNS to TNC or from TNC to TNS should be avoided otherwise the design may become too complicated.
- Type TT earthing.

  This method is commonly used in the oil industry because of the predominance of steelwork in a typical installation. In this method the power system is earthed separately from the equipment frames and cubicles. The star point at the source is the only common earthing point. The IEC standard requires the circuit to be protected by a residual earth fault current device at the switchboard or motor control centre, where the consumer is located in a Zone 1 area.
- Type IT earthing.

  In this method the occurrence of a line-to-ground fault will normally cause a small earth return current to flow. Its magnitude will be determined by the impedance of the neutral earthing device, which will be a resistor or inductor. A device for detecting this current should be fitted in the switchboard or motor control centre, where the consumer is located in a Zone 1 or a Zone 2 area. Note that a solidly earthed low voltage three-wire system will normally have a very small current flowing in the insulation materials of all the line conductors in the network. If the insulation degrades or is damaged then an increase in the insulation current will occur, which will give rise to an unbalanced distribution of currents in the three lines. A sensitive core-balance device should be fitted in the switchgear to detect this current and to isolate the circuit. This precaution should be used for Zone 1 and Zone 2 areas.

13.3.3.2 SELV and PELV systems and equipment

The definitions of SELV and PELV as given in Reference 10 are:-

A SELV system is an extra-low voltage system (50 Vac or 120 Vdc free of ripple when measured between any two conductors), which is electrically separated from the earth (or ground) and other systems (such as the primary winding of an isolating transformer) in such a way that a single fault cannot give rise to the risk of electric shock. A PELV system is also an extra-low voltage system, but is one that is not electrically separated from earth. In all other respects it must satisfy the requirements of a SELV system.

SELV systems generally consist of double-wound isolating transformers where the secondary winding is not connected in any manner to earth, motor-generator sets where the mechanical coupling serves the same purpose as two windings of an isolating transformer, batteries that are isolated from the low or high voltage source of their chargers, and certain types of electronic supply units that have high speed control of overvoltages. (See clause 411-02-02 for the actual wording and cross-referencing to other clauses.) In general the practical significance of PELV versus SELV is unnecessarily complicated and a suitable SELV should be chosen in preference to a PELV alternative.

13.3.3.3 Four-pole circuit breakers and isolators

Where a four-wire supply is needed in a hazardous area it is necessary to use four-pole circuit breakers and isolators so that the neutral is completely isolated when maintenance work is required to be undertaken. If the neutral is not electrically separated and a fault occurs elsewhere in the same network then the neutral in the hazardous area could have its potential elevated sufficiently above zero to cause a spark (or even an electric shock). This aspect is especially important when a switchboard or motor control centre is supplied from more than one source such as two parallel transformers.

13.3.4 Earth Loop Impedance

A key factor in the design and choice of earth continuity conductors, e.g. cable armouring, bonding straps, and fault current protective devices is the 'earth loop impedance'. This is especially the case for solidly earthed low voltage systems, whether they be three-phase, single-phase or even direct current systems.

The earth loop impedance is the total impedance seen by the source of voltage in a faulted circuit which involves the earthing conductors. Figure 13.10 shows the situation for a three-phase cable supplying a load such as a motor or static load.

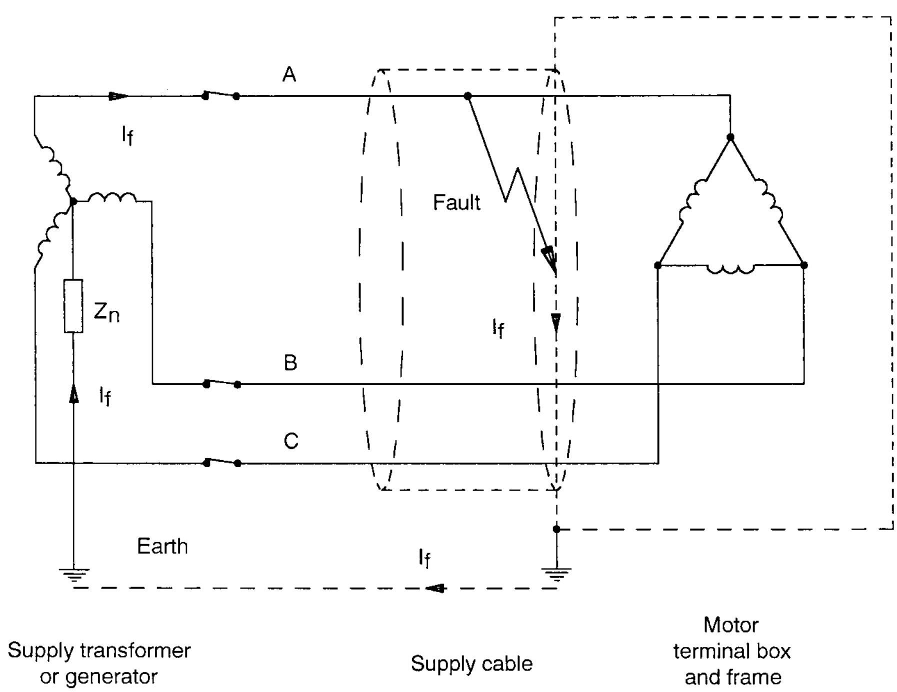

Figure 13.10 Earth loop impedance of a three-phase circuit.

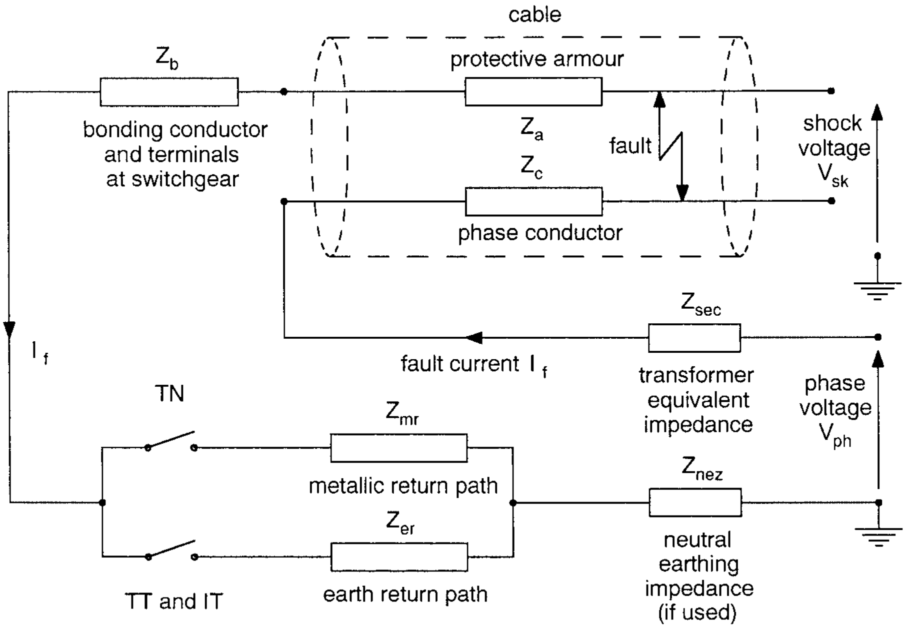

Figure 13.11 Equivalent circuit of the earth return paths in the earth loop impedance circuit involving a cable and its armouring. This is an interpretation of BS7430 Clause 3.13.

The worst design case is shown wherein the fault occurs at the far end of the cable. The fault is assumed to be a line-to-earth fault having zero fault impedance. The equivalent circuit for this example is shown in Figure 13.11.

A pessimistic assumption can be made that the steelwork impedance Z_e between the fault and the source is large compared with the parallel-connected cable armouring impedance Z_a. This implies that the current will only return to the source through the cable armouring and the copper bonding connection, of impedance Z_b, at the source-end of the cable. The impedance Z_b includes the local steelwork at the source. The bonding is assumed to be in tact and of very low impedance compared with Z_a. Hence Z_b can be ignored, and so earth loop impedance Z_{loop} simply becomes:-

$$Z_{\text{loop}} = Z_s + Z_c + Z_a \quad \text{ohms}$$

The driving voltage is the phase voltage. The source impedance Z_s is fixed and is usually that of the upstream supply cables and transformers, or generators (or the output impedance of supplies such as a UPS). Z_s can often but not always be neglected. The cable conductor impedance Z_c is easily calculated from the cable data for one phase conductor and its route length. Similarly the armouring impedance Z_a can be calculated from the data, which is predominantly resistive for most types of power cables. For typical cable data see the tables in Chapter 9.

In order to safeguard against electric shock at the far end of the cable, where the AC root mean square voltage may exceed 50 V, the earth loop impedance must be limited to a particular value. This value is such that the fault current should only be passed by the protective device at the supply for a specific period of time, i.e. to satisfy the I-squared-t criterion given in sub-section 13.1.1. The correlation of loop impedance, current and time varies with the type of protective device, e.g. fuse, moulded case circuit breaker, miniature circuit breaker. The international standards such as IEC 60364 and Reference 10 give tables for the limiting values of the earth loop impedance for common ratings of fuses and circuit breakers. Once the limiting value for the circuit is determined from these tables it is a simple calculation procedure to find the maximum length of the cable that can be allowed, as demonstrated in 9.4.3.6.

13.3.5 Earthing Rods and Grids

An essential aspect in the design of earthing systems for land-based plants in particular is the minimisation of the risk of electric shock due to the creation of potential along the surface of the ground and between the ground and metallic structures such as switchgear, overhead line poles and fences. The creation of potential along the surface of the ground gives rise to what is defined as the 'step potential or voltage', and between the ground and metallic structures, the 'touch potential or voltage'.

13.3.5.1 Touch and step voltages

Situations arise where the soil resistivity (ρ) is very high, for example in desert locations. In these situations the concepts of 'touch' and 'step' voltages are important, see the international standard IEEE80, section 5. A person may be standing on a conductive surface and touching electrical equipment with one or both hands. At the same time a fault occurs and its current passes through the equipment casing to the ground, thereby creating a potential difference across the person. This is the touch potential difference or touch voltage. In a second type of fault situation a person is standing on conductive ground with his feet spread one metre apart. The fault current, or part of it, passes horizontally at or near the surface of the ground. The local resistance of the ground in the path of the current creates a potential difference across the feet of the person. This is the step potential difference or voltage.

The magnitude and duration of these voltages, together with the resistance of the person between his points of contact, will determine whether the person receives a minor or even a fatal shock. If the surface layer of the ground can be reduced in conductivity by a significant amount then the current along the surface will be small, and most of the fault current will be forced down to a lower level in the ground. A small level of surface current and an inherently high source resistance will tend to restrict the amount of the surface current that can be shunted into the person, thereby reducing the risk of shock. The surface layer may be the addition of dry crushed rocks or stones, and it should be kept reasonably shallow, e.g. 100 to 150 mm or rubber mats as used in switchrooms. Chapter six in Reference 3 gives an excellent coverage of the subject of earthing, mathematic derivations of complex formulae and the topics of step and touch voltages. The equations presented are well suited to hand calculations or simple computer programming.

IEEE80 sub-divides the touch and step voltages into two categories, one for heavier persons of typical weight 70 kg and one for lighter persons at 50 kg. The reference illustrates the fact that the heavier the body the higher the threshold of fibrillation of the heart. For calculation purposes it is conservative to use the 50 kg equations. The results will be about 25% lower, which will eventually require a little more conductive material in the ground for a given situation. The reference also introduces an additional term to the standard body resistance of 1000 ohms, which takes account of the 'crushed rock layer' and the resistivities of the crushed rock (ρ_s) and the main mass of earth below that has the resistivity (ρ). This term is:-

$$R_{2Fs} = 6(\rho_s)C_s(h_s, K) \text{ for use in the step voltage case, and}$$

$$R_{2Fp} = 1.5(\rho_s)C_s(h_s, K) \text{ for use in the touch voltage case}$$

Where : $-$ $h_s =$ the thickness of the crushed rock layer
$K = (\rho - \rho_s)/(\rho + \rho_s)$.

Which is negative when the upper layer is more resistive then the lower layer. If no crushed rock is used then $C_s(h_s, K) = 1$. The resistances R_{2Fs} and R_{2Fp} are added to the 1000 ohms in equation (13.2) and the resulting threshold voltages are then denoted as E_{step50} and as E_{touch50} (using the same notation as in IEEE80). The function $C_s(h_s, K)$ is derived from a convergent infinite series and can be expressed as:-

$$C_s(h_s, K) = \frac{1}{0.96}\left[1 + 2\sum_{n=1}^{n=\infty}\frac{K^n}{u_s}\right] \tag{13.3}$$

Where

$$u_s = \sqrt{1 + \left(\frac{2nh_s}{0.08}\right)^2}$$

13.3.5.2 Soil resistivity

Soil resistivity varies greatly with the material, e.g. rocks, sand, clay, and its moisture content, as in coastal areas, high annual rainfall, dry deserts. Table 1 of BS7430 gives comprehensive values for these variations. For dry desert conditions a value of 1000 ohm-metres is generally considered acceptable for design calculations, unless site measurement data are available. Table 3 of IEEE80 gives typical values of crushed rock that would be used as a surface layer, and recommends in its sub-section 10.5 a value of 3000 ohm-metres for a wetted layer. Hence a dry layer would be very much higher e.g. 10^6 to 10^7 ohm-metres.

13.3.5.3 Resistance to earth

The resistance to earth R_e as measured or calculated for a conductor buried in the ground depends upon its shape, volume and orientation in the ground. In favourable conditions the resistance should be less than one ohm. With unfavourable conditions and small sites such as the bases of pylons a value between 1 and 5 ohms should be considered. For simple shapes such as uniform rods, strips and plates, there are formulae available for calculating the resistance. For example a vertical round rod or hollow pipe the resistance is:-

$$R_e = \frac{\rho}{2\pi L}\left[\log_e \frac{8L}{d} - 1\right] \quad \text{ohms} \tag{13.4}$$

Where ρ is the soil resistivity in ohm-metres
L is the buried length of the rod or pipe in metres
d is the diameter of the rod or pipe in metres.

Annex A of BS7430 gives formulae for various shapes of buried conductors. See also Appendix H of Reference 1. Reference 2 shows the mathematical derivations of some basic cases. Reference 3 provides much useful information regarding buried materials. If the rod or pipe is surrounded by a casing or backfill of more conductive material such as Bentonite, then a lower resistance is obtained for the same depth, the formula is:-

$$R_e = \frac{1}{2\pi L}\left[(\rho - \rho_c)\left(\log_e\left(\frac{8L}{d}\right) - 1\right) + \left(\rho_c \log_e\left(\frac{8L}{d}\right) - 1\right)\right] \quad \text{ohms} \tag{13.5}$$

Where ρ_c is the back fill resistivity in ohm-metres
d is the diameter of the back fill or casing in metres.

This equation can also applied to reinforced concrete in which a steel rod is encased. A single rectangular strip of width (ω) buried horizontally has a resistance to earth of:-

$$R_e = \frac{\rho}{2\pi L}\left[\log_e\left(\frac{2L^2}{\omega h}\right) - 1\right] \quad \text{ohms} \tag{13.6}$$

Where L is the horizontal length of the strip in metres
h is the depth of burial in metres.

One difficulty with a small site such as a ring main station with an overhead line pole, a transformer and a switchgear unit is the spacing between the vertical rods tends to be small compared with their buried length. This reduces the effectiveness of each rod due to its proximity to the adjacent rods, see sub-section 10.2 of BS7430. The best results are obtained when the rod spacing is approximately equal to the depth of the rod.

An arrangement of conductors for a difficult site would generally consist of a grid of horizontal strips with vertical rods connected at the corners and sides of the grid. Hence the overall resistance will then be a function of equations (13.4) and (13.6) (or (13.5) if necessary).

Malhothra in Reference 3, sub-section 6.12, comments that in a system comprising rods and a horizontal grid, the rods can in some situations be deleted because they have little effect compared with the grid acting on its own.

The current that passes into the earth causes a voltage difference across the resistance. Since a point or region a long way from the connection to the conductor is at zero reference potential, the connection must be at an elevated potential. This potential is called the 'ground potential rise or GPR'. At distances close to the point of connection the potential will be high, but further away it will be much lower. When the earthing conductor includes a horizontal grid buried near to the surface, the surface voltage decays in a more complicated manner. Within the grid itself are squares or rectangles of conductors. Consequently the potential at the centre of a square or rectangle is less than at their metallic sides. Outside the frame of the grid the decay is greater, and this creates a region if high risk of shock. It is therefore necessary to calculate the potential at the corner of the frame as a percentage of the full potential due to the total resistance. Two potentials are needed, the 'corner mesh voltage or E_m' and the 'corner step voltage E_s'. E_m and E_s are obtained by calculating per-unit or percentage factors that relate to the grid geometry. These are then used to scale down the GPR by simple multiplication. The mesh voltage E_m is usually more of a constraint on the design than the step voltage E_s. The IEEE80 standard provides graphs of E_m and E_s for different mesh configurations, (Figures B1 to B5 therein).

In Reference 3 a typical design of a grid of large area would be to bury it to about 0.5 m and choose each mesh in the grid to have sides of length about 5 or 6 m. This would give a good starting point for a series of calculations.

13.3.5.4 Fault current entering the ground

For most practical designs the calculation of a 'single line-to-ground or L-G' fault current should be adequate. Assume the fault occurs at the pole location and that the pole is at a long distance from the source of power. Assume for a simple example that the overhead line is a simple radial circuit fed only from one end, and that the line is furnished with an overhead earthing conductor. To be conservative assume that the earthing conductor is only bonded to the pole in question and to the neutral earthing point at the source end. The source is considered to be earthed through a neutral earthing resistor (NER) having a resistance R_n.

The overhead earthing conductor will divert some of the L-G fault current from entering the ground at the foot of the pole. The extent of diversion will be in proportion to the impedance of the overhead line compared with that of the earth resistance path back to the source. The calculations required for determining the fault current and its diverted amounts are shown in Appendix H by way of an example, and Figure 13.12.

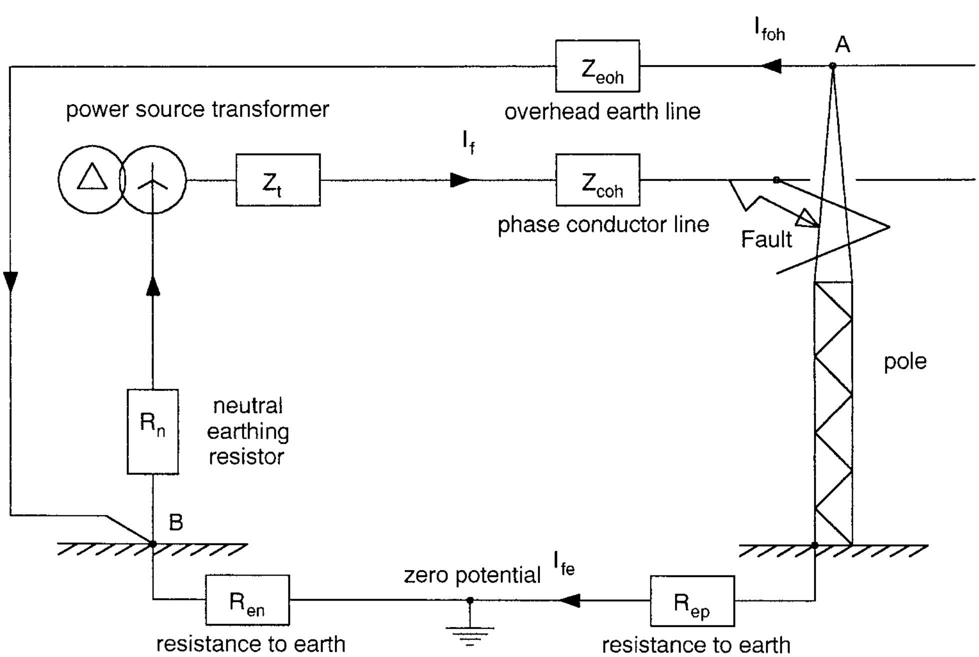

Figure 13.12 Earthing circuit of an overhead transmission route.

13.4 CONSTRUCTION DETAILS RELATING TO EARTHING

This section describes some of the practical construction and installation details that are required with metallic frames, casings, cubicles, terminal boxes and cables.

13.4.1 Frames, Casings and Cubicle Steelwork

Frames and casings are the steel or cast iron enclosures of motors and generators in particular. Frames can also include the base plate of machines and transformers, and these are often channel iron-welded fabrications. Cubicles are usually fabricated sheet steel box type enclosures used for switchgear, distribution boards, control panels, fuse boards and terminal chambers.

In all locations these constructions must be connected to the earthing system. Most frames and casings are bolted to the supporting structure, e.g. steel deck beams, concrete foundation block or plinth. They are usually fitted with at least two large earthing bosses, which are welded or cast into the fabrication, separated as far apart from each other as possible, and having threaded entries for bolts of typically 10 to 15 mm diameter. The size of the bolts is related to the maximum fault current that can flow in the fabrication. Copper bonding straps are connected to these bosses and similar ones welded nearby on the deck beams, or onto nearby earth rods or busbars. In some situations the frames are welded to the deck beams and so the use of bosses may not be necessary. Casings of machines are seldom welded because the machine will need to be removed for major maintenance, repair or re-alignment.

Cubicle steelwork is invariably bolted to the floor, a floor frame or to a wall structure, and therefore bolted bonding straps are used in a similar manner as described above. Most cubicles are fitted with an internal copper busbar which is bonded internally to the steel. The busbar is used to receive the bonding connections from internal components, partitions, screening panels, cable glands, cable armouring, cable screens and gland plates.

13.4.2 Screwed and Clearance Hole Entries

A major part of any power system installation is the termination of all the cables. Cables are terminated at equipment by the use of cable glands. There are many different types of cable glands, and they must be carefully chosen to suit their function and environment. Factors influencing their choice are:-

- Indoor or outdoor installation.
- Power or instrumentation cables.
- Weather and particle ingress proofing.
- Mechanical vibration or movement of the equipment.
- Non-hazardous or hazardous environment.
- Corrosive atmosphere.
- Internal construction of the cable, e.g. type of armour, use of core screens.
- Equipment submerged in liquids, e.g. sump pumps, down-hole pumps.
- Gland material, e.g. brass, stainless steel, plastic.
- Total length and type of the entry thread.

Cubicles and light duty terminal or junction boxes often use stainless steel or painted mild steel gland plates for receiving cable glands, occasionally brass plates are used for single-phase and DC cables. Stainless steel may also be used for special services. These plates are chosen to be between about 2 and 5 mm thick, to provide adequate rigidity and resistance to the ingress of dust and liquids, as defined for example in the international standard IEC60529, see also Chapter 10. The glands pass through plain or clearance holes and are secured by lock-nuts and spring washers on the inside surface. Since the entry is a plain hole with a painted surface, it is necessary to use earthing tabs. Each cable should have a tab and all the tabs should be bonded to a common earthing boss nearby. The tabs may be on either the outer or the inner surface, depending on the type of equipment and its environment. Care must be taken to ensure that water and other liquids cannot pass along the entry hole.

Casings and heavy-duty terminal boxes are often made of cast iron or fabricated from thick steel plates. Occasionally cast bronze may be used, in services offshore where sea water corrosion may be a problem. In these cases the entry is usually threaded. The gland is screwed into the threaded hole. A washer may be required between the outer surface of the box and the gland, to satisfy the requirements for ingress of liquids and particles, and for the hazardous area. When Ex (d) glands are used with Ex (d) boxes it is necessary to ensure that the prescribed number of threads on the gland enter the hole.

Most casings, terminal boxes and gland plates are provided with one or two earthing studs for bonding them to the earthing system. If a terminal box is cast integral with the frame or casing of a motor, a generator or other machine, then an earthing stud is not necessary at the box, but the frame will have one or two studs or bosses for the same purpose.

13.4.3 Earthing Only One End of a Cable

Multi-core cables used for control, instrumentation, computers and telecommunications carry very small currents in their conductors, when compared with power cables, and these currents feed into very sensitive electronic circuits. The system design of these electronic circuits must take account of interference that can be induced or circulated in the cable conductors. Screens are provided around groups of typically two, three or four conductors, which are mainly intended to discharge static charges that can otherwise accumulate and create noise or damage at the terminal equipment. Screens are also provided around all the conductors in the cable for a similar reason.

If a screen is earthed at both ends of its cable then a ‘stray’ current may be caused to flow in the screen. This is because the earth potential at each end of the cable may not be exactly the same or both zero. A few millivolts difference due to random stray currents, or worst still fault currents, in the local earth or steelwork is enough to cause difficulties with the electronic signals. The stray current flowing along the screen will magnetically induce currents into the core conductors. It is therefore common practice to earth the cable screens only at one end of the cable. The bonding of each screen is made at a specially designed ‘clean earth’ busbar mounted inside, for example, a control panel or marshalling box.

High voltage power cables that operate at voltages above about 3000 V are provided with graphite semiconducting screens at the surface of the conductor and on the outside surface of the insulation. The purpose of the screen around the conductor is to control the potential gradient, or electric stress, in the insulation that is close to the conductor. The high surface voltage is accompanied with a very rapid fall in potential just inside the insulation (measured or defined in volts/mm). The natural insulating property of the insulating material is limited by the maximum potential gradient at any point within its structure. If the maximum gradient is exceeded then local breakdown and discharge will occur at the site, which is sometimes called 'partial discharging'. If this is allowed to continue for a long time the insulation will eventually fail. In a cable the stress is greatest at the surface of the conductor. This screen is not earthed. It must be bonded to the inner surface of the insulation very carefully so that no pockets or gaps exist, which could also promote local discharges.

A similar screen is placed around the outer surface of the insulation, especially with multi-core high voltage cables so as to maintain a radial stress pattern in each core. A metallic tape is placed over the semiconducting screen. The tape may be made of tinned copper, bronze or aluminium. The semiconducting screen is used to ensure a good electrical contact is made with both the insulation and the tape. This is necessary to avoid local highly stressed areas on the surface of the insulation, so that it is not weakened. The tape is usually bonded to earth at the switchgear end of the cable. At the switchgear the bonding will be taken to the internal earth busbar.

13.5 SCREENING AND EARTHING OF CABLES USED IN ELECTRONIC CIRCUITS

Since about 1980 power system switchgear, control panels, uninterruptible power supplies, power management systems, variable speed drives, protective relays, SCADA, and the like, invariably use instrumentation cables to transfer low level signals between equipment. These cables can 'pick-up' stray signals by interference from nearby sources. These stray signals will be called 'noise' hereinafter, and they occur due to several different forms of coupling:-

- Common circuit conduction.
- Electrostatic or capacitive coupling.
- Electromagnetic or mutual inductive coupling.

Reference 19 gives a comprehensive coverage of these complex subjects. References 20 to 24 are recommended as further reading. Reference 23 gives a full descriptive treatment of these subjects together with useful numerical data, and a reference list of over 160 articles, books and papers. A few of these topics that relate to oil industry practice and equipment are described below.

Instrumentation cables used for power system signal transmission are usually of two basic types, multi-core twisted pairs, triples and quadruples, and coaxial cables.

13.5.1 Capacitance and Inductance Mechanisms

There are three basic conductor configurations to consider; a single conductor located above a flat plane, two conductors running in parallel with each other, and a conductor running inside a cylindrical screen or shield. Let the following notation be used for the inductances and capacitances that will be referred to later. See Reference 19 for formulae that relate these inductances and capacitances to the physical dimensions of the conductors. Reference 25, chapters 10 and 11 give full details of how to calculate the magnetic and electric field patterns of simple and complex shapes, such as,

a) Single conductor above a flat plane.

Leakage capacitance.

Self-inductance.

b) Two conductors in parallel.

Coupling capacitance between the conductors.

Self-inductance of each conductor.

Mutual inductance between the conductors.

b) One screened conductor in a cylinder.

Coupling capacitance.

Self-inductance of the conductor.

Mutual inductance between the conductor and the cylinder.

Invariably the cable length is very much greater than the radius of a conductor and its separation from other conductors in the cable or its screening. Therefore all the capacitances and inductances are distributed along the length of the cable. The conductor resistance and the insulation leakage resistance are also distributed. For practical calculations it is adequate to 'lump' these parameters into single elements of inductance, capacitance and resistance.

13.5.2 Screening against External Interference

Instrumentation cables frequently run in parallel along the same routes as heavy current power cables. The routing is designed in such a manner that a prespecified spacing is used between power cables and instrument cables. Table 13.1 gives typical minimum spacings between the cables that run in the same trench or set of racks. There are situations where a power cable can radiate interference, particularly in the form of mutually induced currents, for example:-

- Single-core cables run in groups.
- Cables carrying unbalanced currents.
- Cables carrying harmonic currents, e.g. drilling power systems.
- Cables carrying surge currents, e.g. starting large motors direct-on-line.
- Cables carrying fault currents of high magnitude, particularly if they flow in the armouring.

Table 13.1. Separation of electronic and power cables

Power cables and control cables	Minimum Separation of cables (mm)
110 V or 10 A	300
240 V or 50 A	450
415 V or 500 A	600
3300 V to 33,000 V	1000
Currents above 200 A	1000

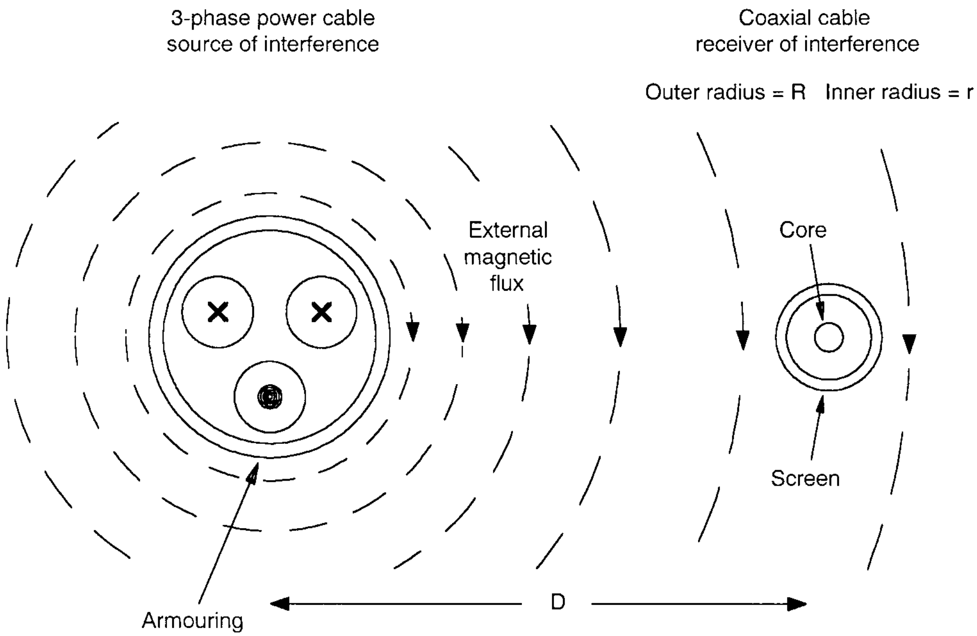

Figure 13.13 Mutual coupling between spaced out cables.

In these examples the situation of interest is a combination of a single conductor above a plane and another single conductor above the same plane but running in a cylinder or screen, as shown in Figure 13.13.

The source of interference in the example is a three-phase cable in which unbalanced currents flow. The currents that are unbalanced can be replaced by one equivalent current, which is the sum or resultant of all the three phase currents. The three-phase cable is assumed to be armoured, which is generally the case, and the armouring is assumed to be earthed at one or both ends. Earthing the armour reduces the external electric field to zero, and so only mutual inductive coupling needs to be considered.

The equivalent circuit of the various conductors and screening is shown in Figure 13.14.

Where:

For the interference source cable

I_3 is the three-phase resultant interference current source.
R_3 is the resistance of the source circuit.
L_3 is the self-inductance of the source circuit.

For the signal instrumentation cable

R_s is the resistance of the cable screen.
L_s is the self-inductance of the cable screen.
R_s is the resistance of the cable core.

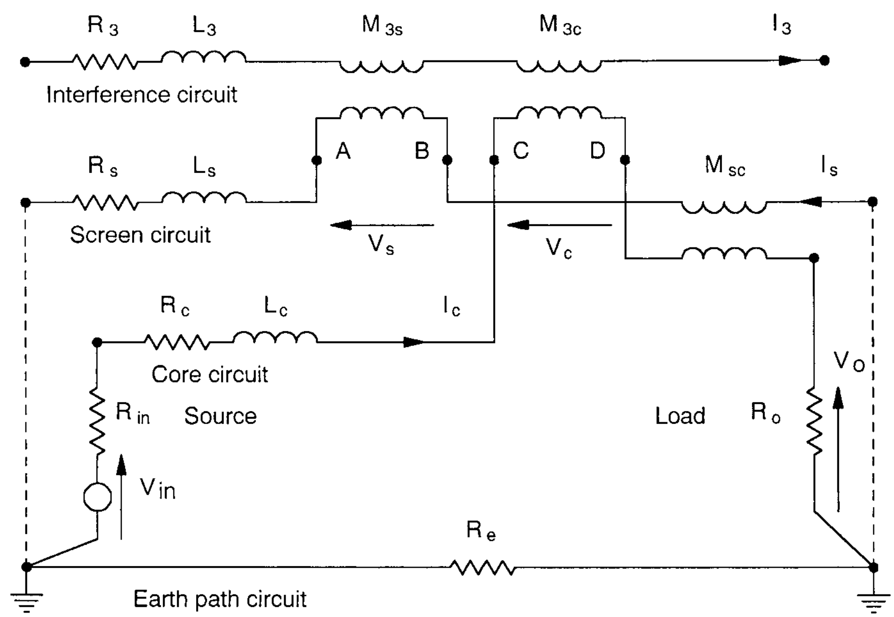

Figure 13.14 Interference and screening circuit of cables that are run in parallel with each other.

L_s is the self-inductance of the cable core.
M_{sc} is the mutual inductance between the screen and the core.

For the couplings between the cables

M_{3s} is the mutual inductance between the interference cable and the screen of the signal cable.
M_{3c} is the mutual inductance between the interference cable and the core of the signal cable.

For the components connected to the cables

R_{in} is the internal resistance of the signal source.
R_o is the output or load resistance on the signal source.
R_e is the resistance of the common earth path of the signal cable.

Consider two cases, firstly a cable without a screen and secondly one with a screen. The two cases will then be compared.

Case A. Signal cable without a screen.
The summation of voltages and emfs in the signal cable is:-

$$V_{\text{in}} = (R_{\text{in}} + R_c + j\omega L_c)I_c + j\omega M_{3c}I_3 + (R_o + R_e)I_c$$

Find I_c in terms of I_3. Assume $V_{\text{in}} = 0$ in order to determine the amount of current induced from I_3. Let this amount be called I_{co}.

$$I_{co} = \frac{-j\omega M_{3c} \cdot I_3}{R_{in} + R_c + R_o + R_e + j\omega L_c} \quad \text{amps} \tag{13.7}$$

Let the voltage appearing across the load be V_{oo}:-

$$V_{oo} = \frac{-j\omega M_{3c} - R_o \cdot I_3}{R_{\text{in}} + R_c + R_o + R_e + j\omega L_c} \quad \text{volts} \tag{13.8}$$

Let the core loop resistance be called R_{cc}:-

$$R_{cc} = R_{\text{in}} + R_c + R_o + R_e \quad \text{ohms} \tag{13.9}$$

Note that the components R_3 and L_3 of the source are not included in this result because the interference is a current source, which is known.

Case B. Signal cable with a screen.
Assume that the screen is earthed at both ends at the same points as the signal source and the output load. Hence the common earth resistance R_e is shared by both the screen and the core circuits. Again assume that V_{in} is zero for the same reason as above.

The summation of voltages and emfs in the core loop of the signal cable is:-

$$\begin{aligned} V_{\text{in}} &= (R_{\text{in}} + R_c + j\omega L_c)I_c + (R_o + R_e)I_c \\ &\quad + j\omega M_{3c}I_3 - j\omega M_{sc}I_s = 0, \text{ which upon rearranging is,} \\ &\quad - j\omega M_{3c}I_3 = (R_{cc} + j\omega L_c)I_c - j\omega M_{sc}I_s \end{aligned}$$

This has the form:-

$$y_1 = a_{11}I_c + a_{12}I_s \tag{13.10}$$

Where

$$\begin{aligned} y_1 &= -j\omega M_{3c}I_3 \\ a_{11} &= +(R_{cc} + j\omega L_c) \\ a_{12} &= -j\omega M_{sc} \end{aligned}$$

The summation of voltages and emfs in the screen loop of the signal cable is:-

$$0 = (R_s + j\omega L_s)I_s - j\omega M_{3s}I_3 - j\omega M_{sc}I_c + R_eI_s$$

which upon rearranging is,

$$-j\omega M_{3s}I_3 = +j\omega M_{sc}I_c - (R_{ss} + j\omega L_s)I_s$$

This has the form:-

$$y_2 = a_{21} I_c + a_{22} I_s \tag{13.11}$$

Where

$$\begin{aligned} y_2 &= -j\omega M_{3s} I_3 \\ a_{21} &= +j\omega M_{sc} \\ a_{22} &= -(R_{ss} + j\omega L_s) \\ R_{ss} &= +R_s + R_e \end{aligned}$$

The solution of the simultaneous equations (13.10) and (13.11) for the two currents I_s and I_c is:-

$$I_s = \frac{y_1 a_{21} - y_2 a_{11}}{a_{12} a_{21} - a_{11} a_{22}} \quad \text{amps} \tag{13.12}$$

and

$$I_c = \frac{y_2 a_{12} - y_1 a_{22}}{a_{12} a_{21} - a_{11} a_{22}} \text{ amps} \tag{13.13}$$

Some simplifications can be made after comparing the various mutual and self-inductances. The following assumptions are valid:-

$M_{sc} = L_s$ because the majority of the flux between the screen and the core couples the screen and the core.

Let $M = M_{3s} \approx M_{3c}$

And $M_{sc} \gg M_{3s}$ or M_{3c} because of the relative dimensions and separation distances.

The denominator of (13.12) and (13.13) becomes:-

$$a_{12} a_{21} - a_{11} a_{22} = R_{ss} R_{cc} + j\omega (R_{cc} L_s + R_{ss} L_c) + \omega^2 (L_s (L_s - L_c))$$

In which the extreme right-hand term is very small in the range of frequencies of interest, and can be ignored. Therefore the denominator becomes:-

$$a_{12} a_{21} - a_{11} a_{22} = R_{ss} R_{cc} + j\omega (R_{cc} L_s + R_{ss} L_c)$$

The I_s numerator of (13.12) becomes:-

$$y_1 a_{21} - y_2 a_{11} = (+\omega^2 M (L_s - L_c) + j\omega M R_{cc}) I_3$$

The I_c numerator of (13.13) becomes:-

$$y_2 a_{12} - y_1 a_{22} = (-\omega^2 M (L_s - M) + j\omega M R_{ss}) I_3$$

If the cable core terminates at a high impedance device such as the input channel of an operational amplifier, then R_o is large when compared with R_c, R_{in}, R_e and R_s.

Therefore $R_{cc} \gg R_{ss}$ unless the cable is extremely long.

Let the voltage appearing across the load be V_{os}:-

$$\begin{aligned} V_{os} = I_c R_o &= \frac{-j\omega M R_{ss} I_3}{R_{ss} + j\omega L_s} \quad \text{volts} \\ &= \frac{-j\omega M I_3}{1 + j\omega \dfrac{L_s}{R_{ss}}} \quad \text{volts} \end{aligned}$$

And revising the expression for V_{oo}:-

$$\begin{aligned} V_{oo} &= \frac{-j\omega M R_{cc} I_3}{R_{cc} + j\omega L_c} \quad \text{volts} \\ &= \frac{-j\omega M I_3}{1 + j\omega \dfrac{L_c}{R_{cc}}} \quad \text{volts} \end{aligned}$$

It can be seen from these two expressions that the screening effectiveness is mainly determined by the separation of the signal cable from the interference cable, which is not surprising and supports the standard practice of laying these cables. It is also seen that at low frequencies the screen and the core have the same magnitude of induced current and load voltage. Attenuation begins at a high frequency for both the screen and the core. The cut-off (or 3 db) frequency is typically in the range 0.5 kHz to 2.0 kHz for coaxial and twisted pair screened cables.

The overall armouring of a typical offshore signal cable is phosphor-bronze, copper or galvanised steel braid. Steel wire armouring is used where extra mechanical protection is required. The armouring provides some of the screening effect. An inner overall tinned copper, copper or aluminium tape is also frequently used. Paired, tripled and quadrupled conductors are often screened with similar tapes. However, all these various layers of screening are not very effective against low frequency interference from sources such as adjacent power cables.

13.5.3 Earthing of Screens

In some situations the core of a coaxial cable and the screen are used as a two-wire circuit, e.g. antenna cables, computer cables. In this case the signal current flows in one direction along the inner core and returns in the opposite direction in the screen. In this way the induced noise is reduced.

It is often necessary to earth one end of the screen for practical reasons. If the end at A_e in Figure 13.15 is earthed then the earth path resistance R_e shunts the screen completely and some of the screen current will flow along the earth path. This will unbalance the core and screen currents and so noise cancellation will not occur. A noise voltage will appear in the core circuit. Earthing the screen at the end B_e overcomes this difficulty because the positive channel of the amplifier is a virtual earth. In some cases the connection at B_e is made at a 'clean' or 'instrument' earth if the receiving device has only one channel or input terminal (the chassis or framework would be the second channel or

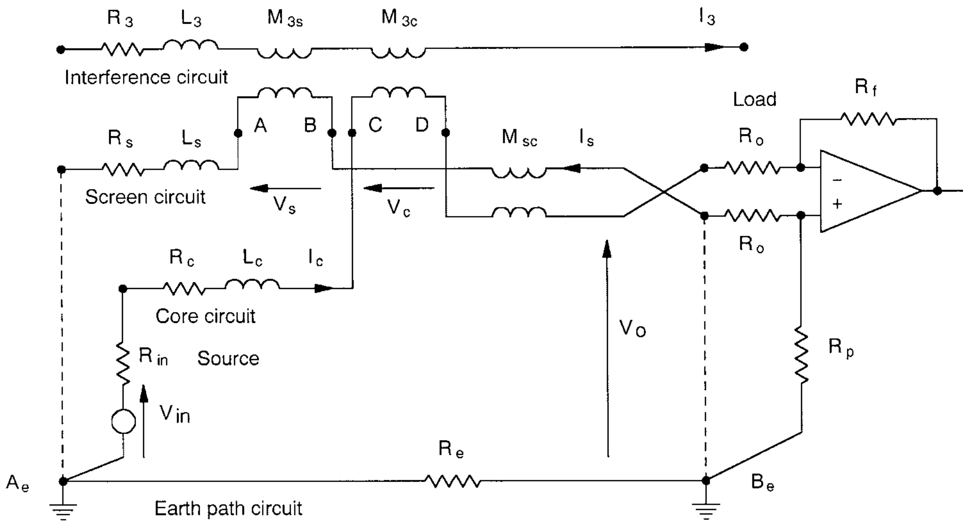

Figure 13.15 Interference and screening circuit of cables that are run in parallel with each other. The signal cable is terminated by an amplifier at the far end.

terminal). The connection at A_e also has the disadvantage that stray currents frequently flow in earth paths and so a conductive noise voltage can appear between points A_e and B_e, and will therefore add to the signal voltage V_{in}. The same principles of cancellation can be used with twisted pairs (triples and quadruples). The use of a screen around the pairs slightly improves the attenuation of induced noise, but this depends upon which end or both are earthed. Earthing the screen at the receiving device end has the best attenuation due to the same reasoning as for the two-wire coaxial circuit. Earthing the screen also discharges any electrostatic charge that may build up in the insulation, which will also appear as noise at the receiving device.

13.5.4 Screening of High Frequencies

It was mentioned in sub-section 13.5.2 that the cut-off frequency for effective screening is in the range of 0.5 kHz to 2.0 kHz for external interference. At frequencies higher than about 1 MHz it is useful to consider the coupling between the screen and the core as an impedance that relates the screen current to the core open-circuit voltage. In such a case it is not specified how the current appears in the screen. It could be by mutual induction from nearby cables, but more often by radio waves received from local radio transmitters, radio telephones, or a radar antenna. The impedance is called the 'shield transfer impedance Z_T' and it can be measured by a relatively simple test procedure. The expression for the impedance Z_T is:-

$$Z_T = \frac{V_{o/c}}{I_s l} \quad \text{ohms}$$

Where $V_{o/c}$ is the open-circuit voltage seen between the screen and the core
I_s is the screen current
and l is the length of the cable

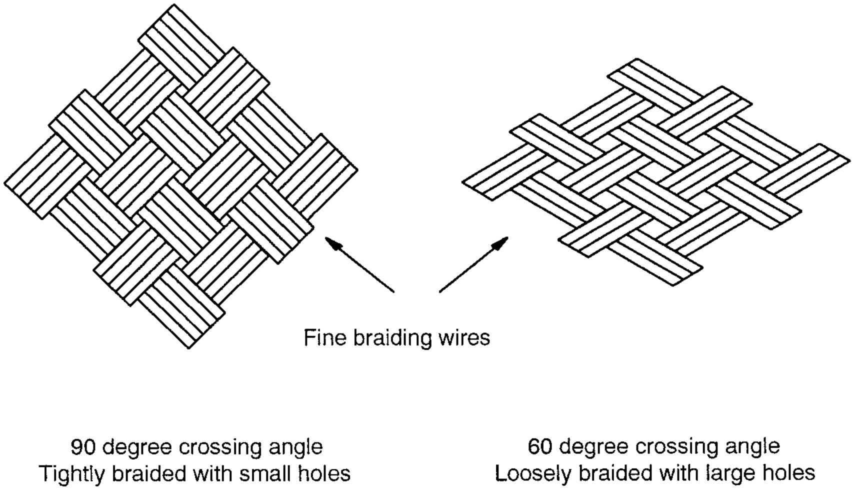

Figure 13.16 Holes in the braided armouring of instrumentation cables.

This impedance can be used to analyse the effect of laying cores close together in a multi-core cable, and whether or not to use individual screens for pairs, triples and quadruples. The impedance is a complex function of skin effect in the screen and wave propagation through the holes or gaps in a screen material such as braiding. As the frequency rises the skin effect causes the screen current to flow on the outer surface of the screen and not to penetrate towards the core. This lack of penetration prevents the currents from being mutually induced into the core. The effect is similar to placing a non-linear resistance in the primary or secondary terminals A-B and C-D of the mutual inductances shown in Figures 13.14 and 13.15. This resistance would decrease in value as the frequency increases due to the increased presence of eddy currents. The effectiveness of the screen due to skin effect reaches a maximum at about 1 MHz for typical braided screens, and about 5 MHz for aluminium foil screens. Braids vary in construction as shown in Figure 13.16. It is almost impossible to avoid 'holes' or gaps in the braiding. Even an amount as low as 2% to 5% for the area of holes in the braiding will have a significant effect on the transfer impedance and will cause it to rise when the frequency is above about 1 MHz. The effectiveness of the screen will therefore decrease significantly and VHF and UHF radiation will penetrate to the cores of the cable. If it is anticipated that the electronic equipment in a plant may be influenced by VHF or UHF radiation, for example from a local transmitting station, then the screens should be made of tightly meshed braid or non-ferrous overlapped tape.

13.5.5 Power Earths, Cubicle and Clean Earths

Plants frequently have areas where large motors, switchgear, control panels and SCADA panels are located in close proximity, especially in offshore platforms. In such cases the equipment and its internal electronic circuits needs to be earthed. If all the earthing connections are to be made locally at each item of equipment, e.g. to an earthing boss next to a control panel, then there is a possibility that control and signal circuits will pick up noise due to stray currents in the common earth circuit. This possibility can be minimised by taking special precautions in the design of the earthing systems.

a) Switchboards and motor control centres

It is the normal practice to provide a copper busbar at the base of the switchboard or motor control centre for earthing all the high power circuits, e.g. cable armouring, motor earthing cables, and low power circuits that are not sensitive to noise pick-up. This busbar is insulated from the frame, and at one or both ends there is an isolating link with bolts that bonds the busbar to the steel frame. The steel frame is bonded to the local earthing system, e.g. steel decking in a marine installation, earthing conductor or rod in a land-based installation. The isolating link can be opened for checking the earth-loop impedance or for making measurements of the noise voltages. It is often the practice to install one or two external earthing busbars in the locality of the switchgear. For example in a switchroom a busbar would be located near to each of the two opposite walls, and in reasonable proximity to the switchgear. Equipment such as switchgear, neutral earthing resistors, transformers, have their internal earth busbars or star points connected by single cables of large cross-sectional area to the external earthing busbars described above. These external earthing busbars are often mounted on insulators or bushings and fitted with bolted isolating links that are again used for testing purposes.

A typical offshore platform will have several modules or large equipment rooms and so all the external earthing busbars will be interconnected by single-core insulated cables of large cross-sectional area. The interconnections are preferably made in the form of a ring circuit so that continuity is highly assured. A similar ring circuit approach can be used for land-based plants where the items of equipment are located near to each other, otherwise a radial interconnection system or one with local grids and rods would be more economical.

b) Earthing within cubicles and panels

Instrumentation cubicles, SCADA cubicles, control panels, computer equipment and the like require to be earthed in a particular manner so as to avoid or minimise the pick up of noise. Some of the internal circuits may be very sensitive to noise pick-up from earth sources, e.g. input amplifiers, signal conditioning units. These circuits may have their own special noise elimination devices, as described in References 20 and 22, but it is better to assume that they have not for the purposes of designing a good earthing system in the first place. It is common practice therefore to provide two separate internal earthing busbars, one for general earthing and the other for the special circuits. These will be isolated and insulated from each other.

The general earthing busbar would be used for earthing the framework, chassis metalwork and cable armouring. The special earthing busbar, often called the ‘clean earth’ busbar, would be used for signal core screens, earth reference points of input circuits, and earth reference points of output circuits. Both the ‘general’ and the ‘clean’ earthing busbars would be mounted near the cable gland plate on insulated bushes. The level of insulation need not be high because in practical testing the potential to earth with the links removed would only be a few volts. (It is more governed by the expected level of cleanliness in the area at ground level, which may contaminate the bushings and cause a leakage current to pass and upset the measurements taken.) If the plant is not prone to earth pick-up noise then the general busbar could be bonded to the same local earthing boss as the main frame or cubicle. However, where earth pick-up is a problem then the clean earth busbar would be interconnected by a large section cable to the copper ring system. The general and clean busbars serve as ‘single-point’ earths, thereby eliminating pick up between distributed earthing points due to conducted noise.

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