

Code of practice for  
**Earthing**

ICS 13.260; 91.140.50

# Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee GEL/600, Earthing, upon which the following bodies were represented:

BEAMA Ltd.  
 BEAMA Electrical Cable and Conductor Accessory Manufacturers' Association  
 BG plc  
 British Broadcasting Corporation  
 British Telecommunications plc  
 Copper Development Association  
 Electrical Contractors' Association  
 Electrical Installation Equipment Manufacturers' Association (BEAMA Ltd.)  
 Electricity Association  
 Engineering Equipment and Materials Users' Association  
 Institute of Petroleum  
 Institution of Lighting Engineers  
 Institution of Incorporated Executive Engineers  
 National Federation of Master Steeplejacks and Lightning Conductor Engineers  
 National Inspection Council for Electrical Installation Contracting  
 Department of Trade and Industry (Engineering Inspectorate)  
 Department of the Environment, Transport and the Regions (Highways Agency)  
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## Foreword

This British Standard has been prepared by Technical Committee GEL/600. It supersedes BS 7430:1991 which is withdrawn. This edition incorporates various changes necessary to ensure that the standard remains authoritative in the light of recent developments, but it does not constitute a comprehensive revision.

Since the preparation of the previous edition of BS 7430, the Electricity at Work Regulations (Northern Ireland) were introduced in 1991, and the Electrical Equipment (Safety) Regulations were introduced in 1994.

Protective multiple earthing (PME) is widely adopted in the UK for public electricity supply at low voltage and this British Standard contains recommendations on appropriate earthing practices for consumers' installations. However, this standard describes all three types of electrical supply systems standardized by the International Electrotechnical Commission (IEC).

The development of international electrical installation standards by the International Electrotechnical Commission (IEC) and their adoption by the European Committee for Electrotechnical Standardization (CENELEC) have been recognized in BS 7671, *Requirements for electrical installations (IEE Wiring Regulations, Sixteenth Edition)*. This edition of BS 7430 has been adapted to align with the latter document.

BS 7430 gives recommendations for earthing temporary structures. The clause on generation covers standby generators, machines operating in parallel with an incoming supply, asynchronous machines and both three-phase and single-phase portable generators.

BS 7671, *Requirements for electrical installations (IEE Wiring Regulations, Sixteenth edition)* is not statutory, but compliance may satisfy the requirements of certain statutory regulations. It is advisable therefore to comply with BS 7671 where appropriate.

As a code of practice, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

**Compliance with a British Standard does not of itself confer immunity from legal obligations.**

### Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 82, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.



## 1 Scope

This British Standard gives guidance on the methods that may be adopted to earth an electrical system for the purpose of limiting the potential (with respect to the general mass of the earth) of current-carrying conductors forming part of the system, and non-current-carrying metalwork associated with equipment, apparatus, and appliances connected to the system.

NOTE 1 The former object is normally essential to the proper operation of the system, and this aspect is generally known as "system earthing". The latter concerns the safety of human life, of animals and of property, and this aspect is sometimes known as "equipment earthing".

NOTE 2 The term "earthing" is used in this regard whether or not reliance is placed on the earth itself as a low impedance return path for earth fault currents.

BS 7430 applies only to land-based installations; it does not apply to ships, aircraft or offshore installations, nor does it deal with the earthing of medical equipment (see BS 5724) or the special problems encountered with solid state electronic components and equipment due to their sensitivity to static electricity.

This standard does not address electromagnetic compatibility requirements for earthing, nor does it give recommendations for functional earthing.

## 2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of this British Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 729, *Specification for hot dip galvanized coatings on iron and steel articles.*

BS 951, *Specification for clamps for earthing and bonding purposes.*

BS 3019-1, *TIG welding — Part 1: Specification for TIG welding of aluminium, magnesium and their alloys.*

BS 3288-1, *Insulator and conductor fittings for overhead power lines — Part 1: Performance and general requirements.*

BS 3535, *Isolating transformers and safety isolating transformers.*

BS 3571, *MIG welding.*

BS 4293, *Specification for residual current-operated circuit-breakers.*

BS 4727, *Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms.*

BS 5345, *Code of practice for selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosive processing and manufacture).*

BS 6651, *Code of practice for protection of structures against lightning.*

BS 7375, *Code of practice for distribution of electricity on construction and building sites.*

BS 7671:1992, *Requirements for electrical installations. IEE Wiring Regulations. Sixteenth edition.*

BS EN 10025, *Hot rolled products of non-alloy structural steels — Technical delivery conditions.*

## 3 Definitions

For the purposes of this British Standard, the definitions given in BS 4727 apply, together with the following.

### 3.1 bonding conductor

<sup>1)</sup>protective conductor providing equipotential bonding

### 3.2 caravan

trailer leisure accommodation vehicle, used for touring, designed to meet the requirements for construction and use of road vehicles

### 3.3 caravan park

<sup>1)</sup>area of land that contains two or more caravan pitches

### 3.4 caravan pitch

<sup>1)</sup>plot of ground upon which a single leisure accommodation vehicle or leisure home may stand

### 3.5 caravan pitch electrical supply equipment

<sup>1)</sup>equipment that provides means of connecting and disconnecting supply cables from a leisure accommodation vehicle to a fixed external power supply

<sup>1)</sup> Identical with the definition given in BS 7671:1992.

### 3.6 class I equipment

<sup>2)</sup>equipment in which protection against electric shock does not rely on basic insulation only, but which includes means for the connection of exposed conductive parts to a protective conductor in the fixed wiring of the installation (see BS 2754)

### 3.7 class II equipment

equipment in which protection against electric shock does not rely on basic insulation only, but in which additional safety precautions such as supplementary insulation are provided, there being no provision for the connection of exposed metalwork of the equipment to a protective conductor, and no reliance upon precautions to be taken in the fixed wiring of the installation (see BS 2754)

### 3.8 double insulation

<sup>2)</sup>insulation comprising both basic insulation and supplementary insulation

### 3.9 Earth

<sup>2)</sup>conductive mass of the Earth, whose electric potential at any point is conventionally taken as zero

### 3.10 earth electrode

<sup>2)</sup>conductor or group of conductors in intimate contact with, and providing an electrical connection to, Earth

### 3.11 earth electrode resistance

<sup>2)</sup>resistance of an earth electrode to Earth

### 3.12 earth fault current

<sup>2)</sup>fault current which flows to Earth

### 3.13 earth fault loop impedance

<sup>2)</sup>impedance of the earth fault current loop starting and ending at the point of earth fault

this impedance is denoted by the symbol  $Z_s$

the earth fault loop comprises the following starting at the point of fault:

- the circuit protective conductor; and
- the consumer's earthing terminal and earthing conductor; and
- for TN systems, the metallic return path; or

— for TT and IT systems, the earth return path; and

— the path through the earthed neutral point of the transformer and the transformer winding; and

— the phase conductor from the transformer to the point of fault

### 3.14 earth grid

earth electrode in the form of two overlapping groups of buried, parallel, horizontal electrodes in the same rectangular area, usually laid approximately at right angles to each other, with the electrodes bonded at each intersection

### 3.15 earth leakage current

<sup>2)</sup>current which flows to Earth, or to extraneous-conductive-parts, in a circuit which is electrically sound.

this current may have a capacitive component including that resulting from the deliberate use of capacitors

### 3.16 earthed concentric wiring

<sup>2)</sup>wiring system in which one or more insulated conductors are completely surrounded throughout their length by a conductor, e.g. a metallic sheath, which acts as a PEN conductor

### 3.17 earthing conductor

<sup>2)</sup>protective conductor connecting the main earthing terminal of an installation to an earth electrode or to other means of earthing

### 3.18 earthing system

one or more earth electrodes with their earthing conductors, capable of being connected to a main earthing terminal

### 3.19 electrically independent earth electrodes

<sup>2)</sup>earth electrodes located at such a distance from one another that the maximum current likely to flow through one of them does not significantly affect the potential of the other(s)

### 3.20 equipotential bonding

<sup>2)</sup>electrical connection maintaining various exposed-conductive-parts and extraneous-conductive-parts at substantially the same potential

<sup>2)</sup> Identical with the definition given in BS 7671:1992.



**3.21****exposed-conductive-part**

<sup>3)</sup>conductive part of equipment which can be touched and which is not a live part but which may become live under fault conditions

**3.22****extraneous-conductive-part**

<sup>3)</sup>conductive part liable to introduce a potential, generally earth potential, and not forming part of the electrical installation

**3.23****fault**

<sup>3)</sup>circuit condition in which current flows through an abnormal or unintended path

this may result from an insulation failure or the bridging of insulation

conventionally the impedance between live conductors or between live conductors and exposed or extraneous-conductive-parts at the fault position is considered negligible

**3.24****final circuit**

<sup>3)</sup>circuit connected directly to current-using equipment, or to a socket-outlet or socket-outlets or other outlet points for the connection of such equipment

**3.25****functional earthing**

<sup>3)</sup>connection to Earth necessary for proper functioning of electrical equipment

**3.26****ground potential**

electric potential with respect to the general mass of Earth which occurs in, or on the surface of, the ground around an earth electrode when an electric current flows from the electrode to the ground

**3.27****leisure accommodation vehicle**

<sup>3)</sup>unit of living accommodation for temporary or seasonal occupation which may meet requirements for construction and use of road vehicles

**3.28****live part**

<sup>3)</sup>conductor or conductive part intended to be energized in normal use, including a neutral conductor but, by convention, not a PEN conductor

**3.29****main earthing terminal**

<sup>3)</sup>terminal or bar provided for the connection of protective conductors, including equipotential bonding conductors, and conductors for functional earthing, if any, to the means of earthing

**3.30****motor caravan**

<sup>3)</sup>self-propelled leisure accommodation vehicle, used for touring, designed to meet requirements for the construction and use of road vehicles

the accommodation may be fixed or demountable

**3.31****neutral conductor**

conductor connected to the neutral point of a system and capable of contributing to the transmission of electrical energy

the term also means the equivalent conductor of an IT or d.c. system unless otherwise specified in BS 7671

**3.32****nominal voltage**

voltage by which an installation (or part of an installation) is designated

the following ranges of nominal voltage (r.m.s. values for a.c.) are defined:

- a) extra-low normally not exceeding 50 V a.c. or 120 V ripple free d.c., whether between conductors or to Earth;
- b) low normally exceeding extra-low voltage but not exceeding 1 000 V a.c. or 1 500 V d.c. between conductors, or 600 V a.c. or 900 V d.c. between conductors and Earth;
- c) high exceeding 1 000 V a.c. or 1 500 d.c. between conductors, or 600 V a.c. or 900 V d.c. between conductors and Earth

the actual voltage of the installation may differ from the nominal value by a quantity within normal tolerances

**3.33****PEN conductor**

<sup>3)</sup>conductor combining the functions of both protective conductor and neutral conductor

**3.34****portable equipment**

<sup>3)</sup>electrical equipment which is moved while in operation or which can easily be moved from one place to another while connected to the supply

**3.35****potential gradient (at a point)**

potential difference per unit length measured at that point in the direction in which it is a maximum

**3.36****protective conductor**

conductor used for some measures of protection against electric shock and intended for connecting together any of the following parts:

<sup>3)</sup> Identical with the definition given in BS 7671:1992.

- exposed-conductive-parts;
- extraneous-conductive-parts;
- the main earthing terminal;
- earth electrode(s);
- the earthed point of the source, or an artificial neutral

NOTE See Figure 24.

### 3.37 reinforced insulation

<sup>4)</sup>single insulation applied to live parts, which provides a degree of protection against electric shock equivalent to double insulation under the conditions specified in the relevant standard the term “single insulation” does not imply that the insulation has to be one homogeneous piece it may comprise several layers that cannot be tested singly as supplementary or basic insulation

### 3.38 residual current device (RCD)

<sup>4)</sup>mechanical switching device or association of devices intended to cause the opening of the contacts when the residual current attains a given value under specified conditions

### 3.39 residual operating current

<sup>4)</sup>residual current which causes the residual current device to operate under specified conditions

### 3.40 resistance area (for an earth electrode only)

<sup>4)</sup>surface area of ground (around an earth electrode) on which a significant voltage gradient may exist

### 3.41 simultaneously accessible parts

<sup>5)</sup>conductors or conductive parts which can be touched simultaneously by a person or, in locations specifically intended for them, by livestock

NOTE Simultaneously accessible parts may be:

- live parts;
- exposed-conductive-parts;
- extraneous-conductive-parts;
- protective conductors;
- earth electrodes

### 3.42 supplementary insulation

<sup>4)</sup>independent insulation applied in addition to basic insulation in order to provide protection against electric shock in the event of a failure of basic insulation

### 3.43 switchgear

<sup>4)</sup>an assembly of main and auxiliary switching apparatus for operation, regulation, protection or other control of an electrical installation

## 4 Supply system earthing

### 4.1 Relevant legislation

In Great Britain earthing of an electricity supply system is governed by the following legislation and regulations:

- a) Regulations 4 to 8 of the current Electricity Supply Regulations;
- b) the Electricity at Work Regulations 1989.

In Northern Ireland, regulations made by the Ministry of Commerce for Northern Ireland apply. The general provisions in the Electricity Supply Regulations apply to both overhead and underground systems of supply. The regulations require at least one point of every system to be connected with Earth. This requirement is designed primarily to preserve the security of the system by ensuring that the potential on each conductor is restricted to such a value as is consistent with the level of insulation applied.

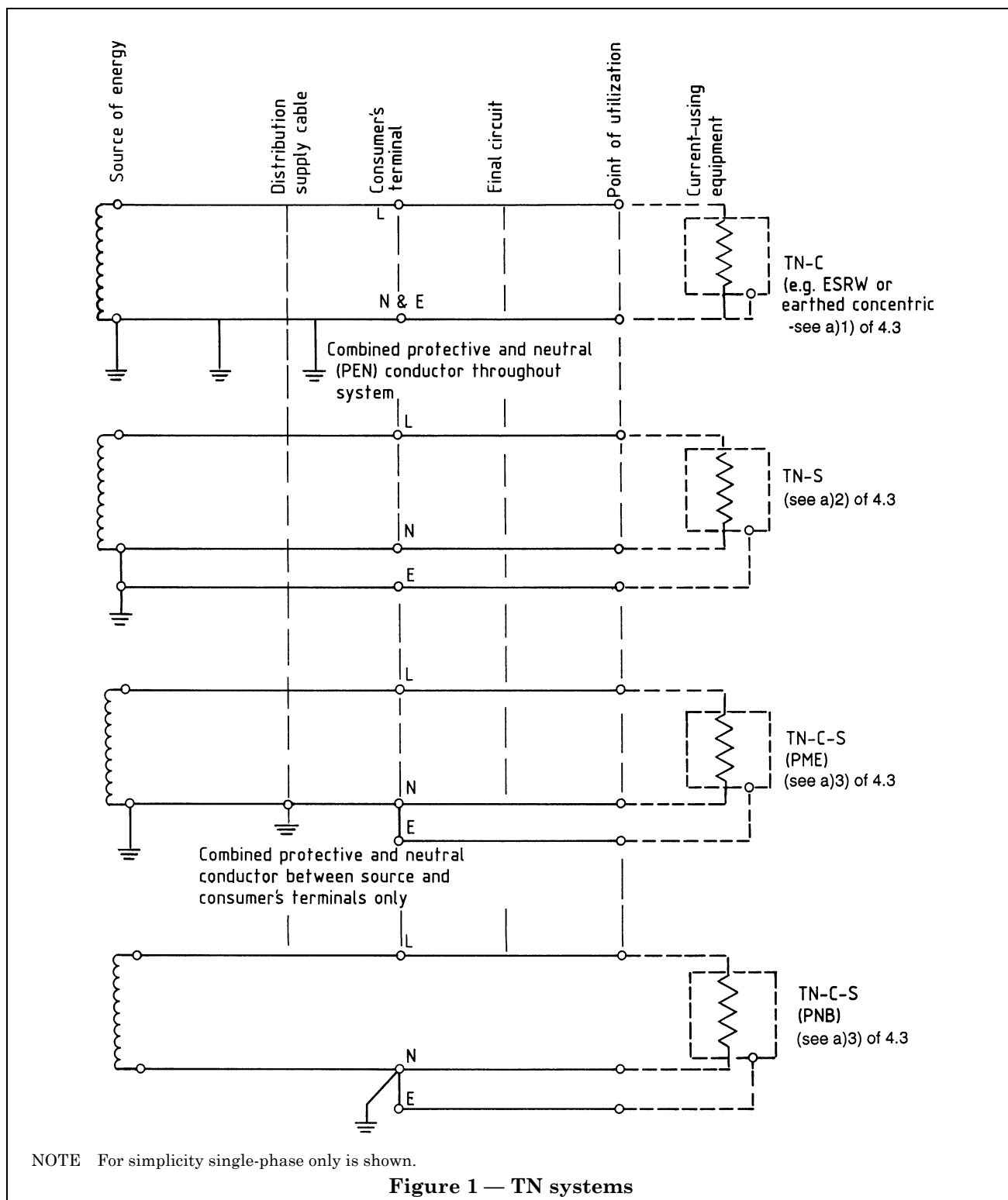
The regulations include requirements for multiple earthing of low voltage (LV) systems and for the use of protective multiple earthing (PME), and this is the usual designation of the system shown in Figure 1. In such cases there are requirements controlling the relative size of the phase and neutral conductors and the earthing of the system. In the case of protective multiple earthing, the sizes of bonding connections in the consumer's installation are specified.

### 4.2 General

A system is satisfactorily earthed if the protective gear operates to remove danger in the event of a fault to any metalwork having a continuous metallic connection to the system neutral. An earthed metallic sheath of an underground cable, the neutral of a PME system or an earth wire in a transmission line may provide a low resistance path from a fault back to the system neutral. With some overhead lines, because of high soil resistivity, it may not be possible economically to attain a sufficiently low resistance fault path and the operation of overcurrent protection may be slowed down or inhibited.

<sup>4)</sup> Identical with the definition given in BS 7671:1992.

<sup>5)</sup> Effectively identical with the definition given in BS 7671. The latter incorporates the substance of the note within the text.



For the purposes of this standard it is convenient to consider a system as comprising a source of energy and an installation; the former including the supply conductors to the latter.

In the overwhelming majority of cases the source of energy is the property and responsibility of an electricity supplier, and the installation is a consumer's installation. Even in those industrial

installations where the source of energy is owned and controlled by the user it is still convenient to consider the source separately from the circuit and current-using equipment in the installation.

#### 4.3 Classification of low voltage systems

BS 7671 has adopted the internationally agreed classification of low voltage system types as follows.

a) A *TN system* has one or more points of the source of energy directly earthed and the exposed and extraneous-conductive-parts of the installation are connected only by means of protective conductors to the earthed point(s) of the source, i.e. there is a metallic path for earth fault currents to flow from the installation to the earthed point(s) of the source (see Figure 1).

TN systems are subdivided into the following.

1) TN-C systems where the neutral and protective functions are combined in a single conductor throughout the system. Earthed concentric wiring or earthed sheath return wiring (ESRW) are both examples of a TN-C system.

2) TN-S systems where there are separate neutral and protective conductors throughout the system. A system where the metallic path between the installation and the source of energy is the sheath and armoring of the supply cable is a TN-S system.

3) TN-C-S systems where the neutral and protective functions are combined in a single conductor but only in a part of a system. The type of distribution that is commonly called protective multiple earthing is TN-C-S, the supply itself being TN-C and the arrangement in the installation being TN-S. The protective neutral bonding (PNB) system is a variant of the TN-C-S system with single point earthing.

b) A *TT system* has one or more points of the source of energy directly earthed and the exposed and extraneous-conductive-parts of the installation are connected to a local earth electrode or electrodes that are electrically independent of the source earth(s).

c) An *IT system* has the source either unearthed or earthed through a high impedance and the exposed-conductive-parts of the installation are connected to an electrically independent earth electrode (see Figure 2). Attention is drawn to the requirements of the current Electricity Supply Regulations, which do not permit the use of this system for public supply networks in the UK.

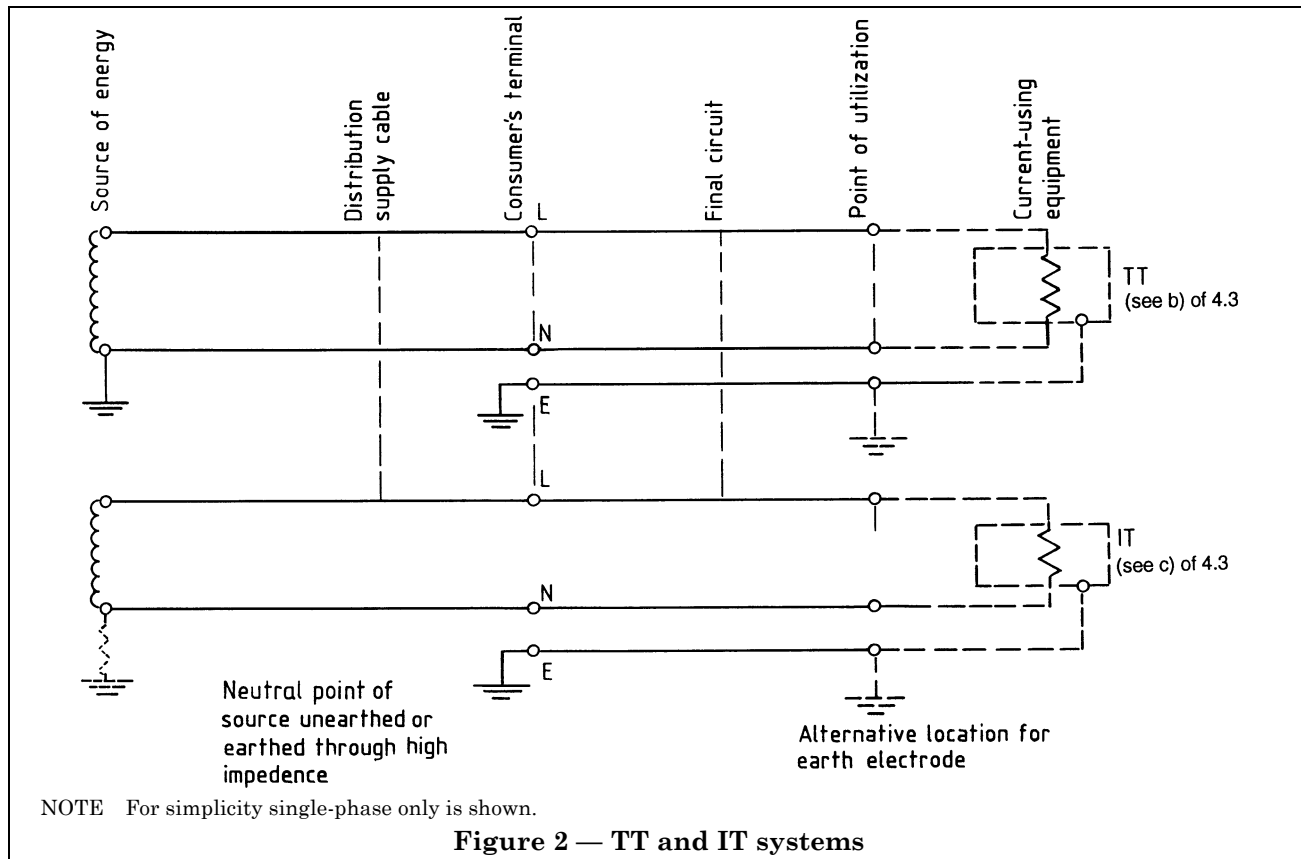


Figure 2 — TT and IT systems

In practice a system may be a combination of types, one example of this being an installation that is part of a TN system where a particular circuit or circuits may need to be protected by a residual current device. If the exposed-conductive-parts of that circuit or those circuits are connected to an independent earth electrode, that part of the installation has then to be treated as being in a TT system. The great majority of installations form a part of TN-S, TN-C-S or TT systems.

Attention is drawn to the requirements embodied in the current Electricity Supply Regulations, which cover the installation when the supplier provides multiple earthing. An individual exemption is required when it is intended to use earthed concentric wiring in the installation, this being a TN-C system and this exemption has to be obtained from the supplier concerned.

## 5 Electrical equipment earthing

The object of electrical equipment earthing is to ensure effective operation of the protective gear in the event of earth fault currents that might otherwise cause damage to property, and to protect against danger to life through shock due to installation metalwork being maintained at a dangerous potential relative to earth. The method used to connect such metalwork to earth has to be compatible with the type of installation and its supply system. The requirements for the connection of metalwork of electrical equipment, other than parts that are normally live or current carrying, to an earthing terminal, are specified, in general, in the regulations referred to in 4.1.

BS 7671 also deals with the earthing of installations.

## 6 System and equipment protection

### 6.1 General

A primary purpose of earthing is to enable a system or equipment to be disconnected from the source of energy so as to avoid the effects of excessive currents produced under earth fault conditions. The apparatus performing this task is referred to as the protection equipment.

### 6.2 Electrical protection of systems

This subject is highly specialized particularly in respect of high voltage (HV) systems, and readers requiring further information should refer to IEC 255-20:1984, *Electrical relays* — Part 20: *Protection (protective) systems*, BS 142, relevant text books and equipment manufacturers.

### 6.3 Equipment protection: selection of devices for automatic disconnection of supply

The selection of suitable protective devices depends upon the characteristics of the electricity supply system (see clauses 4 and 5), the distribution circuits and the equipment being protected (see clause 21).

The selection of the various devices for the automatic disconnection of the supply in the event of a fault, and their characteristics is outside the scope of this standard, but relevant information can be obtained from relevant British Standards, including the following:

BS 88, *Cartridge fuses for voltages up to and including 1 000 V a.c. and 1 500 V d.c.*

BS 842, *Specification for a.c. voltage-operated earth-leakage circuit breakers.*

NOTE 1 The use of voltage-operated earth-leakage circuit breakers is not recommended for LV a.c. installations.

BS 1361, *Specification for cartridge fuses for a.c. circuits in domestic and similar premises.*

BS 1362, *Specification for general purpose fuse links for domestic and similar purposes (primarily for use in plugs).*

NOTE 2 Although the fuses covered by this standard are used in plugs they can also be used in fixed installations as part of fuse connector units, etc.

BS 3036, *Specification. Semi-enclosed electric fuses (ratings up to 100 amperes and 240 volts to earth).*

BS 3938, *Specification for current transformers (obsolescent).*

BS 4293, *Specification for residual current-operated circuit-breakers.*

BS 4444, *Guide to electrical earth monitoring and protective conductor proving.*

NOTE 3 BS 4752 covers both moulded case circuit breakers and conventional air breakers.

BS 5311, *Specification for high-voltage alternating-current circuit-breakers.*

BS 5486, *Low-voltage switchgear and controlgear assemblies.*

BS 7626, *Specification for current transformers.*

BS EN 60269-1, *Low voltage fuses — Part 1: General requirements.*

BS EN 60269-2, *Low voltage fuses — Part 2: Supplementary requirements for fuses for use by authorized persons (fuses mainly for industrial application).*

BS EN 60439-1, *Specification for low-voltage switchgear and controlgear assemblies — Part 1: Specification for type-tested and partially type-tested assemblies.*

BS EN 60694, *Common specifications for high-voltage switchgear and controlgear standards.*

BS EN 60898, *Specification for circuit-breakers for overcurrent protection for household and similar installations.*

BS EN 60947-2, *Specification for low-voltage switchgear and controlgear — Part 2: Circuit-breakers.*

BS EN 60947-5-1, *Specification for low-voltage switchgear and controlgear — Part 5: Control circuit devices and switching elements — Part 5.1: Electromechanical control circuit devices.*

BS EN 61008-1, *Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) — Part 1: General rules.*

BS EN 61009-1, *Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBOs) — Part 1: General rules.*

## 7 Factors involved in effective earthing

Earthing of either a system or equipment involves the provision of a connection to the general mass of earth. This connection should have a resistance not greater than the design value and should be capable of carrying the expected maximum fault current.

It is therefore necessary to consider the various factors which affect the resistance to earth and fault current capacity of the buried conductor, designated the earth electrode. These include the size and shape of the earth conductor, the soil in which it is buried and the connection of the system to it. It is also necessary to give consideration to the current density at the surface of the earth electrode and the ground potentials in its vicinity.

## 8 Soil resistivity

**8.1** The resistance to earth of a given electrode depends upon the electrical resistivity of the soil in which it is installed. This factor may therefore be important in deciding which of many protective systems to adopt.

The composition of the soil largely determines its resistivity and examples are given in Table 1. Earth resistivity is, however, essentially electrolytic in nature and is affected therefore by the moisture content of the soil and by the chemical composition and concentration of salts dissolved in the contained water. Grain size and distribution, and closeness of packing are also contributory factors since they control the manner in which the moisture is held in the soil. Many of these factors vary locally and some vary seasonally, so that Table 1 should only be taken as a general guide. For this purpose, columns 2 and 3 apply to most of the British Isles, but column 5 is applicable to certain areas, such as marshy flats around river estuaries.

Local values should be verified by measurement (see clause 17), and this is especially important where the soil is stratified as, owing to the dispersion of the earth current, the effective resistivity depends not only on the surface layers but also on the underlying geological formation. Stratification of the soil should be taken into account when the type of electrode and its depth are being considered.

It should also be noted that soil temperature has some effect, but is only important near and below freezing point, necessitating the installation of earth electrodes at depths to which frost will not penetrate. It is therefore recommended that any part of an earth electrode system within 1 m of the soil surface should not be regarded as being effective under frost conditions.

While the fundamental nature and properties of a soil in a given area cannot be changed, use can be made of purely local conditions in choosing suitable electrode sites and of methods of preparing the site selected to secure the optimum resistivity. These measures are summarized in 8.2 to 8.5.

**8.2** Where there is any option, a site should be chosen in one of the following types of soil in the order of preference given:

- a) wet marshy ground (but see 8.3);
- b) clay, loamy soil, arable land, clayey soil, clayey soil or loam mixed with small quantities of sand;
- c) clay and loam mixed with varying proportions of sand, gravel, and stones;
- d) damp and wet sand, peat.

Dry sand, gravel, chalk, limestone, whinstone, granite and any very stony ground should be avoided if possible, also all locations where virgin rock is very close to the surface.

Table 1 — Examples of soil resistivity ( $\Omega\cdot\text{m}$ )

Type of soil	Climatic condition			
	Normal and high rainfall (i.e. greater than 500 mm a year)		Low rainfall and desert conditions (i.e. less than 250 mm a year)	Underground waters (saline)
	Probable value	Range of values encountered	Range of values encountered	Range of values encountered
Alluvium and lighter clays	5	See note	See note	1 to 5
Clays (excluding alluvium)	10	5 to 20	10 to 100	1 to 5
Marls (e.g. Keuper marl)	20	10 to 30	50 to 300	
Porous limestone (e.g. chalk)	50	30 to 100		
Porous sandstone (e.g. Keuper sandstone and clay shales)	100	30 to 300		
Quartzites, compact and crystalline limestone (e.g. carboniferous sediments, marble, etc.)	300	100 to 1 000		
Clay slates and slaty shales	1 000	300 to 3 000	1 000 upwards	30 to 100
Granite	1 000			
Fissile slates, schists, gneiss and igneous rocks	2 000	1 000 upwards		

NOTE Depends on water level of locality.

**8.3** A site should be chosen that is not naturally well drained. A water-logged situation is not, however, essential unless the soil is sand or gravel, as in general no advantage results from an increase in moisture content above about 15 % to 20 %. Care should be taken to avoid a site kept moist by water flowing over it (e.g. the bed of a stream) as the beneficial salts may be entirely removed from the soil in such situations.

**8.4** Where constructional work has taken place, or cut and fill or imported fill operations have been carried out, the resulting disturbance may alter site conditions. In these cases deeper driving of the electrode may be necessary to reach layers of reasonable resistivity and also to reach stable ground, such that the value of the earth electrode resistance remains stable if the top layers of the ground dry out.

**8.5** Soil treatment or replacement to improve earth electrode contact resistance may be used in special or difficult locations. Migration and leaching of applied chemicals over a period of time reduces the efficiency of soil treatment progressively, requiring constant monitoring and replacement of the additives. Ecological considerations should be considered before such treatment is commenced and any deleterious effect upon electrode material has to be taken into account. However, for some temporary electrical installations in areas of high ground resistivity, this may be the most economic method for obtaining satisfactory earth contact over a short period. If a greater degree of permanence is envisaged, it may be desirable to replace the soil immediately around an electrode with a lower resistivity material, such as:

- a) a clay based material formed by the decomposition of volcanic ash, such as bentonite;
- b) concrete (see 12.2 and 16.1);
- c) a conductive concrete or cement made with graded granular carbonaceous aggregate in place of the conventional sand or aggregate (see 19.6.1).

Such treatment may be used to advantage in rocky terrain. Where holes are bored for insertion of vertical earth electrodes, or where strip earth electrodes are laid radially under shallow areas having a low resistivity which overlay rock strata, suitable treatment will reduce the contact resistance with respect to the general mass of ground.

The use of coke breeze as an infill is not recommended as it may result in rapid corrosion not only of the electrode itself but also of cable sheaths.

The resistance,  $R$ , expressed in ohms ( $\Omega$ ), of a vertical electrode surrounded by an infill of material such as bentonite or concrete is given approximately by the following equation:

$$R = \frac{1}{2\pi L} \left[ (\rho - \rho_c) \left( \log_e \left[ \frac{8L}{D} \right] - 1 \right) + \rho_c \left( \log_e \left[ \frac{8L}{d} \right] - 1 \right) \right]$$

where

- $\rho$  is the resistivity of soil, in ohm metres ( $\Omega$  m);
- $\rho_c$  is the resistivity of infill material, in ohm metres ( $\Omega$  m);
- $d$  is the diameter of electrode, in metres (m);
- $D$  is the diameter of infill, in metres (m);
- $L$  is driven length of electrode, in metres (m).

The resistivity of bentonite varies from about 3  $\Omega$  m upwards, depending on its moisture content. It is hygroscopic and will absorb available moisture from the surrounding soil. Should it become dry, due to a complete absence of moisture in the surrounding soil, its resistivity rises appreciably and it will shrink away from the electrode.

The resistivity of concrete is in the range 30  $\Omega$  m. to 90  $\Omega$  m.

## 9 Effect of shape on electrode resistance

With single electrodes the greater part of the fall in potential occurs in the soil within a metre or so of the electrode surface, since it is here that the current density is highest. To obtain a low overall resistance, the current density should be as low as possible in the medium adjacent to the electrode, which should be so designed as to cause the current density to decrease rapidly with distance from the electrode. This condition is achieved by making the dimensions in one direction large compared with those in the other two, thus a pipe, rod or strip has a much lower resistance than a plate of equal surface area. The resistance is not, however, inversely proportional to the surface area of the electrode.

## 10 Resistance of common types of earth electrodes

NOTE Examples of calculations for various types of electrodes are given in Annex A.

**10.1 Plates** The approximate resistance to earth of a plate ( $R$ ) in ohms ( $\Omega$ ) can be calculated from the following equation:

$$R = \frac{\rho}{4} \sqrt{\left( \frac{\pi}{2A} \right)}$$

where

- $\rho$  is the resistivity of the soil (assumed uniform), in ohm metres ( $\Omega$  m);
- $A$  is the area of one face of the plate, in square metres ( $\text{m}^2$ ).

The value of  $\rho$  varies with climatic conditions and therefore calculations using site measured values should be rounded up to the nearest whole number. If calculations are based on predictions using values from Table 1, the highest value of  $\rho$  for a given type of soil should be used.

Where the resistance of a single plate is higher than the required value, two or more plates may be used in parallel, and the total resistance is then inversely proportional to the number employed, provided that each plate is installed outside the resistance area of any other. This normally requires a separation of about 10 m, but for sizes of plate generally employed a separation of 2 m is sufficient to ensure that the total resistance will not exceed the value obtained from the above equation by more than 20 %. Even at the latter spacing, it is generally more economical to use two plates in parallel, each of a given size, than one of twice that size. The size employed is therefore normally not greater than 1.2 m  $\times$  1.2 m.



Connections to copper plate electrodes should be by a copper conductor, welded, rivetted or otherwise attached without involving materials likely to cause corrosion. Such joints should be protected by a heavy coat of bitumen, or similar suitable material.

The connection between the earth plate and an above ground disconnecting link should be insulated to reduce electrolytic action. The plates should be set vertically and the depth of setting should be such as to ensure that the surrounding soil is always damp. The minimum cover should be 600 mm except that, where the underlying stratum is solid, e.g. chalk or sandstone, and near the surface, the top of the plate should be level with the top of the solid stratum. Sufficient solid stratum should be removed and replaced with fine soil or other suitable infill to obtain an acceptably low resistance.

The resistance to Earth  $R$ , expressed in ohms ( $\Omega$ ), of a 1.2 m  $\times$  1.2 m plate is given approximately by the following equation:

$$R = \frac{\rho}{4}$$

where

$\rho$  is the resistivity of the soil (assumed uniform), in ohm metres ( $\Omega$  m).

For conventional sizes the resistance is approximately inversely proportional to the linear dimensions, not to the surface area, i.e. a 0.9 m  $\times$  0.9 m plate would have a resistance approximately 25 % higher than a 1.2 m  $\times$  1.2 m plate.

## 10.2 Rods or pipes

The resistance to earth of a rod or pipe electrode  $R$ , in ohms ( $\Omega$ ), is given by the following equation:

$$R = \frac{\rho}{2\pi L} \left[ \log_e \left( \frac{8L}{d} \right) - 1 \right]$$

where

$L$  is the length of the electrode, in metres (m);

$d$  is the diameter, in metres (m);

$\rho$  is the resistivity of the soil, in ohm metres ( $\Omega$  m) (assumed uniform).

The curves shown in Figure 3 are calculated from this equation for electrodes of 12.5 mm, 25 mm and 100 mm diameter in a soil of 100  $\Omega$  m resistivity. Change of diameter has a relatively minor effect, and size of pipe is generally governed by mechanical resistance to bending or splitting. It is apparent that the electrical resistance diminishes rapidly with the first metre or so of driving, but less so at depths greater than 2 m to 3 m in soil of uniform resistivity.

A number of rods or pipes may be connected in parallel and the resistance is then practically proportional to the reciprocal of the number employed so long as each is situated outside the resistance area of any other. In practice this is often assumed to be satisfied by a mutual separation equal to the driven depth. Little is to be gained by separation beyond twice the driven depth. A substantial gain is effected even at 2 m separation. Figure 4 shows the effect of inter-electrode spacing for two rod electrodes 3 m long by 15.9 mm diameter.

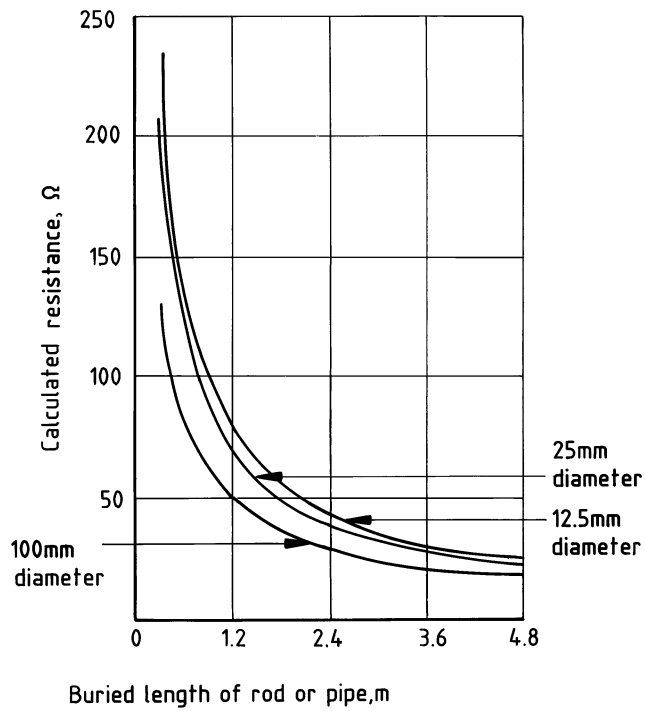


Figure 3 — Effect of buried length of rod or pipe electrode on calculated resistance for soil resistivity of 100 Ω·m (assumed uniform)

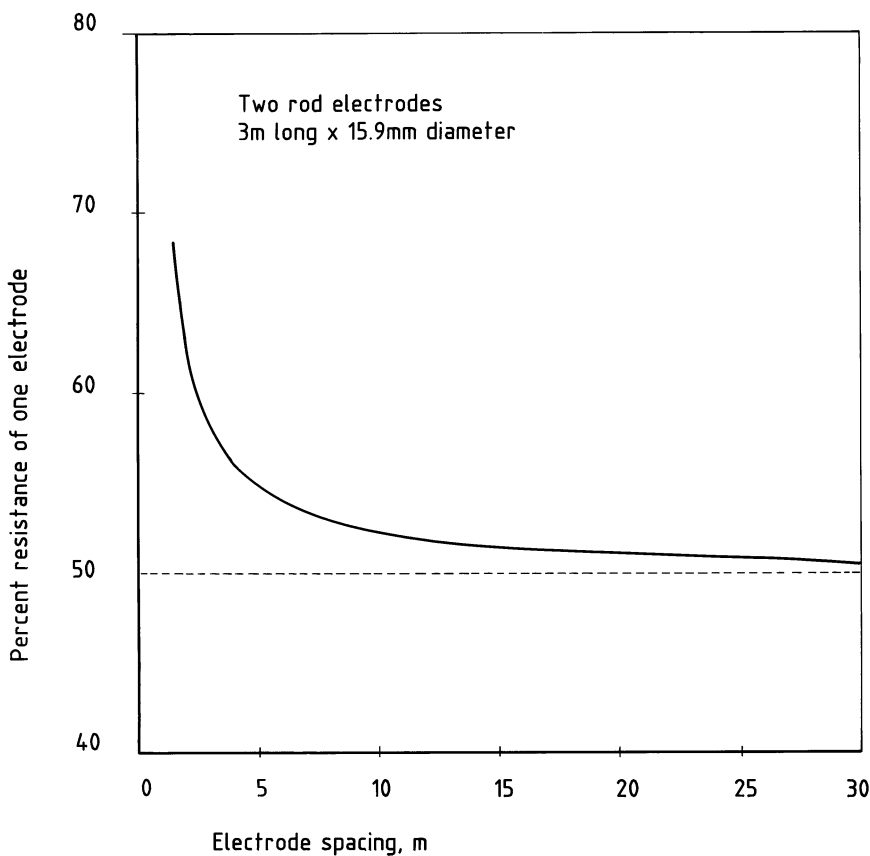


Figure 4 — Effect of inter-electrode spacing on combined resistance

The combined resistance of rod electrodes in parallel  $R_n$ , expressed in ohms ( $\Omega$ ), can be obtained from the following equation:

$$R_n = R \left( \frac{1 + \lambda a}{n} \right)$$

$$\text{in which } a = \frac{\rho}{2\pi R s}$$

where

- $R$  is the resistance of one rod in isolation, in  $\Omega$ ;
- $s$  is the distance between adjacent rods, in m;
- $\rho$  is the resistivity of soil,  $\Omega \text{ m}$ ;
- $\lambda$  is a factor given in Table 2 or Table 3;
- $n$  is the number of electrodes (as given in Table 2 and Table 3).

The above equations assume that rod electrodes can be represented approximately by hemispherical electrodes, having the same earthing resistance, located in the soil surface. This assumption is satisfactory provided that the spacing between the rods is not less than their length.

If the rods are equally spaced in a straight line an appropriate value of  $\lambda$  may be taken from Table 2.

**Table 2 — Factors for parallel electrodes arranged in line**

Number of electrodes ( $n$ )	Factor $\lambda$
2	1.00
3	1.66
4	2.15
5	2.54
6	2.87
7	3.15
8	3.39
9	3.61
10	3.81

For electrodes equally spaced around a hollow square, e.g. around the perimeter of a building, the equations given above are used with a value of  $\lambda$  taken from Table 3.

For three rods placed in an equilateral triangle, or in an L formation, a value of  $\lambda = 1.66$  may be assumed.

**Table 3 — Factors for electrodes arranged in a hollow square**

Number of electrodes ( $n$ ) along each side of the square	Factor $\lambda$
2	2.71
3	4.51
4	5.48
5	6.14
6	6.63
7	7.03
8	7.36
9	7.65
10	7.90
12	8.32
14	8.67
16	8.96
18	9.22
20	9.40

NOTE The total number of electrodes around the square is  $4(n - 1)$ .

The reduction in combined earth resistance provided by additional electrodes inside the square is small, but such electrodes will reduce the potential gradient over the soil surface inside the square. A practical example of this is the use of strip electrodes forming an earth grid within the square. Table 3 may also be used for electrodes arranged in a rectangle, where  $n$  is given by (total number of electrodes/4) + 1. Provided that the length to width ratio of the rectangle does not exceed 2, the error will be less than – 6 %.

Pipes may be of cast iron of not less than 100 mm diameter, 2.5 m to 3 m long and 13 mm thick (see BS 143 and BS 1256). Such pipes cannot be driven satisfactorily and may therefore be more expensive to install than plates for the same effective area. Alternatively, steel tubes up to 50 mm diameter, whose dimensions permit them to be driven, are sometimes employed (e.g. see BS 1387); these are less durable than copper rods.

Driven earth rods generally consist of solid circular copper, molecular bonded clad steel, stainless steel, or galvanized steel (see clause 11). The preferred nominal diameters for earth rods are 9 mm, 12.5 mm and 15 mm for copper and copper-clad steel rods and 16 mm for galvanized and stainless steel rods; departures from these preferred diameters should be limited to those necessary for the provision of rolled screw threads, or taper fit tolerances.

The preferred lengths of extensible earth rods are 1.2 m for 9 mm rods and 1.2 m or 1.5 m for 15 mm rods.

Minimum sizes for these components should conform to the data given in Table 4.

**Table 4 — Minimum sizes of components for earth electrodes**

Electrode type	Cross-sectional area mm <sup>2</sup>	Diameter or thickness mm
Copper strip	50	3
Hard drawn or annealed copper rods or solid wires for driving or laying in ground	50	8
Copper-clad or galvanized steel rods (see notes) for harder ground	153	14
Stranded copper	50	3 per strand

NOTE 1 For copper-clad steel rods the core should be of low carbon steel with a tensile strength of approximately 600 N/mm<sup>2</sup> and a quality not inferior to grade S275 conforming to BS EN 10025. The cladding should be of 99.9 % purity electrolytic copper, molecularly bonded to the steel core. The radial thickness of the copper should be not less than 0.25 mm.

NOTE 2 Couplings for copper-clad steel rods should be made from copper-silicon alloy or aluminium bronze alloy with a minimum copper content of 75 %.

NOTE 3 For galvanized steel rods, steel of grade S275 conforming to BS EN 10025 should be used, the threads being cut before hot-dip galvanizing in accordance with BS 729.

Cruciform and star-shaped sections are more rigid while being driven, but the apparent additional surface does not confer a noticeable advantage in current-carrying capacity or reduction of resistance. In some circumstances the addition of horizontal electrodes is advantageous.

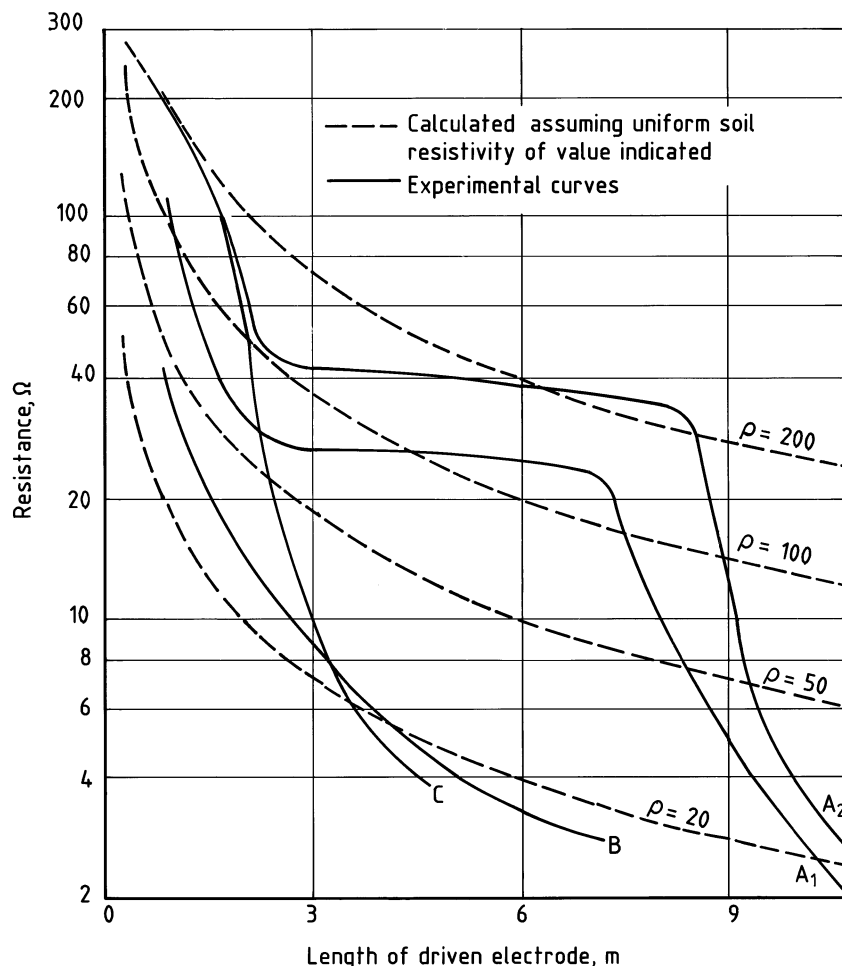
Rods may be coupled together to give longer lengths. Except in special conditions, a number of rods in parallel is to be preferred to a single long rod. Deeply driven rods are, however, effective where the soil resistivity decreases with depth or where substrata of low resistivity occur at depths greater than those to which rods, for economic reasons, are normally driven. In such cases the decrease of resistance with depth of driving may be very considerable as is shown by the measurements plotted in Figure 5 for a number of sites. For curves A<sub>1</sub> and A<sub>2</sub> it was known from previously sunk boreholes that the soil down to a depth of between 6 m and 9 m consisted of ballast, sand and gravel, below which occurred London clay. The rapid reduction in resistance when the electrodes penetrated the latter was very marked. The mean resistivity up to a depth of 8 m in one case was 150 Ω m; at 11 m the mean value for the whole depth was 20 Ω m owing to the low resistivity of the clay stratum. Similarly for curve C the transition from gravelly soil to clay at a depth of about 1.5 m was very effective. In the case of curve B, however, no such marked effect occurred although there was a gradual reduction in average resistivity with increase in depth, as can be seen by comparison with the dotted curves, which are calculated on the assumption of uniform resistivity.

Other factors that affect a decision of whether to drive deep electrodes or to employ several rods or pipes in parallel are the steep rise in the energy required to drive them with increase in depth and the cost of couplings. The former can be offset by reducing the diameter of the rods, since a 12.5 mm diameter rod can be driven to considerable depths without deformation or bending if the technique of using a large number of comparatively light blows is adopted rather than a smaller number of blows with a sledge hammer. Power-driven hammers suitable for this purpose are available.

In cases where impenetrable strata or high resistivity soil occur at relatively small depths, considerable advantage may result from driving rods at an angle of about 30° to the horizontal, thus increasing the length installed for a given depth.

### 10.3 Horizontal strip or round conductor electrodes

Horizontal strip or round conductor electrodes have special advantages where high resistivity soil underlies shallow surface layers of low resistivity. They are frequently in the form of untinned copper strip of not less than 25 mm by 3 mm section, but may be of bare copper conductor as used for overhead lines. The minimum size should conform to the value given in Table 4.



NOTE Values of  $\rho$  are in  $\Omega$  m

**Figure 5 — Calculated and experimental curves of resistance of 12.5 mm diameter driven rod electrodes**

For a strip or round conductor electrode the resistance  $R$ , in ohms ( $\Omega$ ) is given by the following equation:

$$R = \frac{\rho}{P\pi L} \left[ \log_e \left( \frac{2L^2}{wh} \right) + Q \right]$$

where



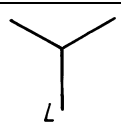
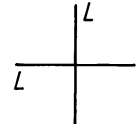
- $L$  is the length of the strip or conductor, in metres (m);
- $h$  is the depth of electrode, in metres (m);
- $w$  is the width of strip or diameter of conductor, in metres (m);
- $\rho$  is the resistivity of soil, in ohm metres ( $\Omega$  m);
- $P$  and  $Q$  are coefficients given in Table 5 for different arrangements of electrode.

The thickness of a strip electrode is usually not greater than about one-eighth of the width. Within this limitation it has a negligible effect on the electrode earth resistance. Earthing resistance is principally affected by length. For the values most frequently used, the depth of burial and diameter or width have a relatively minor effect. Figure 6 compares the effects of these parameters for strip electrodes.

If the required resistance needs a number of electrodes connected in parallel, they may be installed either in parallel lines or radiating from a point. Figure 7 shows the effect of spacing between two parallel electrodes, each 20 m long. The improvement with increase in spacing is relatively small for spacings greater than about 15 % of the length.

Care should be taken in positioning these electrodes, especially to avoid damage by agricultural operations.

**Table 5 — Coefficients for strip or round conductor electrodes**

Electrode arrangement	Coefficient		
	P	Q	
		Strip	Round
Single length <sup>a</sup> 	2	- 1	- 1.3
Two lengths at 90° 	4	0.5	0.9
Three lengths at 120° 	6	1.8	2.2
Four lengths at 90° 	8	3.6	4.1

<sup>a</sup> Where two or more straight lengths, each of length  $L$  in metres (m) and of separation  $s$  in metres (m), are laid parallel to each other and connected together the combined resistance can be calculated from the following equation:

$$R_n = FR_1$$

where

$R_n$  is the resistance of  $n$  straight conductors in parallel, in  $\Omega$ ;

$R_1$  is the resistance of one straight conductor in isolation calculated from the equation and coefficients given above, in  $\Omega$ .

$F$  has the following value:

$$\text{for two lengths, } F = 0.5 + 0.078(s/L)^{-0.307}$$

$$\text{for three lengths, } F = 0.33 + 0.071(s/L)^{-0.408}$$

$$\text{for four lengths, } F = 0.25 + 0.067(s/L)^{-0.451} \text{ provided that } 0.02 \leq (s/L) \leq 0.3.$$

## 11 Selection of a material for an earth electrode or a buried uninsulated earthing conductor

### 11.1 General

Although the material does not affect the earth resistance of an electrode, care should be taken to select a material that is resistant to corrosion in the type of soil in which it will be used. Some recommended materials for the manufacture of earthing components are listed in Table 6.

There are two aspects which should be considered regarding the corrosion resistance of an earth electrode or an earthing conductor, compatibility with the soil itself and possible galvanic effects when it is connected electrically to neighbouring metalwork. The latter is most likely to come about when the earthing system is bonded to exposed metal structural components.

### 11.2 Corrosion and type of soil

The factors associated with the corrosion of metals in contact with soil are the chemical nature of the soil, in particular acidity and salt content, differential aeration, and the presence of anaerobic bacteria.

A general picture of the aggressiveness of soils is given by the following list, which places various types of soil in increasing order of aggressiveness:

- gravelly soils;
- sandy soils;
- silty soils (loam);
- clays;
- peat and other organic soils;
- made up soils containing cinders.

Calcium carbonate in a soil will reduce the rate of corrosion. Non-cohesive soils, made from mixtures of the first three items above, are generally the least aggressive providing they are well drained and contain little or no dissolved salts. Location of electrodes should be chosen to avoid the drainage of fertilizer and other materials into the area. Top soil should not be mixed with the backfill around an electrode. The least aggressive soils tend to be those having a high resistivity.

More detail can be obtained by measuring the electrical resistivity of the soil, which provides an indication of corrosivity under aerated conditions, and the redox potential, which indicates the risk of corrosion due to the presence of anaerobic bacteria. These tests are described in BS 1377.

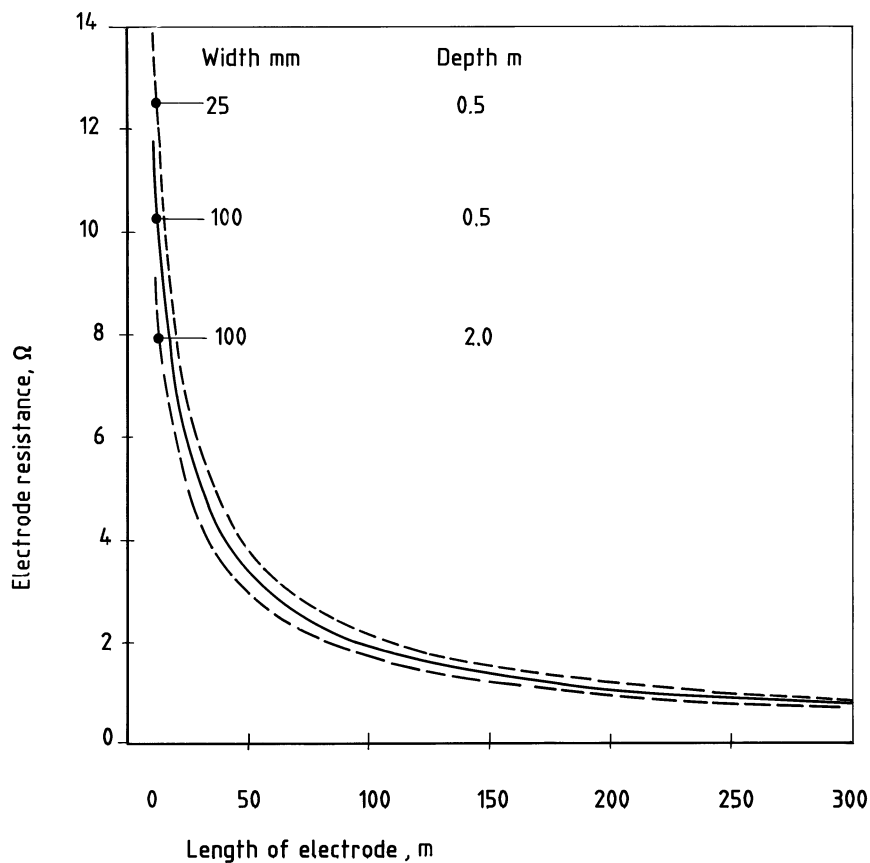


Figure 6 — Resistance of horizontal strip electrodes

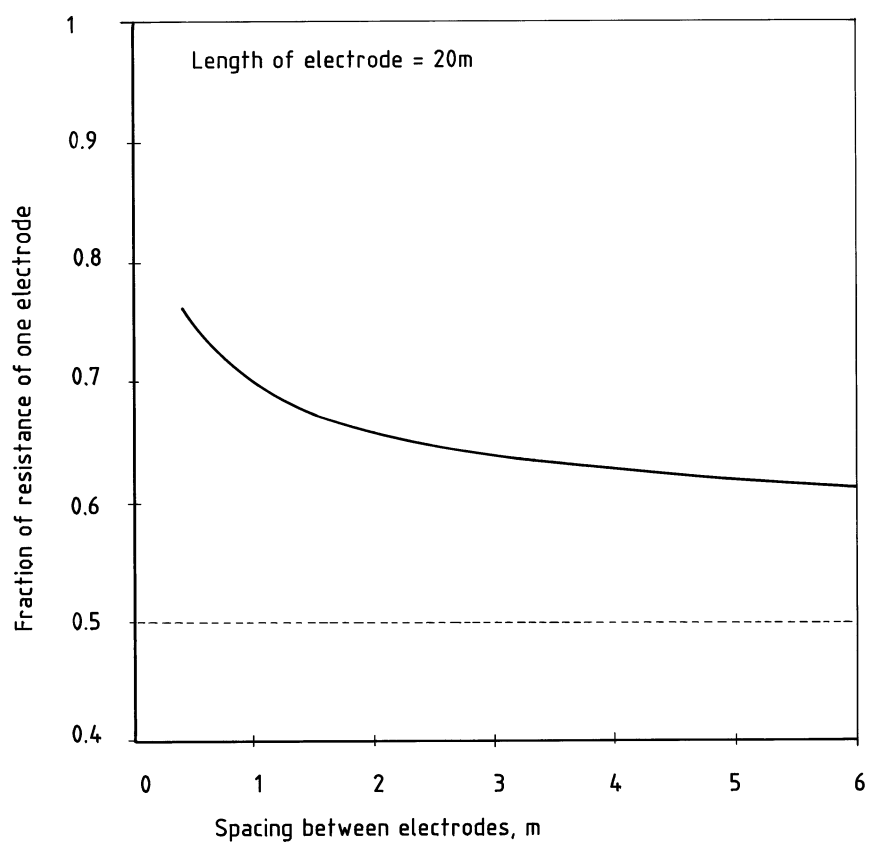


Figure 7 — Effect of spacing on combined resistance of two horizontal strip electrodes



Table 6 — Recommended materials for the manufacture of earthing components

Materials and processes	BS		BS EN	
	BS No.	Grade or type	BS EN No.	Designation
<b><i>Ingots for cast components</i></b>				
Leaded gunmetal	1400	LG1, LG2		
Aluminium silicon bronze	1400	AB3, AB1		
Aluminium alloy	1490	LM6M, LM25		
Cast iron			EN 1561	
Malleable iron			EN 1562	
<b><i>Forgings and stampings (hot or cold formed)</i></b>				
Copper	2872	C101, C102, C103	12165, prEN 12420	CW003A, CW004A, CW005A, CW008A, CW024A
Aluminium	1474	6082-TF	586-2	EN AW-6082-T6
Steel	970-1	All grades		
<b><i>Pressings and fabrications (from strip, coil, foil and sheet)</i></b>				
Annealed copper	2870	C101, C102, C103	1172, 1652, 1653, 1654	CW003A, CW004A, CW005A, CW008A, CW024A, CW006A
Aluminium	1474	6082-TF	485-2	EN AW-6082-T6
Stainless steel	1449-2	316S11		
Steel (for galvanizing)	1449-1		10025	Fe430A
<b><i>Bars, rods and tubes (for machined components and fittings)</i></b>				
Copper, hard drawn or annealed	2871, 2874	C101, C102, C103	12163, 12164, 12167	CW003A, CW004A, CW005A, CW008A, CW024A
Copper silicon	2871, 2874	CS101	12163, 12164, 12167	CW451K
Phosphor bronze	2871, 2874	PB102M	12163, 12164, 12167	CW116C
Aluminium bronze	2871-3	CA102		
Aluminium	1474	6082-TF	755-2	
Steel (for general use)	970	All grades		
Steel (for galvanizing)	970	All grades		
Stainless steel (general use)	970-1	325S31		
Stainless steel (austenitic)	970-1	325S11		

Table 6 — Recommended materials for the manufacture of earthing components

Materials and processes	BS		BS EN	
	BS No.	Grade or type	BS EN No.	Designation
<b><i>Nuts, bolts, washers, screws, rivet fixings and internal dowels in earth rods</i></b>				
For use on copper:				
Phosphor bronze	2874	PB102M	12163, 12164, 12167	CW451K
Copper silicon	2874	CS101	12163, 12164 12167	CW116C
For use on aluminium:				
Aluminium alloy	1473	6082-T6		
Stainless steel	3111-2			
Galvanized steel (see Note 2)	3111-1			
<b><i>Solid rounds, flats and stranded conductors</i></b>				
<i>Copper</i>				
Annealed copper	1432	C101, C102, C103		
Hard drawn copper	1433	C101, C102, C103		
Copper (stranded)	6360	Insulated		
Copper (flexible)	6360			
Hard drawn copper strand and copper cadmium	7884			
	2873	C108		
<i>Aluminium</i>				
Aluminium strip/rod		1350, 6101A		
Aluminium	3988	Insulated		
Aluminium (steel reinforced)	215-2			
Aluminium alloy	2898			
<i>Steel</i>				
Galvanized steel (see Note 2)	3242			
	215-1			
Galvanized strip (see Note 2)	302-2			
	1449-1			
NOTE 1 Some of the BS standards and designations listed in this table are likely to be superseded by their European equivalents during the life of this British Standard. For current information please contact the Technical Information Group at BSI.				
NOTE 2 The recommended finish is galvanized in accordance with BS 729, which has to be done after manufacture or fabrication.				
NOTE 3 Stainless steel in contact with aluminium or aluminium alloys is likely to cause additional corrosion to the latter materials (see PD 6484). It is therefore important to take protective measures such as the use of inhibitors.				
NOTE 4 Copper alloys, other than those listed above, are permissible as long as they have a minimum copper content of 75 % and similar tensile properties.				

Guidance on the corrosivity of some electrode materials in relation to these soil parameters is given in Table 7.

Further information can be obtained from the TRRL Supplementary Report "A review of soil corrosiveness with particular reference to reinforced earth" by R A King [1], from which the above Table has been summarized.

Copper is one of the better and commonly used materials for earth electrodes and underground conductors. Solid copper is particularly suitable where high fault currents are expected; for other installations copper-covered steel (e.g. as earth rods) is effective and provides better mechanical strength in the smaller sections. However, the adverse effect of dissolved salts, organic acids and acid soils generally should be noted.

Steel in concrete foundation work is generally protected against corrosion by the concrete and can act as a satisfactory electrode, if provision is made to ensure electrical continuity and adequate conductivity. Steel in concrete has an electropotential similar to that of copper and may therefore be bonded to copper or copper-covered earth electrodes. Note, however, that galvanized steel is strongly electronegative to both copper and steel in concrete so that an earth electrode of bare galvanized steel should not be bonded to either of them.

### 11.3 Corrosion due to interconnection with another metallic item

The possibility of damage to cables, other underground services and structural metalwork in the vicinity of earth electrodes, to which the earthing system is to be bonded, due to electrolytic action between dissimilar metals should not be overlooked. The rate of corrosion depends on the metals involved and to some extent on their relative surface areas. In some cases connection of neighbouring underground metalwork may also increase the rate of corrosion of earth electrode material. Materials compatible with the neighbouring items should be selected or other precautions taken.

Table 8 summarizes the situation for some construction and earthing materials.

**Table 7 — Corrosion resistance of some electrode materials related to soil parameters**

Soil parameter		Electrode material			
		Copper	Galvanized steel	Austenitic steel	Mild steel
Resistivity, $\Omega$ m	< 7	g	n	g	nn
	7 to 40	g	n	gg	n
	> 40	gg	gg	gg	gg
Redox potential, mV	< 200	n	nn	n	nn
	200 to 400	g	g	gg	g
	400	gg	gg	gg	gg
Moisture content, %	< 10	gg	gg	gg	gg
	10 to 80	g	n	g	n
	> 80	g	g	g	g
Dissolved: salts chlorides		n	n	g	n
		n	n	n	n
pH	acidic < 6	n	nn	g	n
	neutral 6 to 8	gg	gg	gg	gg
	alkaline > 8	g	n	gg	g
Organic acids		nn	n	g	n
<b>Key</b>					
gg indicates corrosion resistance generally unaffected;					
g indicates corrosion resistance only slightly reduced;					
n indicates corrosion resistance moderately reduced;					
nn indicates corrosion resistance considerably reduced.					

Table 8 — Suitability of materials for bonding together

Material assumed to have the larger surface area	Electrode material or item assumed to have the smaller surface area			
	Steel	Galvanized steel	Copper	Tinned copper
Galvanized steel	✓	✓	✓	✓
Steel in concrete	×	×	✓	✓
Galvanized steel in concrete	✓	✓ <sup>a</sup>	✓	✓
Lead	✓	✓ <sup>a</sup>	✓	✓
<p><i>Key</i></p> <p>× = not suitable for bonding;  ✓ = suitable for bonding.</p> <p><sup>a</sup> The galvanizing on the smaller surface may suffer.</p>				

## 12 Miscellaneous types of electrode

### 12.1 Cable sheaths

Metallic sheaths and armour of cables are generally used to provide a path for the fault current returning to the source neutral at the transformer position.

**NOTE** Where an extensive underground cable system was available, with exposed conducting sheaths and armour, these have been used to form an earth electrode. However, the present general use of polymeric oversheaths on cables makes it impossible to obtain adequate contact with earth.

### 12.2 Structural steelwork

Foundation metalwork in concrete can provide a ready made and effective earth electrode. The total electrode area formed by the underground metalwork of large structures can provide an earth resistance lower than that obtainable by other methods. Overall values well below 1  $\Omega$  are obtainable.

It is important that consideration be given to the possibility of corrosion of steelwork in concrete encased foundations. The products of corrosion occupy a greater volume than the original metal and may cause cracking. In particular, continuous earth currents call for attention. A possible source of such current may be incompatibility with other buried metalwork, including other types of earth electrode, to which foundation metalwork may be bonded (see 11.3).

**NOTE 1** Protection against the effects of corrosion of steelwork by cathodic protection is dealt with in clause 13.

Alternating current is not expected to cause corrosion. However, rectification sufficient to produce a very small proportion of direct current may take place. Wherever a significant continuous earth leakage current is expected it is recommended that a main electrode, of the types described in clause 10, be provided to which the foundation electrodes can be bonded to provide auxiliary electrodes, thus giving assistance with high fault currents. Corrosion of concrete encased steelwork, subject to a.c. fault currents within its carrying capability, has been found to be negligible.

Damage to the concrete in the form of cracking, due to arcing or to the rapid evaporation of moisture, can occur where either long-term or short-duration earth fault currents exceed the carrying capability of an electrode. This situation is unlikely to arise if the electrode has a resistance sufficiently low to avoid dangerous voltages to earth.

The resistance to earth of concrete encased steelwork or of concrete reinforcing bars will vary according to the type of soil and its moisture content and the design of the foundation. Concrete is hygroscopic and, except in dry locations, can be expected when buried in soil to have a resistivity of about 30  $\Omega$  m to 90  $\Omega$  m at normal temperatures, which is lower than that of some types of soil.

It is essential to measure the resistance to earth of any metalwork it is intended to employ as an electrode, and to monitor its value at regular intervals afterwards, in order to confirm that it continues to provide an adequate connection to earth (see 17.1).

It is desirable to confirm by measurement the combined resistance of all the electrodes. However, the earth resistance of a structure covering a large area may be quite low and an accurate measurement on the completed structure may be difficult or impossible. Where the structure is supported on many similar footings, it may be feasible and more satisfactory to measure the resistance of one footing before it is electrically connected to others and before there are other electrically paralleled footings close by. If possible, it is advantageous to measure the resistance of several such footings to gain an indication of the likely variation of resistance. On the assumption that a representative value of footing resistance can be obtained, the combined effect of all similar footings  $R_{\text{tot}}$ , in ohms ( $\Omega$ ), assumed to be arranged in an approximately rectangular plan, can be determined from the following equation:

$$R_{\text{tot}} = R_1 \times \frac{(1 + \lambda a)}{n}$$

$$\text{in which } a = \frac{\rho}{2\pi R_1 s}$$

where:

- $R_{\text{tot}}$  is the combined resistance of  $n$  similar electrodes, in ohms ( $\Omega$ );
- $R_1$  is the resistance of an individual electrode, in ohms ( $\Omega$ );
- $\lambda$  is the factor given in Table 3;
- $\rho$  is the soil resistivity, in ohm metres ( $\Omega$  m);
- $n$  is the number of electrodes formed by footings;
- $s$  is the average distance between adjacent electrodes, in metres (m).

NOTE 2 This equation is based on the assumption that spacing between adjacent electrodes is such that  $a$  is less than about 0.2. A large proportion of the resistance to earth is due to the concrete immediately around the metalwork and is dependent on its moisture content. After construction and with passage of time this moisture content will approach equilibrium with that of the soil, and will usually be drier than when first laid. Allowance should be made for the consequent increase in electrode resistance due to such changes in moisture content when using measurements made during the installation of a structure.

It is important to ensure electrical continuity between all metalwork considered to be part of the electrode. In the case of contacts between metalwork within concrete or below ground, such as reinforcing bars, this is best effected by welding; above ground and at anchor bolts it is generally done by attaching a bonding conductor to bypass each structural joint. This applies particularly to surfaces which may have been primed before assembly.

The resistance to earth of a reinforced concrete foundation  $R$ , in ohms ( $\Omega$ ) can be estimated by assuming that only the vertical reinforcing rods are bonded to the building structure or to the earthing system. The effect of other reinforcement, which may be attached with wire ties only, is neglected. It is assumed that the rods are equally spaced in a symmetrical pattern. This gives the following equation:

$$R = \frac{1}{2\pi L} \left[ (\rho_c - \rho) \log_e \left( 1 + \frac{\delta}{z} \right) + \rho \log_e \left( \frac{2L}{z} \right) \right]$$

where

- $\rho$  is the resistivity of the soil, in ohm metres ( $\Omega$  m);
- $\rho_c$  is the resistivity of concrete, in ohm metres ( $\Omega$  m);
- $L$  is the length of reinforcing rod below ground level, in metres (m);
- $\delta$  is the thickness of concrete between rods and soil, in metres (m);
- $z$  is the geometric mean distance of rod cluster, in metres (m) (see Table 9).

**Table 9 — Geometric mean distance  $z$  for closely spaced reinforcing rods**

Number of rods	Arrangement of rods	$z$ m
2	○ s ○	$2\sqrt{as}$
3	○ s ○ ○	$3\sqrt{as^2}$
4	○ ○ s ○ ○	$4\sqrt{(\sqrt{2}as^3)}$
6	○ ○ s ○ ○ ○ ○	$6\sqrt{(6as^5)}$
8	○ ○ s ○ ○ ○ ○ ○ ○ ○	$8\sqrt{(52as^7)}$
8	○ ○ ○ ○ ○ ○ ○ ○ ○	$8\sqrt{(23as^7)}$
<b>Key</b> $a$ = radius of a reinforcing rod, in metres (m). $s$ = distance between adjacent rods, in metres (m). $z$ = geometric mean distance, in metres (m).		

**12.3 Sheet steel piling and steel reinforcement of concrete piling**

In consultation with the engineer in charge of works, it is often possible to secure an effective earth electrode by providing a suitable means of connection to steel reinforcement in concrete piles or to sheet steel piling.

**12.4 Water pipes**

For new installations a public water supply pipe may not be used as the sole means of earthing. In areas where a public piped water supply was available, the use of the public water supply pipe as an installation earth electrode was common in the past. Though this was generally very effective when these pipes were all metal with metal-to-metal joints, the use of public water supply pipes as a means of earthing has not been acceptable for many years because of the use of non-conducting materials by Water Supply Undertakings for new installations and for replacement purposes. Modern jointing techniques do not ensure electrical continuity of metallic pipes.

The use of a non-public underground water supply system of suitable metallic construction is acceptable provided that the person responsible for the electrical installation can ensure that the integrity of the earthing is maintained.

For existing installations for which a public water supply pipe is used as a sole earth electrode, an alternative means of earthing should be provided. In many cases the electricity supplier will be able to provide an earthing facility derived from the public electricity supply system provided equipotential bonding has been carried out in accordance with the current Electricity Supply Regulations, or, for non-PME systems, BS 7671 (see 21.4). Information concerning these requirements should be sought from the electricity supplier.

**12.5 Service pipes**

In general, metallic pipes, e.g. for oil, gas, compressed air or drainage, should be bonded to the protective conductors but not used as the sole means of earthing. Where, in an existing installation, a service pipe has been used as the sole earth electrode, another means of earthing should be provided.

**13 Earthing cathodically protected structures**

Cathodic protection is normally applied to wholly or partly buried ferrous structures in order to counteract electrolytic corrosion. Such a protection system relies on the metalwork being maintained at a slightly more negative potential with respect to the ground than it would exhibit if it were unprotected.

The application of cathodic protection depends upon the circumstances, which can vary from bare metal in direct contact with the soil to metal that has been coated or wrapped against corrosion. In the latter case cathodic protection is used to supplement the coating by preventing localized corrosion due to faults in the coating.

Current drain from the source of protective current is proportional to the area of bare metal in contact with the soil so that, in the case of a well-coated structure, the current which has to be provided may be relatively low. The connection of an earth electrode to such a structure might involve an increase in current drain which could be unacceptable.

Nevertheless it may be necessary to attach an earth electrode for one or more of the following reasons:

- a) to divert to ground earth fault currents from electrical equipment which has to be mounted in electrical contact with the structure;

- b) to prevent the structure attaining unacceptable voltages with respect to ground due to induction from other equipment such as power lines running alongside;
- c) to prevent such voltages attaining values which might be dangerous in the event that the structure is located in a hazardous area;
- d) to prevent damage by such voltages to low voltage circuits of measurement and control equipment associated with the structure and to the equipment providing the cathodic protection current;
- e) to provide a functional earth connection for equipment on the structure.

The provision of an adequate low impedance earth connection that avoids an unacceptable current drain on the cathodic protection system calls for special consideration of the type of earth electrode or its connection. The passage of excessive cathodic protection current to the ground can be avoided by making the earthing electrode of a material such as zinc, in the form commonly used for sacrificial anodes. If the material and the voltage at which the cathodic protection operates are suitably chosen, the sacrificial action will be slight. It may even be possible to give a degree of cathodic protection to the electrode. The electrode should be surrounded with a backfill material, such as bentonite, which minimizes corrosion due to local cells. Under these conditions an adequate life can be obtained but, in line with good practice for cathodic protection systems, testing at intervals of about 12 months is recommended.

For ferrous structures an electrode of austenitic stainless steel rods can have a galvanic potential near to that of the structure and at the same time, if only a moderate earthing resistance is required, may not involve an unacceptable increase in current drain.

Electrodes of bare copper should not be connected directly to protected structures, as this material is strongly cathodic to ferrous materials and may require a quite unacceptable current drain if the protection of the structure is to be maintained. In the event of failure of the source of protective current, a copper electrode will accelerate the rate of corrosion of the structure.

However, if for other reasons a copper electrode is to be used, the connection to the structure should be made through a polarization cell. This will drain only a small current from the cathodic protection source, but will pass alternating current with a low voltage drop.

The earthing of cathodically protected structures is discussed in greater detail in BS 7361-1.

## 14 Selection of an earthing conductor and connection to an electrode

Selection of the material for an earthing conductor should take into account compatibility with the material of the earth electrode and, for a conductor installed in the ground, the corrosive effect of the soil. Information provided in clause 11 for electrodes is relevant to bare earthing conductors also.

Aluminium or copper-clad aluminium conductors should not be used in contact with soil or in damp situations and in any case should not be used to make the final connection to an earth electrode.

The cross-sectional area of an earthing conductor and the type of support should be chosen so as to carry without danger the greatest earth fault currents and leakage currents likely to occur having regard to thermal and electromechanical stresses. It should be sufficiently robust to withstand mechanical damage and corrosion.

Table 10 provides a guide to acceptable maximum fault current temperatures for bare earthing conductors, according to the environmental conditions and the type of connections used. For a conductor covered to provide corrosion or mechanical protection, or an insulated conductor, the maximum temperature may be limited by the covering or insulating material.

The current densities ( $k$ ) in r.m.s. amperes per square millimetre, for a 1 s duration, are given in Table 10 for copper, aluminium and steel conductors assuming an initial temperature of 30 °C. The corresponding conductor cross-sectional area ( $S$ ) in square millimetres is given by the following equation:

$$S = \frac{I(\sqrt{t})}{k}$$

where

$I$  is the average fault current, in A r.m.s.;

$t$  is the fault current duration, in s.

Fault current capacities, for 1 s and 3 s durations, for a selection of standard sizes of copper and aluminium strips are given in Table 11 and Table 12.

**Table 10 — Earth fault current densities for 1 s duration for earthing conductors with initial conductor temperature of 30 °C**

Type of joint <sup>a</sup>				Maximum temperature <sup>b</sup>  C	Environmental conditions, in accordance with IEC 364, appropriate to the use of bare conductors at temperatures up to and including the values marked	R.M.S current density <i>k</i>		
Welded	Brazed	Bolted	Soft soldered			Copper  A/mm <sup>2</sup>	Aluminium  A/mm <sup>2</sup>	Steel  A/mm <sup>2</sup>
✓				700		254	—	91
✓				600		252	—	87
✓				500	c	228	—	82
✓	✓			450		220	—	79
✓	✓			400		211	—	76
✓	✓			350		201	—	73
✓	✓			300		190	125 <sup>d</sup>	69
✓	✓	✓		250		176	116	64
✓	✓	✓		200	e	159	105	58
✓	✓	✓	✓	150	f	138	91	50
✓	✓	✓	✓	100		—	—	—

<sup>a</sup> A tick indicates that the type of joint is suitable for use at temperatures up to and including the value indicated.

<sup>b</sup> It should be verified that a material likely to be in the same location as the conductor will not be damaged or present a fire risk at the temperature selected.

<sup>c</sup> At temperatures in excess of 200 °C the conductor should be visible throughout its length, have ceramic or metallic supports (or an equivalent) and there should be no risk of organic materials being in contact with or adjacent to the conductor. Temperatures higher than 500 °C are not recommended.

<sup>d</sup> The mechanical strength of conductivity quality aluminium is seriously reduced at higher temperatures.

<sup>e</sup> For normal conditions where the conductor is not visible throughout its length.

<sup>f</sup> Certain building materials likely to be adjacent to the conductor may present a fire risk if 150 °C is exceeded.



For other durations the fault current capacity ( $I$ ) in amperes r.m.s. can be calculated from one of the following equations:

$$I = I_1/(\sqrt{t}) \text{ or } I = kS/(\sqrt{t})$$

where

$I_1$  is the fault current for 1 s duration, in A r.m.s. (given in Table 11 and Table 12);

$S$  is the conductor cross-sectional area, in  $\text{mm}^2$ ;

$k$  is the r.m.s. current density, in  $\text{A}/\text{mm}^2$  (given in Table 10).

For other initial and final temperatures the current density  $k$  for a 1 s duration can be obtained from the following equation:

$$k = K \sqrt{\log_e \left( \frac{T_2 + \beta}{T_1 + \beta} \right)}$$

where

$T_1$  is the initial temperature, in  $^{\circ}\text{C}$ ;

$T_2$  is the final temperature, in  $^{\circ}\text{C}$ ;

$K$  and  $\beta$  have the values given in Table 13.

Where there are continuous earth leakage currents it should be confirmed that the conductor has a current-carrying capacity adequate for such currents without exceeding a temperature appropriate to its insulation or supports or, if it is bare and exposed to touch, that its temperature should not exceed  $70^{\circ}\text{C}$ . Such continuous earth currents may increase the value of the initial temperature to be considered when selecting the conductor size to carry earth fault currents.

In addition to conforming to the thermal constraints described above, the earthing conductor should have a cross-sectional area of not less than  $4 \text{ mm}^2$  where protection against corrosion only is provided or  $2.5 \text{ mm}^2$  where mechanical protection is also provided.

Where an earthing conductor is installed in the ground and is protected against corrosion, but has no mechanical protection, it is advisable to use a size not less than  $16 \text{ mm}^2$  for copper or coated steel. If corrosion protection is not provided the size should be not less than  $25 \text{ mm}^2$  for copper and not less than  $50 \text{ mm}^2$  for steel.

It is advisable for unprotected strip conductors to be not less than 3 mm thick.

**Table 11 — Earth fault currents (in kA) for copper strip earthing conductors**

(a) 1 s duration					
Size of conductor mm × mm	Maximum conductor temperature:				
	150 C	200 C	250 C	450 C	500 C
20 × 3	8.3	9.5	10.6	13.2	13.7
25 × 3	10.4	11.9	13.2	16.5	17.1
25 × 4	13.8	15.9	17.6	22	22.8
25 × 6	20.7	23.9	26.4	33	34.2
31 × 3	12.8	14.8	16.4	20.5	21.2
31 × 6	25.7	29.6	32.7	40.9	42.4
38 × 3	15.7	18.1	20.1	25.1	26
38 × 5	26.2	30.2	33.4	41.8	43.3
38 × 6	31.5	36.3	40.1	50.2	52
50 × 3	20.7	23.9	26.4	33	34.2
50 × 4	27.6	31.8	35.2	44	45.6
50 × 6	41.4	47.7	52.8	66	68.4
(b) 3 s duration					
Size of conductor mm × mm	Maximum conductor temperature:				
	150 C	200 C	250 C	450 C	500 C
20 × 3	4.8	5.5	6.1	7.6	7.9
25 × 3	6	6.9	7.6	9.5	9.9
25 × 4	8	9.2	10.2	12.7	13.2
25 × 6	12	13.8	15.2	19.1	19.7
31 × 3	7.4	8.5	9.5	11.8	12.2
31 × 6	14.8	17.1	18.9	23.6	24.5
38 × 3	9.1	10.5	11.6	14.5	15
38 × 5	15.1	17.4	19.3	24.1	25
38 × 6	18.2	20.9	23.2	29	30
50 × 3	12	13.8	15.2	19.1	19.7
50 × 4	15.9	18.4	20.3	25.4	26.3
50 × 6	23.9	27.5	30.5	38.1	39.5

**Table 12 — Earth fault currents (in kA) for aluminium strip earthing conductors**

(a) 1 s duration				
Size of conductor mm × mm	Maximum conductor temperature:			
	150 C	200 C	250 C	300 C
20 × 3	5.5	6.3	7	7.5
25 × 3	6.8	7.9	8.7	9.4
25 × 6	13.7	15.8	17.4	18.8
50 × 6	27.3	31.5	34.8	37.5
60 × 6	32.8	37.8	41.8	45
80 × 6	43.7	50.4	55.7	60
(b) 3 s duration				
Size of conductor mm × mm	Maximum conductor temperature:			
	150 C	200 C	250 C	300 C
20 × 3	3.2	3.6	4	4.3
25 × 3	3.9	4.5	5	5.4
25 × 6	7.9	9.1	10	10.8
50 × 6	15.8	18.2	20.1	21.7
60 × 6	18.9	21.8	24.1	26
80 × 6	25.2	29.1	32.1	34.6

**Table 13 — Values of  $K$  and  $\beta$** 

Metal	$K$ A/mm <sup>2</sup> (r.m.s.)	$\beta$ C
Copper	226	254
Aluminium	148	228
Steel	78	202

The materials used for making connections should be compatible with the materials of the earth electrode and of the earthing conductor so that galvanic corrosion is minimized. Where copper alloy connectors are used they should not contain more than 15 % zinc.

Connectors should be mechanically strong and securely fastened. All earth clamps should be inherently corrosion resistant. Where bolted connections are used, the bolts should withstand a torque of at least 20 N m.

For large earthing installations, such as at major substations, it is common to make provision for the testing of earth electrodes. This is achieved by connecting a group of rod driven electrodes to the main earth grid through a bolted link adjacent to the electrodes in a sunken concrete box. Simpler disconnecting arrangements may be acceptable for small earthing installations.

Further details are given in 19.7 for large installations and in 21.6.2 for installations within the scope of BS 7671.

NOTE The sizes of 16 mm<sup>2</sup> and 25 mm<sup>2</sup> relate to those given in BS 7671. BS 6651 recommends earthing conductors buried in the ground to have a minimum cross-sectional area of 50 mm<sup>2</sup>. This takes into account possible corrosion and mechanical damage.

## 15 Current density at the surface of an earth electrode

An earth electrode should be designed to have a loading capacity adequate for the system of which it forms a part, i.e. it should be capable of dissipating the electrical energy in the earth path at the point at which it is installed under any condition of operation on the system. Failure of an electrode to meet its purpose is fundamentally due to excessive temperature rise at the surface of the electrode and is thus a function of current density and duration as well as electrical and thermal properties of the soil.

In general, soils have a negative temperature coefficient of resistance so that sustained current loading results in an initial decrease in electrode resistance and a consequent rise in the earth fault current for a given applied voltage. However, as soil moisture is driven away from the soil-electrode interface, the resistance increases and will ultimately become infinite if the temperature rise is sufficient. For short-duration loading this occurs in the region of 100 °C and results in complete failure of the electrode.

Three conditions of operation require consideration, i.e. long-duration loading, as with normal system operation, short-time overloading, as under fault conditions in directly earthed systems, and long-time overloading, as under fault conditions in systems protected by arc-suppression coils.

The little experimental work which has been done on this subject has been confined to model tests with spherical electrodes in clay or loam of low resistivity and has led to the following conclusions.

a) Long-duration loading due to normal unbalance of the system will not cause failure of earth electrodes provided that the current density at the electrode surface does not exceed  $40 \text{ A/m}^2$ . Limitation to values below this would generally be imposed by the necessity to secure a low-resistance earth.

b) Time to failure on short-time overload is inversely proportional to the specific loading, which is given by  $J^2\rho$  where  $J$  is the current density at the electrode surface and  $\rho$  the resistivity of the soil. For the soils investigated the maximum permissible current density  $J$ , in amperes per square metre ( $\text{A/m}^2$ ), is given by the following equation:

$$J = 10^3 \sqrt{\left(\frac{57.7}{\rho t}\right)}$$

where:

$t$  is the duration of the earth fault, in seconds (s);

$\rho$  is the resistivity of the soil, in ohm metres ( $\Omega \text{ m}$ ).

Experience indicates that this equation is also appropriate for plate electrodes.

## 16 Potential gradient around earth electrodes

### 16.1 General

Under fault conditions an earth electrode is raised to a potential with respect to the general mass of Earth that can be calculated from the prospective fault current and the earth resistance of the electrode. This results in the existence of potential differences in the ground around the electrode that may be injurious to telephone and pilot cables, whose cores are substantially at earth potential. Such a risk arises mainly in connection with large electrode systems, as at power stations and substations. The potential gradient over the surface of the ground is also important because personnel or livestock can be in contact with two points sufficiently far apart that the potential difference constitutes a danger to life; cattle are most at risk.

Figure 8 demonstrates the nature of the potential gradient at or near the ground surface around an isolated 3 m rod electrode. The high potential gradient within the first few centimetres of the rod is clearly seen and, depending on the electrode voltage, a barrier to prevent contact by personnel or livestock may be advisable out to a radius of 1 m or 2 m.

NOTE Further comments on reducing this gradient by placing the top of the electrode below ground level are made later in this clause.

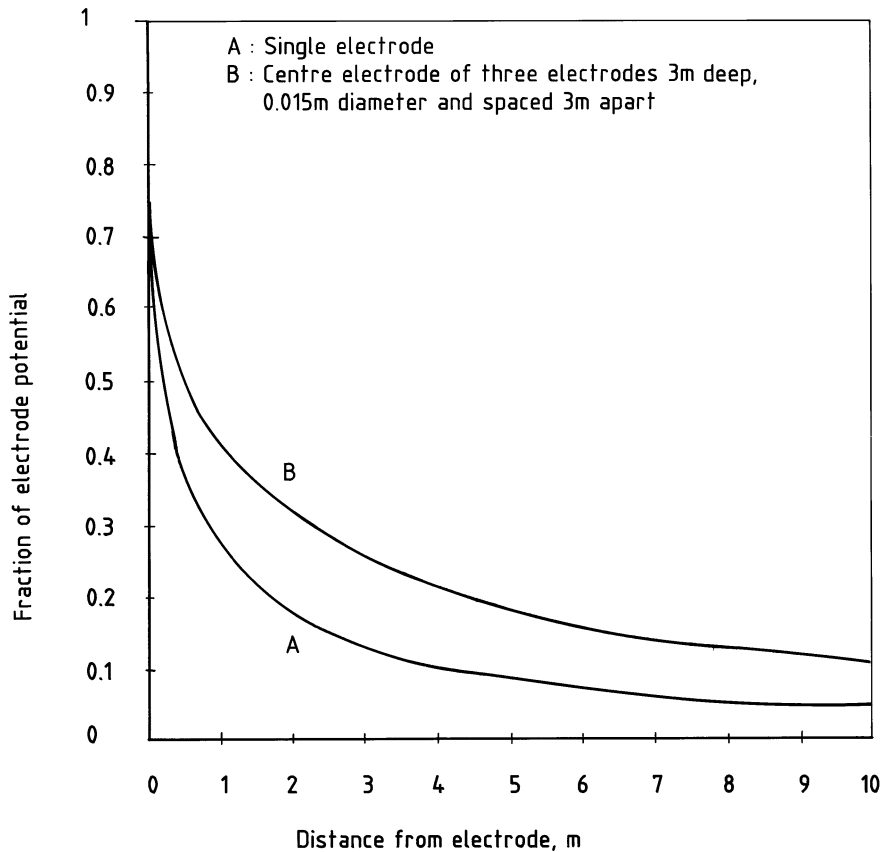


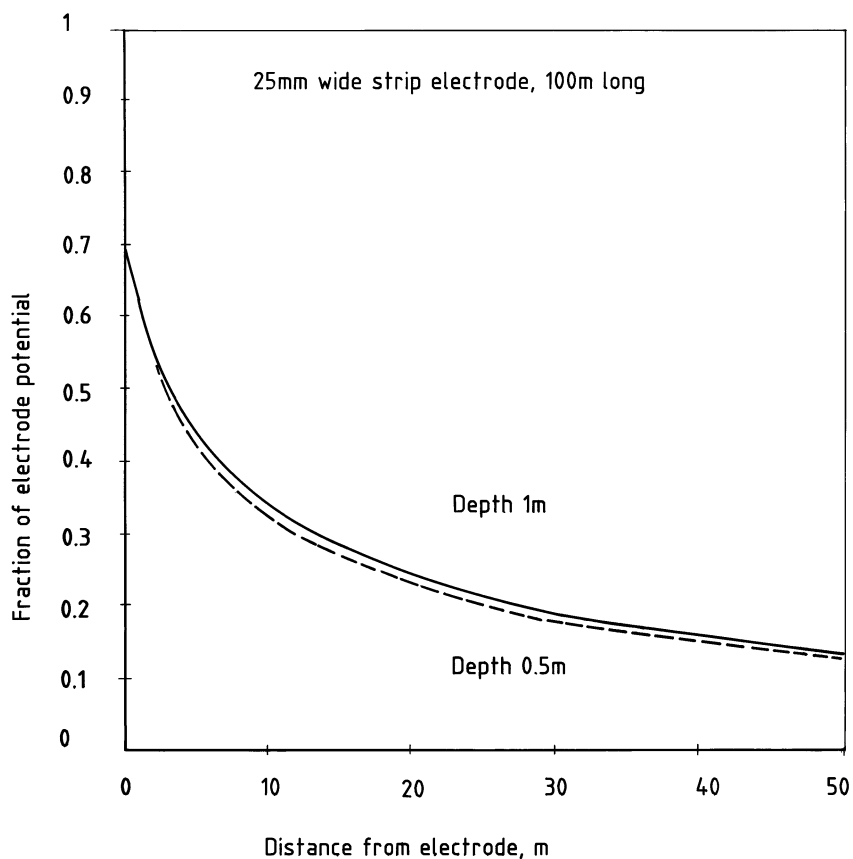
Figure 8 — Ground surface potentials around a single rod and three rods in line

The potential gradient on a perpendicular to a line of three electrodes is also given in Figure 8. This shows that, for a given electrode voltage, although the initial gradient within about 2 m of the rods is slightly reduced, the general effect at greater distances is to increase both the ground potential and the gradient. However, for a given fault current the multiple electrode arrangement could have a lower resistance and would result in considerably smaller ground potentials and gradients than those of a single electrode.

The distribution of ground surface potential in the vicinity of a horizontal electrode (wire or strip) (see Figure 9) shows gradients much smaller than those of a vertical electrode, the highest gradient occurring at a distance from the electrode equal to its depth. Likewise, the potential gradients between horizontal electrodes are smaller. Depth of laying, within the range normally used, has little effect on ground surface potential.

The ground potential contours associated with installations of more than one electrode consist of isolated areas around each electrode where the potential and its gradient are high, possibly dangerous. Between these areas there are troughs of minimum potential which may nevertheless have a value which presents a danger to a person or animal touching conducting items in contact with either the electrode or the mass of earth at a more remote location, e.g. a metallic fence. Figure 10 illustrates the profile of the ground surface potential over the middle span of a line of four 15 mm diameter vertical rod electrodes 3 m long and spaced 5 m apart.

Such variations in ground potential within and close to an installation may be unacceptable and measures to reduce them may be necessary. This is more conveniently effected by the use of additional electrodes in the form of buried horizontal strip or wire, possibly 0.25 m to 0.6 m below the surface. See 19.7.3.2 for further comment on the laying of such electrodes.



**Figure 9 — Potential gradient in the vicinity of a horizontal strip electrode**

The large fraction of the electrode potential developed over the few centimetres of soil next to the electrode indicates the importance of the resistivity of the material in this region. In high resistivity soils, for cases where the use of additional rods is not practicable and it is desired to reduce the electrode resistance by soil treatment or by replacement with concrete, only the soil in this region need be considered. Since soil conductivity is affected by soil density (except for very wet soils), it is clear that good compaction, or lack of disturbance, of soil in contact with the electrode is important (see also 8.5).

Earth electrodes should not be installed close to a metal fence, unless they are used for earthing that fence. This is to avoid the possibility of the fence becoming live and thus dangerous at points remote from the substation, or alternatively giving rise to danger within the resistance area of the electrode by introducing a good connection with the general mass of the earth.

In rural areas, danger to animals in the vicinity of earthed poles can be minimized by the use of insulated earthing connections and by having no earth electrode less than 0.6 m below the surface of the ground.

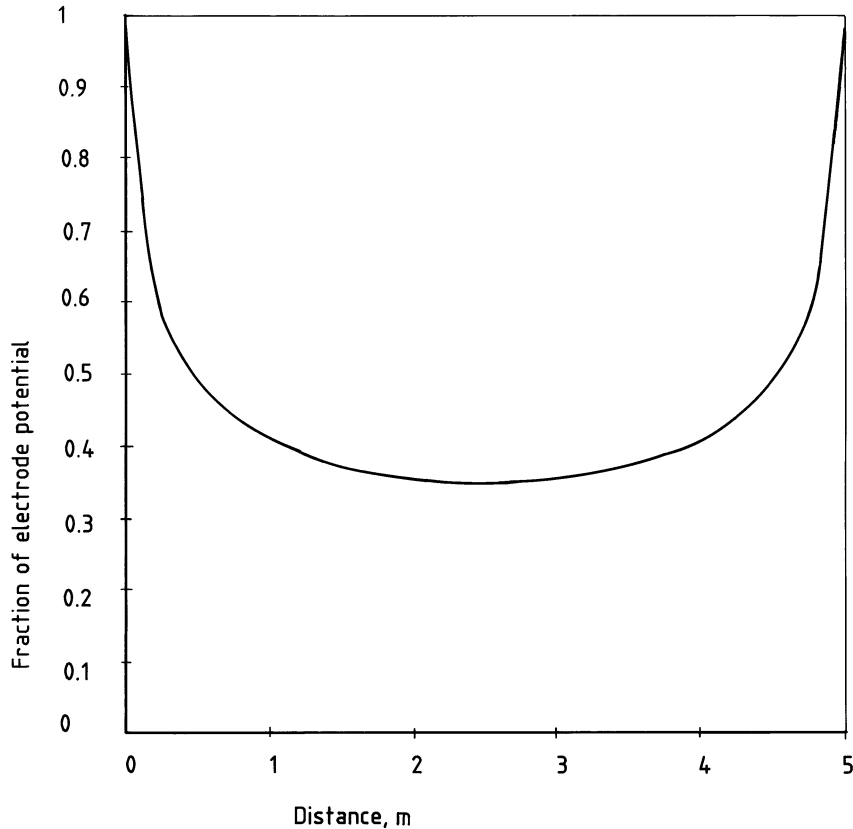


Figure 10 — Potential distribution between rod electrodes

## 16.2 Calculation of ground surface potentials

### 16.2.1 Vertical electrodes

For vertical electrodes, the fraction  $E$  of the potential arising on the electrode(s) which appears at a point P on the ground surface is estimated approximately by the following equation:

$$E = \frac{\sum_{i=1}^n \log_e (v_i + \sqrt{v_i^2 + 1})}{(1 + \lambda\beta) \log_e \left( \frac{4L}{d} \right)}$$

where

$$v_i = \frac{L}{r_i}$$

$n$  is the number of electrodes;

$L$  is the buried length of an electrode, in metres (m);

$r_i$  is the distance of point P on the ground surface to the  $i^{\text{th}}$  electrode, in metres (m) ( $r_i$  is greater than the radius of an electrode);

$\lambda$  is the grouping factor given in Table 2 or Table 3;

$$\beta = \frac{L}{s \log_e \left( \frac{4L}{d} \right)}$$

$d$  is the diameter of the electrode(s), in metres (m);

$s$  is the spacing between the electrodes, in metres (m). It is assumed that the electrodes are equally spaced (see 10.2).

It is assumed that spacing between electrodes is not less than two-thirds of the electrode length and that electrode currents are equal.

For a single electrode,  $n = 1$ ,  $\lambda = 0$  and  $E$  is the fraction of the electrode potential for an equipotential at a radius  $r$  around the electrode.

### 16.2.2 Horizontal electrodes

For horizontal electrodes, the fraction  $E$ , of the electrode potential, at a point P on a line perpendicular to the line of the electrodes, is obtained from the following equation:

$$E = \frac{\sum_{i=1}^n 2 \log_e (u_i + \sqrt{v_i^2 + 1})}{F \log_e \left( \frac{L^2}{hd} \right)}$$

where

$n$  is the number of electrodes;

$$v_i = \frac{L}{2\sqrt{h^2 + r_i^2}}$$

$h$  is the depth of electrodes from the ground surface, in metres (m);

$r_i$  distance along the ground surface from point P to a point vertically above the  $i^{\text{th}}$  electrode, in metres (m);

$L$  is the length of each electrode, in metres (m);

$F$  is the group factor given in Table 5;

$d$  is the diameter of each electrode, in metres (m);

For a strip electrode  $d = 2w/\pi$

where

$w$  is the width of a strip electrode, in metres (m).

Where there is one electrode, i.e.  $n = 1$ , the group factor is unity, i.e.  $F = 1$ .

These equations assume that electrode depth is small compared with its length and that electrode currents are equal.

## 17 Periodic inspection and testing of the earthing system and measurement of resistance of installed electrodes and earthing conductors

### 17.1 Periodic inspection and testing

NOTE Danger can arise when removing a conductor connected to earth unless suitable precautions are taken.

A calculated value of electrode resistance can be expected to be of only limited accuracy because of uncertainty as to the true value of soil resistivity and its homogeneity. Soil resistivity is dependent on moisture content and temperature as well as on soil constituents, so that it can vary seasonally and progressively due to hydrological trends such as changing water tables or continuous drainage. It is therefore advisable to check the resistance of an electrode both on installation and at regular intervals thereafter. In the case of new installations the measurement provides important confirmation of the efficacy of the earthing system.

Since moisture has a predominant effect it is advisable to arrange for testing to be done during a particular season, preferably after the end of the driest period in the year. In this way comparison between records will show if there is a trend which may require attention at some time in the future. It will also give a worst case value of resistance on which to check the proper functioning of circuit disconnection equipment.

Inspection should include not only the integrity of earthing conductors, and all associated connections, where accessible or liable to damage, but also any visible features which may lead to deterioration of the electrode or to an increase in resistivity of the soil around it.

### 17.2 Measurement of electrode resistance

#### 17.2.1 General

In some cases the voltages involved when testing earth electrodes may present a risk of shock and care should be exercised to take the necessary precautions.

Once installed, electrodes are almost certain to be connected, either deliberately or fortuitously, to other items in contact with the general mass of earth. For a new installation it is generally possible to arrange for a measurement to be made before the electrode is so connected and is still electrically isolated. For existing installations it is not permissible to disconnect earth electrodes unless the installation is also disconnected from all sources of power. The problem can sometimes be solved by installing multiple electrodes so that, with one disconnected for testing, the remaining electrodes provide an adequately low resistance.

The accuracy of measurement is subject to a number of features which should be borne in mind when assessing the implications of the value obtained. Apart from seasonal variations and trends in soil resistivity, an electrode is influenced by the presence of other conducting items in the ground, such as cables, pipes and foundations, as well as other electrodes connected together. A value obtained with existing installations, although not of great accuracy, may nevertheless provide useful information on the stability of the earthing.

For a new installation, a measurement should provide better information than a calculated value based on a measured value for the soil resistivity, because any unknown inhomogeneity in the soil is taken into account.

### 17.2.2 Measurement of earth electrode resistance

Measurement of the resistance to earth of an earth electrode is not necessarily a simple matter. While certain fairly simple rules can be laid down, circumstances frequently arise which make it necessary to modify them. The resistance of an earth electrode is unique in that only the terminal provided by the electrode itself is definite, the other terminal of the resistance being theoretically at an infinite distance. In practice a measurement has to be made which includes the greater part, say 98 %, of the total resistance. There is no point in striving for a high degree of accuracy with such a measurement since, within the volume of such a resistance, there may be considerable non-uniformity in the soil and other disturbing features. An accuracy of 2 % is more than adequate, and accuracies of the order of 5 % are usually quite acceptable.

The best method of measurement is illustrated in Figure 11. A measured current is passed between electrode X, the one being tested, and an auxiliary current electrode Y. The voltage drop between electrode X and a second auxiliary electrode Z is measured and the resistance of the electrode X is then the voltage between X and Z divided by the current flowing between X and Y. The source of current and the means of metering either the current and voltage or their ratio are often, but not necessarily, combined in one device.

The accuracy of the measurement is influenced by the following considerations.

a) *Distances between electrodes.* The distance between electrodes X and Y has to be such that the resistance area of each, i.e. the area within which roughly 98 % of its resistance lies, is independent of the other. If X is a simple rod or plate Y should be placed 30 m to 50 m from X, with Z about midway between. A reading should be taken, followed by two further readings with Z moved, say, 7 m nearer to X and then 7 m nearer to Y. If the three readings give values for the resistance which agree within the accuracy required, then the mean value can be assumed to be the resistance of X.

If the results do not agree, then Y should be moved further away and the procedure repeated. This whole procedure should be repeated until the three readings do agree.

The above procedure is not satisfactory when X has a low resistance, say, 1  $\Omega$  or less. This usually occurs when X is an extended electrode or is composed of a system of electrodes which cannot be measured individually; generally occupying a large area. This problem is usually solved by obtaining earth resistance curves.

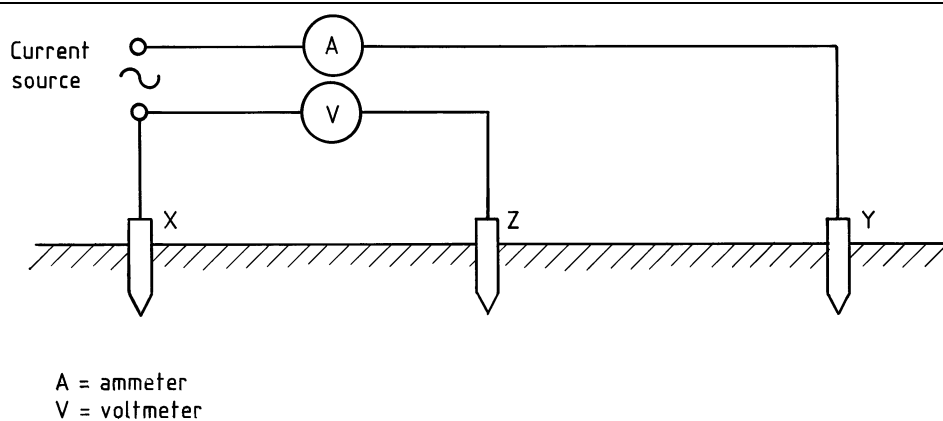
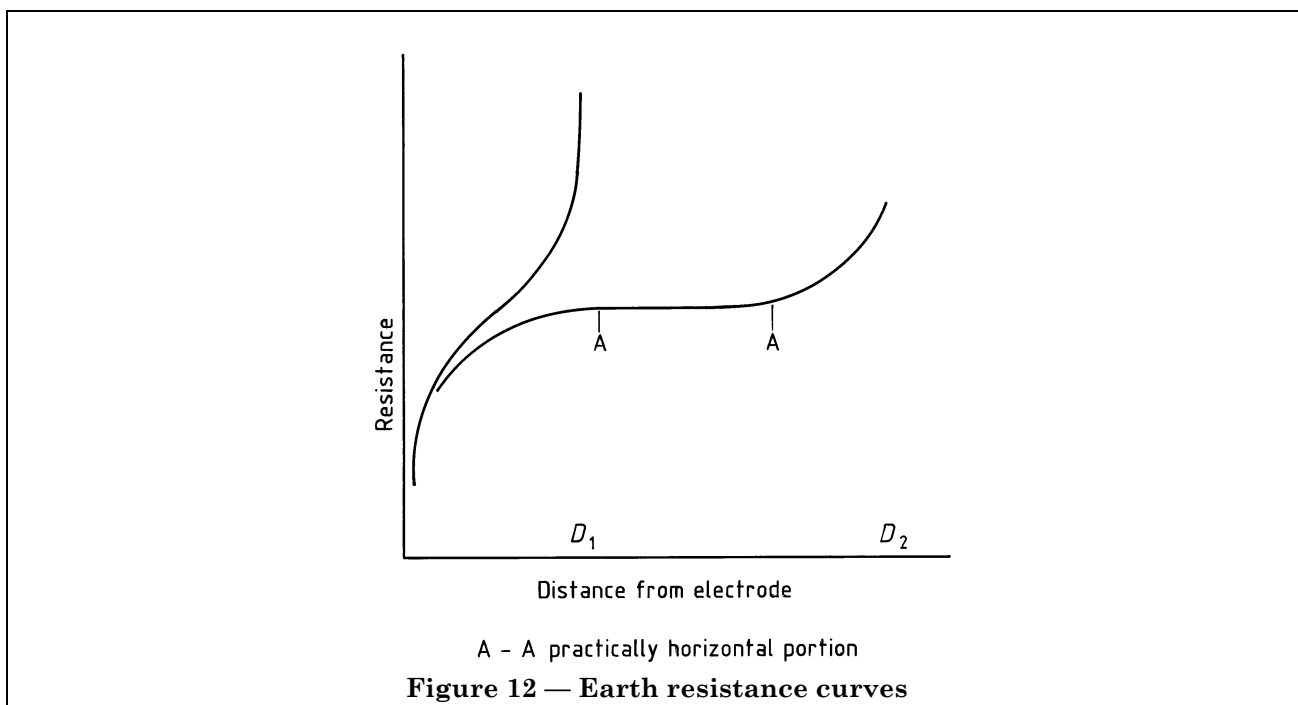


Figure 11 — Measurement of earth electrode resistance





To do this Y should be placed some arbitrary distance, usually some hundreds of metres, away from X and a series of measurements made with Z at various locations along the line X–Y. If the curve of resistance plotted against the position of Z has a substantially horizontal portion, this will give the required value of resistance. If the curve does not show such a horizontal section, Y has to be moved further away from X and the process repeated until a horizontal portion is obtained (see Figure 12). The horizontal portion does not necessarily occur where Z is midway between X and Y. As an example, in a test on a power station electrode system, ultimately found to have a resistance of  $0.05 \Omega$ , it was necessary to place Y 700 m away and the horizontal section of the curve was found for potential electrode distances of 70 m to 100 m.

b) *Interference by stray earth currents.* Soil conduction is an electrolytic phenomenon and hence small d.c. potentials arise between the electrodes, and stray a.c. or d.c. potentials are picked up by the electrodes if there is a traction system in the area. Both of these forms of interference can be eliminated by testing with alternating current at a frequency different from that of the interfering power currents and their harmonics. This is usually achieved by using a frequency of about 60 Hz to 90 Hz.

If the source of power for the measurement is a hand driven generator, the frequency of the measuring current can be varied to obtain the best result. An alternating current instrument usually incorporates a synchronous rectifier or equivalent in its metering circuits so that it responds only to voltage signals of its own frequency.

c) *Resistance of the auxiliary electrodes.* The resistance of Y and Z are in series with the measuring and power supply circuits. These electrodes are often, for convenience, single rod electrodes which may have quite a high resistance, depending on the resistivity of the soil in which they are driven. Resistance at Y increases the power supply requirements needed to ensure an accurately measurable voltage between X and Z. Resistance at Z is in series with the voltage measuring circuit and may affect its accuracy. Information on the highest acceptable values of auxiliary electrode resistance are usually provided with instruments designed for earth resistance measurement.

### 17.2.3 Measurement of soil resistivity

Soft resistivity is generally measured by the same method as is used for electrode resistance. Four equally spaced test spikes are driven to a depth of up to 1 m, the depth not exceeding 5 % of their separation  $a$  (see Figure 13). (It is important to ensure that their resistance areas do not overlap.) Current is passed between the two outer electrodes and the resistance  $R$  is given by the ratio of the voltage between the inside electrodes to the current. In homogenous soil the average resistivity ( $\rho$ ) in ohm metres ( $\Omega$  m) is given by the following equation:

$$\rho = 2\pi aR$$

where

- $a$  is the spacing between electrodes, in metres (m);
- $R$  is the resistance measured between the middle electrodes, in ohms ( $\Omega$ ).

The resistivity found applies to a soil depth  $a$ , so by repeating the measurement with different values of  $a$ , the average resistivity to various depths can be found and the results will indicate whether any advantage is to be gained by installing deeply driven electrodes in order to reach strata of a lower resistivity.

### 17.3 Measurement of resistance of earthing conductor

The following types of instrument may be used to measure the resistance of an earthing conductor:

- a) direct reading d.c. ohmmeter incorporating a hand driven generator;

- b) direct reading ohmmeter supplied from a battery; or

- c) a.c. test set generally mains driven and incorporating a suitable transformer providing isolation conforming to BS 3535.

Tests which give no quantitative result (e.g. bell or lamp tests) should never be used to prove the adequacy of earthing conductors.

Of the above instruments the first two differ only in the magnitude of the test current and they measure only the resistance of the conductor. A.C. mains testers can provide high test currents, but are usually limited to about 25 A because of the weight of the transformer.

An accuracy of about 5 % in the measured value is desirable. To achieve such an accuracy with low resistance conductors, correct selection of the method of measurement is important and the instrument manufacturer's instructions should be consulted to confirm the conditions under which it can be achieved.

The measured impedance or resistance, except for four-terminal measurements, is usually for a loop consisting of the conductor under test, the return conductor and probably some test leads. The resistance of the conductor under test is obtained by subtracting a separately measured value for the return conductor and leads from the loop resistance. In order that this process does not introduce too great an error, the resistance of the return conductor and leads should be as low as practicable. For a similar reason all connections should be made so as to have a low resistance.

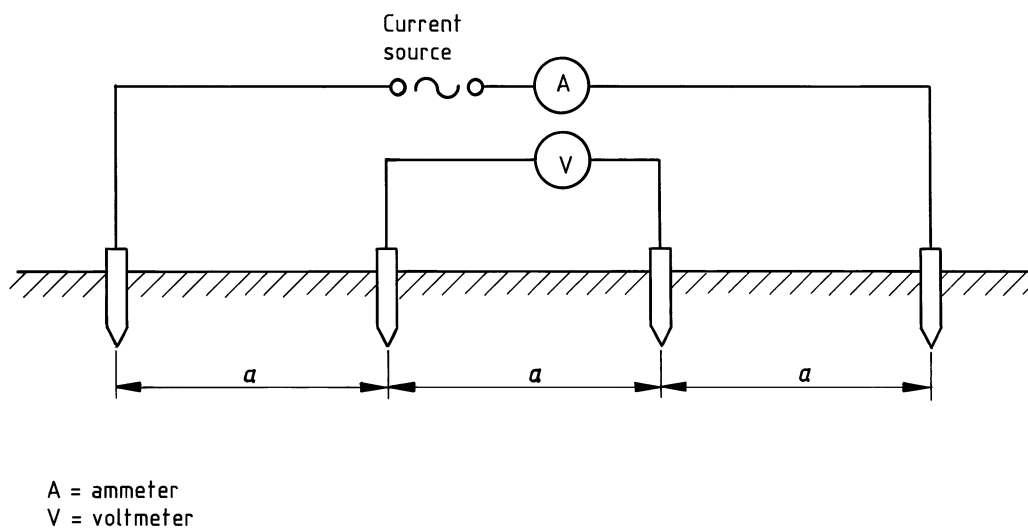


Figure 13 — Measurement of earth resistivity

The impedance of a ferromagnetic conductor varies with the current; with the sizes of conductor likely to be involved, the highest impedance generally occurs at currents in the region of 25 A to 50 A. Measurement with such a value of current will provide a worst case value, since the magnetic effect decreases as the current increases to fault current values. If measurements are made with d.c., and a substantial part of the length of the conductor is of ferrous material, it is recommended that the measured value be doubled to take account of magnetic effects.

## 18 Generating plant

### 18.1 General

Earthing of generating plant is provided to limit the potential of current-carrying conductors with respect to the general mass of earth and is generally necessary as an integral part of the protection against shock by indirect contact.

Generator protective earthing is achieved by connecting the frame of the generator, associated exposed-conductive-parts and extraneous-conductive-parts to a main earthing terminal. The earthing terminal or bar is connected to an independent earth electrode and, where appropriate, to other earthing facilities associated with the installation.

The earthing of the electrical system may require that the neutral point of the generator is connected to earth, either directly or via an impedance.

Where an installation is supplied by more than one source of energy (e.g. a public supply and a generator), the earthing system of the installation should be designed so that each source which can operate independently of other sources remains earthed if all the other sources are not connected.

There are many variations in system design and, for any particular application, the precise method of earthing of each energy source is subject to the recommendations of the equipment supplier and to the system parameters.

Public low voltage distribution networks are directly earthed in compliance with the current Electricity Supply Regulations. Since an installation connected to a public distribution network may be expected to be designed accordingly, direct earthing is also normally adopted for any generator which will supply such an installation.

**Whenever it is intended that a private generator be used to supply any part of a consumer's system normally supplied by an electricity supplier, the supplier should first be consulted. The current Electricity Supply Regulations require that, where operation in parallel with a public supply network is intended, the agreement of the supplier has first to be obtained.**

### 18.2 Low voltage generators

#### 18.2.1 *Earth electrode*

Generator earthing calls for the provision of an independent earth electrode. It is necessary that the earth loop impedance at any point of the installation is low enough to ensure operation of the earth fault protection, and this should be taken into account when the earth electrode forms part of the earth fault loop.

For independent earth electrodes associated with the local earthing of the star point of generating plant, it is recommended that the earth resistance should not exceed 20  $\Omega$ , see Figure 14 to Figure 17.

#### 18.2.2 *Generators which cannot operate independently of an incoming supply (mains excited asynchronous or synchronous machine)*

The parallel operation of a mains excited asynchronous or synchronous machine with an incoming supply is generally permitted; such a machine is normally provided where the prime mover is driven by wind, water or biochemical plant, but may be provided with any suitable prime mover. If there is a neutral point on the machine windings it should not be earthed. The machine framework, associated exposed-conductive-parts and extraneous-conductive-parts should be connected to the main earth terminal of the installation including the electricity supplier's earth terminal if provided.

#### 18.2.3 *Generators which can operate independently of an incoming supply*

##### 18.2.3.1 *Generator intended to operate in isolation from external supplies*

In this mode of operation the generating plant is the only source of supply to an installation. If there is only one machine, both protective and system earthing are achieved by connecting the generator neutral, the generator frame and extraneous metalwork to a main earthing terminal and by the use of an independent earth electrode.

Where there is more than one generator operating in parallel, the subject of neutral/earth circulating currents can be dealt with by the methods described in 18.2.3.2.

**18.2.3.2 Generator intended to provide an alternative or changeover supply**

In this mode of operation the generating plant may provide a full alternative supply to either the whole or part of an installation. Special attention to the changeover arrangements is necessary so that operation in parallel with the incoming supply is not possible and, in general, phase and neutral isolation from the incoming supply is necessary.

However, for PME supplies or where an earth terminal is provided from a multiple earthed supply system, isolation of the phase conductors only is satisfactory.

Where there is only one low voltage generator, the neutral point of its windings, the generator frame, all exposed-conductive-parts and extraneous-conductive-parts should be connected to the main earthing terminal. This earthing terminal should be connected to an independent earth electrode and, where appropriate, to the protective earth terminal provided by the electricity supplier.

When generation is by a number of sets which may operate in parallel, protective earthing of the generator frames and associated metalwork follows the same lines as that described for one machine. However, the method of system earthing for the windings is influenced by the magnitude of the circulating currents, commonly third harmonic, which can flow in the neutral/earthing conductors. This problem may be overcome by the selection of generating sets with low harmonic output (e.g. zig-zag wound machines). Alternatively one of the following arrangements may be used.

- a) A neutral earthing transformer connected between the phases and earth. This enables the neutral of the installation to be permanently earthed, with the generators connected to the busbars as three-wire machines.
- b) Star-point switching to connect the star point of only one generator to earth during parallel operation. It is essential that electrical and mechanical interlocks on the star-point switches ensure the integrity of the neutral/earth connection at all times and under all possible operating conditions.
- c) A suitable reactor in the neutral connection of each generator which will attenuate higher frequency currents without offering significant impedance at mains frequency.

An earthing arrangement for a single machine operating in changeover mode is given in Figure 14. For multiple machine installations, where circulating currents are not expected to create difficulties or where machines with low harmonic output are selected, a typical arrangement of the neutral/earth connections is shown in Figure 15. Typical methods of connection where options a) or b) are adopted are shown in Figure 16 and Figure 17.

**18.2.3.3 Generator capable of operating in parallel with an external supply**

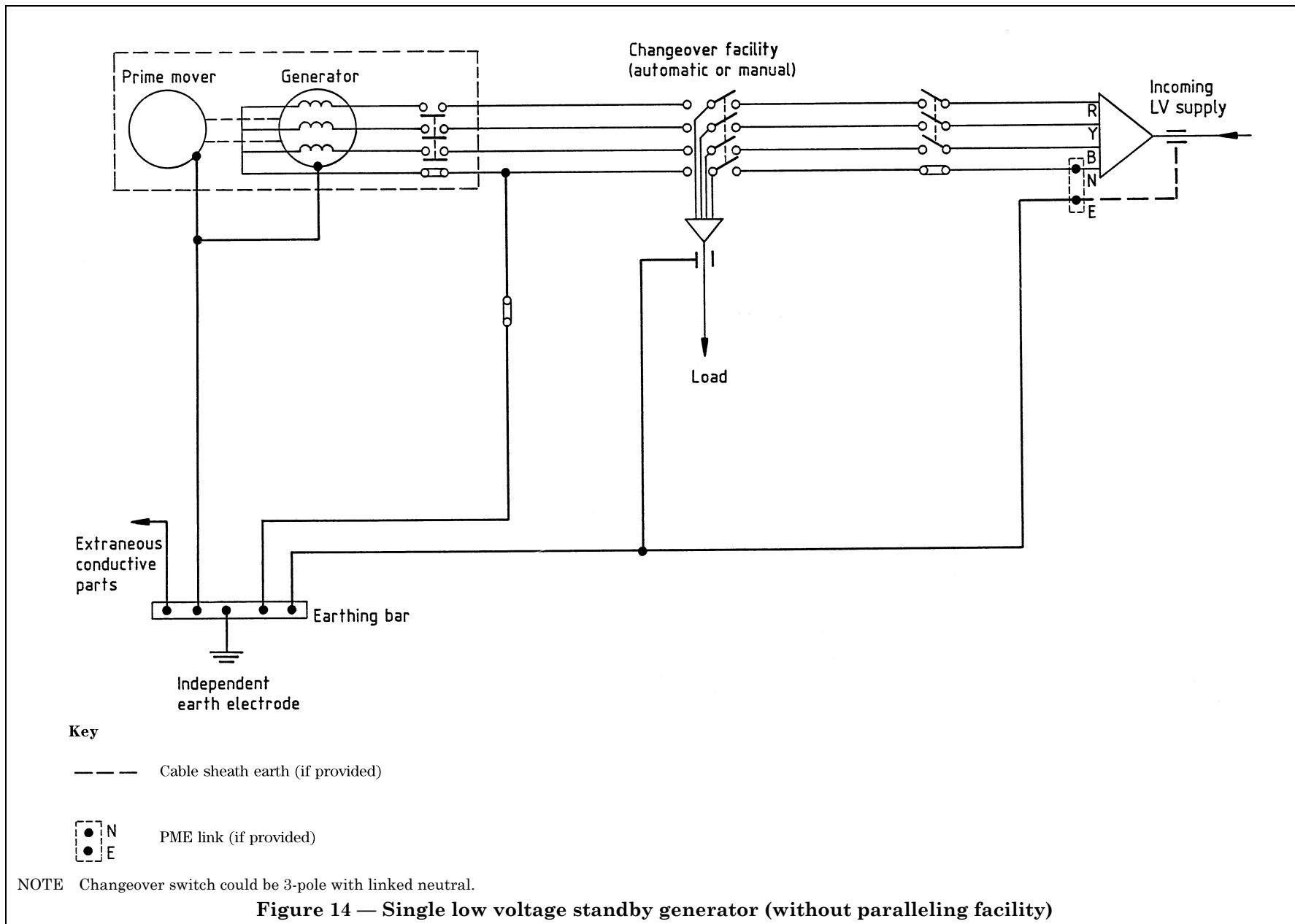
Parallel operation of synchronous and self-excited asynchronous generators is possible if protection is provided to disconnect the incoming supply in the event of its loss or partial failure.

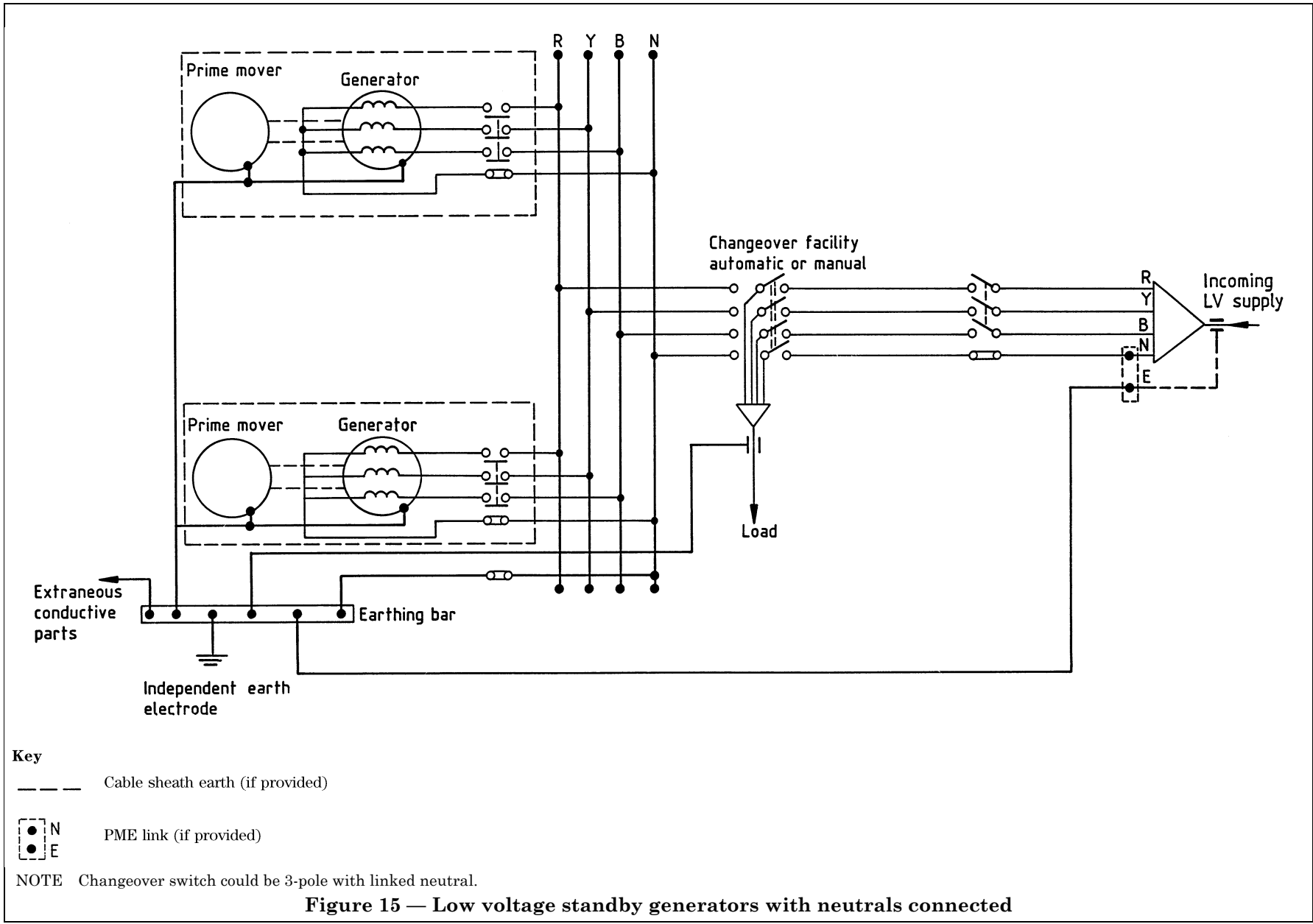
Problems of neutral/earth circulating currents, similar to those with parallel generators dealt with in 18.2.3.2, arise when a low voltage generating set is operated in parallel with an incoming supply. Where the magnitude of the circulating currents would be excessive, the options described in 18.2.3.1 may be employed. If the generating set is also required to operate in the changeover mode the recommendations of 18.2.3.2 should be followed.

**18.2.4 Low voltage three-phase mobile generators****18.2.4.1 Connections to generator windings**

These units may be trailer, skid or vehicle mounted with outputs from about 15 kV A upwards. As supplied, the generator windings may not be connected to the machine frame. The three-phase terminals and the neutral connections are brought out independently to the generator terminal box or, on smaller units, to a socket-outlet conforming to BS 4343.


To limit the potential of the conductors to the metallic enclosures and to ensure correct operation of protective devices, the star point of the generator windings should be connected to a common reference point. The generator frame, all exposed metalwork, the under frame or vehicle chassis and all protective conductors should be connected to form this reference point, and earthed when reasonably practical.



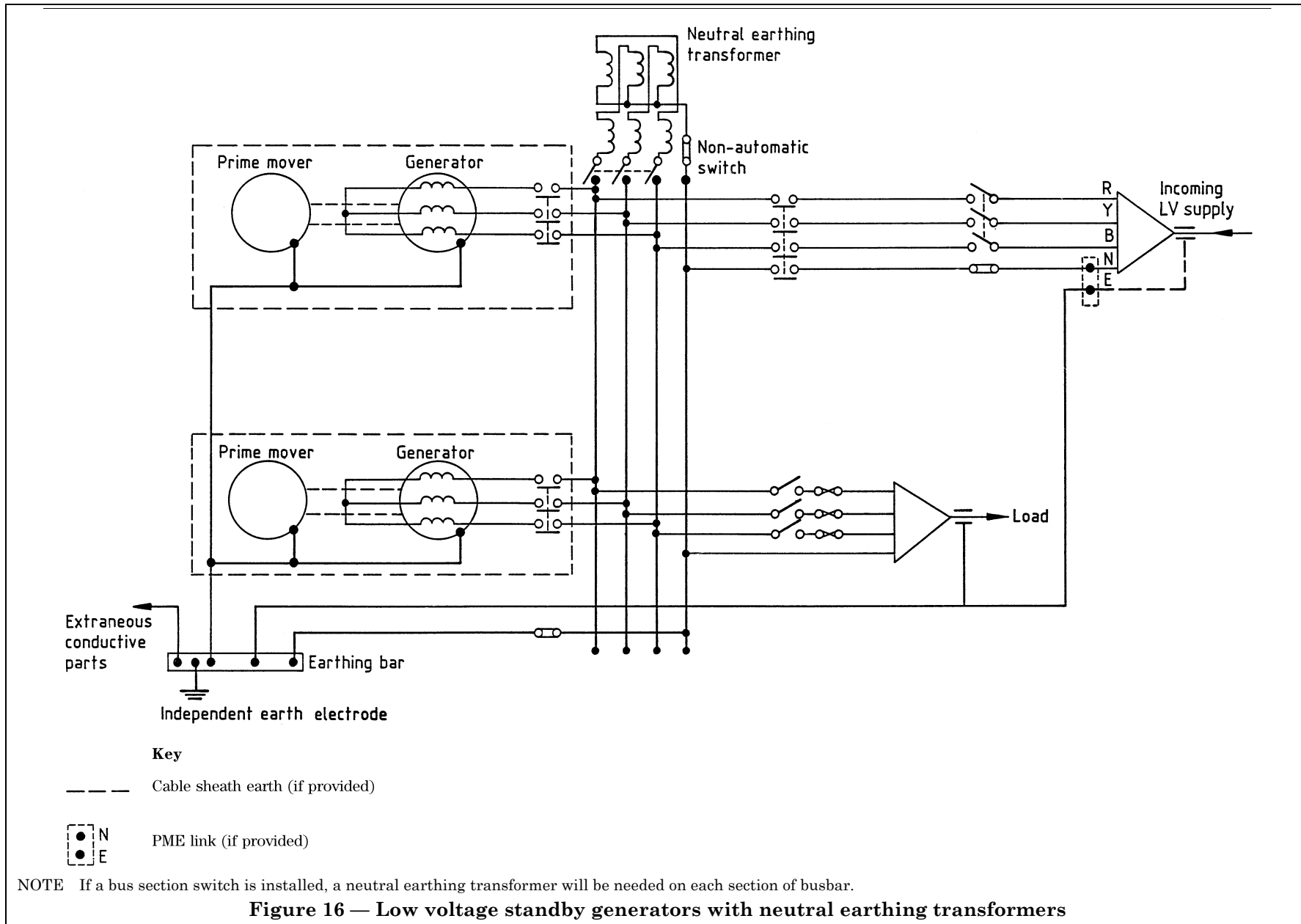


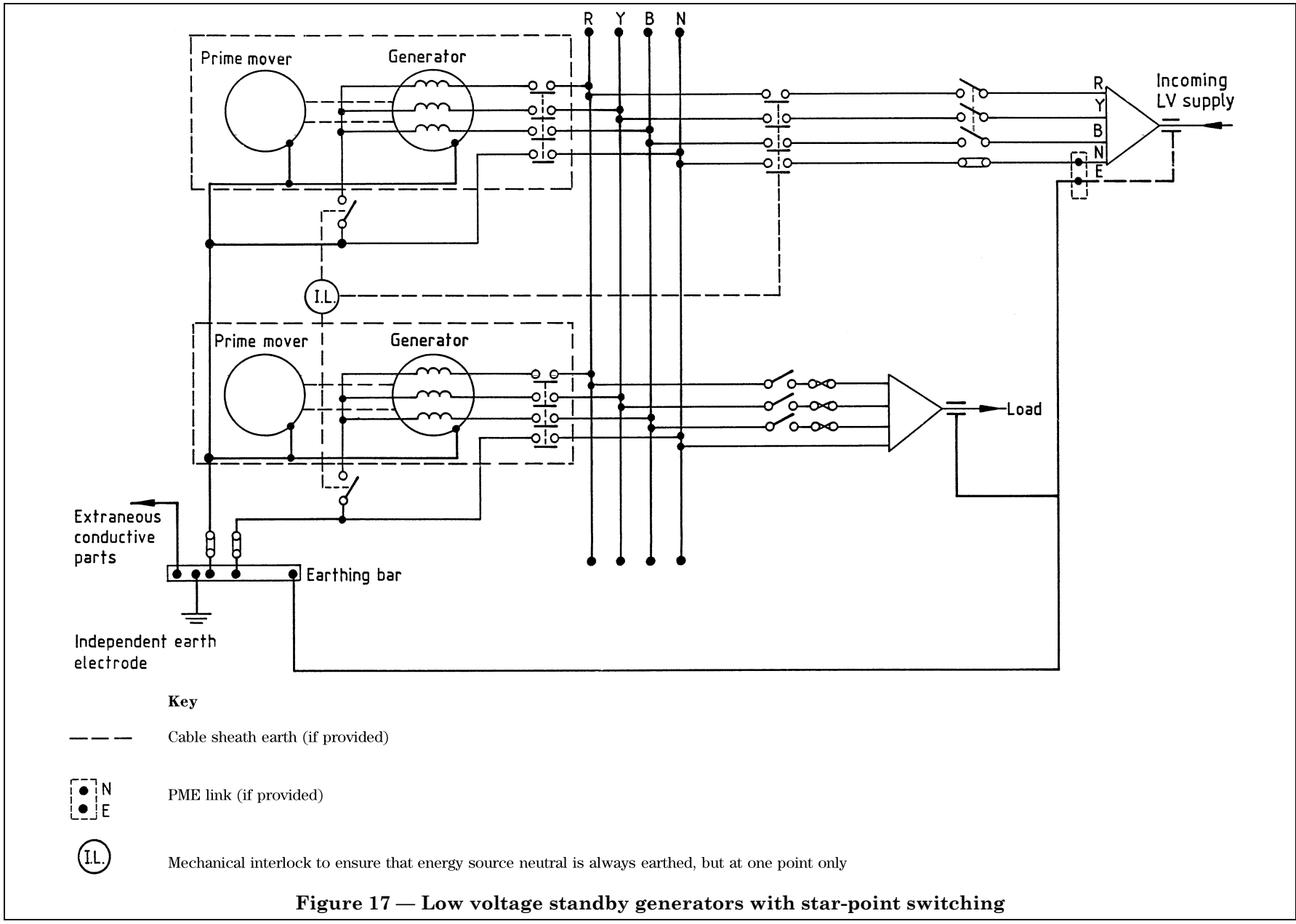
**Figure 15 — Low voltage standby generators with neutrals connected**

**Key**  
 - - - Cable sheath earth (if provided)


 PME link (if provided)

NOTE Changeover switch could be 3-pole with linked neutral.





**Figure 17 — Low voltage standby generators with star-point switching**



It is recommended that the terminal box or socket-outlet should make provision for five connections, i.e. there should be a separate connection for a protective conductor in addition to the usual four connections for the three phases and the neutral. Where connections for only four conductors are provided, the generator should be used to provide balanced three-phase loads only, the fourth connection being reserved for the protective conductor. The fourth connection and conductor should not be used for combined neutral/protective purposes, because of the risk which can arise if this conductor fails.

The use of separate neutral and protective conductors is particularly important if it is wished to provide supplementary protection against shock by the use of a three-phase RCD, because the neutral current, but not any fault current, has to be summed by the RCD. It is essential that the connection between the common reference point and true earth is made at the generator and that there is no connection between neutral and earth on the load side of the RCD.

The recommendations given here for mobile and portable generators assume that the remainder of the system (generator, cables and load equipment) are installed so as to conform to the appropriate requirements of BS 7671.

#### 18.2.4.2 Selection of cables

In line with the recommendation that a terminal box or socket-outlet should have separate ways for connecting the neutral and the protective conductor, all cables for three-phase loads should have four cores and either flexible metallic braid or steel wire armour which can act as the protective conductor. By this means the risk of contact with live conductors when a cable is damaged is minimized and it is possible to achieve an earth fault loop impedance low enough to ensure fault-current disconnection within the limits specified in BS 7671. Similarly, for single-phase loads, a cable should include either flexible metallic braid or wire armour which can be connected as a separate protective conductor.

Where, with long runs of cable, the resistance of the metallic braid makes it difficult to achieve a low enough earth fault loop impedance, a five-core (or, for single-phase, a three-core) cable should be chosen so that the additional conductor can be connected in parallel with the braid.

Care should be exercised to ensure adequate and reliable connection of the flexible metallic braid or steel wire armour to the protective terminal or contact at the terminations.

If a cable which does not have metallic braid or wire armour has to be used it is important to select a type which has a tough abrasion resistant covering and includes a separate protective conductor. In this case it is advisable to provide supplementary protection by means of an RCD.

A type of cable should be selected which is suitable for the environmental conditions.

#### 18.2.4.3 Operation with a residual current device

Where cables and equipment are likely to be subjected to risk of damage, supplementary protection should be provided by the installation of an RCD. It should be noted, however, that RCDs are relatively delicate electromechanical devices and may not survive rough conditions or vibration. Care should therefore be taken in the selection, application and mounting of RCDs on or near generators. The advice of the RCD manufacturer should be sought.

Some three-phase generators are supplied with a built-in RCD and the star point of the windings is internally bonded to the generator frame and the protective conductor terminal. Alternatively, it may be necessary to install a separate RCD and to make the appropriate connections externally.

To obtain full benefit of the RCD, the common reference point described in 18.2.4.1 should also be connected to true earth.

The RCD should conform to BS 4293 and should be selected to have a rated tripping current not exceeding 30 mA and an operating time not exceeding 40 ms at a residual current of 150 mA.

The RCD should operate not only when a fault develops between a phase conductor and earth or a metallic enclosure but also to reduce the risk of shock by personal contact with live conductors of damaged unarmoured cables or of equipment not completely surrounded by a metal enclosure.

Although, in the absence of a deliberate connection between the protective conductor and earth, fortuitous contact between metal cladding of equipment and earth may be such that any earth fault current likely to involve a risk of shock would be sufficient to cause the RCD to operate, it is better to ensure operation by making the earth connection wherever it is at all practicable.

In order to ensure that, in the event of a fault to earth, the RCD operates to prevent a danger of shock from exposed metalwork, the resistance of the earth connection should be less than  $50/I_{\Delta n} \Omega$ , where  $I_{\Delta n}$  is the rated operating current of the RCD. With  $I_{\Delta n}$  equal to 30 mA the resistance of the earth connection should not be greater than 100  $\Omega$  since a resistance in excess of this value may be unstable and therefore unsuitable.

It is strongly recommended that users of transportable and portable equipment incorporating an RCD should arrange for a competent person to carry out trip and timing tests on the RCD using a proprietary instrument designed for that purpose. These tests should be made at frequent intervals (e.g. every 3 months), and they are independent of any other specified trip test using the trip button on the RCD.

#### 18.2.4.4 *Connections to Earth*

The following are examples of feasible methods for making the connection with the general mass of earth recommended in 18.2.4.1 and 18.2.4.3:

- a) an earth rod, driven to a depth of not less than 1 m;
- b) permanent structural steelwork in foundations;
- c) exposed reinforcement bars in concrete foundations;
- d) metallic items which are known to extend at least 1 m down into the ground. Gas or oil pipes may not be used because of the risk of ignition in the event of fault current flowing;
- e) the earth terminal of an adjacent fixed electrical installation, provided that the earth connection of that installation is not likely to be disconnected.

#### 18.2.4.5 *Operation without a residual current device*

The star point of the winding should be connected to the generator frame, all exposed metalwork and the protective conductor.

Cables should be selected which include a covering of steel-wire armour or metallic braid which can be connected to, or used as, the protective conductor.

All load equipment should be either metal clad, with the exposed metalwork connected to the protective conductor, or double insulated. It should be suitable for the environmental conditions to which it will be exposed.

Shock protection is dependent on the enclosure of all live parts by suitable conductive parts, and bonding by the protective conductors, or the use of suitable double-insulated equipment. The fault loop impedances for both short circuit and faults to exposed metalwork should ensure disconnection conforming to BS 7671. Under these conditions it is acceptable to run these units without making a connection to an independent earth.

#### 18.2.5 *Portable and transportable low voltage single-phase generators*

These units range in size from about 0.3 kV·A to 10 kV·A. The generator winding is usually isolated from the frame and brought out to three-pin sockets, which should conform to BS 4343. The protective ("earth") conductor contact tubes are connected internally to the generator frame. A voltage selector switch is often fitted to enable outputs to be obtained at 240 V and 120 V.

It is accepted that small single-phase generators can be run satisfactorily as floating systems, i.e. without the winding connected to the frame or to earth. The generator frame and enclosure should be bonded to all exposed-conductive-parts of the load equipment, using a correctly terminated protective conductor in the connecting cable.

Cable, plugs, sockets and cable couplers should be suitable for their environmental exposure. It is recommended that the cable should be a flexible type which includes a metallic braid or screen suitable for use as a protective conductor. The termination of braided cable in domestic type plugs can be difficult. For this reason it may be preferable to select plugs and sockets conforming to BS 4343.

If a cable without a metallic screen is used it should be flexible with an extruded oversheath capable of high abrasion resistance and should contain a separate protective conductor.

The cable, plugs and sockets should be inspected frequently and if defective should be replaced, not repaired. Equipment and cables which are in good condition are vital for the continued safety of an unearthed system and form the first line of protection against the risk of shock.

All cables should be as short as practicable and supply compactly located loads, since experience has shown that a compact installation is less likely to suffer insulation damage, causing earth faults, than an extensive one.

Hand-held 110 V (industrial use) or 230 V (domestic use) portable electrical equipment used with systems supplied by an independent single-phase generator should preferably be of class II construction in accordance with BS 2754.

Contact with a conductor exposed through damage or misuse, subsequent to a fault (possibly undetected) in the equipment, introduces a risk of shock and the installation of an RCD may reduce this risk. For such supplementary personal protection the RCD should have an operating current of 30 mA and a disconnecting time of 40 ms at an operating current of 150 mA. (See 18.2.4.3 for recommendations on the application of RCDs.)

It is unusual for a small single-phase generator to have a built-in RCD, so that when this form of supplementary protection is desired a separate RCD assembly has to be provided. This should be installed by a competent person.

Connections should be made on the generator side of the RCD between an unswitched pole of the generator winding, the protective conductor and earth. The pole thus connected becomes a neutral. These connections will provide paths for fault current to return to the generator windings and enable the RCD to operate when a fault occurs to the enclosing metalwork or to earth, or if contact is made with exposed live parts.

A suitable enclosure should be provided for the RCD, either all insulated or metallic.

In practice it is often better to use an unearthed or floating system, provided that adequate care is taken. Cables and accessories should be selected and used with regard to the environmental conditions. The system should be inspected frequently and care should be taken to use cable routes which minimize the risk of damage.

### **18.3 High voltage generators**

#### **18.3.1 Earth electrodes and earthing resistors**

High voltage distribution networks may be earthed directly or through resistors, reactors or earthing transformers, the type of earthing being related to the sensitivity of the earth fault protection and designed to limit the localized rise of potential under earth fault conditions.

It is essential that the earthing system for an installation incorporating an HV generating set is compatible with the earthing of any other installation or of any distribution system to which the generator set will be connected.

#### **18.3.2 Single high voltage generator systems (synchronous machines with star-connected alternators)**

##### **18.3.2.1 Generator intended to operate in isolation from external supplies**

The star point of the generator should be connected (via a resistor or reactor if necessary) and through a bolted link for test purposes to an earthing conductor and the independent earth electrode.

Where a resistor or reactor is used for earthing the star point of a high voltage generator, it is normally designed to limit the earth fault current to the same order of magnitude as the machine's full load current. In general, however, earthing via resistors or reactors is not necessary for single generators of 1 MW or less in rating.

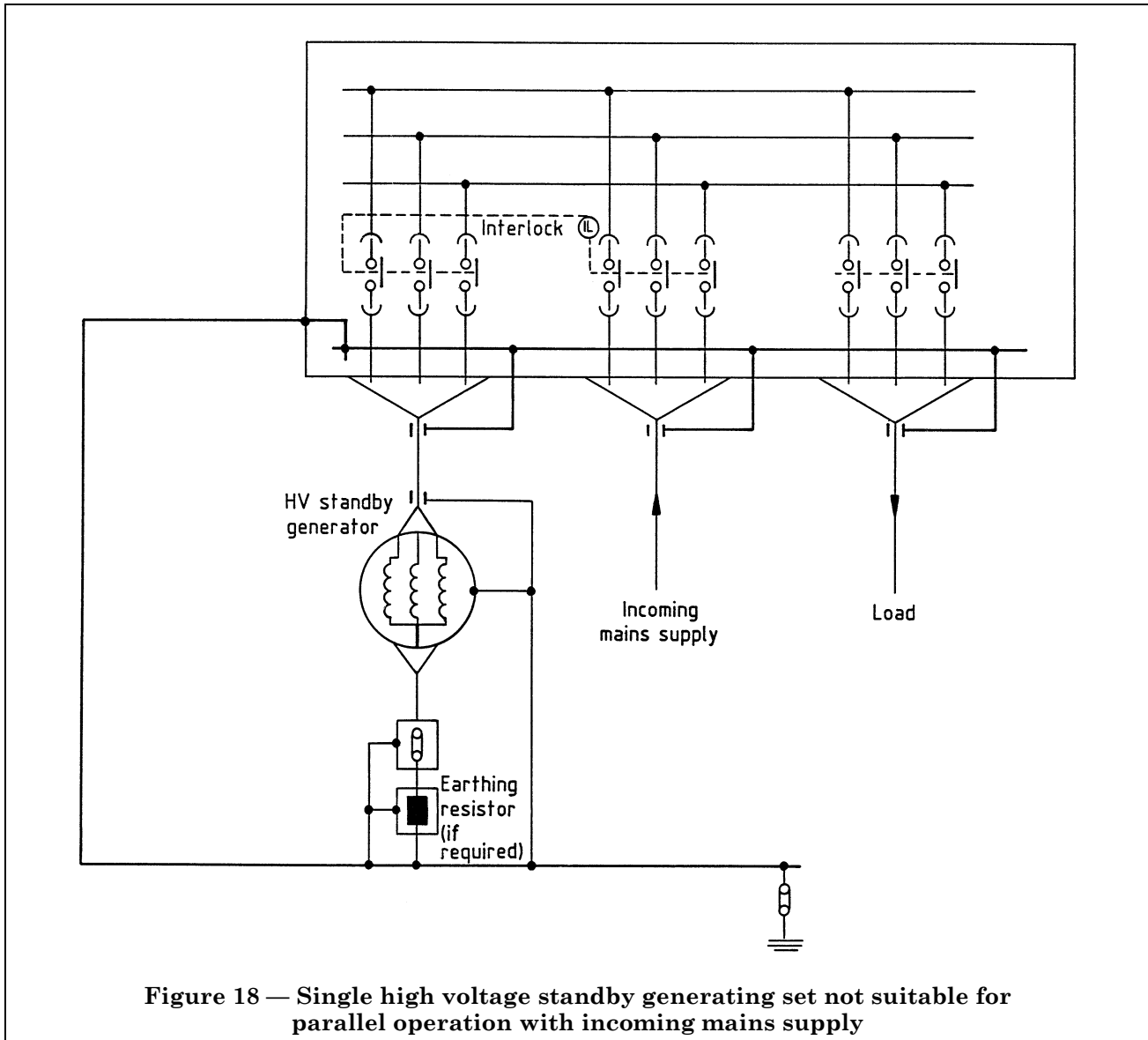
##### **18.3.2.2 Generator intended to provide an alternative or changeover supply**

In this mode of operation the generating set may provide a full alternative supply to either the whole or part of an installation. In addition to the earthing recommendations described for a set operating in isolation from other supplies, the presence of an incoming external supply makes necessary the interlocking of the standby supply and external supply circuit breakers to prevent inadvertent parallel connection (see Figure 18).

##### **18.3.2.3 Generator capable of operating in parallel with an external supply**

The operation of a generator in parallel with an external high voltage system is subject to the approval of the electricity supply undertaking.

In most cases where parallel operation with an external supply is required, an earthing contactor is necessary between the generator star point and the bolted test link (see Figure 19). The contactor should be interlocked with the incoming supply circuit breaker so that it is open during periods of parallel operation but closed at all other times. In the event of the electricity supply being lost during a period of parallel operation, the earthing contactor should be arranged to close automatically. The form of generator earthing (direct or resistance) is dependent upon the system parameters and the machine manufacturer's recommendations.



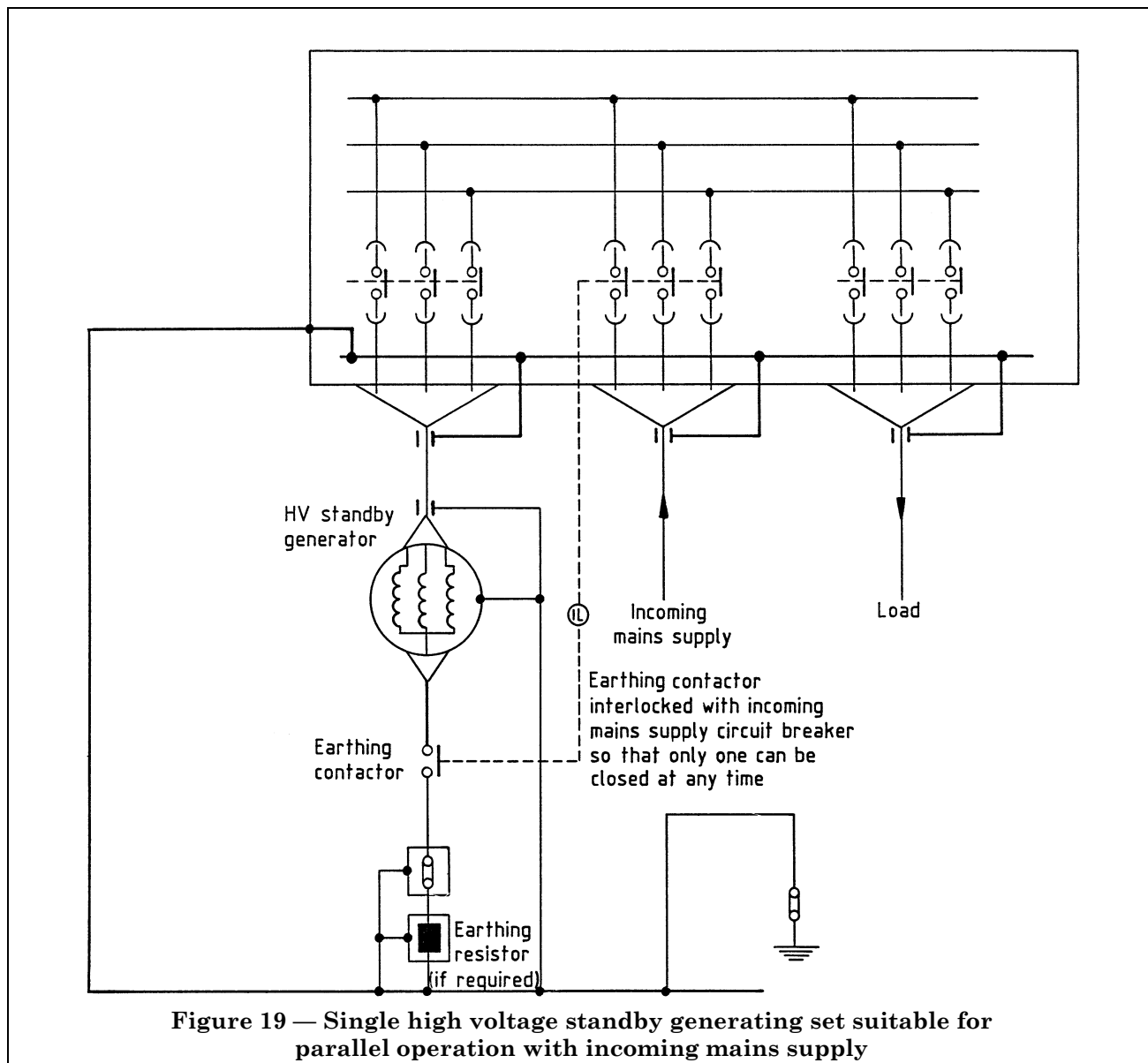
**Figure 18 — Single high voltage standby generating set not suitable for parallel operation with incoming mains supply**

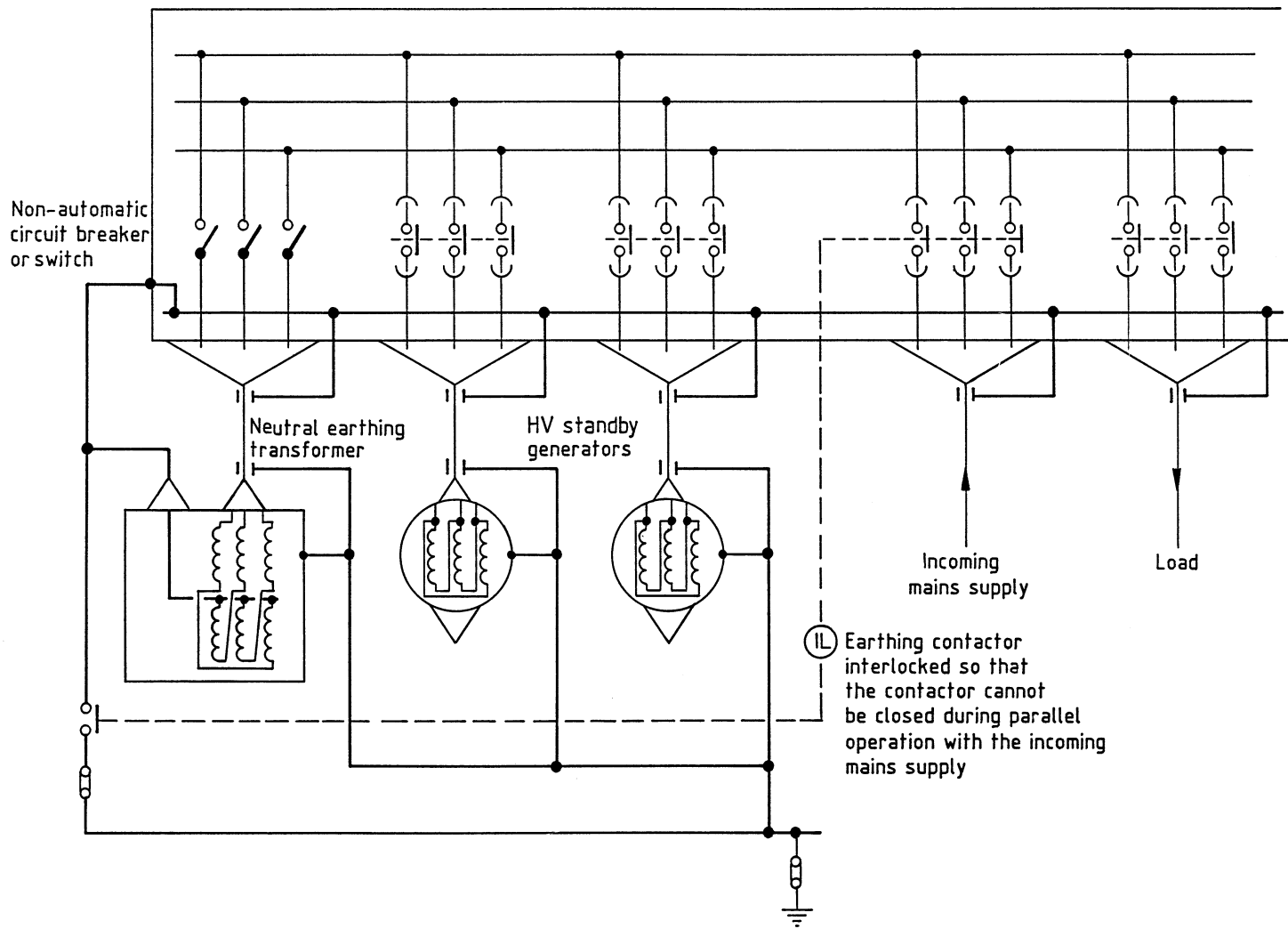
### 18.3.3 Multiple high voltage generator system earthing

#### 18.3.3.1 Generators intended to operate in isolation from external supplies

When it is required to operate two or more generators in parallel and the method of energy source earthing is direct or resistance earthing, then earthing contactors should be installed between each generator star point and the earthing conductor/earth electrode. Unless other precautions are taken to limit circulating current, the contactors should be interlocked so that only one can be closed when the generators are running in parallel, to maintain a single energy source earth.

If a neutral earthing transformer is to be used for energy source earthing, it should be connected as shown in Figure 20 except that in the case of an isolated generating system, the earthing contactor is not required.





NOTE The arrangement shown is not necessarily the preferred method of providing alternative generation.

**Figure 20 — Multiple high voltage standby generating sets with neutral earthing transformer suitable for parallel operation with each other and with the incoming mains supply**

### 18.3.3.2 *Generators intended to provide an alternative or changeover supply*

When the generating sets are not to be operated in parallel with the mains supply and have direct or resistance earthing, the standby generator circuit breakers and mains circuit breaker have to be interlocked.

If a neutral earthing transformer is used the recommendations are the same as described for a single standby generator in 18.3.2.2; as shown in Figure 20, but without the earthing contactor.

### 18.3.3.3 *Generators capable of operating in parallel with an external supply*

When the generating sets have direct or resistance earthing and are used as standby to the mains, earthing contactors are needed where there is to be parallel running. These should be interlocked with the external supply circuit breaker so that they are open during parallel operation of the set with the external supply, but one of them is closed at all other times (see Figure 21).

If a neutral earthing transformer is used, the earthing arrangements should be as shown in Figure 20.

### 18.3.4 *Single or multiple low voltage generating sets with low voltage/high voltage generator transformers*

#### 18.3.4.1 *General*

Figure 22 shows an arrangement for neutral earthing when there are two low voltage generating sets but is equally applicable to a single set arrangement. The delta/star configuration of the generator transformer windings prevents circulation of third harmonic currents in the low voltage system.

#### 18.3.4.2 *Generating sets operated in isolation from external supplies*

In this case the star points of the high voltage transformer windings on the generator transformers should be connected together and to an earthing conductor via a bolted link. Low voltage generators are normally star connected and in this case their star point should be individually connected to the earthing conductor via bolted links.

#### 18.3.4.3 *Generators intended to provide an alternative or changeover supply*

The incoming mains circuit breaker and the standby generator circuit breaker have to be interlocked to prevent inadvertent parallel operation. In other respects the recommendations are as described for generating sets operating in isolation from a mains supply (see 18.3.4.2).

#### 18.3.4.4 *Standby generators (capable of parallel operation with the incoming supply)*

In general the recommendations are as described for standby generators without a paralleling facility except that, an earthing contactor is necessary and should be interlocked with the mains supply circuit breaker. This ensures that the contactor is open during parallel operation with the mains supply but closed at all other times. A bolted link should be fitted between the neutral earthing contactor and the earth bar.

## 19 Power stations and substations

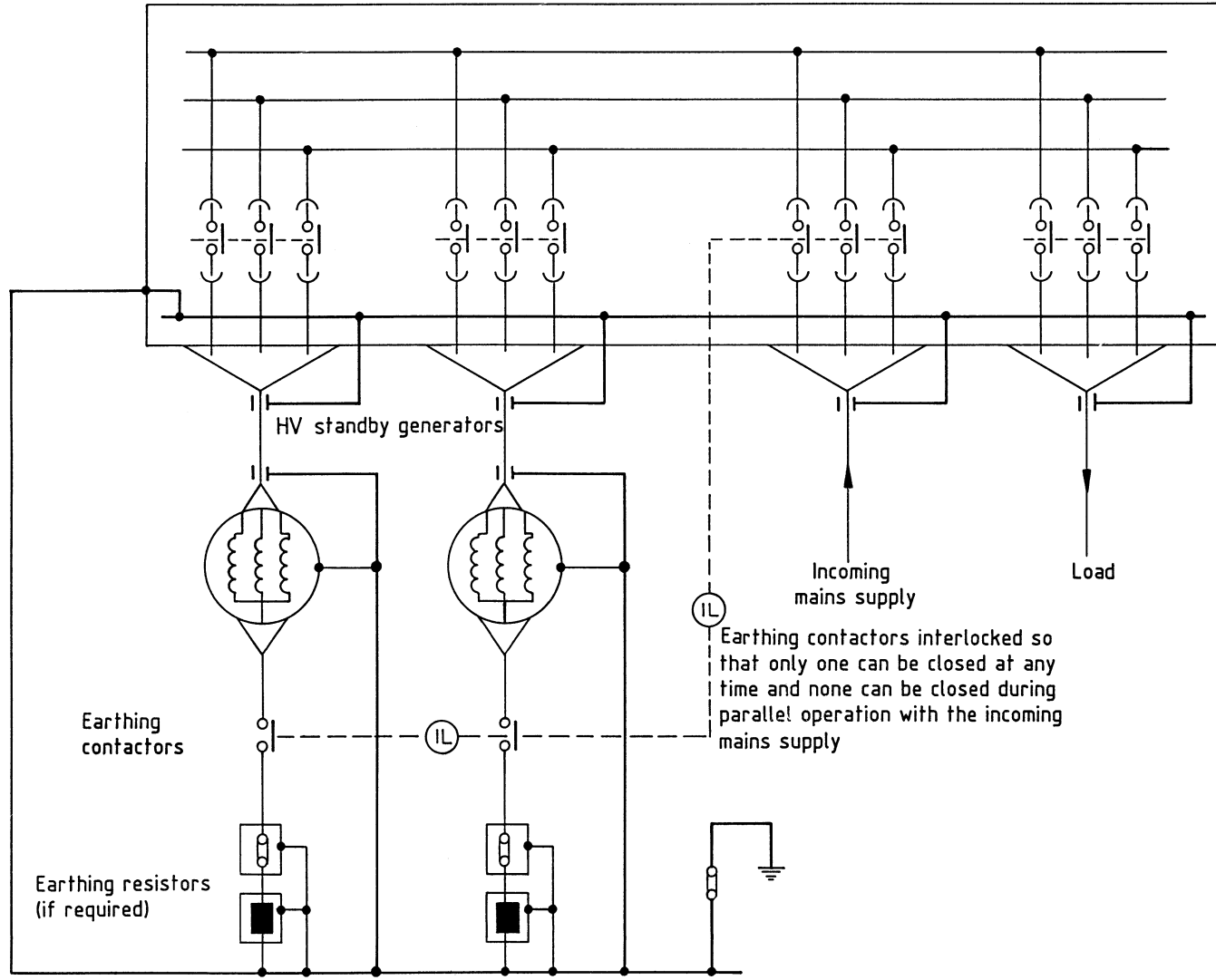
### 19.1 General

In general, earthing installations will be required at power stations and substations for the following:

- the neutral points of each separate electricity system which has to be earthed at the power station or substation;
- metallic enclosures, supports or other non-current-carrying metalwork associated with each system, e.g. transformer tanks, cable sheaths;
- extraneous metalwork not associated with the power systems, e.g. water and gas installations, boundary fences, sheaths of control or communication cables.

For safety, the objective of earth bonding is to ensure that, in normal or abnormal conditions, any voltage appearing on equipment to which there is access should be below a dangerous level. It is not practicable to ensure that earth-bonded metal parts remain at near true earth potential during the passage of earth fault currents, particularly on high voltage systems with directly earthed neutrals. The objective should therefore be to provide effective bonding of low impedance and adequate current-carrying capacity between parts with which anyone may be in simultaneous contact, and to arrange as far as possible that large fault currents do not flow between such points.

To minimize risk of damage to certain auxiliary plant, the rise and duration of potential of a station earthing installation above true earth potential should be as low as practicable, since this potential will be applied across protective insulation of any plant with connections to earth external to the substation, e.g. plant with connections to pilot or telephone cables or cable sheaths. For similar reasons, the potential difference between earthed points in the station should also be kept to a minimum.



**Figure 21 — Multiple high voltage standby generating sets suitable for parallel operation with each other and with the incoming mains supply**



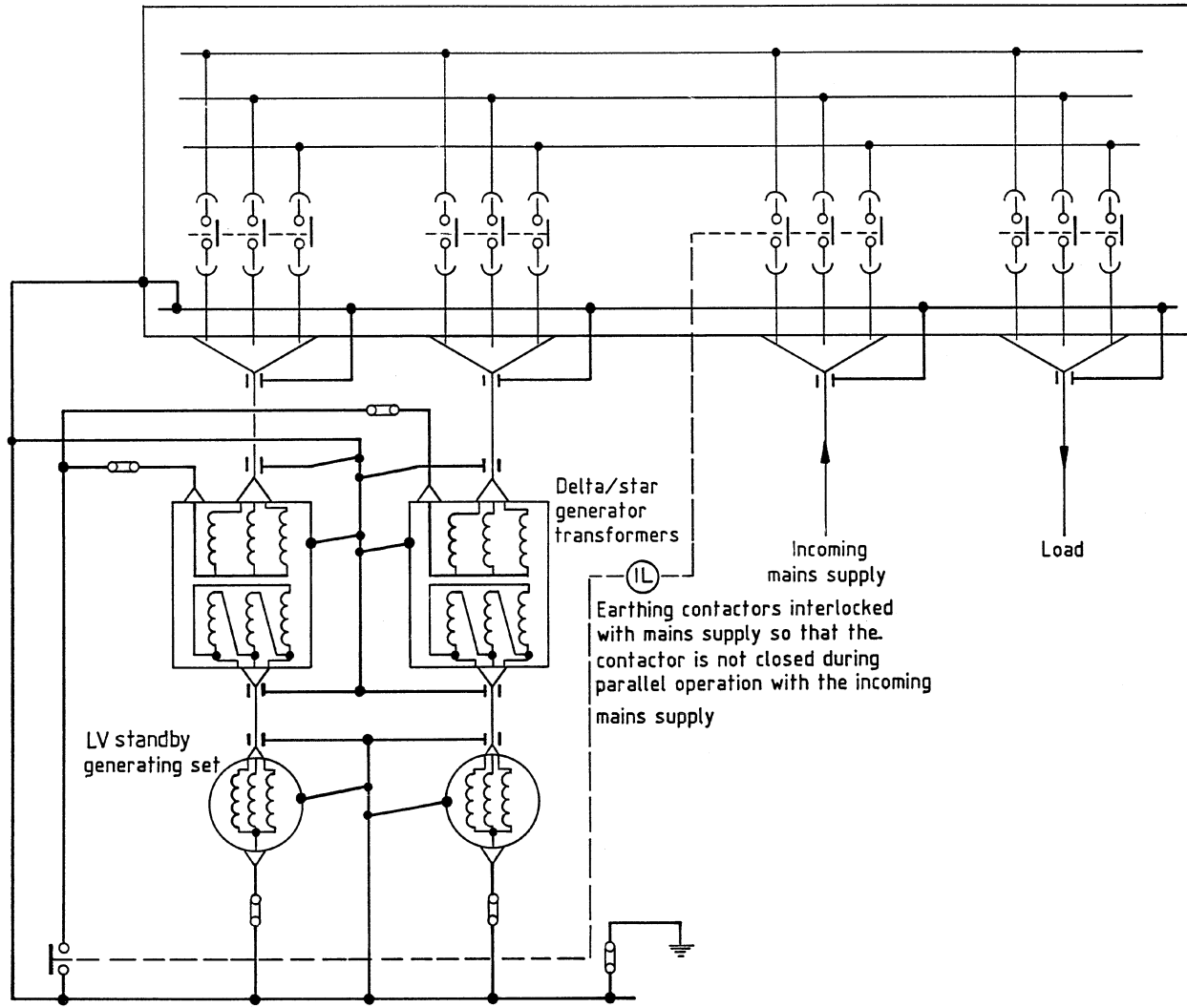


Figure 22 — Low voltage standby generating sets with generator transformers giving a high voltage supply and suitable for parallel operation with the incoming mains supply

Where surge protection is provided, the connection of the protective devices to earth should be as direct as possible. The discharge of high currents with high frequency components requires earth connections of low resistance and reactance, i.e. short connections with as few changes of direction as possible.

Where the neutral points of two electrically separate electricity systems are connected to a common earth electrode at a site, there is a coupling of the systems and a common rise of one earth potential due to the passage of the fault current through the earth electrode. Similarly if non-current-carrying metalwork is bonded to the same earth electrode as the neutral point of the supply the metalwork will experience the same rise of earth potential. If complete separation of electrical systems were required, it would be essential that the neutral points of each system and its associated metalwork be separately earthed. If such a method were adopted, each earthing system would require insulation from the other sufficient to withstand the maximum rise of earth potential occurring in either system by virtue of lightning discharges or power system fault currents. Insulation between earthing systems to this level is rarely practicable.

The choice of using a common earth or separate earths for the systems of different voltages at a transforming point affect the following:

- 1) the probability of breakdown occurring in a transformer between the higher and lower voltage sides due to lightning or other surges;
- 2) the safety of consumers or their property supplied by any low voltage system distributed from the station against a rise of potential of the earthed neutral by a high voltage system earth fault at the station.

The former risk is reduced by use of a common earth system, and the latter risk only arises if the resistance of the earth electrode system is not sufficiently low to limit the rise of earth potential to a safe value. There is advantage in using a common earth where the earth electrode resistance, including the parallel resistance of any bonded metalwork, etc. to earth, is  $1 \Omega$  or less, as is usual at power stations, large outdoor substations or substations supplying a network of cables whose sheaths have a low impedance to earth.

The rise of potential of a substation earth system is not excessive if the combined resistance of the earth electrode system is small compared with the total earth fault circuit impedance. In high voltage systems at voltages of 66 kV and below, this is generally achieved by insertion of resistors or reactors between the system neutral and the earth electrode, the connection from neutral to the resistance or reactor being suitably insulated. Systems of higher voltage (100 kV and above) generally have the neutral directly earthed, since the increase in costs of insulation that would be needed for the transformer winding would be considerable.

A special system of reactor earthing of a system neutral is the arc-suppression coil system in which the inductance of the reactor is chosen such that in the event of an earth fault on one phase of the system, the product of reactor impedance and the unbalanced system capacitive current is as close as practicable to the system phase voltage. In a perfectly tuned situation, there is zero earth fault current at the point of fault and the system supply is maintained, with the faulted phase held at earth potential and the healthy phases elevated in potential to line voltage above earth. Special attention is required to the long-time fault capacity of earth electrodes used on systems protected by arc-suppression coils. Provision is sometimes made for the automatic short circuiting of arc-suppression coils after a suitable time delay.

In rural situations where overhead lines are used, it may, in certain circumstances, be inadvisable to use a common earth.

The earthing arrangements are therefore best considered separately for the following types of substations:

- i) where low voltage is confined to auxiliary supplies within the substation;
- ii) substations that provide an external low voltage supply; and
- iii) power stations.

The use of neutral earthing switchgear in public supply systems is avoided where possible, since a direct earth is simple, reliable and cheaper than a switched earth. The circumstances in which neutral earthing switchgear may be necessary are so broad that it is not practicable to give general recommendations on type and application.

## 19.2 General earthing arrangement of substations

The low voltage supply systems of distribution transformers and their associated neutral earthing may require specific installation measures to exclude them from possible dangerous transfer potentials arising from earth faults on adjacent higher voltage systems. This is especially relevant where the distribution transformer is located within or in close proximity to a higher voltage substation.

The following six cases may have to be considered.

a) *A distribution transformer (ground mounted or pole mounted) not associated as above with higher voltages*

1) Where the combined resistance of the earth electrode in parallel with any cable sheaths is  $1\ \Omega$  or less and the rise of earth potential does not exceed 430 V, the low voltage neutral and high voltage/low voltage transformer tank and other high voltage metalwork may be bonded together and to the same earth electrode.

2) Where the rise of earth potential exceeds 430 V, the low voltage neutral earth connection should be insulated and its electrode separated from the high voltage/low voltage transformer tank and other high voltage metalwork electrode by at least 3 m.

b) *A distribution transformer (ground mounted or pole mounted) supplying an external network only but located within the earth electrode area of a higher voltage system.* This case is the same as for items a) 1) and a) 2) except that for item a) 2) the separation distance of the low voltage neutral earth electrode from the electrode area of the higher voltage system should be such as to limit the rise of potential to 430 V or less.

c) *A distribution transformer (ground mounted or pole mounted) located within a major substation and used solely for auxiliary supplies.* In this case the low voltage neutral should be connected to the main earth grid of the major substation irrespective of any potential rise.

d) *A distribution transformer (ground mounted or pole mounted) located within a major substation and used for auxiliary supplies and for an external low voltage network.* In this case the low voltage neutral should be connected to the main earth grid of the major substation. Only if the possible potential rise is below 430 V may the transformer also feed an external low voltage network. If the possible potential rise exceeds 430 V the major substation should not contain a source of supply to an external low voltage network.

e) *A pole mounted transformer located outside the earth electrode resistance area of a major substation and used solely for auxiliary supply to the latter.* In this case, the low voltage neutral has to be connected to the main earth grid of the major substation.

f) *An independently located distribution substation giving normal external low voltage supplies and, at the same time, giving auxiliary supplies to a nearby higher voltage substation.* This is permissible only if the possible potential rise of the higher voltage substation is below 430 V.

A tertiary winding of a power transformer should be connected to the transformer tank by a connection of sufficient cross-sectional area to carry the primary short circuit current.

In the case of a pole mounted transformer on an overhead line system difficulty may arise in an area of high soil resistivity. Here, if the pole also carries isolating switchgear with a low-level operating handle, up to three separate earth electrodes may be required. That for the neutral of the low voltage system is usually provided not nearer than one pole span away on the low voltage line. That for the high voltage metalwork (transformer tank, switch framework, support metalwork) is located at or near the pole. Earth resistances of  $5\ \Omega$  to  $50\ \Omega$  are sometimes the lowest that are economically possible.

In addition, an earth mat should be provided, near the ground surface, in the position taken up by a person operating the switch handle; this mat should be connected to the switch handle. The mat should be electrically separated from the main electrode; this is considered to be achieved by spacing the nearest element of that electrode at least 1 m from the periphery of the mat and by placing the two earthing conductors on opposite sides of the pole. The tops of the main electrodes should be at least 225 mm and preferably 750 mm below the ground, and the earthing conductors to the main electrodes should be suitably insulated and protected up to a point at least 2 m above ground level.

The maximum voltage gradient over a span of 2 m adjacent to a 25 mm diameter pipe electrode is reduced from 85 % of the total electrode potential when the top of the electrode is at ground level to 20 % and 5 % when it is buried 0.3 m and 1.0 m respectively.

Potential gradients around earth electrodes are considered in clause 16.

### 19.3 Fences

Earthing of fences can follow either of the following two procedures.

a) *Independent earthing*. This method has the advantage that a person on the outside of the fence can come into contact with a lower potential than that associated with method b).

Where a metallic fence including its stays is separated from a station earthing system and equipment by at least 2 m, the fence, its stays and anti-climbing fittings may be separately earthed by electrodes at 50 m intervals, at each of its corners and wherever an overhead conductor crosses the fence. Gate posts should be bonded together by a conductor laid below ground. Metal gates should be bonded by flexible connections to adjacent fence sections

A cable having a metallic covering effectively in contact with the ground or a bare conductor, associated with station equipment, should be covered with suitable insulation for a distance of not less than 2 m in both directions where it passes underneath such a fence.

Pole stays that are outside but within 2 m of the fence should be bonded to the fence, but insulators should be inserted in the stay wires.

b) *Connection to the station earthing system*. Where a fence is situated within the area of a station earthing system or cannot be separated from it by at least 2 m, the fence, its stays and anti-climbing fittings should be bonded to the earthing system at intervals not exceeding 50 m with additional bonds at the fence corners and wherever an overhead conductor passes over the fence. Gate posts should be bonded together by a conductor laid below ground. Metal gates should be bonded by flexible connections to adjacent fence sections.

If desired, the potential with which a person outside the fence can make contact may be reduced by the use of a bare conductor buried 0.5 m deep and 1 m outside the fence, bonded to the fence at intervals of not more than 50 m and wherever an overhead conductor passes over the fence. Such a conductor may be subject to interference or theft and may require suitable additional protection and maintenance. For this reason it should not be considered as contributing to the station earth.

If such a fence abuts an independently earthed fence they should be electrically separated by the use of either a non-metallic fence or wall or insulating fixings which provide a 5 cm gap at each end of a 2 m section which is not connected electrically to either of the fences.

Terminal pole stay wires external but within 2 m of the fence should be bonded to the fence, having regard to the possible need to connect additional earth electrodes should the potential between the fence and the ground exceed the appropriate safety limit.

Plastics covered chain link fencing should be considered in the same way as bare metallic fencing, so that support posts, stays and anti-climbing fittings should be bonded according to one of the methods described above.

### 19.4 Protective multiple earthing system

Attention is drawn to the requirements of the current Electricity Supply Regulations, for the earthing of overhead and underground low voltage distribution systems where protective multiple earthing is applied. Each electricity supplier may have a code of practice for the detailed engineering and technical procedures to be adopted.

### 19.5 General earthing arrangements at power stations of public electricity supplies

#### 19.5.1 Neutral earthing of generator circuits

In large power stations, generator circuits usually comprise a star-connected stator circuit with an operating voltage up to about 23.5 kV, directly or through a circuit breaker connected to a step-up delta/star transformer, the higher voltage winding generally operating at 132 kV, 275 kV or 400 kV, with the transmission system neutral point directly earthed.

The following two methods have been used for earthing the neutral of the generator windings:

- a) earthing through the primary winding of a matching transformer, with a resistor connected across the secondary winding;
- b) earthing through a resistor.

Method a) is current practice, the design being such that the maximum sustained earth fault current in the generator circuit is restricted to 10 A to 15 A, thus limiting the damage at the point of fault. The neutral and earthing connections, however, are of adequate capacity to withstand for 3 s the earth fault current that would flow in the event of the matching transformer terminals flashing over during an earth fault. The resistor used for the arrangement is of the metallic grid non-inductive type.

Method b) can be used to achieve the same degree of fault current limitation, by design of a suitable high voltage resistor, but is not preferred on the grounds of cost and its less robust construction than that of the equipment used in method a).

### 19.5.2 Earthing of power station auxiliary systems

There are in common use the following two methods of earthing the neutral point in power station auxiliary systems:

- a) solid earthing;
- b) resistance earthing.

Both methods involve the automatic disconnection of the individual fault circuit.

Method a) is normally used in power stations with smaller generating sets and method b) is used in the larger power stations.

A common earth is used for the neutral earthing of generators and power station auxiliaries, and for all equipment framework, cladding, power cable sheaths and extraneous metalwork not associated with the power systems, other than the perimeter fence (see 19.6.1). The sizes of earthing connections are normally based on the unrestricted fault current.

## 19.6 Power station and substation earth electrodes

### 19.6.1 General

The characteristics of earth electrode systems should exhibit the following features:

- a) a suitably low resistance under all climatic variations for the fault currents envisaged;
- b) a current-carrying capability for all currents and durations that may arise in normal operating conditions or during fault or surge discharge conditions, without undue increase in resistance;
- c) a suitable location in the vicinity of any devices for the discharge of high frequency currents such that earth connection conductors from the devices are as short and straight as possible to minimize surge impedance;
- d) earth electrode installations should be durable and of such materials and design so as to avoid corrosion.

For a high voltage system the value of the resistance of the earth electrode system should be such that the rise in potential of the electrode system above the potential of remote earth is as low as can be achieved reasonably and economically. If, under short-duration earth fault conditions, the rise of earth potential does not exceed 430 V r.m.s. or, in the case of very short duration faults of less than 0.2 s, it does not exceed 650 V r.m.s., then no further measures are necessary to reduce the electrode resistance. These voltages can be tolerated by appropriately designed telecommunications systems. For further details see BS 6701-1. If the rise of earth potential exceeds the above values, special procedures such as line guards should be arranged in consultation with the telecommunication system operator.

Where the soil of a site is of high resistivity or is hostile because of alkalinity or acidity it may be necessary to use a soil conditioning agent.

Earth electrode systems can also represent some hazard to adjacent underground services or structural steelwork through electrolytic action between dissimilar metals (see clause 13). Where this risk cannot be avoided by selection of compatible metals, the adoption of cathodic protection or other remedial action may be necessary.

At power stations buried metalwork, such as piling or steel reinforcing or earthing meshes in concrete foundations, can provide an electrode system (see clause 12).

Exposed structural steelwork should be effectively connected to the earthing system.

### 19.6.2 Choice of design

Usually, copper-clad steel driven rods are suitable. They are generally driven in groups, preferably with a spacing of not less than their length, although this is not always achievable. Closer spacing reduces their effectiveness. The use of driven rods is advantageous where the deeper strata of a site have a lower resistivity than the upper strata, but they may not be suitable if the site is stony or has a rock substratum.

At large substation compounds it is usual to lay a mesh of underground earth strips to which system neutral terminals and the earth bonding conductors from above-ground structures are connected. In addition to providing an approximately equipotential surface over the substation, the earth strip mesh frequently suffices as an electrode of suitable resistance and current-carrying capacity.

## 19.7 Earthing conductors for power stations, substations and industrial installations operating at similar voltages

### 19.7.1 Disposition

#### 19.7.1.1 General

It is necessary to provide permanent and substantial connections between all equipment and the earth electrodes so as to afford a low resistance path for fault currents both to earth and between items of equipment. The most efficient disposition of earthing conductors depends on the layout of equipment, but the following may be taken as a guide.

Where the current-carrying capacity of a main aluminium or steel member or welded sections forming a structure is at least equal to that of the required earthing conductor, the structure may form part of the connection and there is no need to fix an earth conductor along this section.

Where, in structures made of bolted sections, the electrical continuity of the structural joints cannot be relied upon to form permanent and reliable earth bonds it is necessary to install loops bonding across these joints.

#### 19.7.1.2 Indoor equipment

Main earth conductors, which may be in the form of a ring, should be provided and connected to the metalwork of each piece of equipment and to the earth electrodes. Except for the smallest installations there should be a connection to the earth electrodes at each end of the earth conductor or, if the conductors form a ring, at several points. These connections may, depending on the layout, be buried cables having a rating adequate for the short circuit current. Where the structure of a switchboard is extensive or occupies more than one floor, a further parallel main earth conductor may be necessary which should be connected to the main earth conductor at one or more points in each section of the switchboard.

The main earth conductors should be so placed that metallic cable sheaths can be reliably and readily connected to it by bonds made off to the cable gland. Where the cable incorporates metallic armoring this should be clamped to the cable gland.

Earthing conductors should be accessible for the connection of any detachable earthing devices used with the electrical equipment.

Branch connections from the main earth conductor should be provided to all ancillary equipment, such as control and relay panels, constructional steelwork and fire-extinguishing installations.

Where phase to earth busbar protection is effected at switchboards by frame leakage devices, two earth conductors are necessary. The frame bar interconnecting the framework of the switch units is connected to the main earth bar through a current transformer or other protective device and through bolted links for test purposes. The main earth conductor should be run separately from the frame earth bar in a convenient position for the connection of cable sheaths and earthing devices. Where it is mounted on the switch enclosure it should be insulated therefrom by insulation capable of withstanding a test voltage of 4 kV r.m.s. 50 Hz for 1 min. Care is necessary to avoid parallel paths for earth currents which may adversely affect the operation of the protection. It is recommended that insulated cable glands should be of a kind that can be tested without breaking the main earth connections. Such glands consist of two sections of insulation separated by a metal island layer, which is joined to the main switchgear metalwork by a link connection, thus enabling the insulation between the metal layer and the cable sheath and between the metal layer and the switchgear metalwork to be tested by opening the link.

#### 19.7.1.3 Outdoor equipment (excluding pole mounted transformers)

A main earth bar should be provided, so disposed as to allow the shortest subsidiary connections to all major equipment, such as transformers or circuit breakers. Wherever possible, this should be arranged to form a ring round the station. The main earth bar (or ring) should be connected where required to earth electrodes. For larger stations the ring should be reinforced by one or more cross-connections.

From the main earth bar, branch connections should be taken to each item of apparatus, and where several such items lie together, a subsidiary ring with short branches is preferable to a number of longer individual branches from the main bar. The aim should be to provide a mesh system wherever this can be contrived with reasonable economy.

The operating mechanisms for outdoor disconnectors and earth switches and circuit breaker control kiosks, etc. not integral with the circuit breaker should be connected to the main earth grid by a branch earth connection entirely separate from that employed for earthing the disconnector or earth switch base, or the circuit breaker structure.

Where the earth wire of an incoming line ends at the terminal supports and is not connected to a point on the substation structures, a subsidiary earth connection should be provided between the substation earth system and the base of the support. If the latter lies outside the substation fence, the earth connection should be buried where it passes under the fence and should be kept well clear of the latter.

Earth connections to surge arrestors should be of ample cross-section and should be as direct and straight as possible; they should not pass through iron pipes or other steel or iron parts which would increase the surge impedance of the connection. The earth connections of the arrestors should be connected with the main earth system since, for the effective protection of the substation equipment, it is essential that there is a connection of low impedance between the equipment and the arrestors.

### 19.7.2 Size

#### 19.7.2.1 Conductors installed above ground

Earthing conductors for power stations and substations will normally be selected from unsheathed copper or aluminium sections adequately rated in size to carry the designed earth fault or three-phase fault current for the appropriate designed maximum duration without attaining an excessive temperature rise. Conformity to this criterion will additionally ensure satisfactory bonding without excessive voltage difference along any conductor. In some cases it may be possible to utilize galvanized steel structures as earthing conductors.

The minimum cross-sectional area of the earthing conductor is determined by the choice of conductor material and the maximum duration of the fault current. The generally accepted durations for design purposes are 1 s for 400 kV and 275 kV systems and 3 s for systems of lower voltage. The minimum cross-sectional area can be determined from the current densities given in Table 14.

**Table 14 — Values of current densities for earthing conductors**

Material	Rated duration s	Current density A r.m.s./mm <sup>2</sup>
Copper	1	200
Copper	3	115
Aluminium	1	130
Aluminium	3	75
Galvanized steel	1	80
Galvanized steel	3	45

For short-time temperature rise purposes the physical shape of the earth conductor cross-section is not important, and can comprise strip, stranded wires, etc. as desired.

#### 19.7.2.2 Conductors buried as electrodes

Conductors buried to form earth electrodes have to be more generously rated to restrict the temperature rise under fault conditions in order to ensure that the conductor remains an effective electrode. In this application the temperature rise is a function of both the heating effect of the current flowing in the conductor and the heating effect of the current dissipating from the surface of the conductor to the general mass of earth (see clause 15).

### 19.7.3 Construction

#### 19.7.3.1 General

It is essential for the safety of personnel and plant that an earth system should remain effective throughout the life of the plant. It is difficult in many cases to make a check of continuity after installation. The system therefore has to be robust and protected from mechanical damage and corrosion where necessary. Any joints should be capable of retaining low resistance after many passages of fault current.

#### 19.7.3.2 Laying conductors

A buried bare copper or steel conductor forming part of the earthing system should be at about 600 mm deep, which in addition to giving protection to the conductor and connections should ensure that it will normally be below the frost line. In general an aluminium conductor should be used only above ground and the connections to earth electrodes should be made above ground with bimetallic connectors. Aluminium should be used below ground only if protected or sheathed against contact with soil and moisture.

Where an adequate earthing installation is provided, subsidiary conductors connecting the main earth grid to equipment may be laid at a depth and by routes most appropriate to site conditions. For convenience in connecting to equipment they may be laid at a depth of the order of 250 mm, and as they are therefore in ground more subject to seasonal or progressive changes of resistivity, it should be assumed that they make negligible contribution towards reducing station earth resistance. On the other hand they do serve to reduce ground surface voltage gradients within the station site. Conversely where these conductors are intended to reduce the value of the earth resistance of a station, their minimum depth should be 600 mm. The above recommendations deal mainly with stations on normal sites. Where ground conditions restrict the installation depth or where the soil resistivity is excessive, additional measures may be needed to achieve acceptable ground surface potential gradients.

Where a bare metal conductor is buried under metal fencing, and the fencing is independently earthed, the conductor should be insulated by threading through a non-metallic pipe extending for at least 2 m each side of the fence or alternatively an insulated conductor may be used.

When laying stranded conductor for earthing purposes, care should be taken to avoid "birdcaging" of the strands.

#### 19.7.3.3 Fixing conductors

Aluminium or copper conductors should not be drilled for fixing to structures. Clips should be used that prevent contact between conductor and structure and which are of suitable material so that there is no electrolytic action between clip and conductor. Fixings should be spaced not more than 1 m apart.

Earth conductors in trenches containing power and/or multi-core cables should be fixed to the walls near the top (e.g. 100 mm from the top).

Copper earth strip supported from or in contact with galvanized steel should be tinned to prevent electrolytic action.

If sharp bends are required in aluminium strip they should be formed by the use of a bending machine to avoid stress concentration.

Aluminium is prone to corrosion when in contact with Portland cement and mortar mixes. Contact of aluminium conductors with such materials should, therefore, be avoided by the use of stand-off fixings.

Unless it is protected, an aluminium earthing conductor should not be installed within 250 mm of ground level.

#### 19.7.3.4 Jointing conductors

##### 19.7.3.4.1 General

All crossings of conductors in the main earth grid should be jointed. Compression type joints may be used for stranded conductors and when compressed firmly onto its associated conductor the joint should conform to BS 3288-1.

No conductor strip should be drilled for a bolt having a diameter greater than one-third of the width of the strip. If this diameter would be exceeded then a flat should be jointed to the strip.

##### 19.7.3.4.2 Aluminium to aluminium

When possible, joints on strip conductors should be arc welded using either the inert-gas tungsten-arc (TIG) or inert-gas metal-arc (MIG) techniques in accordance with BS 3019-1 and BS 3571-1 respectively. Oxy-acetylene gas welding brazing or cold pressure welding may also be used.

Ranges of compression fittings and tools are available for circular conductors. Circular conductors can also be flattened and punched with suitable tools to form a terminal.

Circular and rectangular conductors can be joined with bolted clamps.

Rectangular conductors can be joined or terminated by drilling and bolting. When making a bolted type joint, the surface of the aluminium should be cleaned thoroughly by wire brushing and an approved jointing compound applied immediately to both mating surfaces. Bolts should then be tightened and all excess grease or compound wiped off and discarded.

To ensure adequate contact pressure and avoid overstressing, torque spanners should be used. The conductor manufacturer's literature should be consulted for further details of the joints and procedures.

Cold pressure welding and explosive bonding can be used for jointing rectangular conductors. The appropriate manufacturer should be consulted for details of these procedures.



**19.7.3.4.3 Aluminium to copper**

Joints between aluminium and copper should be bolted, cold pressure welded or friction welded and should be installed with mating faces in the vertical plane at a minimum distance of 250 mm above ground level. For bolted joints the aluminium mating surface should be cleaned thoroughly (e.g. by wire brushing) and a suitable grease or jointing compound applied; the copper surface should be hot tinned. After applying the correct torque to the bolt(s) the excess grease or compound should be wiped off. Where appropriate the protection of the joint from ingress of moisture can be achieved by the application of suitable mastic compound or irradiated polyethylene sleeve with mastic lining, over the complete joint. Alternatively, the joint can be protected by a bitumastic paint or a suitable protective wrapping.

Aluminium conductor connections to equipment should, where possible, be arranged so that joint faces are in the vertical plane. Surface preparation of the aluminium, joint fabrication and protection against moisture should be as previously described.

**19.7.3.4.4 Copper to copper**

The following methods have been found to be satisfactory:

- a) brazing, using zinc-free brazing material with a melting point of at least 600 °C;
- b) bolting;
- c) rivetting and sweating;
- d) thermic welding;
- e) cold pressure welding.

Earthing conductor connections to equipment should, as far as practicable, be arranged so that mating surfaces are vertical. In the case of painted metal, the paint should be carefully removed. Earthing conductors should be tinned when connected to galvanized steelwork.

No connector point should be less than 250 mm above ground level. In any installations where the finished joint is subject to corrosion, it should be protected by a bitumastic paint or a suitable protective wrapping.

**19.7.3.4.5 Loops for portable earths**

Loops of aluminium or copper should be provided on the earth conductor at each location where portable earth leads may be applied. The loops should be of a length appropriate to the earthing devices which will be used, should be at a convenient height and should be separately formed, not by bending the earth strip itself. Loops should be jointed to the earth conductor using one of the methods given in 19.7.3.4.4.

**19.8 Earthing of sheath and/or armour of cables****19.8.1 Three-core cables**

A modern high voltage power cable is generally provided with a polymeric insulating oversheath. The sheath or armour of a solid type cable is generally directly earthed at its terminations, and the cable sheaths are also bonded across the joints. The earth connections of pressure type cables are generally made via a removable link in a lockable box to permit periodic testing of the oversheath insulation. The joints are insulated from earth and the sheaths are bonded across the joints. The need to make such a test implies that insulating glands should be provided at the cable termination boxes of transformers, switchgear, etc. and at cable sealing ends or joints.

**19.8.2 Single-core cables**

A voltage is induced along the length of both the metallic sheath and the armour of a single-core cable carrying a.c. Except in the presence of ferromagnetic materials, the open-circuit value of this voltage does not depend upon the material (e.g. lead, aluminium, copper) since it arises from a single-turn inductive coupling with the cable live conductor. However, the differing conductivities of differing materials would affect the current which would flow if a complete circuit were available.

The more common situation is where the sheaths or armour of single-core cables are permanently connected to each other and to the circuit protective conductor at both ends of the run. Repeating such connections at intermediate points along a run does not affect the result. This is usually referred to as solid bonding. As a result, any voltage between the sheath or armour and earth along the run and at the ends is small and usually of negligible significance regarding safety. Such induced voltages, and the earth currents that result, are more important when there are significant harmonics in the line currents, and may be very important in respect of electromagnetic interference (e.m.i.). The principal adverse effect of solid bonding is the reduction in cable current carrying capacity, due to the circulating currents, and the consequential power losses in the sheaths or armour. A secondary and beneficial effect is a small reduction in circuit impedance and line voltage drop.

Where it is important to achieve the best possible current carrying capacity, single point bonding may be used where the sheaths or armour at one end of the cable are left unbonded. Care has to be exercised to avoid fortuitous connections at any other point. The penalty with this method is the need to ensure adequate and reliable sheath or armour insulation, and to limit the magnitudes of the sheath or armour voltages to safe values. In addition to the shock risk, the effect of corrosion should be considered. Except in very wet situations, an undamaged outer plastics sheath usually provides adequate protection against corrosion due to either sheath or armour voltages to ground, and the earlier limit of 12 V is not generally necessary. This longitudinal voltage can be calculated by reference to suitable text books, but the exercise is seldom justified for LV installations.

A rule-of-thumb is that a longitudinal voltage with respect to single-point bonding of about 0.5 V is developed per 100 A per 100 m for cables in trefoil formation, and about 2.5 times this value for an outer cable in flat spaced formation. From this, it is clear that for LV cables there will seldom be any difficulty in meeting the BS 7671 requirement that sheath voltage to earth shall not exceed 25 V at full load. Where a single-core LV circuit is designed to meet the voltage drop requirement of BS 7671, the sheath or armour voltage will always be at less than 25 V under full load conditions. It follows that low voltage single-core cables do not normally require any special sheath earthing arrangements. However, it is essential to avoid the use of both steel wire or tape armouring, and of ferrous ducts or conduits which enclose single cables. Non-ferrous gland plates are necessary at single-core cable terminations. Bonding and earthing at both ends of multiple runs of single-core cables are usual.

Under fault conditions, longitudinal sheath or armour voltages are proportionately much higher, (perhaps 15 to 20 times), so it is essential that appropriate measures are taken to provide protection against electric shock, and the insulation at terminations has to be adequate to avoid breakdown or flashover.

Different provisions apply to HV single-core cables, since they may be considerably longer and the sheath to earth voltages on single-point bonded cables correspondingly higher. The reduction in current carrying capacity with solidly bonded sheaths or armour is often less acceptable and it may be necessary to resort to single-point bonding. For this to be effective, it is necessary that the cables have insulating outer sheaths throughout their lengths if they are buried, or are secured in insulating cleats where they are open to the air. Consideration concerning possible deterioration may be necessary in respect of bitumen or hessian which have to serve for long periods.

Although running cables in trefoil formation reduces the sheath to earth voltage, since the magnetic flux of the cores is to some extent self-cancelling, this formation may not be practicable for high voltage, high current circuits where the cables have to be spaced some distance apart to obtain adequate heat dissipation. This arrangement increases the sheath to earth voltage, and there are three methods of bonding for such installations, as follows.

- a) End point bonding, where all sheaths are bonded and earthed at one termination while at the other termination each sheath is insulated and connected to earth via a sheath voltage limiter (non-linear resistor) usually chosen to “conduct” at any voltage exceeding 65 V (which is the accepted maximum sheath to earth voltage for HV systems).

Link disconnecting boxes are necessary to provide sheath insulation test facilities, and all metalwork not directly connected to earth has to be insulated. Since the standing voltage depends directly on the line current and the cable length, the maximum length should be approximately 500 m. Due to the discontinuity of the cable sheaths, an independent protective conductor is necessary between the circuit terminations. Its size will depend on the earth fault protection applied to the circuit. Figure 23 shows that in the event of a core to sheath insulation failure anywhere on the single-core cables, the fault path includes the test links (in Figure 23 c), also the transposition links) and the bonding connections from the cable glands to link boxes. The protective conductors and connections should be sized according to the proportion of prospective earth fault current that they are likely to carry under fault conditions.

b) To double the permissible cable run, mid-point bonding may be used. This is basically the same as end point bonding except that at both terminations the sheaths are insulated and connected to earth via test-link boxes and sheath voltage limiters. The earthing and bonding position for all sheaths is at the mid-point of the run. As with end point bonding, all metalwork not directly earthed at the mid-point has to be insulated and an independent protective conductor connected between the terminations [see Figure 23 b)].

c) For longer cable runs, cross-bonding has no restriction on permissible length between terminations. With this method, the sheaths at both terminations are connected via test-link boxes to earth, and the cable run is divided into multiples of three separate and equal lengths, each up to 500 m. At the section joints, each cable sheath is insulated from its continuation, and the six insulated sheath connections are transposed in rotation, in pairs, so that on completion, there are three continuous earth connections via the sheaths between the terminations. Due to the transposition of the phases, the resultant sheath voltage to earth is minimal, and does not anywhere exceed 65 V. (The voltage is unlikely to be low because, due to deviations in the route, variations in cable spacing at joint bays, etc., there will not be complete symmetry and total cancellation will not result.) The design of such systems and their accessories is highly specialized and appropriate advice should be obtained.

### 19.9 Miscellaneous matters in power stations and substations

If two or more stations are adjacent on what may be considered to be one site, the earthing systems should be interconnected so that the whole area is enclosed by one earthing system. Where the stations actually adjoin, the extremities of their earthing systems should be connected together so that the whole area is enclosed by the earthing system. Where the separation is too large to treat them as adjoining stations, an interconnecting earth conductor of substantial cross-section should be run to ensure that as far as practicable fault currents are diverted from cable sheaths and armour. This is of particular importance where fault current flowing in one station is provided from the adjoining station, e.g. where a switching station adjoins power or transforming station sites so that an earth fault in the switchgear causes current flow between the two sites in order to reach the system neutral at the generators or transformers. Such interconnections between sites can include links suitably disposed to assist in testing.

Except where special insulation is called for (see item b) of 19.2 and 19.8), sheaths or armour of all main cables should be connected to the station earth system. With multi-core cables the connection is usually made at the termination.

Where high earth fault currents are to be expected, and an appreciable rise of potential of the station system with respect to the general body of the earth may ensue, special care is necessary with connections other than main cables or lines entering the station, such as water pipes and telephone or pilot cables. Water pipes should include an insulated section; polymeric piping is often suitable. In severe cases isolating transformers may be necessary for telephone connections. British Telecom provides isolation equipment at their circuit terminations when the potential rise exceeds 430 V (650 V for high-reliability lines) (see BS 6701-1). Pilot cables should be provided with insulated glands and should be so disposed as to minimize the possibility of fault currents being carried by the sheaths.

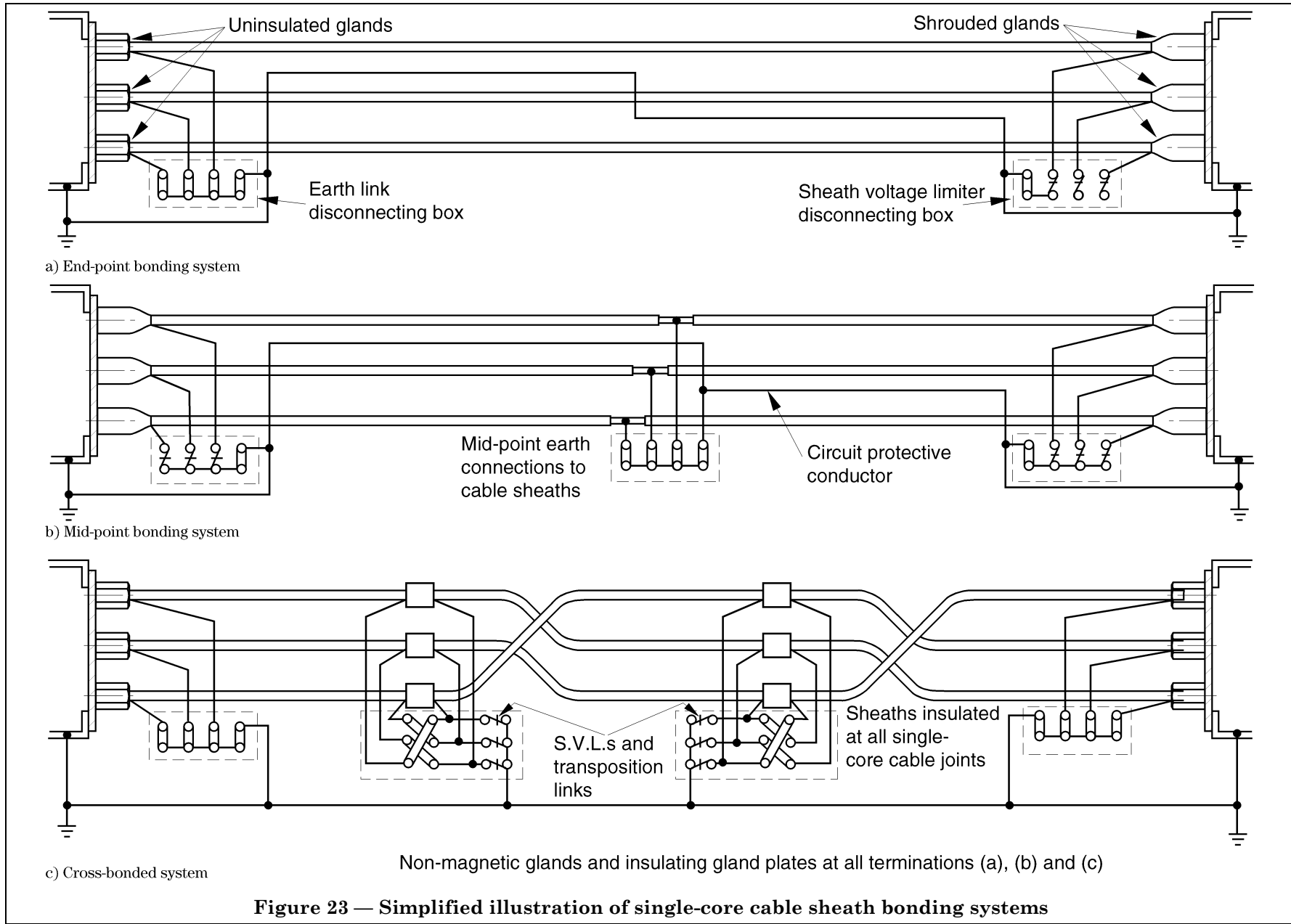
## 20 Earthing associated with overhead power lines

### 20.1 Type of support

Any consideration of whether metalwork associated with overhead power lines should be earthed and/or bonded has to take account of the type of support. Some overhead lines are supported by lattice towers of metallic construction, others by poles, which may be of steel, wood, concrete or of fabricated construction, e.g. glass-reinforced plastics; brackets attached to buildings are also used to support conductors.

### 20.2 Insulation failure

Following an insulation failure, a voltage may exist between any supporting metalwork and earth. The public are generally protected if no metalwork within 3 m of the ground is liable to become live on failure of insulation. If the supports are close to buildings, etc. the particular circumstances have to be considered.



### 20.3 Lattice steel structures

There will often be satisfactory earthing of lattice steel structures, poles of metallic construction and reinforced concrete poles through their contact with the ground. In areas of high earth resistivity special earthing arrangements may be necessary; an overhead protective conductor attached at each support and connected to the neutral at the supply end of the line may be the most economical solution. This conductor, if positioned above the live conductors, will also provide a measure of lightning protection. Terminal towers of steel tower lines are bonded to the substation main earthing system.

### 20.4 Poles of non-conducting material

#### 20.4.1 General

Where a pole is of non-conducting material, e.g. wood or glass-reinforced plastics, the pole will act against the flow of leakage current and can be expected to prevent danger near ground level due to leakage across or failure of any insulator supporting a line conductor, except where there is intervening equipment or metalwork that is or may become live.

For the reasons given in 20.4.2 to 20.4.5, there are advantages in not earthing the pole-top metalwork of such poles and in not making bonding connections to it. However, in some designs where metal cross-arms support insulators on double circuit unearthed lines, these should be bonded together.

#### 20.4.2 Omission of bonding

Where insulators are attached to a pole of non-conducting material or to non-conducting cross-arms, etc. attached to the pole, omission of bonding of pole-top metalwork gives a greater impulse withstand voltage, so there is less risk of faults due to phase-to-phase flashover.

#### 20.4.3 Omission of earthing

If pole-top metalwork is not earthed, transient faults due to birds, flying branches, etc. bridging the clearance between line conductors and the metalwork are greatly reduced.

#### 20.4.4 UK practice

In the UK, insulator steelwork on the 400 V three-phase and 230 V single-phase distribution system is in general neither bonded nor earthed, and several thousand kilometres of 11 kV wood pole lines are operating satisfactorily with metal cross-arms that are not earthed. Some of these 11 kV lines have been in use for 40 years. There are also 33 kV and 66 kV lines with the same arrangement.

### 20.4.5 Transformers, rod-operated switchgear and cable terminations

In cases where equipment such as transformers, rod-operated switchgear or cable terminations are mounted on a wooden or reinforced plastics pole, the impulse flashover value of the additional insulation provided by the pole is impaired, and all the metalwork on the pole needs to be bonded and earthed. HV and LV earths associated with pole-mounted transformers should be separated.

### 20.5 Stays

Regulation 16 of the current Electricity Supply Regulations requires that stay insulators be fitted in stay wires on poles. No part of the stay insulator should be less than 3 m above ground; it should be fitted as high up the stay as possible, but the stay insulator should be so positioned that there can be no contact below the stay insulator between the stay wire, any phase conductor (including a jumper connection) and live equipment, should either of them break or become loose.

### 20.6 Metal brackets attached to buildings

A metal bracket attached to or adjacent to any metalwork on or joining part of any building or structure and supporting a phase conductor has to be earthed unless the conductor is both insulated and supported by an insulator, each form of insulation being suitable for the conditions under which it will be required to operate in the event of failure of the other.

### 20.7 Earth wires and earth connections

Any connection between metalwork and earth has to be of low resistivity both to provide for prompt operation of protective equipment and to minimize inductive interference with communications circuits in the event of a flow of fault current.

Electromagnetic interference is reduced if the resistance of the earth return path is small compared with its reactance. At 50 Hz or 60 Hz inductive interference may be caused by the use of a high resistivity wire (for example, steel wire) even if it is perfectly earthed. A single low resistivity earth wire made of copper, aluminium, etc. should be used and it should avoid passing close to conductors or cables belonging to other circuits. It should be protected against mechanical damage for a distance of 3 m above ground level.

## 20.8 Lightning protection

An over-running aerial earth wire on overhead power lines, besides forming part of the earth return path also gives a degree of lightning protection. The lower the impedance between aerial earth wire and earth, the better is the protection since this reduces the possibility of a back flashover from the earthed metalwork to line conductors on the occasion of a direct strike to the earth wire. For information on the design of lightning protection, see BS 6651.

## 21 Consumers' electrical installations

### 21.1 Introduction

Two hazards may be present should an earth fault occur in an installation. Firstly, voltages appear between conductive parts and if these parts are simultaneously accessible these voltages constitute a shock hazard, this condition being termed "indirect contact". The severity of any shock experienced by a person at risk depends on, among other factors, the type of current (i.e. a.c. or d.c.), the magnitude of these voltages and the time for which they are allowed to persist.

Secondly, the earth fault current may be of such magnitude and duration as to cause an excessive temperature rise in the conductors through which it flows thereby creating a fire hazard.

BS 7671 includes a number of protective measures against indirect contact but this standard considers only the measure most commonly used, i.e. "earthed equipotential bonding and automatic disconnection of the supply", because most other measures do not depend on earthing. In fact, functional extra-low voltage apart, they require a high degree of isolation from earth and, in any event, some of these measures have a very limited application.

The fundamental requirement concerning earthed equipotential bonding and automatic disconnection of the supply is, to quote the BS 7671, as follows.

"The characteristics of each protective device for automatic disconnection, the earthing arrangements for the installation and the relevant impedance of the circuit concerned shall be co-ordinated so that during an earth fault the voltages between simultaneously accessible exposed-conductive-parts and extraneous-conductive-parts occurring anywhere in the installation shall be of such magnitude and duration as not to cause danger."

BS 7671 gives very detailed specific guidance as to how this fundamental requirement is to be met. A brief summary is given in 21.2 to 21.11.

In designing the protective system of any installation due account should be taken of the need to ensure that periodic inspection, testing and maintenance can be readily and safely undertaken.

### 21.2 Earthing of installations

The great majority of installations are part of either a TN system or a TT system and in both types of installation the exposed-conductive-parts of all the electrical equipment of an installation are connected by means of circuit protective conductors to the main earthing terminal (see clause 4). Class II equipment, whether metal encased or insulation encased, embodies in its construction not only basic insulation but also supplementary or reinforced insulation and exposed metalwork of such equipment is not considered to become live under fault conditions, i.e. is not considered to be an exposed-conductive-part.

In an installation which is part of an IT system, exposed-conductive-parts are also connected to the main earthing terminal, but such a system is not permitted for public supply networks in the United Kingdom (see item c) of 4.3).

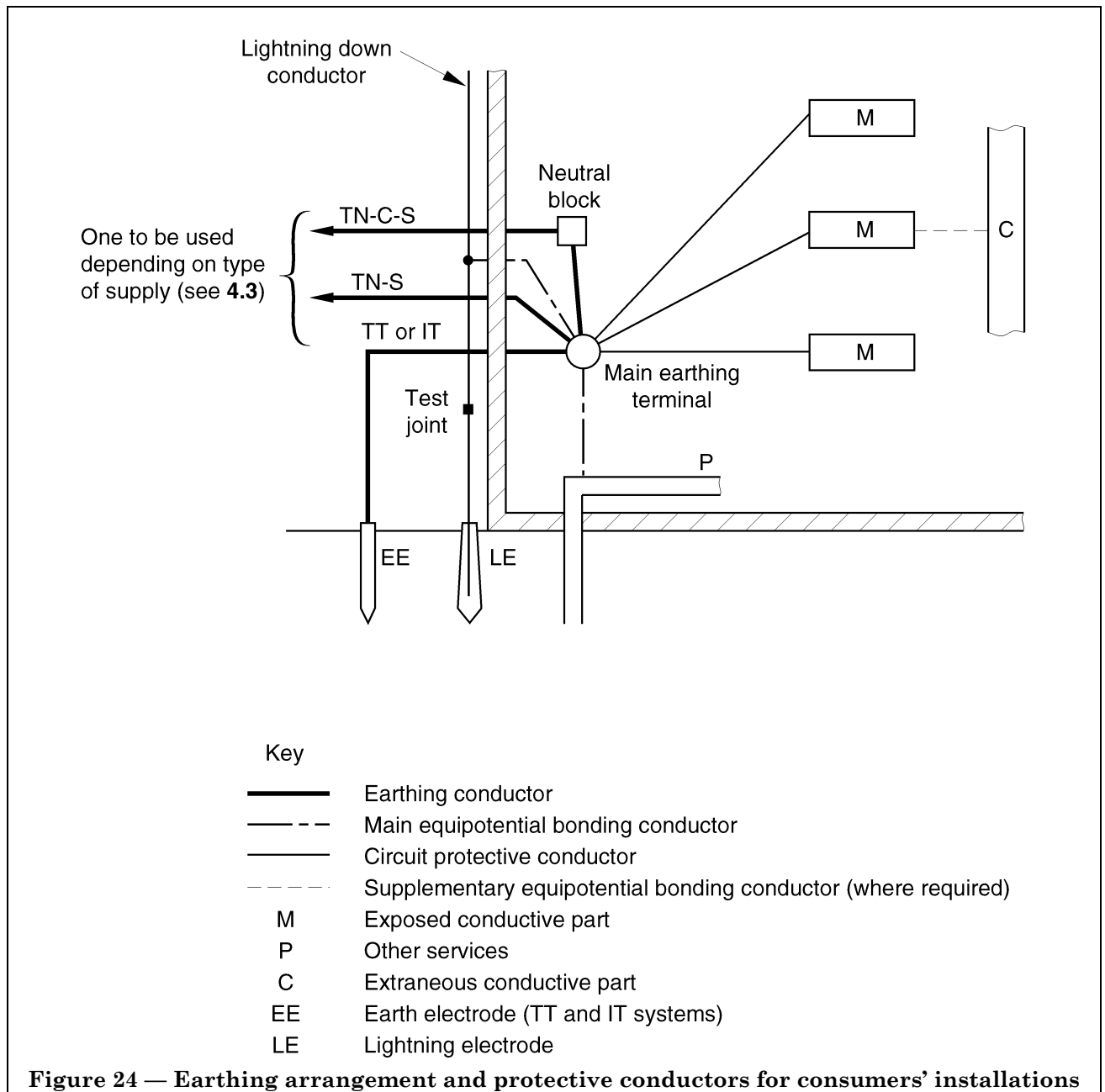
As shown in Figure 24, an installation is earthed by connecting its main earthing terminal, using an earthing conductor, to the means of earthing.

In a TN-S system, that means of earthing is usually the metallic sheath and/or armouring of the cable between the installation and the source of energy.

In a TN-C or TN-C-S system, the means of earthing is the combined neutral earth conductor (the PEN conductor) of the cable between the installation and the source of energy.

In a TT or IT system, the means of earthing is an earth electrode at the installation.

It is emphasized that an installation with its source of energy is not necessarily categorized as one particular type of system. For example, in an installation which is in general part of a TN system, a particular circuit may need protection by a residual current device and the exposed-conductive-parts of that circuit need not be connected to the protective conductors of the TN system but are connected instead to an independent earth electrode. That circuit has then to be considered to be part of a TT system and should be designed accordingly.



### 21.3 Exchange of information

It is frequently necessary for the owner of an installation or a contractor to consult a supply undertaking regarding the earthing arrangements of that installation. It is the responsibility of the owner or his agent to satisfy himself that the characteristics of the earth fault current path, including any part of that path provided by a supply undertaking are suitable for operation of the type of earth fault protection it is intended to use in the installation concerned.

Again, where the owner intends to install sources of energy for safety and standby supplies intended to operate in parallel with the normal source provided by a supply undertaking, that undertaking should be consulted regarding appropriate switching and earthing arrangements (see also 12.1).

The main bonding to other services, considered in the following section, may require permission of the undertakings responsible for those services, and such bonding to telephone and telegraphic circuits should not be undertaken unless authorized by those undertakings.

### 21.4 Main equipotential bonding

The second essential aspect of the protective measure of earthed equipotential bonding and automatic disconnection of supply, which is valid irrespective of the type of system of which the installation concerned is a part, is the bonding, by means of main equipotential bonding conductors, of extraneous-conductive-parts to the main earthing terminal of the installation. These extraneous-conductive-parts include the following:

- a) main water pipes;
- b) main gas pipes;
- c) other service pipes and ducting;
- d) risers of central heating and air conditioning systems;
- e) exposed metallic parts of the building structure;
- f) lightning conductors.

Where both main gas pipes and main water pipes enter a location, a common bonding conductor may be used, but in such cases that conductor should be continuous or should be permanently jointed (by soldering or crimping) in order to preserve continuity. Such a bonding conductor may also be used in association with other extraneous-conductive-parts.

The bonding connections to the water and gas pipes should be made as near as possible to their point of entry into the premises. If there is an insulating section or insert at that point, the bonding connection should be made to the metallic pipes on the consumer's side of the section or insert.

The main equipotential bonding connections to the main water pipes should normally be on the consumer's side of the stop tap but connection on the Water Authority's side of the stop tap is acceptable, as long as there is satisfactory electrical continuity across the tap.

With gas services the bonding connection should be made on the consumer's side of the meter before any branch pipework. For external meter boxes and/or meters the connection should be inside the building as near as practicable to the point of entry; for inside meters the connection should be within 600 mm of the meter. This means that the incoming service pipe on the supply side of the insulating section or insert is not bonded but in general this is acceptable, although if the pipe extends well into the premises, and is situated such that it is simultaneously accessible to other metalwork connected to the main earthing terminal, it should be insulated in such a manner that the insulation cannot easily be removed.

In some cases while the gas service pipe is available it is not used but is capped. The gas service pipe should then not be bonded but should be similarly insulated if it extends into the premises.

### 21.5 Installations and locations of increased shock risk

For installations and locations of increased shock risk, additional measures may be necessary. These include the following:

- a) supplementary equipotential bonding;
- b) RCDs with a rated residual current of 30 mA or less;
- c) a reduction of the maximum fault clearance time.

When an installation supplies a number of buildings, main equipotential bonding is necessary in each building, so that each has a reference point to which are connected the conductive parts referred to in 21.4. In order to reduce still further the voltages occurring in the event of an earth fault, it is sometimes necessary to install supplementary local equipotential bonding.

### 21.6 Protective conductors

#### 21.6.1 General

The generic term "protective conductor" embraces the specific types shown in Figure 24 and it is necessary, in any particular case, to identify correctly the function intended, because this determines which of the numerous requirements prescribed in BS 7671 are applicable.

BS 7671 requires that all protective conductors be suitably protected against mechanical and chemical deterioration and electrodynamic effects.

Two methods are given for determining the cross-sectional area of a protective conductor. In the first the cross-sectional area is related empirically to that of the associated phase conductor and in the second method it is calculated using the so-called adiabatic equation:

$$k^2 S^2 \geq I^2 t$$

where

- $S$  is the conductor cross-sectional area, in square millimetres ( $\text{mm}^2$ );
- $I$  is the fault current, in amperes (A) (for a.c. in A r.m.s.);
- $t$  is the time of disconnection, in seconds (s), of the associated protective device at the current  $I$ ;
- $k$  is the appropriate current density in amperes per square millimetre ( $\text{A}/\text{mm}^2$ ), which is dependent on the conductor and insulation materials, the assumed initial temperature and the permitted final temperature (see clause 14).



The advantage of the second method is that it will frequently permit the use of smaller conductor cross-sectional areas but it is not applicable to supplementary bonding conductors.

### 21.6.2 *Earthing conductors*

The primary concern is with the sizing of an earthing conductor; where such a conductor is buried in the soil there are additional considerations if it is not mechanically protected and/or not protected against corrosion (see clause 14).

It should be remembered that plain uncoated buried copper is electro-positive to plain uncoated buried steel and when interconnected by a current-carrying conductor, these metals will form an electrochemical cell that can cause accelerated corrosion of steel (see BS 7361-1). As a rough guide a direct current of 1 A leaving a buried steel structure can remove nearly 9 kg of metal in 1 year.

Aluminium or copper-clad aluminium conductors should not be used for final connections to earth electrodes. Where a copper conductor is to be joined to aluminium the procedure described in 19.7.3.4.3 should be followed.

The connection of the earthing conductor to the earth electrode or other means of earthing should be soundly made by the use of plumbed joints or substantial dams of non-ferrous material. Where the earthing conductor is to be connected to the metal sheath and armour of a cable, the sheath and armour should be bonded together and the principal connection between the cable and the earthing conductor should be to the metal sheath and should be plumbed.

Alternatively, if a clamp is used for this connection it should be so designed and installed as to provide reliable connection without damage to the cable.

Earthing and bonding clamps are specified in BS 951.

Whilst the connection referred to may be in a link box underground and therefore not readily accessible, BS 7671 stipulates that provision is made in an accessible position for disconnecting the main earthing terminal of an installation from the means of earthing to facilitate measurement of the resistance of the earthing arrangements.

### 21.6.3 *Circuit protective conductors*

When the metallic sheath of a cable is used as a circuit protective conductor, every joint in that sheath should be so made that its current-carrying capacity is not less than that of the sheath and, where non-metallic joint boxes are used, means such as a metal strip having the same effective current-carrying capacity as the largest cable entering the box should be provided to maintain continuity.

When using the metallic sheath or armour, attention should also be paid to the ability of the cable glands and connections to carry prospective earth fault currents and it may be necessary to seek advice from the manufacturers on this aspect. Special precautions may be necessary with metal parts of the assembly, particularly gland plates where abrasion resistant finishes, e.g. powder coatings, are used.

Metallic enclosures for cables, such as conduit, ducting and trunking, may be used as circuit protective conductors but where flexible or pliable conduit is used separate protective conductors should be included inside the conduit to maintain the integrity of the earth path. Where conduit and trunking are used a high standard of workmanship in installation is essential. Joints should be so made that their current-carrying capacity is not less than that of the conduit itself. Joints should also have the same properties, as regards insulation, mechanical strength and protection, as those of the wiring system or conduit of which they are part. Slackness in joints can result in deterioration in, and even complete loss of, continuity. Plain slip or pin-grip sockets should not be used. In the case of unscrewed conduit, the use of lug-grip fitting is recommended, but for outdoor installations and where otherwise subjected to atmospheric corrosion, screwed conduit should always be used, suitably protected against corrosion. In screwed conduit installations the liberal use of locknuts is recommended. Joints in all conduit systems should be painted overall after assembly.

These precautions should be adequate, but periodical tests should be made to verify that electrical continuity is satisfactorily maintained.

Electrolytic corrosion is liable to occur under damp conditions at contacts between dissimilar metals. Copper and alloys having a high copper content are particularly liable to cause corrosion under these conditions when in contact with aluminium alloys.

When dissimilar metals form part of an electrical circuit, the joints should be clean and assembled free of moisture, and then immediately treated with a suitable medium against the ingress of moisture.

Where damp conditions prevail, the fittings, fixing screws and saddles used to secure aluminium-based alloy conductors should be made of aluminium alloy or suitably protected steel (zinc coated) and the surfaces which are in contact with a conductor should be painted before assembly.

## 21.7 Industrial and commercial installations

### 21.7.1 General

Many industrial installations take their electrical power from a public supplier at a voltage which may be above 1 000 V a.c. Fault capacities may also be greater than those encountered in domestic premises and great care should be exercised in the design of all protective conductors and their terminations.

Equally important is the need to consider the effect that earthing may have on the processes employed in some factories.

Where problems related to flammable liquids and gases are concerned, or if there is a need for detailed knowledge of protective earthing that is not directly related to electrical safety, reference should be made to the relevant British Standards. Further information is obtainable from the Health and Safety Executive concerning statutes, codes and standards that apply to particular processes. (See also clause 27.)

Where instrumentation and data circuits are involved, particular care should be exercised when interconnecting earthing systems. Transients or circulating currents in the earthing system may introduce unwanted voltages within electronic circuits by magnetic induction.

There may be occasions when direct earthing of exposed metalwork could interfere with other systems that employ the general mass of earth as a current transmission path. Typical examples are telephony and cathodic protection.

### 21.7.2 Industrial distribution systems

#### 21.7.2.1 High voltage systems

During the exchange of information (see 21.3) prior to the design of an installation initially connected to or subsequently operating at high voltage (typically 11 kV) the supplier will indicate the design fault level at its terminal equipment.

Discussion should also take place upon the compatibility of the consumer's earth system and that of the supply undertaking especially where the consumer may wish to install private generating plant.

Industrial high voltage distribution systems are normally connected to earth at the star point of the generator or transformer secondary, to create a reference for the economic design of insulation of equipment based on the phase to neutral voltage of the system. In unearthed systems insulation design is based on the phase to phase voltage.

On any power system, breakdown of insulation between a phase conductor and earth is potentially dangerous as it may lead to the following problems:

- a) elevated voltages on the exposed-conductive-parts of the faulty equipment with subsequent shock risk to personnel; and
- b) the flow of relatively high earth fault currents which may damage equipment (including cables) due to the heating and electromagnetic stresses caused by these high currents, leading possibly to permanent damage and the risk of fire.

In order to minimize the risks due to items a) and b) it is necessary to connect the exposed-conductive-parts of the system to earth via the protective conductors. This connection limits the rise of potential of the exposed-conductive-parts and provides a path of suitably low earth loop impedance to ensure the flow of fault current of sufficient magnitude to give rapid operation of a suitably chosen protective device, e.g. fuse, circuit breaker or residual current device, without reliance on any circuit overcurrent protection.

To ensure rapid clearance of earth faults in high voltage circuits an earth fault relay should be provided which can be set to detect current flow in the earth fault path of 10 % to 15 % full-load current. The achievement of an earth loop impedance low enough for fast operation of this protection is not usually a problem.

In addition, the extraneous-conductive-parts of the system should be in direct metallic contact with all simultaneously accessible exposed-conductive-parts. If this contact is not achieved by the equipment being connected to a common steelwork structure, then bonding conductors between the extraneous and exposed-conductive-parts have to be used.

It is normal practice to connect the neutral of a high voltage distribution system to earth at one point only in order:

- 1) to prevent circulating currents between the star points of transformers and/or generators operating in parallel; and
- 2) to provide a single return path for earth fault currents.

These arrangements allow discrimination of the system earth fault current protection to be established.

The most convenient point for earthing is the star point of the generator or supply transformer secondary winding. This earthing may be either direct, or via a metallic grid, liquid resistor or reactor. In individual high voltage networks with large input capacities and low impedances it is normal to earth the system via an impedance. The ohmic value should be such as to restrict the fault current to a level which reduces the thermal and mechanical stresses on the equipment to an acceptable level and ensures that earth faults do not significantly depress the system voltage. There should be sufficient earth fault current to ensure satisfactory operation of the protection and this current should normally not exceed 1 to 1.5 times the full-load current of the largest unit in the system. However, direct earthing is acceptable if the earth fault current is of the order necessary to operate the protective devices and does not produce unacceptably high electromagnetic stresses in the system apparatus.

If the system source is delta rather than star connected, an earthing transformer should be connected between the phase conductors and earth to provide a neutral point for earthing.

If there is more than one supply source, as in an 11 kV power station with several generators, it may be necessary to introduce switchgear in the connection to earth in order to comply with the principle of operating with one earthing point under all operating conditions.

#### **21.7.2.2 Low voltage systems**

As in the case of high voltage supplies, the use of low resistance paths for the return of earth fault current in low voltage industrial systems is necessary, and the total loop impedance should be sufficiently low as to allow the operation of a suitably chosen protective device, fuse or circuit breaker within the time given in BS 7671. In addition to the path for earth fault current provided by conductive cable or armour, sheath or screen, an acceptable earth loop impedance is achieved by the connection of equipment to a common steelwork structure and the installation of bonding conductors between extraneous and exposed-conductive-parts. In such situations it is essential to bond the steelwork to the earthing system. Where circuits supply a connected load of 75 kW or more, consideration should be given to the provision of an earth fault relay.

It is usual to earth the star point of each individual step-down transformer on the lower voltage side by means of an earth electrode system. The resistance to earth should be as low as possible and should never exceed 20  $\Omega$ . Several transformers may share the same electrode system, but if routine testing of earth resistance is intended without complete disconnection of both high and low voltage supplies, at least one spare electrode system having a maximum resistance of 20  $\Omega$  should be available so it can take over during testing. At no time should the star point or neutral connection to earth be removed from an energized transformer and it is strongly recommended that these earth conductors be ring connected with the individual equipment equipotential bonds tied around the ring or rings. Attention is also drawn to such earthing that may be supplied by means of conductive cable armouring, sheathing, screening or where equipment is being connected to a common steelwork structure.

Where single-core cables are used in a low voltage installation it is generally preferable to bond and earth all metallic sheaths or armour at both ends of each run (solid bonding). Induced voltages in the sheaths or armour are reduced to low values and the sheaths or armour may then be used as a protective conductor, in parallel if necessary with an additional conductor. Currents circulating in the armour or sheath will reduce the current-carrying capacity of the cables. Where this reduction is not acceptable, sheaths and armour may be bonded at one end of a run only (single-point bonding) and a separate protective conductor is then necessary. Consideration of the values of standing voltage which will appear at the open circuit ends of the sheaths or armour is covered in 19.8.2.

#### **21.8 Impedance earthing of the supply to large mobile or transportable plant**

Where mobile or transportable plant is being fed high voltage via a long supply cable, which is usually a combination of fixed and trailing cables, it may be desirable to earth the source through an impedance such that, during fault clearance of a fault to frame, the voltages between the frame of the plant and ground are limited to a safe value.

The value of the impedance, normally a liquid earthing resistance, is chosen so that the product of the zero-sequence fault current and the resistance of the metallic earth path provided by cable screens and armour corresponds to a safe value of that voltage at the plant. If reasonably practicable, this value should not exceed 50 V. It is generally not advisable to rely on fortuitous parallel earth paths arising from contact between the plant and ground to limit that voltage to a safe value.

Impedance earthing may also be used to limit the risk of equipment damage during circuit breaker clearance time after the occurrence of an earth fault. The use of impedance earthing is relevant to flexible cables for large HV mobile or transportable plant where the fault current-carrying capacity of trailing cable screens is limited.

The cabling and intermediate switchgear has to be suitable for use on impedance-earthed systems and where necessary manufacturers should be consulted for further advice.

### 21.9 Construction sites

Early discussions with the supply undertaking are essential so that agreement on the type of supply, including earthing facilities, can be obtained.

Because of the difficulty of creating an equipotential zone in a construction site it is unlikely that the developer will be able to make full use of a PME facility, but the supplier may provide a PME terminal to site offices if the condition that it will not be used for general earthing purposes can be satisfied.

Where the supply is at high voltage the developer will have to provide an earth connection for the neutral.

In the often damp and rough environment of construction sites all equipment has to be robust and regularly inspected and continual attention should be paid to the earthing arrangements and protective circuits generally.

BS 4363 gives details of the distribution units and outlet units intended for use on construction sites, while BS 7671 and BS 7375 deal with all aspects of electricity supplies on such sites.

### 21.10 Mobile (touring) caravans and caravan parks

The electrical protection of persons and livestock using, or in contact with, a caravan has to be reliable since a fault to earth of equipment within that caravan can result in its frame rising to a dangerous voltage above that of the ground on which it is sited. Any person then touching any metalwork of the caravan while standing outside is open to the risk of electric shock.

Because of the special hazards associated with caravans, the current Electricity Supply Regulations do not permit the use of PME systems for their supply.

Permanent buildings on a caravan park may be treated as if they are ordinary premises and may be supplied and protected by generally adopted methods. In such cases the main earthing terminal of an installation which is part of a TN-C-S system may be used.

NOTE Residential caravans which are not normally intended to be moved from a caravan park are regarded as permanent buildings.

Figure 25 shows the method of supplying electricity to typical caravan pitch electrical equipment.

### 21.11 Yacht marinas

The electrical installation in marinas should take into account the hazards presented by the damp environment. Additionally, in tidal marinas all conductors should be so arranged and be of such materials as to avoid any deleterious effects caused by the cyclical rise and fall of those elements of the marina affected by tidal conditions.

Because of the special hazards associated with boats, the current Electricity Supply Regulations do not permit the use of PME systems for their supply.

There are the following three types of installation supplied at mains voltage to be considered:

- a) those used for working purposes, e.g. those on walkways from which portable tools may be used;
- b) supplies to boats for casual use, e.g. for dehumidifiers;
- c) supplies to boats which are wired to accept mains voltage supplies while in the marina.

No protective conductor in a marina should be of aluminium or form part of an inflexible cable of the mineral insulated copper-covered type. Joints in protective conductors should be avoided but where necessary should be made within properly protected enclosures.

Any metalwork on the pontoons of the marina that contains or may come into contact with electrical apparatus has to be bonded to the system protective conductor.

## 22 Temporary scaffolding and similar metallic structures

### 22.1 Metallic structures assembled by means of bolted joints or screw clamps

Where structures are assembled using bolted joints or screw clamps, a multiplicity of such connections is likely to provide several paths of relatively low resistance. Although such structures are not designed to be electrically continuous, it is reasonable to assume that they have a low value of electrical resistance.

Whatever type of structural fastenings or footings in contact with the ground are employed, and however a temporary structure may be fastened to a permanent structure, it should not be assumed that a temporary metallic structure is effectively earthed.

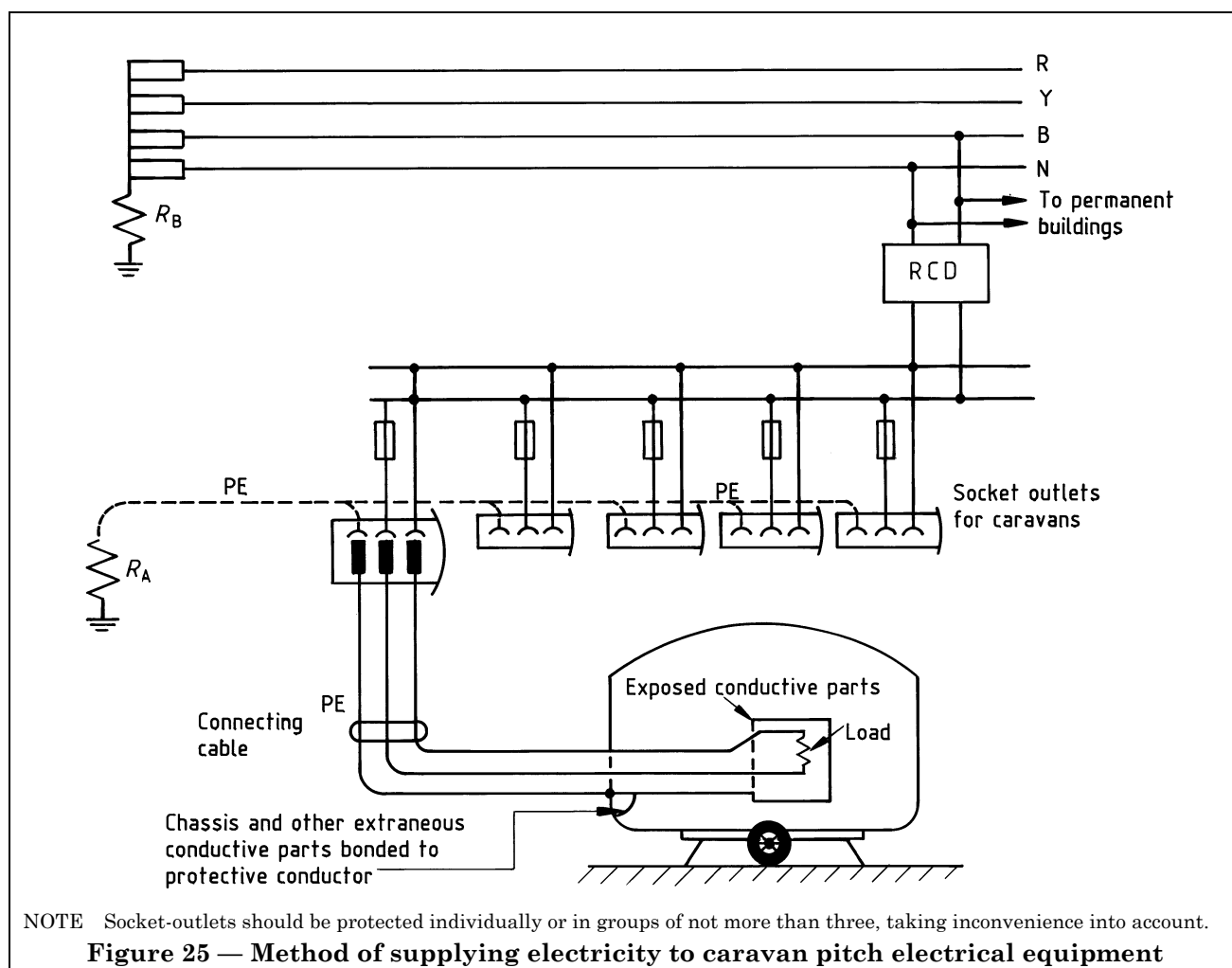
Most erections of metallic scaffolding are the subject of statutory Regulations concerning construction work. The distribution of electricity on construction sites should conform to BS 7375:1996.

Except where it is necessary for lightning protection purposes (see 22.3), scaffolding external to a structure should not be connected to the means of earthing within the structure that is afforded by supply authorities.

Where scaffolding is erected against or around a structure which does not have electrical services, and electrical equipment is not likely to be used for construction work, electrical bonding for shock protection purposes is not necessary.

Where protective conductors are required, they should be of copper and protected against corrosion by a covering at least equivalent to the insulation of a single non-sheathed cable, and should be routed to avoid damage from work equipment and work activities. A conductor should be connected to scaffolding by a corrosion-resistant clamp conforming to BS 951, and which is suitably protected against mechanical damage.

For extensive scaffolding structures, where earthed, connections should be made at points not more than 20 m apart laterally.



## 22.2 Structures forming part of precautions to avoid danger from live overhead electric lines

The Health and Safety Executive's Guidance Note GS6 [6] is a guide to compliance with the Construction (General Provisions) Regulation 44 (2) of the Factories Act.

Paragraph 25 b) of this Guidance Note refers to the use of a tensioned wire fence as a high level barrier, and notes that the electricity supplier has to be consulted about the erection and earthing of the barrier.

## 22.3 Lightning protection

If scaffolding is associated with an existing structure which has an external lightning protection system (LPS), it should be bonded to the earth termination network and the air termination network of the LPS. Lightning protection should otherwise be provided where indicated by risk assessment performed in accordance with BS 6651.

Other temporary tall metallic structures may require separate earthing electrodes to afford adequate lightning protection. This will depend on the construction of the temporary foundations and footings. BS 6651 should be consulted for further guidance and expert opinion should be obtained if necessary.

## 22.4 Other temporary structures

Structures which do not require lightning protection, which are not in the vicinity of electric overhead lines and which do not carry electrical circuits operating at a voltage in excess of 25 V a.c. to earth do not require special earthing or bonding arrangements.

## 23 Telecommunication circuits and equipment

Recommendations for installing the cabling and earthing of telecommunication equipment, including equipment associated with high voltage stations, are given in BS 6701-1.

Where the telecommunication equipment is associated with high voltage generating, transmission or distribution equipment, special precautions have to be taken to prevent the rise of voltage on the earthing system of the high voltage equipment being transferred to the telecommunication circuits.

## 24 Lightning protection and earthing

Installation of earth electrodes and earthing conductors for lightning protection systems should follow the principles set out in clauses 6 to 16.

Details of the design and earthing of lightning systems are given in BS 6651, to which reference should be made.

## 25 Mines and quarries

### 25.1 Introduction

Earthing arrangements for mines and quarries are based on the broad principle that exposed-conductive-parts of apparatus should be efficiently connected to earth, or otherwise protected by equally effective means to prevent danger resulting from a rise in potential (above earth) of these conductive parts. See also 21.8 for earthing of large mobile and transportable plant.

In some mines and certain quarries (quarries include open cast coal sites), in addition to shock risk there are also dangers associated with the possible presence of flammable gas and explosive materials. In these cases separate local earthing may be necessary to avoid incendive sparks caused by static electrical discharge.

### 25.2 Relevant legislation

In addition to the generality of the Health and Safety at Work etc. Act 1974 and the Mines and Quarries Act 1954 which require places of work to be made safe, the relevant regulations are the Electricity at Work Regulations 1989. These are accompanied by the following Approved Codes of Practice (ACOPs) written specifically for Mines and Quarries:

- The Use of Electricity in Mines;
- The Use of Electricity in Quarries;

of which sections 8 and 9 (relating to Regulations 8 and 9) are particularly relevant.

### 25.3 Power system earthing

At most mines and quarries the incoming supply is provided by a separate supplier who will install switchgear and metering for his own purpose. It is important to establish clearly in all cases the point at which the supplier's responsibilities terminate and where the consumer's responsibility commences.

If the supply is from a transformer (or generator) that is the property of the supplier and is on site, a request should be made for him to facilitate connection of the consumer's earthing system to the neutral or mid-voltage point. In some cases the supplier will allow joint use of his earth electrode. If the supply is from a transformer that is not the property of the supplier, or if the consumer generates electricity privately, the consumer should provide and maintain an earth electrode which has the neutral or mid-voltage point bonded to it.

If the supply transformer (or generator) is distant from the consumer's premises, provision of an earth terminal at the premises should be requested. Where this is possible, the earth terminal should be made available by means of an additional earthing conductor in the supply cable or overhead line.

**NOTE** The supply cable sheath and armouring may serve as this earthing conductor, provided that they are bonded to the supply source earth, neutral or mid-voltage point and meet the 50 % conductivity requirement of the ACOP.

If the provision of such an earth terminal is impracticable, then it is imperative that the earth electrodes at the supply source and consumer's premises are maintained such that their resistance to the general mass of earth is as low as possible and that appropriate earth fault protection is provided.

In all cases, the aim should be to maintain earth electrode resistance as low as practicable taking account of site soil electrical resistivity. Except however for the instance quoted above, the achievement of a low resistance is not so important as adequate bonding of all exposed metallic parts back to the supply source neutral or mid-voltage point earth electrode.

The mains supply system neutral or mid-voltage point should be earthed at one point only and in the case of a mine this should be at the surface. The connection to earth may either be a direct connection or via an impedance to limit the prospective earth fault current. In the case of an impedance earthed system suitable earth fault protection should be provided that is capable of detecting the restricted flow of earth fault current.

No switch or circuit breaker or fuse should be placed in any earthing conductor, although an interlocked changeover linked device may be used where two or more earth electrodes are provided. Such a device would be used to facilitate periodic testing of an electrode to the general mass of earth.

## 25.4 Apparatus earthing

Every metallic covering, including any screens or armouring, of a cable should be earthed. Cable screens or armouring may be considered as forming part of the earthing conductor in a cable and can be taken into account in the calculation of the earth conductivity for the purpose of establishing the acceptability of a cable.

For fixed apparatus and cables, earthing conductors should have a conductivity throughout (including joints) of not less than half that of the conductor having the greatest current-carrying capacity, to which that earth conductor is related. In the case of flexible cables, the conductivity of the earth conductor should be equal to that of the largest current-carrying conductor in that cable unless equivalent safety can be ensured, taking into account factors such as the cable's ability to carry fault current and the voltage rise at the apparatus during fault conditions.

A cable incorporating steel tape armour (unless this is supplementing steel wire), aluminium armour or having a copper sheath (mineral insulated cable) is unsuitable for use below ground. Generally single or double steel wire armoured cables are used. The use of a paper-insulated lead-covered cable is also discouraged below ground owing to the poor mechanical strength of the insulant.

In the case of an electrical circuit used for control, interlocking and indicating instruments, one pole of the auxiliary transformer secondary winding serving such a circuit may be connected to earth as an alternative to mid-point earthing.

Where mobile apparatus containing its own source of electricity, e.g. a mobile generator set or a diesel-electric vehicle/crane, is used bonding together of all exposed metallic parts is necessary (equipotential bonding). This is to prevent operators from being able simultaneously to touch exposed metalwork at different potentials.

Below ground in mines, where self-contained mobile apparatus is used, e.g. a battery locomotive, this should be operated as a totally insulated system (to avoid sparks between metal parts of the apparatus). A warning system should be provided to give an indication of leakage to frame.

At any place below ground in a mine where flammable gas may occur in dangerous quantities (usually deemed to be a place where 0.25 % flammable gas (firedamp) could be present in the general body of air) then limitation of the maximum prospective earth fault current is called for on any power system working at a voltage between 250 V and 1 200 V (the range of voltage normally used for coal winning machinery served by a flexible trailing cable). In this case the maximum prospective earth fault current should be limited (normally by impedance earthing) to 16 A at any voltage between 250 V and 650 V and to 2 A at any voltage between 650 V and 1 200 V. In either case the switchgear controlling the circuit should be able to detect and cut off the supply of electricity with less than one-third of the maximum prospective earth fault current flowing.

**NOTE** The ratio between maximum prospective earth fault current and a protection setting is known as the "tripping ratio". In practice it has been found that, in order to take account of voltage depression occurring when a short circuit coincides with an earth fault, the tripping ratio should be set to at least 5 : 1. Multi-point earthing of a power circuit (sometimes referred to as an "insulated" or "free neutral" system) is allowed at any place in a mine, including a place where flammable gas may occur, provided that a transformer is used which has a means to cut off the supply and prevent danger should a breakdown occur between primary and secondary windings.

### 25.5 Testing

The ACOP for Mines and the ACOP for Quarries differ slightly in their requirements regarding the frequency of testing of an earth electrode and circuit conductance. In quarries, the ACOP requires that tests are carried out at 30 week intervals in the case where the apparatus is their property (if the earth electrode is the property of the supplier, testing is the latter's responsibility). In mines, the ACOP requires that tests are carried out in accordance with the manager's planned maintenance scheme for the mine at a frequency determined by the mine manager.

## 26 Street lighting and other electrically supplied street furniture

### 26.1 General

Street furniture includes permanently sited lighting columns, illuminated traffic signs, bollards and other electrically supplied equipment.

Street furniture may be of:

- class I construction, in which exposed-conductive-parts are connected to the earthing terminal within the equipment, as described in **26.2** or **26.3**; or

- class II construction, in which no provision is made for connection of exposed metallic parts of the street furniture to earth. With this form of construction care should be taken to ensure that any protective or PEN conductor in the supply cable has an insulated termination preventing contact with or connection to the metallic parts of the street furniture.

Access panels, covers or doors of street furniture are not a means of protection against direct contact with dangerous live parts within street furniture.

Adequate enclosures or barriers should be provided within the street furniture to give the necessary level of protection (for further details, see BS 7671-611). For street furniture of class II construction there is no requirement for any electrical connection to be made between metallic access panels, covers or doors and other metallic parts of the furniture. For street furniture of class I construction, access panels, covers, doors or other small parts and metallic panels which have to be lifted off to gain access do not require any electrical connection.

In all cases the local supply authority should be consulted before design work on new street furniture is commenced to ascertain the type of system that will supply the new installation.

### 26.2 TN-S systems

Street furniture may be fed from and protected by a TN-S system and in such arrangements a supply cable with separate phase, neutral and protective conductors, i.e. an SNE cable, is used. In class 1 street furniture the wiring on the load side of the protective device in the unit should consist of separate phase, neutral and circuit protective conductors. Exposed-conductive-parts of the item of street furniture being supplied should be bonded to the earthing terminal within the equipment. The earthing terminal is itself connected to the supply protective conductor.

### 26.3 TN-C-S systems

An alternative method of supplying and protecting street furniture is by means of a TN-C-S system. In such cases a combined neutral and earth conductor cable, i.e. a CNE cable, is normally used. Public lighting authorities may operate such systems under the terms of an exemption issued to electricity suppliers in respect of Regulation 7 of the current Electricity Supply Regulations.



In class 1 street furniture the wiring on the load side of the protective device in the units being supplied should use, unless a special exemption has been obtained, separate phase, neutral and circuit protective conductors. For new installations, exposed-conductive-parts should be bonded to the neutral terminal by a conductor with a copper equivalent cross-sectional area of 10 mm<sup>2</sup> or of the same cross-sectional area as that of the supply neutral conductor if this is less.

In the case of circuits feeding more than one item of street furniture, e.g. by looping, an earth electrode should be installed at the last or penultimate unit and this electrode should be such as to make the resistance to earth of the neutral at any point less than 20 Ω before the connection of any circuit protective or bonding conductors to the neutral terminal. Should a single electrode produce a resistance of more than 20 Ω, other earth electrodes equally spaced along the circuit will need to be installed. Alternatively the earth electrode may be omitted if it is possible to connect the neutral at the ultimate unit to a neutral of a different distribution or supply system.

There are two further possibilities that may arise:

- a) where the supply system is TN-C but where the lighting authority wishes to use SNE cable in the installation and does not wish to use the electricity supplier's CNE conductor as a fault path;
- b) where the electricity supplier does not provide an earth terminal.

In both of these cases the lighting authority should provide its own protective earthing electrode and the system will be the TT system. Care is necessary to ensure that both the initial and continuing impedance of the fault path is sufficiently low to ensure the operation of the protective device on the occurrence of a fault in the fixtures.

#### 26.4 Protection arrangements

The neutral earth electrode at the supply transformer is an important part of the fault loop but its resistance to earth is not under the control of the lighting authority. In such circumstances consideration should be given to the use of residual current devices to ensure disconnection of faulty equipment.

The use of metallic street light columns or the metal carcasses of control units, etc. as protective earth electrodes is not recommended.

Reference should also be made to the detailed requirements for street furniture specified in Section 611 of BS 7671.

### 27 Hazardous areas (potentially explosive atmospheres)

Where flammable materials are used, processed or stored, earthing systems may be needed to reduce the danger from potentials which may arise due to leakage currents, which may be induced by operating current, or are due to man-made or naturally occurring static electricity.

Guidance in assessing potential ignition risks in hazardous areas is contained in BS 5345 which should be referred to for guidance on the selection, installation and maintenance of electrical apparatus for use in hazardous atmospheres.

The particular needs of petrol filling stations are dealt with in HSE Publication HS(G)41 "Petrol filling stations" [3], in which the avoidance of PME supplies is recommended. This recommendation has merit for all hazardous areas.

### 28 Earthing of conductors for safe working

#### 28.1 General

This clause deals only with the broad principles of the earthing of conductors for safety purposes. It is intended to cover the safety earthing of both light and heavy current equipment and is generally applicable to high voltage equipment; however, in some circumstances it may, where necessary, be applied as an additional safety feature to low voltage equipment. Where applicable, the use of safety earths should be part of an overall safe system of work, which includes isolation, permits to work or similar documents and liaison between parties in control of the supplies and in control of the work. To ensure that a safe system of work is clearly understood, a set of detailed rules and procedures are necessary.

It should be noted that there are legal duties imposed on occupiers, employers and employees, that require the provision and operation of safe systems of work. These duties are contained in the Health and Safety at Work etc. Act 1974 and the Electricity at Work Regulations 1989.

## 28.2 Safety earthing

When maintenance or repair work, etc. is to be undertaken on or near to high voltage apparatus or conductors, precautions in connection with safety earthing should be taken generally as indicated below. (More detailed recommendations are given in BS 6626 and BS 6867.) All phases or conductors of any apparatus or supply to be worked on should be isolated and earthed and should remain earthed until work is completed. Due regard should be taken of changing conditions during the progress of work which may necessitate revision of earthing arrangements to ensure the continuance of safety measures.

Safety earthing equipment may be available as permanent equipment as follows:

- a) earthing switches in permanent equipment;
- b) provision for integral earthing of a circuit breaker;
- c) portable earthing equipment, e.g. portable earthing leads.

All such equipment needs to receive regular maintenance and should be inspected before use.

Wherever possible, initial earthing should be carried out via a circuit breaker or other suitable fault-rated device.

Earthing leads should always be of adequate cross-sectional area to carry with safety, during the time of operation of the protective devices, the maximum short circuit current that may flow under fault conditions. If possible, they should either be flexible braided or stranded bare copper conductors or aluminium conductors suitably protected against corrosion and mechanical damage. In no case, even for the earthing of light current equipment (e.g. high voltage testing equipment) should the cross-sectional area of the earthing lead be less than  $6 \text{ mm}^2$ .

It has been found in some cases that a copper earthing lead having an equivalent cross-sectional area of  $70 \text{ mm}^2$  is the largest that can be conveniently handled. In such cases, where a larger size of lead is necessary to carry with safety the maximum short circuit current that can occur, it may be necessary to use a number of leads of  $70 \text{ mm}^2$  cross-sectional area or other suitable size in parallel.

Before earthing leads are applied, it should be verified that the circuit has been isolated and, where applicable, a test by means of a suitable type of voltage indicator should be applied (the indicator itself being tested immediately before and after verification) before applying earth connections.

Earthing leads should first be efficiently bolted or clamped to the permanent earthing system or to a substantial electrode of low resistance. Should no convenient permanent earth electrode be readily available, a substantial copper earth-spike driven well into the ground can be utilized to provide a quick and convenient temporary earth electrode.

Whilst such a spike is not generally adequate as a primary safety earth, it will give a degree of protection against energizing by induction.

It is then necessary for earthing leads to be securely bolted or clamped to apparatus or conductors to be worked on and these connections have to be removed in all cases before the earthing leads are disconnected from the earth electrode or earthing system.

A suitable insulated earthing pole or device should be used to apply earthing leads to apparatus or conductors on which work is to be undertaken.

Earthing leads have to be kept as short as possible and be placed in such a position that they cannot be accidentally disconnected or disturbed whilst work is in progress.

Earthing leads should be constructed or installed so that each phase conductor is connected to the other phase conductors of the circuit through a reliable metallic path and not, for example, by means of a path through the earth between adjacent earth electrodes.

## 28.3 Precautions relating to apparatus and cables

In the case of switchgear, all phases of the section in which the work is to be done should be short circuited and earthed to the same earthing system. Self-contained or portable apparatus is generally available for this purpose. Wherever possible, automatic tripping features of circuit breakers should be rendered inoperative by being disconnected from the tripping supply before the circuit breaker is closed and the breaker operating mechanism should be locked in the closed position.

With transformers, if there is any possibility of any winding becoming inadvertently live, the terminals of all windings should be earthed so that no danger from shock can occur. When the neutral points of several transformers are connected to a common bar, which is then earthed through a resistance or an arc suppression coil, the neutral point of any transformer that is to be worked on, as well as the phase terminals, should be disconnected and directly earthed.

When liquid earthing resistors are to be worked on, particularly when they are drained for work inside, the central electrode should be shorted to the tank and not earthed remotely. This is especially important where two liquid resistors are located side-by-side and one remains in commission while the other is opened for maintenance.

When work is to be carried out on equipment that is capable of capacitively storing electrical energy, for example, cables and capacitors, such equipment has to be discharged to earth prior to work commencing. As in some circumstances charge can reappear on such apparatus without reconnecting it to a source of supply, it is important that the equipment should remain earthed whilst work is in progress. The cutting of a cable during the course of work may disconnect conductors from safety earths and precautions should be taken to prevent this happening.

#### **28.4 Precautions relating to overhead power lines**

After a line has been isolated, discharged and earthed at all points of supply, a working earth should be securely attached to each phase of the line at the point or points where work is to be carried out.

The provision of a working earth entails a connection to a running earth wire or to a temporary earth electrode, the resistance of which need not be low. The application of earths to all phase conductors should also be arranged to provide a short circuit between phases.

The connection of the earthing lead to each conductor of the overhead line should be made using a suitable mechanical clamp placed round the conductor by means of an insulated earthing pole which can also be utilized to secure the clamp tightly round the line conductor. When it is necessary to remove the working earth from the line, the mechanical clamp can be unscrewed and released from the conductor by means of this rod. Even when an overhead line is earthed at each point of supply, it is necessary to place a working earth at each and every position where work is being carried out on the line on account of the danger of the line becoming energized by induction from other power lines and to safeguard against the charging of the line by atmospheric disturbances. Where the work entails breaking a conductor, e.g. on the jumper at a sectioning point, it is necessary to provide a working earth on both sides of the working point.

#### **28.5 Safety earthing of low voltage conductors**

In some circumstances, it may be necessary to apply safety earthing to low voltage conductors in order to prevent danger. Such circumstances may include, for example, work on capacitors or work on bare overhead crane trolley wires. Where the earthing of low voltage conductors is adopted, then the general principles set out in **28.2**, **28.3** and **28.4** should be applied and due consideration should be taken of fault current levels (which can be as high or higher than on high voltage systems) when the size of earth conductor is chosen. Further guidance is given in BS 6423.

### **29 Electric traction**

#### **29.1 General**

The principal objectives of the different approaches to earthing electric traction systems are to reduce the risk of electric shock for personnel and livestock and to keep to an acceptable minimum the circulation of return traction current in the ground. The latter may cause damage to or malfunction of equipment of other parties, either by electrolytic corrosion or by electrical interference.

Information on statutory requirements affecting the earthing of electric traction systems can be obtained from The Department of Transport. However, because of the many changes in practice taking place, their requirements contained in "The railway construction and operation requirements for passenger lines and recommendations for goods lines" [4] are now under revision. For light railways the Department issues "Provisional guidance note on the highway and engineering aspects of street-running light rapid transit systems" [5]. These seek to control, among other things, matters relating to electric shock, electrolytic action and electrical interference.

These DoT publications are in the context of d.c. traction systems; but, with the exception of earthing an a.c. traction circuit at its supply, the principles are broadly applicable to a.c. systems as well.

The general approach is to require the best possible conductance for the return traction current and to separate, as far as railway construction will permit, the track and its associated equipment from the mass of earth. Isolation of the return current system from gas, water and other metallic pipes and from electric cables having a metallic covering, whether belonging to the traction system or not, is included.

For d.c. traction, the trend is to unify earthing principles for light and heavy railways and tramways, to bring the UK into line with overseas practice.

The extent to which it has been found possible or necessary to achieve electrical separation from the general mass of earth, and the principles adopted as regards reduction of the risk of electric shock by bonding adjacent metalwork to the track or to a separate earthing conductor, are best seen by considering the following brief descriptions of examples of a.c. and d.c. traction systems in the UK. Variations, particularly as regards methods of bonding to reduce shock risk, usually reflect particular situations.

### 29.2 A.C. overhead system

British Rail operate a 25 kV single-phase a.c. overhead system, with a very few areas running at 6.25 kV. The trains collect current from a contact wire suspended over the track from a catenary supported by insulators from lineside structures. After passing through the equipment on the train the current passes via the wheels of the locomotive or multiple unit train to the running rails. One or more of the running rails is bonded throughout (the traction return rail) to complete the circuit back to the supply point.

The potential of the traction return rail relative to earth therefore varies along the track according to the positions of the trains and the currents drawn by each of them.

In this system overhead return conductors, connected at regular intervals to the traction return rails, are usually provided in association with booster transformers. The return current in the traction return rails is drawn up into the return conductors by the action of the booster transformers, and thence returns to the supply point. There are, however, some cases where booster transformers are not provided and also where neither booster transformers nor return conductors are provided.

The neutral of the electrical supply which is earthed at the electricity supplier's transformer station is connected to the traction return rails and to the return conductors.

Non-current-carrying metalwork at the switching stations is bonded together and also connected to the traction return rail.

The catenary supporting structures are metallic and are bonded to the traction return rails. This together with the low resistance to earth of their foundations prevents them from reaching a dangerous potential should there be an electrical failure of an insulator supporting the catenary system.

Lineside metalwork within touching distance of the traction return rail is also bonded to the traction return rail so as to prevent dangerous touch potentials arising between the two.

Whilst a proportion of the return current does pass through earth in parallel with the running rails and return conductors, difficulties from electrolysis do not normally arise with this system.

Insulated joints are inserted in the traction return rails to isolate non-electrified sections of the railway from the electrified section.

### 29.3 D.C. overhead system

The system used by the Tyne and Wear Metro is electrified at 1 500 V d.c. with traction current return via the running rails.

In order to reduce traction return earth leakage currents to a minimum the running rails are not purposely earthed at any point, and great emphasis is placed on maintaining track-to-earth insulation resistance to a reasonable level, coupled with effective along-track bonding.

**NOTE** The electrical separation of both the track return circuit and the negative supply from earth is characteristic of d.c. systems and should be compared with the practice on the a.c. system described in 29.2.

On open route sections, overhead line structures and signal posts are insulated from earth and bonded to the track. In tunnel sections however, they are bonded to the interconnected station earthing systems.

In order to facilitate traction system earth fault detection and to maintain touch potentials within the safe limits, low voltage spillover devices are connected between the traction return and the following points:

- a) all traction substation earthing systems;
- b) all underground station earthing systems;
- c) any open route station or bridge steelwork which is either near the overhead line, or within 2 m of the track.

Since the inception of the scheme, there has been close liaison with the public utilities to control potential swings on their plant due to traction leakage current. After extensive testing, at some 12 locations diode/resistor drainage bonds have been connected between their plant and the track, which successfully contain the potentials within anti-corrosive limits.

### 29.4 D.C. conductor rail systems

#### 29.4.1 *Third rail d.c. system*

The d.c. conductor rail systems operated by British Rail operate at 650 V to 750 V, or in one case at 1 200 V. The trains collect current from a third rail mounted on insulators on the ends of the sleepers.

In the case of d.c. systems, neither the conductor rail nor the running rails are connected to earth, and hence the potential between the traction return rails and earth depends upon the magnitude of the return current, upon the resistance of the traction return rails and upon the resistance of the insulation, sleepers and the track ballast.

It is an advantage if both running rails of each track can be used for return current purposes since this results in lower circuit resistance thereby providing improved discrimination between load and short circuit current at the protecting circuit breakers, and also reduces the potential between the traction return rails and earth.

A further reason for avoiding a high resistance in the traction return rails is the need to avoid any considerable proportion of the current returning through earth in parallel with the running rails and causing difficulties due to electrolysis of metallic parts in the earth path. The difficulties from this cause have been rare and have been found to be due to particular circumstances at individual locations. Generally these can be cured by appropriate local measures. Circuits most likely to be affected by electrolysis in this way are the metallic sheaths of cables running alongside the track and it is now customary to sheath such cables with an insulating material.

The negative of the electrical supply is connected to the traction return rails at each substation.

Non-current-carrying metalwork at substations is bonded together and is connected to an independent earth electrode system. Care is taken to insulate point rodding, signal wires and lever frames from the return current system. Insulated joints are inserted in the traction return rails to isolate non-electrified sections of the railway from the electrified section.

Cathodic protection may be necessary to prevent corrosion of neighbouring plant due to the passage of traction current through the earth. Such measures could, however, cause false operation of railway signalling and interfere with telecommunication circuits and may be adopted only after consultation with British Railways and other organizations operating buried plant in the vicinity. (See also BS 7361-1.)

#### 29.4.2 *Four rail d.c. system*

The situation in underground systems may justify a further degree of isolation between the traction circuit and earth. London Underground Ltd. uses a four rail system, with positive and negative conductor rails fully insulated from earth. One of the two running rails is divided into short insulated sections for the operation of signal equipment while the other forms a continuous earth maintaining the train at earth potential and providing an earth fault conductor.

The conductor rails are mounted on porcelain insulators. Bleed resistors connected between the two conductor rails and the continuous running rail together with the natural leakage currents establish the system potentials with the positive rail 420 V above earth and the negative rail 210 V below earth. The total conductor rail system is divided into 36 traction feeding sections. These are electrically separated by current rail gaps of sufficient length to prevent current collector shoes on one car bridging two adjacent sections. The bleed resistors are connected at the end of each section. A traction feeding section may be supplied by between five and 12 substations depending on traction demand and substation spacing. Each substation will feed each track in both directions. Positive poles are switched by highspeed circuit breakers with an associated slaved contactor switching the negative pole.

As positive and negative poles are floating above and below earth potential the presence of a single earth fault on a traction feeding section is tolerable. However coincidental positive and negative earth faults form an unacceptable short circuit so it is necessary to detect and remove any earth fault. This is achieved by the use of an earth monitor which measures and records potentials to earth on each traction feeding section. Observation of the earth fault monitor whilst operating track feeding circuit breakers allows a faulty train, or trackside fault, to be located so that corrective action can be taken.

#### 29.5 *Tramways*

Guidance on tramways is given in the following publication from the Health and Safety Executive (HSE): *Railway Safety Principles and Guidance*, part 2 section G *Guidance on tramways* (RSPG 2G) [6]. Particular guidance on electrical matters is given in Chapter 6 *Electrical Traction Systems*, of this document.

### 29.6 Trolleybuses

With one exception, British trolleybus systems grew out of tram systems, which therefore operated with the negative wire earthed. As the tramways closed, some trolleybus systems converted to a “floating” positive and negative arrangement.

The classic safety dilemma for trolleybus systems arises because it is impossible to earth the body of the vehicles. Even on “earthed negative” systems the bodies could not be earthed in view of the need for occasional polarity reversals. The solution lay in double-insulating the traction equipment and carrying out a daily leakage test.

Although British trolleybus services ceased in 1972, trolleybuses were taken into public service vehicle legislation in 1981, having previously been classed as light railways. Their fixed equipment however remains under the aegis of the Health and Safety Executive (Railways Inspectorate) and is covered by the *Guidance for tramways* referred to in **29.5**. This in particular encourages a “floating” system with earth fault monitoring, and subclause 9.7 calls for power circuits on the vehicle to be double insulated.

**Annex A (informative)****Typical calculations for various types of earth electrodes (see clause 10)****A.1 Example calculation for resistance to earth of rods or pipes (see 10.2)****A.1.1 Single electrode**

$$R = \frac{\rho}{2\pi L} \left[ \ln \frac{8L}{d} - 1 \right]$$

where

$R$  is the resistance of single rod or pipe, in ohms ( $\Omega$ );

$L$  is the length of rod, in metres (m);

$d$  is the diameter of rod or pipe, in metres (m);

$\rho$  is the soil resistivity in ohm metres ( $\Omega$  m).

If:

$$L = 2.4 \text{ m};$$

$$d = 0.016 \text{ m};$$

$$\rho = 100 \text{ } \Omega \text{ m};$$

then:

$$\frac{\rho}{2\pi L} = \frac{100}{2 \times 3.142 \times 2.4} = \frac{100}{15.081} = 6.63$$

and:

$$\left[ \ln \left( \frac{8L}{d} \right) - 1 \right] = \left[ \log_e \left( \frac{8 \times 2.4}{0.016} \right) - 1 \right] = \left[ \log_e \left( \frac{19.2}{0.016} \right) - 1 \right] = [\log_e(1200) - 1] = 6.09$$

so that:

$$\begin{aligned} R &= \frac{\rho}{2\pi L} \left[ \log_e \left( \frac{8L}{d} \right) - 1 \right] = 6.63 \times 6.09 \\ &= 40 \text{ } \Omega \end{aligned}$$

**A.1.2 Multiple electrodes**

$$R_n = R \left( \frac{1 + \lambda a}{n} \right)$$

where:

$R$  is the resistance of one rod in isolation, in ohms ( $\Omega$ );

$S$  is the distance between rods, in metres (m);

$\rho$  is the soil resistivity, in ohm metres ( $\Omega$  m);

$n$  is the number of rods;

$\lambda$  is the factor from Table 2 or Table 3.

$$a = \frac{\rho}{2\pi RS}$$

If:

$$R = 40 \, \Omega \text{ (from the previous example);}$$

$$S = 2.4 \text{ m;}$$

$$\rho = 100 \, \Omega \text{ m;}$$

$$n = 10 \text{ rods;}$$

$$\lambda = 3.81 \text{ (Table 2);}$$

then:

$$a = \frac{\rho}{2\pi RS} = \frac{100}{2 \times 3.142 \times 40.38 \times 2.4} = \frac{100}{608.99} = 0.16$$

so that:

$$\begin{aligned} R_n &= 40 \left[ \frac{1 + (3.81 \times 0.16)}{10} \right] \\ &= 40 \left[ \frac{1 + 0.631}{10} \right] \\ &= 40 \times 0.16 \\ &= 7 \, \Omega \text{ for } 10 \times 2.4 \text{ m rods} \end{aligned}$$

#### A.2 Example calculation for resistance to earth of horizontal strip conductor (see 10.3)

$$R = \frac{\rho}{P\pi L} \left[ \log_e \left( \frac{2L^2}{wh} \right) + Q \right]$$

where:

$L$  is the length of conductor, in metres (m);

$h$  is the depth of strip, in metres (m);

$w$  is the width of strip, in metres (m);

$\rho$  is the soil resistivity, in ohm metres ( $\Omega$  m);

$P$  and  $Q$  are the coefficients given in Table 5.

If:

$$L = 50 \text{ m of conductor;}$$

$$h = 0.5 \text{ m;}$$

$$w = 0.025 \text{ m (25 mm} \times \text{3 mm);}$$

$$\rho = 100 \, \Omega \text{ m;}$$

$$P = 2 \text{ (Table 5);}$$

$$Q = -1 \text{ (Table 5);}$$

then:

$$\frac{\rho}{P\pi L} = \frac{100}{2 \times 3.142 \times 50} = \frac{100}{314.2} = 0.32$$

and

$$\left[ \log_e \left( \frac{2L^2}{wh} \right) + Q \right] = \left[ \log_e \left( \frac{2 \times 50^2}{0.025 \times 0.5} \right) + (-1) \right] = \left[ \log_e \left( \frac{10000}{0.125} \right) - 1 \right] = \log_e(80000) - 1 = 10$$



so that:

$$R = \frac{\rho}{P\pi L} \left[ \log_e \left( \frac{2L^2}{wh} \right) + Q \right]$$

$$= 0.32 \times 10$$

$$= 3.2 \Omega \text{ (which can be taken to be } 4 \Omega \text{ for 50 m buried cable.)}$$

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[1] TRRL Supplementary Report “A review of soil corrosiveness with particular reference to reinforced earth” by R A King<sup>6)</sup>.

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<sup>6)</sup> Available from the Transport and Road Research Laboratory, Crowthorne, Berkshire.

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