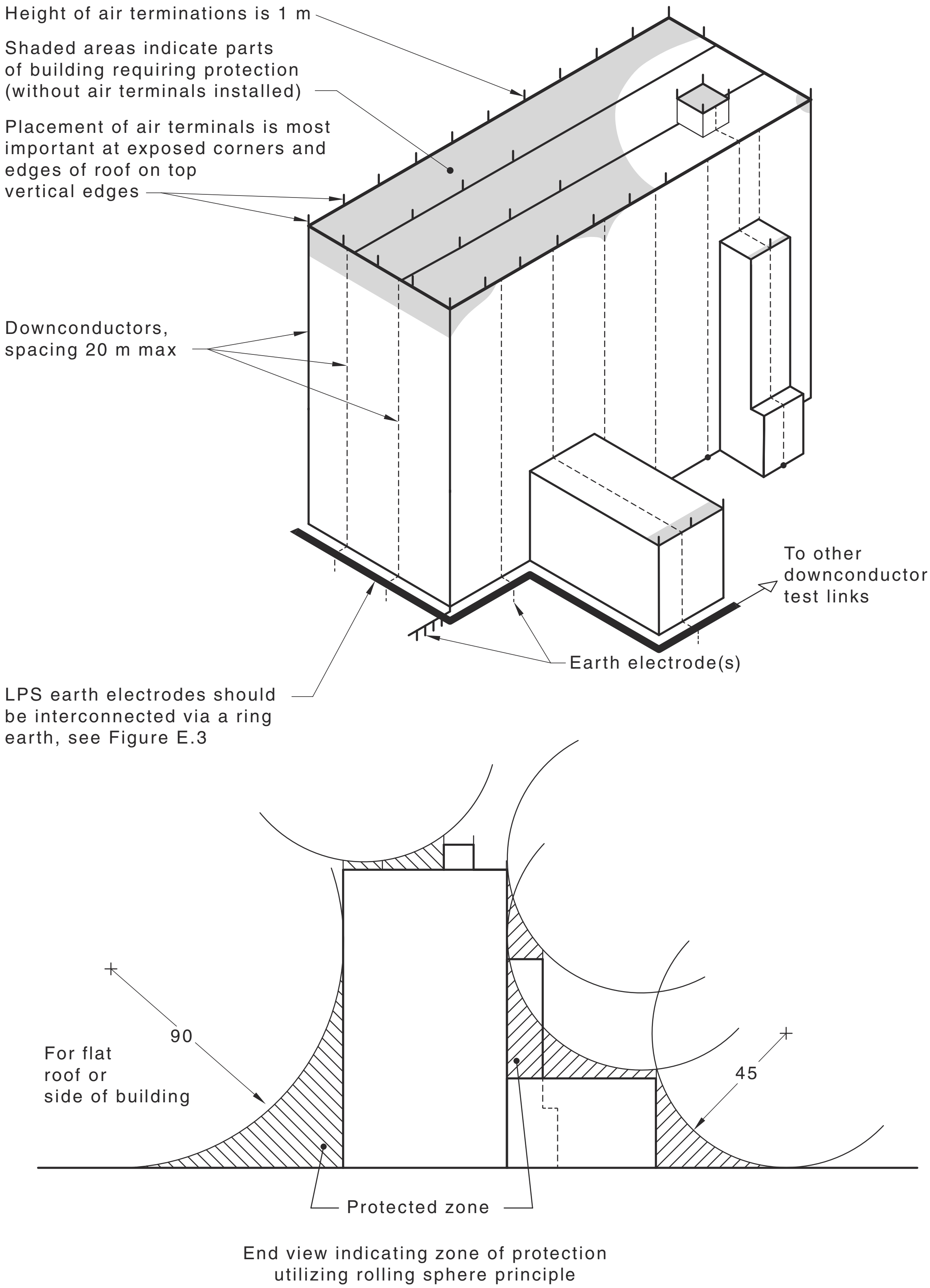

NOTE For spacings of air terminals on roof, see Equation D.3.1.

Figure D.7 — Typical LPS employing vertical air terminals, for LPL III

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Appendix E
(informative)

Earthing for lightning protection — Function, design, construction and measurement

E.1 Scope

This appendix outlines all aspects of earthing as it applies to lightning protection.

An LPS consists of the following three functional components:

(a) Interception.

(b) Conduction.

(c) Dissipation.

The primary purpose of an earth termination network for an LPS is to safely dissipate the charge transferred by a lightning strike.

This appendix describes the function, design, construction and measurement aspects of earthing for an LPS, which are relevant for the installation and maintenance of the earthing system.

E.2 Function

E.2.1 General

The earth termination network provides an electrical connection to the general mass of earth. It consists of one or more earth electrodes, usually a combination of horizontal and vertical elements. The construction is nominally of bare metal, such as copper, so that current is able to leak into the surrounding earth.

The characteristic that primarily determines the effectiveness of an earth termination network is its impedance with respect to the general mass of earth. Minimizing the impedance of the earth termination network minimizes EPR and the step and touch voltages in and around structures.

E.2.2 Side flashes and sparking

The impedance of the earth termination network can be a significant factor with regard to the occurrence of side flashes and sparking within a structure. Therefore, the impedance should be kept as low as possible (≤ 10 Ω) using the reduction measures outlined in Clause E.3.7.

For lightning protection, equipotential bonding of all equipment within a structure per Clause E.3.9 can ensure a uniform potential rise. It is possible to achieve effective lightning protection using this technique even though the absolute earth impedance may be greater than 10 Ω. This is typical of mountain top communications sites.

E.2.3 Safety of personnel

The earth termination network should reduce step and touch voltages around installations sufficiently so that they are not hazardous to personnel. However, there are currently no recognized safety criteria for lightning related EPR events. Therefore, the earth termination network design should utilize techniques such as bonding and voltage grading to ensure these hazards are minimized.

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E.3 Design

E.3.1 General

When dealing with the dissipation of lightning current into the ground, the layout of the earth termination network influences the magnitude and location of EPR and overvoltage. For lightning protection, the earth termination network should be designed so that the impedance is not substantially higher than the resistance (see Clause E.3.2).

E.3.2 Critical length

A common error in the design of an earth termination network for lightning is to simply keep adding vertical and horizontal electrodes until the 10 Ω target is met, when measured at low frequencies. However, at lightning frequencies (typically tens of kHz), a critical length (L_C) of the earth termination network exists. Extension of the network beyond this critical length does not reduce the impedance. For simplicity, the overall length may be considered to be the longest horizontal or vertical electrode in the design.

The value of L_C depends upon soil resistivity, frequency (wave shape) and soil ionization effects. Table E.1 provides an approximate relationship between critical length and soil resistivity when the other parameters are held constant.

The critical length should be taken into account when designing the earth termination network for lightning, in order to ensure that the impedance does not significantly exceed the resistance.

Table E.1 — Approximate relationship between critical length of earth electrodes and soil resistivity

Soil resistivity (ρ) Ωm	Critical earth electrode length (L_C) m
100	10
500	25
1 000	35
2 000	50
5 000	85

E.3.3 LPS design factors

In the design of an LPS earth termination network, the following factors should be considered:

(a) *Durability* — Durability should match the lifetime of the installation it serves or be designed so that it is testable and maintainable.

NOTE 1 See Table 3.3 for component requirements.

NOTE 2 Bare metallic components can be subject to corrosion and mechanical damage.

(b) *Redundancy* — Designs should include redundancy, so that the failure of a single element does not impact the performance of the earth termination network.

(c) *Testability* — The earth termination network should be testable in order to confirm its condition. It should be accessible at test points to allow testing (see Section 5).

NOTE 3 In some built up areas such as CBD locations, it is not possible to carry out meaningful earth resistance testing due to the proliferation of services in the ground surrounding a structure. In such cases, electrical continuity to the earth termination network should be tested during construction.

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(d) *Maintainability* — The earth termination network is checked for the presence and correct functioning of the earth termination network components as originally designed and installed (see Section 5).

NOTE 4 Special consideration should be given to maintenance aspects when an earth termination network is to be buried in an aggressive soil or environment.

E.3.4 Factors influencing earth impedance

The impedance of the earth termination network to lightning currents varies with time and current magnitude. It is also dependent on the —

(a) resistance and surge impedance of the earth electrodes and connecting conductors;

(b) contact resistance between the earth electrode(s) and the surrounding soil;

(c) resistivity of the soil surrounding the earth electrode(s); and

(d) degree of soil ionization that occurs when lightning current is injected into the earth electrode(s).

The injection point into the earth termination network also has an influence on the impedance. Central injection often achieves better results than end injection.

Fortuitous alternate paths to earth, such as via bonded electricity reticulation low-voltage neutrals, may give false readings for the earth termination network impedance.

NOTE For measurement techniques, see Clause E.5.

E.3.5 Soil resistivity

Soil resistivity is another term for the specific resistance of soil. It is usually expressed in units of Ωm (i.e. the resistance in ohms between opposite faces of a cube of soil with 1 m sides).

Soil resistivity depends on its chemical and mechanical composition, moisture content and temperature. Therefore, there can be a very large variation in resistivity between and within soils types (see Table E.2 for some common soil types differences).

NOTE Earth electrodes should not be located near brick kilns or other installations where the soil can be dried out by the operating temperatures involved.

Resistivity measurements should be carried out in order to determine the soil profile (resistivity layering of the soil) *before* designing the earth termination network.

For example, if it is determined that a low-resistivity layer exists 5 m below grade, then the use of vertical electrodes greater than 5 m in length will produce a good result. Testing procedures are given in Clause E.5.

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Table E.2 — Resistivity values for various materials

Material	Resistivity Ωm	
	Typical	Usual limits
Salt sea water	0.2	0.15 to 0.25
Estuarine water	0.5	0.2 to 5
Artesian water	4	2 to 12
Damp black inland soil[a]	8	5 to 100
Damp clay	10	2 to 12
Inland lake water, reservoirs	20	10 to 500
River banks, alluvium	25	10 to 100
Clay/sand mixture[b]	30	20 to 200
River water (upstream)	40	30 to 200
Concrete[c]	100	40 to 1 000
Dry inland soil[a]	100	20 to 1 000
Moraine gravel	2 000	1 000 to 10 000
Coal	2 000	1 000 to 5 000
Secondary rock	3 000	1 000 to 50 000
Sand[b]	3 000	1 000 to 10 000
Solid volcanic rock[d]	20 000	10 000 to 50 000
Ice[e]	100 000	10 000 to 100 000

[a] Black soil is a non-specific term applicable to large areas of Queensland and New South Wales. The soil is characterized by a high level of dissolved salts and undergoes considerable contraction on drying out, therefore causing a significant increase in resistivity when dry.

[b] Resistivity values for a clay/sand mixture and for sand are based on measurements from several sites in Queensland. The resistivity of dry sand is intrinsically very high and it will serve to increase the resistivity of any material in which it may be interspersed.

[c] Values of resistivity for concrete apply to the cast material and do not include the effect of any reinforcing bars. The values given will assist in determining the discharge resistance from steel reinforcement to the general body of earth.

[d] Solid volcanic rock is often subject to fissures and faults, the contents of which substantially reduce the resistivity, though not to a very satisfactory level for earth electrode performance for lightning protection.

[e] Ice is included for reference.

E.3.6 Calculation of earth resistance

Simple equations exist for estimating the earth resistance for common electrode arrangements. However, they require a knowledge of the soil resistivity, or more precisely, a representative value of soil resistivities in the common case of a multi-layer soil profile.

The earth resistance (R) (in Ω) for common earth electrode arrangements may be calculated using the following Equations E.3.6(1) to E.3.6(4):

(a) Single vertical rod of length (L) and diameter (d), in metres, where the top of the rod is (h) metres below the surface:

$$R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right)-1\right]\left(\frac{2h+L}{4h+L}\right) \qquad \text{E.3.6(1)}$$

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where

R = resistance, in ohms

ρ = soil resistivity, in ohm-metres

L = buried length of earth electrode, in metres

d = diameter of earth electrode, in metres

(b) Straight horizontal electrode (e.g. flat strip, stranded conductor, circular conductor) of length (L) and diameter (d), in metres, buried to a depth (h) metres below the surface:

$$R = \frac{\rho}{\pi L}\left[\ln\left(\frac{4L}{\sqrt{dh}}\right) - 1\right] \quad \text{E.3.6(2)}$$

NOTE 1 For a thin strip earth electrode, the diameter may be replaced with half the width of the strip.

(c) Ring electrode, where the radius of the ring (r), in metres:

$$R = \frac{\rho}{4\pi^2 r}\ln\left(\frac{16r}{d}\right) \quad \text{E.3.6(3)}$$

When the ring electrode is buried at a depth (h), the diameter of the wire should be replaced by the equivalent diameter:

$$d' = \sqrt{dh} \quad \text{E.3.6(4)}$$

NOTE 2 Equations E.3.6(1) to E.3.6(4) apply to low-frequency current energization. However, for a properly designed earth termination network, the impedance will be similar to the resistance values.

E.3.7 Measures for reducing earth impedance

E.3.7.1 General

Lightning currents have rise-times of the order of 10 kA/µs. Under these conditions, an earth termination network can best be regarded as a leaky transmission line. The conductors and electrodes have resistance, inductance and capacitance to earth, and current leakage through non-insulated contact (conductance) with the surrounding soil.

Impedance may be lowered by use of the following:

(a) A flat strip rather than circular conductor.

This increases surface area, reduces high-frequency resistance due to skin effect, and increases both capacitive coupling and the earth contact area for a given cross-section of conductor.

(b) A centre-point feed.

This concept may be further enhanced by using several radial conductors emanating from the injection point.

(c) Use of natural elements such as the footings, foundations and ground slabs of a structure to provide multiple paths and a large contact area with the earth.

(d) Low-resistivity backfill around earth electrodes.

The reduction in impedance is achieved by improved contact with the electrodes, the presence of a lower resistivity medium in the immediate area of the electrodes, and an increase in the electrode's effective surface area.

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E.3.7.2 Electrode arrangement

The design of a dedicated earth termination network comprises a combination of radials and vertical electrodes (e.g. a rod of appropriate depth at the injection point, two or more radials from that point that go in different directions, and rods installed at the end of each radial). The spacing between rods should be at least twice the driven depth of the rods.

Regardless of the layout, the design of the earth termination network should take into account the critical length criterion.

NOTE Since electric field interaction between individual earth electrode segments can influence performance, the optimum design may be quantified via software modelling.

E.3.7.3 Low-resistivity backfills

In areas of moderate-to-high soil resistivity, where the 10 Ω impedance target is unlikely to be met, lower resistivity backfills may be used. Most backfills fall into one of the four following categories:

(a) Chemical additives, typically some type of salt or an industrial by-product.

(b) Chemical rods or electrolytic electrodes, which are essentially copper tubes filled with electrolytic salts which permeate into the surrounding soil through weep holes in the tube.

(c) Earth enhancing compounds (EECs) (e.g. bentonite, bentonite-based formulations, carbon-based formulations, or other electrically-conductive aggregates).

(d) Lower-resistivity, externally sourced fill.

The efficacy of backfills can be quite variable. Hence it is important to ensure that certain key criteria are met. Apart from having a sufficiently low resistivity, the most important criterion is to ensure that the corrosion performance of the chosen backfill is satisfactory.

NOTE 1 For earth enhancing product testing, refer to IEC 62561-7.

A bland backfill material such as calcium or sodium bentonite clay, or montmorillonite with finely ground gypsum will reduce resistance for a considerable period in high resistivity soils, maintain some moisture adjacent to earth electrodes, and provide a uniform and non-corrosive environment for the earth electrodes.

NOTE 2 For further information and recommendations relating to the backfilling of galvanic anodes, refer to AS 2239.

NOTE 3 Bentonite backfill requires moisture to be present in order to activate its low resistance properties. In hot arid climates, and at the end of the dry season when soil moisture is low, earth resistance of electrodes installed within Bentonite backfill is often higher than expected.

E.3.8 Service separation

Minimum separation distances should be maintained between LPS earth termination networks and other earthed services (e.g. pipelines). The minimum separation distance for an LPS earth termination network should be 3 m.

NOTE For hazards created by power system EPR, refer to AS/NZS 3835.1 and AS/NZS 4853.

E.3.9 Methods of equipotential bonding

E.3.9.1 General

Equipotential bonding is used to reduce the potential difference between various parts of the structure and the main earth bar (MEB).

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The potential difference should be kept below 1.5 kV under direct strike conditions to ensure coordination with equipment insulation specified in AS/NZS 60950.1.

The inductance of bonding conductors gives rise to a potential difference of 1 kV per metre of length for typical lightning transients, so the maximum conductor length between the part being bonded and the MEB is 1.5 m. This length is achievable if all services enter at the same point in a small structure, but may not be practicable in larger structures. In the latter case, earth impedance reduction measures are crucial, see Clause E.3.7.

NOTE AS 4262.1 and AS/NZS 60950.1 allow a maximum bonding conductor length of 10 m.

E.3.9.2 Using a bonding bar

A bonding bar is used to achieve bonding of various utility services. This bonding bar may be the MEB in the MSB. A separate bar should be provided and mounted as close as practicable to the MSB.

NOTE 1 Figure E.1 shows the bonding bar and the connection of the various bonding conductors.

The bonding conductor requirements are as follows:

(a) The bonding bar should be connected to the MEB via a disconnect link.

(b) The MEB is to be connected directly to the electrical earth electrode in accordance with AS/NZS 3000.

(c) All bonding conductors should be kept short (preferably less than 1 m long)

NOTE 2 All bonding conductors should be labelled at the point of connection to the bonding bar, the main earthing conductor or the electrical earth electrode.

NOTE 3 Figure E.2 illustrates a typical overall bonding scheme that should be employed in practical scenarios involving many bonding bars.

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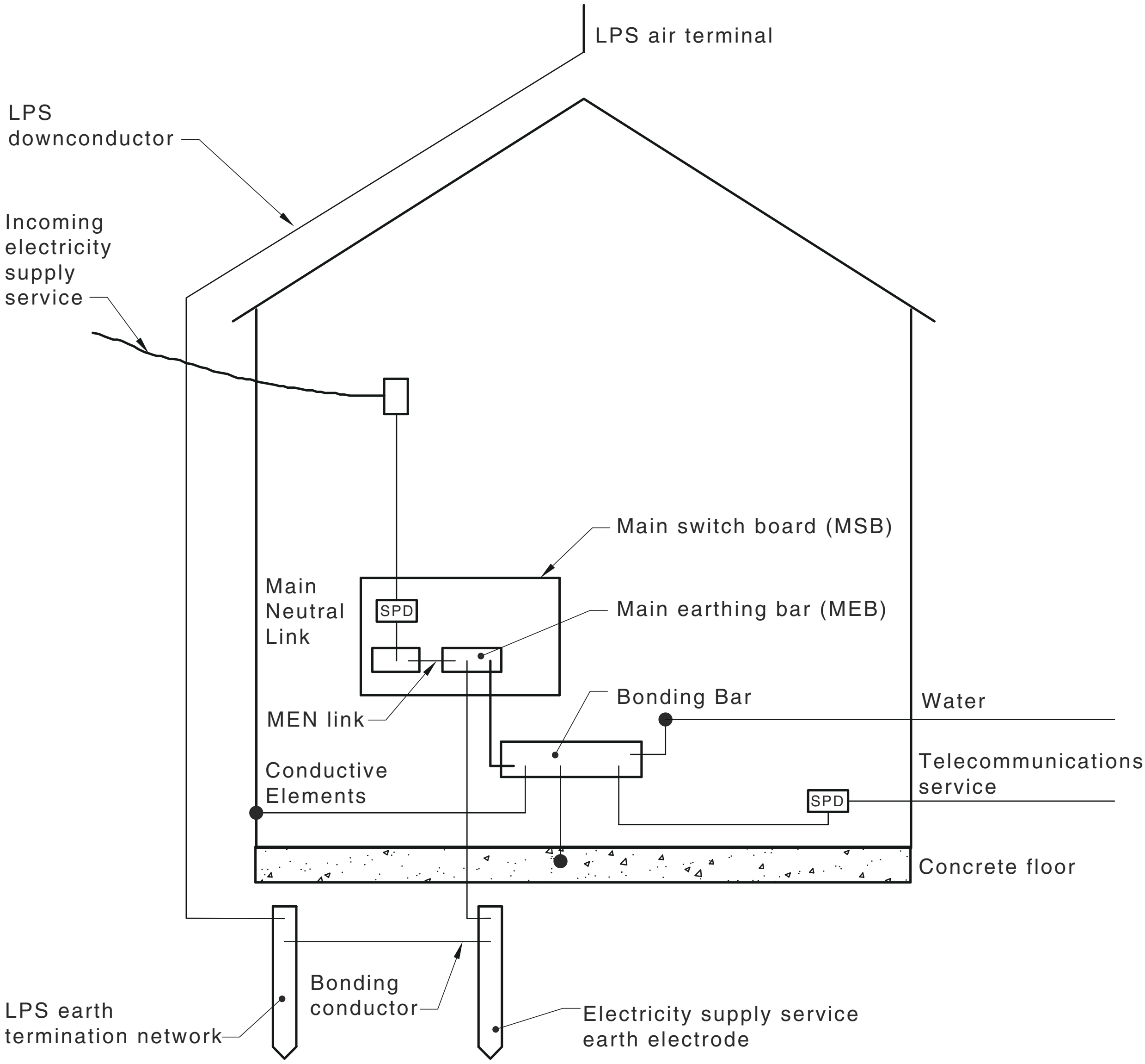

Figure E.1 — Typical bonding of services

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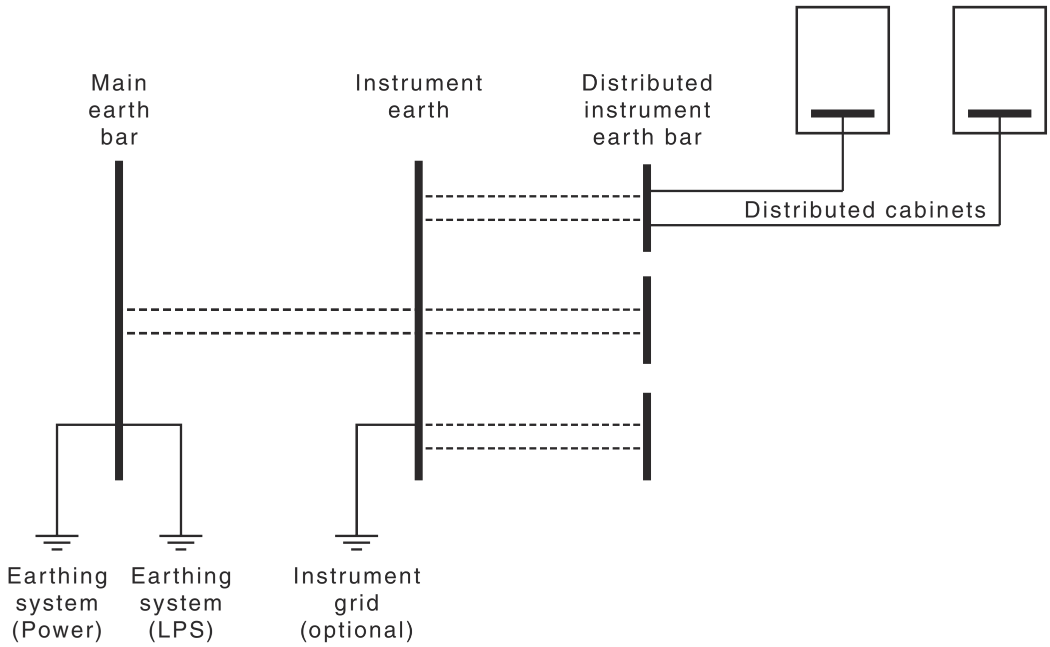

Figure E.2 — Typical overall bonding scheme

E.3.9.3 Common bonding network

A structure with a bonded, reinforced-concrete floor effectively creates a common bonding network (CBN).

Bonding is achieved by interconnecting the various services and SPDs directly to the CBN.

If the reinforcing mesh is not used as a CBN, a ring earth should be installed in accordance with Clause E.3.9.4 and bonded to the slab reinforcement at every earth electrode.

E.3.9.4 Use of a ring earth

A ring earth should be installed to —

(a) interconnect an LPS earth electrode system (typically vertical rods); and

(b) provide effective bonding of services to the MEB or local earth when this cannot be achieved by co-location.

NOTE A typical ring earth implementation is shown in Figure E.3.

Clause 3.5. outlines the requirements for a ring earth.

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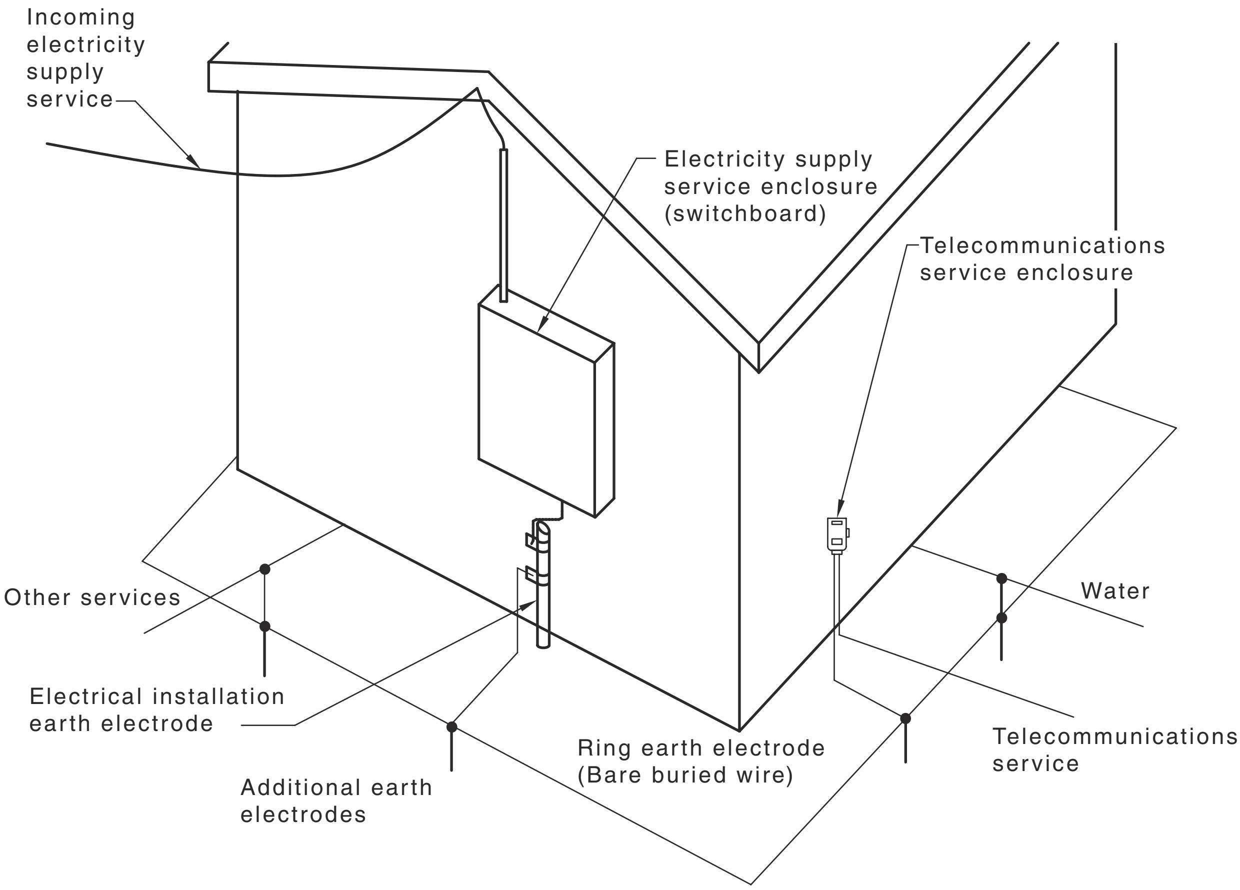

NOTE The electricity supply service and telecommunications service protection are installed inside respective enclosures if required.

Figure E.3 — Typical use of a ring earth

E.4 Construction

E.4.1 General

The construction of an earth termination network impacts its performance, quality and maintainability. This clause discusses how construction impacts these factors and presents the issues that need to be considered.

Design lifetime may be impacted when installing an earth termination network in low resistivity (< 50 Ωm) soil, as the degree of electrode corrosion increases with decreasing resistivity.

E.4.2 Driven or drilled earth electrodes

E.4.2.1 General

The use of driven or drilled earth electrodes combines economy of surface space with efficiency of performance, particularly in locations with low resistivity layers at depth (e.g. clays or water table).

E.4.2.2 Safety

The indiscriminate driving of earth electrodes, or drilling for their placement, can lead to damage of other services and, in the case of electricity supply cables, to the creation of a significant hazard to the operator. Since the drilled or driven rod will not normally be earthed to a low impedance system, it will

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