ENGINEERING DESIGN STANDARD

EDS 06-0013

GRID AND PRIMARY SUBSTATION EARTHING DESIGN

Network(s): EPN, LPN, SPN

Summary: This standard details the earthing design requirements for grid and primary substations and 132kV and 33kV connections.

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- Portable earth connections added (Section 10.2).
- Cable bridges added (Section 10.4.3).
- Design assessment criteria included (Section 11).
- Solar and wind farm guidance included from EDS 06-0019 (Appendix A.3).
- High-rise development guidance included from EDS 06-0019 (Appendix A.4 / EDS 06-0013A).
- Pipeline requirements expanded (Appendix A.11).
- Cathodic protection guidance included (Appendix A.12).
- Earth tape and conductor sizes reviewed, and aligned with ECS 06-0022 (Appendix E).
- Document reviewed.

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- Reference to generating station exclusion removed.
- Scope expanded to specifically include 132kV and 33kV connections including solar and wind farm generation.
- Guidance on fault level for electrode sizing added and conductor sizes revised.
- Lightning protection reference updated.
- Mobile phone base stations on towers reference added.
- Bonding requirements for ancillary metalwork, metal trench covers, cable tunnel metalwork and basement cable support systems revised.

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Contents

1 Introduction 6
2 Scope 6
3 Glossary and Abbreviations 7
4 Overview 9
5 Design Criteria 10
6 Design Requirements 11
7 Preliminary Design Assessment 12
7.1 General Requirements for all Installations 12
7.2 Preliminary Site Assessment 13
7.3 New Installations 13
7.4 Substations in Shared Buildings 14
7.5 Customer Substations 15
7.6 Existing Installations 16
8 Design Procedure 18
8.1 Overview 18
8.2 Data Requirements 18
8.3 Fault Levels 19
8.4 Soil Resistivity 19
8.5 Stage 1: Determine Approximate Resistance of the Earthing System 19
8.6 Stage 2a: Calculate Ground Return Current and EPR 20
8.7 Stage 2b: Calculate Transfer EPR 21
8.8 Stage 3: Determine Touch Voltage 22
8.9 Stage 4a: Conductor and Electrode Sizing 23
8.10 Stage 4b: Surface Current Density 23
8.11 Stage 5: Transfer Voltage Assessment 24
8.12 Stage 6: Finalise Design and Produce Reports 25
9 Detailed Earth Grid Design 26
9.1 Approach 26
9.2 Standard Earthing Arrangements 26
9.3 Calculation of the Earth Grid Resistance or Overall Earth Impedance (taking into account parallel paths) 32
10 Installation Requirements 35
10.1 Metalwork Bonding 35
10.2 Portable Earth Connections 37
10.3 Surge Arresters and Capacitor Voltage Transformers 37

10.4 Cables ... 37
10.5 LVAC Supplies ... 38
10.6 Construction and Commissioning ... 38
11 Design Assessment ... 39
11.1 Overview ... 39
11.2 Earthing Drawing ... 39
11.3 Earthing Report ... 39
12 References ... 40
12.1 UK Power Networks Standards ... 40
12.2 National and International Standards ... 40
13 Dependent Documents ... 41
Appendix A – Special Situations ... 42
Appendix B – Calculation of Touch and Step Voltages ... 51
Appendix C – External EPR Impact – Transfer Voltage ... 52
Appendix D – Fence Earthing Design ... 57
Appendix E – Earthing and Bonding Sizes ... 61

Figures

Figure 8-1 – Transfer Voltage 21
Figure 9-1 – Earthing Layout for Bonded Fence 27
Figure 9-2 – Earthing Layout with Separately Earthed Fence 30
Figure C-1 – Scale Plan of Substation Showing Site Boundary Surface Potential Contours 53
Figure D-1 – Use of Separately Earthed and Bonded Fencing Arrangements at the Same Substation 58
Figure D-2 – Separately Earthed Fence 2m away from Earth Grid 59
Figure D-3 – Separately Earthed Fence 500mm away from Earth Grid 59
Figure D-4 – Earth Grid Bonded Incorrectly to Fence 2m away from Earth Grid 60
Figure D-5 – Earth Grid Bonded Incorrectly to Fence 500mm away from Earth Grid 60
Figure D-6 – Fence 2m away from Earth Grid, Fence and Earth Grid Bonded with Potential Grading 1m away 60

Tables

Table 8-1 – Fault Levels for EPR and Safety Voltage Calculations 19
Table 8-2 – Example EPR Summary Table 20
Table 8-3 – Normal Fault Clearance Times and Resultant Touch Limits on Chippings 22
Table 8-4 – Conductor Sizing Parameters 23
Table 9-1 – Resistance of Earthing Grids in Different Soils 32
Table A-1 – Sources of Electromagnetic Radiation 49
Table A-2 – Potential Solutions to Reduce Low and High Frequency Interference 49
Table E-1 – Standard Earthing and Bonding Electrode/Conductor Sizes 61

1 Introduction

This standard details the earthing design requirements for grid and primary substations and associated connections at 132kV and 33kV.

Earthing design is safety critical, since a poor design can give rise to fire and/or shock hazard to staff and to members of public. Whilst the fundamentals of earthing are relatively straightforward, there are many situations where an earthing design is more complex and requires a high level of experience. This document provides guidance for some of these situations, however if there is any doubt advice shall be sought from an earthing specialist.

All earthing designs shall be approved before construction and tested before energisation. Connection **will be refused**, as outlined in Paragraph 26 of the Electricity Safety Quality and Continuity Regulations (ESQC Regulations) 2002, if UK Power Networks considers a design to be unsafe.

All grid and primary substation earthing designs shall be modelled using an industry approved computer software package. This shall include as a minimum an appropriate two or three layer soil model and touch/step voltage plots to demonstrate safety in and around the site. UK Power Networks preferred software package is CDEGS.

This standard is based on ENA TS 41-24 Issue 2.

2 Scope

This standard applies to earthing design for:

- All new grid and primary substations.
- All new customer demand and generation connections at 132kV and 33kV.
- Existing grid and primary substations (or switching stations) where a material alteration is to take place.

This document does not explicitly cover 11kV distribution systems, or LV systems, although the general principles will apply. LV or 11kV supplies to/from grid and primary sites can require special care, particularly at high EPR (or HOT) sites, and shall align with principles outlined in this document. Refer to EDS 06-0014 for further information.

ECS 06-0022 provides guidance on earthing construction for grid and primary substations.

Note: Further information on all aspects of earthing is available in BS EN 50522 and ENA TS 41-24.

3 Glossary and Abbreviations

Term	Definition
COLD Site	A COLD site is a substation where the EPR is less than 430V or 650V (for high reliability protection with a fault clearance time less than 200ms). **Note:** In practice, the 650V limit applies for most 132kV (and higher) earth faults, and 430V for other voltage levels, but exceptions may apply
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis. The CDEGS software package is a powerful set of integrated engineering software tools for modelling earthing systems
CNP	Communication Network Providers (e.g. Openreach)
DigSILENT PowerFactory	The power system analysis software used by UK Power Networks
Earth Conductor	An above ground conductor used to connect plant, equipment and electrodes of the earth electrode system
Earth Electrode	A conductor or group of conductors in direct contact with the soil, examples include rod, tape, cable steel, reinforcing bar etc.
EHV	Extra High Voltage. Refers to voltages at 132kV, 66kV and 33kV
EPR	Earth Potential Rise. EPR is the potential (voltage) rise that occurs on any metalwork due to the current that flows through the ground when an earth fault occurs. Historically this has also been known as rise of earth potential (ROEP)
Grid Substation	A substation with an operating voltage of 132kV and may include transformation to 33kV, 22/20kV, 11kV or 6.6kV
HOT Site	A HOT site is a substation where the EPR is greater than 430V or 650V (for high reliability protection with a fault clearance time less than 200ms). **Note:** In practice, the 650V limit applies for most 132kV (and higher) earth faults, and 430V for other voltage levels, but exceptions may apply
HPR / HEPR	High EPR, generally used to describe a site which has an EPR exceeding 2x permissible touch voltage limits (and therefore requires special care to ensure safe touch and transfer voltages)
HV	High Voltage. Refers to voltages at 20kV, 11kV and 6.6kV
ITU	International Telecommunication Union. ITU directives prescribe the limits for induced or impressed voltages derived from HV supply networks on telecommunication equipment and are used to define the criteria for COLD and HOT sites
LV	Low Voltage. Refers to voltages up to 1000V AC (typically 400V 3-phase and 230V single-phase) and 1500V DC
Normal Protection Operation	Normal operation of primary protection, i.e. detecting and clearing a fault within a defined time without reliance on back-up protection and without ‘stuck’ or abnormally slow circuit-breakers. Usually taken as 1 second for 11kV networks, 0.5 seconds for 33kV and 0.2 seconds at 132KV
POC	Point of Connection
Primary Substation	A substation with an operating voltage of 33kV and may include transformation to 11kV,6.6kV or LV
ROEP	Rise of Earth Potential (see EPR)

Term	Definition
Secondary Substation	A substation with an operating voltage of 11kV or 6.6kV and may include transformation to 400V. Also termed 'Distribution Substation'
Source Substation	The grid or primary substation supplying the new substation or customer connection
Step Voltage	The step voltage is the voltage difference between a person's feet assumed 1 metre apart. **Note:** In practice, in view of revised limits in BS EN 50522 and ENA TS 41-24, step voltage considerations are more of an issue for animal/livestock areas
Stress Voltage	A voltage difference appearing across insulation between conductors with different earth references that could be inside the same item of equipment, e.g. a cable core and earthed screen. If the stress voltage exceeds the insulation strength then breakdown may occur
TN-C-S	Terre Neutral-Combined-Separated. An LV earthing system where the neutral/earth conductor is combined on the DNO network and separated within the customer's installation. Refer to EDS 06-0017
Touch Voltage	The touch voltage is the hand-to-feet voltage difference experienced by a person standing up to 1 metre away from any earthed metalwork they are touching. **Note:** Hand-to-hand voltage differences within substations are generally not considered as they should be avoided by careful design
Transfer Voltage	The transfer voltage is the potential transferred by means of a conductor between an area with a significant earth potential rise and an area with little or no earth potential rise, and results in a potential difference between the conductor and earth in both locations. Voltage can be carried by any metallic object with significant length, e.g. pilot cable sheath, barbed wire fence, pipeline, telecoms cable etc. and needs consideration for all such feeds into/out of and near substations
TT	Terre-Terre. An LV earthing system where no network earth terminal is offered to the customer. Refer to EDS 06-0017
UK Power Networks	UK Power Networks (Operations) Ltd consists of three electricity distribution networks: • Eastern Power Networks plc (EPN). • London Power Network plc (LPN). • South Eastern Power Networks plc (SPN).

4 Overview

Earthing is necessary to ensure safety in the event of a fault.

Earthing serves a safety critical function, and helps to ensure that substations and all electrical installations are safe in terms of a) shock risk, and b) ability to withstand fault conditions (fault current) without damage or fire.

In general terms, the installation should be connected to the general mass of earth via a buried electrode system that provides a suitably low earth resistance value. In addition, bonding (low impedance connections) is required between equipment and metalwork to ensure they remain at the same voltage[1] and to safely conduct fault current without damage or danger.

The terms ‘earthing’ and ‘bonding’ are often used separately to describe these two functions, but, in reality, a well-designed earthing system achieves both.

Earthing is applied to normally de-energised metalwork to control the voltages on equipment, e.g. plant and other metalwork such as fences in and around the substation or installation.

Every substation shall be provided with an earthing installation designed so that in both normal and abnormal conditions there is no danger to persons arising from earth potential in any place to which they have legitimate access.

The terms touch voltage and step voltage are used throughout this document (collectively termed safety voltages). These relate to hand-to-feet or foot-to-foot shock voltages respectively, which can appear briefly during fault conditions. Refer to Section 3 for the standard definitions and EDS 06-0012 for further information.

[1] This aspect is particularly relevant to controlling hand-to-hand voltages to safe levels.

5 Design Criteria

The most general, and overriding requirement is that the installation shall be designed to prevent danger, as required by ESQC Regulations.

The design and installation of an appropriate earthing system will ensure that a suitably low impedance path is in place for earth fault and lightning currents and control touch and step voltage hazards.

The main objectives are to:

a) design and install an earthing system that provides sufficient safety with regard to touch, step and transferred voltage limits;

b) conform with the requirements of UK Power Networks earthing standards, ENA TS 41-24, BS EN 50522 and BS 7430; and

c) ensure that the substation is safe to energise.

In practice, these objectives are usually satisfied by ensuring that:

1. Metallic items are connected together (bonded), as necessary, with dedicated low impedance connections to minimise touch voltages and to provide a path for fault current with adequate thermal capacity.

2. An in-ground earthing (electrode) system is installed and arranged to control touch and step voltages. This serves two purposes:

   - To provide a low resistance connection to the general mass of earth (earthing), in order to a) limit the EPR to design values and b) provide a low impedance path sufficient to operate protection quickly in the event of an earth fault.
   - To minimise the touch voltage at operator positions (e.g. by providing a copper mesh or ring beneath the operator's feet that is bonded to the switchgear), and around metallic items (including fences, where necessary). In this way, the touch voltage experienced by an individual can be much smaller than the substation EPR.

6 Design Requirements

To satisfy the design criteria the earthing system shall satisfy the following requirements:

- The touch and step voltages in and around the substation shall be within the BS EN 50522 limits specified in EDS 06-0012 based on the installed substation earth electrode system and reliable parallel electrode contributions only (see Section 9.3), for normal (main) protection operation.
- The EPR should be limited to 430V (or 650V where high reliability protection clears the fault within 0.2 seconds) as far as reasonably practicable to classify the site as COLD or below 2kV if the site is to be classified as HOT.

  Note: The use of the terms HOT or COLD do not directly translate to safe or unsafe, as it is possible to have a safe HOT site or unsafe COLD site.

- The transfer voltage onto any LV network or customers shall not exceed the applicable touch and stress voltage limits.
- The impact of the EPR that may be transferred to third parties (e.g. telecommunications providers, pipelines, LV customers etc.) shall be considered at the design stage and appropriate mitigation put in place.
- The EPR and safety voltage calculations shall be based on the calculated foreseeable worst-case earth fault level (Section 8.3).
- The substation should be designed with an independently earthed fence where practical.
- The earthing system shall be able to pass the maximum current from any fault point back to the system neutral without damage based on backup protection operation times.
- The earthing system shall be sized to ensure the temperature rise is limited so as not to cause failure of the electrode, conductor or joints (Table 8-4).
- The overall surface area of buried electrode shall be sufficient to dissipate fault current without excessive heat/steam generation.
- The earthing system shall maintain its integrity for the expected installation lifetime with due allowance for corrosion and mechanical constraints.

7 Preliminary Design Assessment

7.1 General Requirements for all Installations

All items of equipment and associated enclosures shall be suitably earthed as outlined in Section 4.

In the case of shared sites, the customer will be expected to provide an earthing system sufficient to ensure safety in and around the installation. The customer earthing is normally bonded to UK Power Networks earthing system (except in some rare cases). Where practicable, UK Power Networks' earthing system should not be reliant on this, or any other system to ensure safety; refer to section 7.4.

The following special situations should be considered before commencing the earthing design as they can be problematic or require additional measures. Refer to Appendix A for further details. This list is not exhaustive; if in doubt contact the author.

- Sites shared with other companies (e.g. National Grid).
- Sites near to pipelines and cathodic protection systems.
- Generation sites.
- High-rise developments.
- GIS substations.
- Where metal supports are used for security lighting, etc.
- Communication masts and towers.
- Reactors and AC to DC converters.
- Railways.
- LV supplies to third party equipment at substations.
- Places frequented by people or animals e.g. caravan parks, campsites, schools, leisure centres, farms, etc.
- Lightning protection.
- Cable tunnels.

Notes:

- In many cases, additional electrode laid in cable trenches, or rod nests outside the footprint of the substation can assist in achieving a safe design, together with rebar or meshed electrode in the substation to control touch voltages. The requirement for external electrode should be identified at an early stage to enable it to be installed during cable laying/ducting works.
- The rise of potential that occurs during fault conditions can extend far beyond the physical boundaries of the site. Substations should be located, where possible, to avoid adverse impact on third party properties and structures. Refer to notes in Section 8.11.
- Pipelines (typically gas/oil) require at least 50m separation from substations, or calculations carried out to satisfy the British Pipeline Authority (BPA) or other relevant parties that danger will not result on their system, or to their operatives under power system fault conditions. Refer to Appendix A.
- High-risk neighbours (e.g. wet areas, paddling pools, or areas where people may be barefoot) should be avoided.
- Electrode should be located clear of livestock areas, noting that step voltage limits for livestock are relatively low.
- If these conditions cannot be met, the EPR should be reduced as much as practicable, and a quantified risk assessment carried out for areas external to the substation where EPR exceeds acceptable touch or step voltage limits.

In addition to the above specific requirements for new and existing installations, substations in shared buildings and alterations and additions are covered in the following sections.

7.2 Preliminary Site Assessment

Before carrying out work at a green field site, a survey should be undertaken to establish the resistivity of the soil and layer thicknesses. Soil resistivity testing is described in EDS 06-0024.

Civil engineers will normally require a geo-technical survey, and if boreholes are to be drilled, it may be possible for their positions to be selected such that they are suitable for earthing, whilst also providing the necessary data for the civil engineer (for example located just beyond the corners of the proposed building). On completion, if required, copper electrode can be installed in each borehole prior to backfilling. Any holes should be backfilled with local soil or material that is non-corrosive to copper and electrically conductive. Concrete, soil, bentonite or Maronite are all suitable for this purpose, as are proprietary conductive concrete mixes.

The design engineer should obtain the Geo-technical Engineer’s report plus any other published geological information relating to the site (e.g. British Geological Survey, BGS). The chemical analysis should include an assessment of the rate of corrosion to copper, lead and steel (normally the above average presence of chemicals such as chlorides, acids or sulphates increase the corrosion rate) and testing the pH value.

At an existing site, the buried electrode should be revealed at a number of locations and inspected to determine the conductor size, type and condition, e.g. any evidence of corrosion. If corrosion is evident, the new electrode size shall be increased and the copper tape surrounded by a minimum of 150mm radius of correct value pH soil. This may need to be imported if sufficient quantity is not available from other parts of the site. Additional measures (e.g. membrane) may be needed to retain imported soil if there is significant groundwater flow through/across the site. Alternatively, Bentonite, Maronite or other agents can be used to protect the copper electrode from corrosion.

At an existing site, it may also be useful to measure the earth resistance so that this can be included in design calculations.

7.3 New Installations

New installations can be designed correctly from the outset, as described above, and generally do not suffer with problems associated with older or legacy practices. However, invariably there will be restrictions on the site footprint, and an absence of lead sheathed cables.

For this reason, the earthing design and installation should commence before cable/ducts are laid, as it may be necessary to lay bare copper electrode in trenches before cables/ducts are installed. The bare copper electrode will serve to reduce the earth resistance of the site and is useful where normal rod electrodes would be insufficient or cannot be driven to adequate depth.

If it is deemed necessary to install electrode outside the immediate area of the substation (and away from cable routes) – this may require wayleaves etc. and planning/co-ordination with third parties.

7.4 Substations in Shared Buildings

It is generally necessary to apply substation design techniques to buildings housing HV equipment, and care is needed (particularly with metalclad buildings) to consider any shock risk which may occur in and around the building under fault conditions. Basement grid/primary substations are increasingly common in urban areas and are a prime example.

For fire/damage prevention, in the context of earthing systems, it is necessary to ensure that all conductors are adequately sized for the current that they will carry in all foreseeable fault conditions. Also, it is necessary to ensure that significant 'stray' current will not flow in parts of any building structure, or other services, that could lead to damage. This is best prevented by the installation of dedicated low impedance bonds in strategic locations to safely convey the majority of fault current.

A dedicated electrode system shall be sized to cope with the maximum earth fault level. It is not sufficient to rely solely on lightning protection systems, piles, support structures, rebar, etc. to carry high fault currents since these can overheat. Electrode sizing calculations should confirm that the surface current density will not cause drying or separation at the electrode-soil interface or other damage if the electrode is encased in concrete or other agent.

Shock and thermal damage risks can be minimised by installing a dedicated and low resistance copper earth grid underneath the footprint of any building, and bonding all items of equipment to it. It may be necessary to install additional horizontal electrode with HV cables or otherwise beyond the footprint of the building; wayleaves or additional permissions may be required which is why it is imperative that the earthing design begins early in the planning phase and **not** after foundations are laid and cable ducts installed.

If externally laid electrode is not practicable, or normal methods are not sufficient to limit the EPR at UK Power Networks substation/switch room, an integrated earthing design (where the customer substation/switch room earthing system is connected to the UK Power Networks substation earthing system) may be considered. This should be a last resort, and then only if there are measures in place to maintain (and test) the integrity of interconnections, since changes to the third party system could render the UK Power Networks installation unsafe (and vice-versa).

Section 7.5 below covers customer substations in more detail.

7.5 Customer Substations

7.5.1 Overview

The customer installation will generally be designed and built by a developer with reference to appropriate standards. It is not UK Power Networks role to carry out design work for a customer. However, UK Power Networks does have a duty of care to ensure that the earthing system of any customer connected to its distribution network is adequate in terms of safety and conforms to current UK earthing standards.

The earthing system for a customer installation shall as a minimum be designed in accordance with BS EN 50522, BS 7430, ENA TS 41-24 or the relevant the UK Power Networks standard.

7.5.2 Design Information

UK Power Networks will usually provide the following information to assist with the customer substation earthing design:

- Maximum earth fault level, earth resistance value, earth potential rise and HOT/COLD classification of the source substation.
- Details of the cable or overhead line network between the source substation and the proposed point of connection.
- Maximum earth fault level at the proposed point of connection.
- Fault clearance time for an earth fault at the proposed point of connection.

Refer to Section 8.2 for further details.

7.5.3 Combining UK Power Networks and Customer Earthing Systems

Ideally, the UK Power Networks and customer earthing systems should be designed as separate systems that are capable of operating safely in the absence of the other. In this way, safety is ensured should they become disconnected from each other or if the customer network is decommissioned. In most situations it is then preferable to connect the customer and UK Power Networks earthing systems together (the exception being certain HOT sites detailed in EDS 08-2108).

However, in some circumstances an integrated earthing design (where safety of the UK Power Networks and/or customer earthing system relies on the interconnection with the other) may be required to achieve an optimal design and is acceptable if the reasons can be justified. As a general rule only the parts of the customer earthing system that are immediately adjacent to the UK Power Networks earthing system should be included in the safety calculations.

Where an integrated earthing system is specified, the customer earthing system shall be constructed to UK Power Networks' standards (in terms of electrode/conductor sizing, method of installation and touch/step considerations). However, care is needed if the customer system should become decommissioned or compromised; clear labelling and test facilities shall be provided to enable UK Power Networks to assess whether any customer contribution has been lost.

7.6 Existing Installations

7.6.1 General

The design approach for earthing systems attached to existing substations is similar to that outlined for new sites. The existing earthing system should first be assessed for efficacy and longevity; if it performs poorly or is found to be heavily corroded it may be best to ignore its contribution. Nevertheless, extensions/additions to existing installations can be straightforward if the existing system is adequate and meets modern standards.

Some existing earthing systems will be found to be unsuitable for various reasons:

- Legacy practice often relied on a single central spine with little or no duplication or potential grading; a mesh or duplicate paths for fault current may be absent.
- Earth fault levels may increase as part of proposed works.
- Older earthing systems may be corroded and suffer increased resistance and reduced current carrying capacity.

Most existing substations have been assessed to establish the earthing resistance and resulting EPR. The results are stored in earthing database (EDS 06-0002).

Modifications to a site may alter the EPR significantly, particularly if the earthing system is reduced, or ground return currents are changed (e.g. revised fault levels or introduction of overhead sections). In most cases it will be necessary to calculate the new earth resistance and EPR(s) that will result from these works.

The design approach outlined in Section 7.3 should be followed for existing installations in addition to the steps described in Section 7.6.2 and 7.6.3 below.

7.6.2 Alterations/Additions

In general the opportunity should be taken to upgrade the substation electrode system when part of it is being extended or altered; this may be as simple as converting a radial/spine system into a loop or adding a perimeter electrode around an existing arrangement. However, such measures are not mandatory provided the new installation does not increase the risk in the existing parts of the substation.

In most cases, a new earthing system should be installed for/around new plant, and connected to the existing system. This tends to augment the existing system and lower its resistance and EPR, meaning that both new and old parts benefit. However, if the EPR remains high, the new system can extend any high EPR zone or HOT zone which may adversely impact neighbours.

Care should be taken if any part of a system is to be removed or decommissioned; refer to Section 7.6.3.

Note: Increases in fault level (e.g. by additional generation capacity, or larger/additional circuits or transformers into/out of the site) will have an impact on the existing part of the substation and this should be considered at design time. Substantial changes to plant, feeding arrangements or switchgear should automatically trigger an earthing assessment and redesign.

7.6.3 Removal of Plant/Reduction in Site Area

In some cases, large parts of a substation (or customer installation) become redundant and are decommissioned/removed (e.g. 132kV or 33kV rafts may be replaced with indoor switchgear, freeing up large areas of open compound). Where possible, their earthing systems should be left in place and remain connected to the main earthing system for the rest of the substation life.

Similarly, lead sheathed cables which are overlaid or otherwise removed from service should be retained as earth electrodes where possible, and their sheaths (and ideally, cores) connected to the main earthing system. Connections should be labelled and be suitable for testing (with a clamp meter) where possible, so the continuing contribution of such systems can be monitored.

Where an area of substation is to be developed or its earthing contribution otherwise reduced/depleted, additional electrode will normally be required to maintain the substation earth resistance. Failure to replace or reinstate a depleted earthing system could result in increased EPR and dangerous step/touch voltages in and around the installation.

Note: Such removal works should trigger a full earthing redesign, because the extent of remedial action required may be difficult to quantify without full assessment.

8 Design Procedure

8.1 Overview

The approach outlined in this section is most relevant to new sites, but should also be adopted where possible for additions/alterations to existing sites.

The aim is to establish a copper mesh and/or ring in the soil around the switchgear and substation (as described in Section 9), and to determine whether a standard design (Section 9.2) is sufficient to ensure safety, or whether additional measures are required.

The design should begin with a data collection exercise to establish the site location, feeding arrangements, and other relevant parameters. A summary of the design process is outlined below. Initial feasibility studies may proceed based on estimated or worst case values, although optimised designs will require accurate data. In some cases, due to the dependency between variables it will be necessary to repeat some stages of the design process until an acceptable design is found.

Whilst a reasonable design can be produced using empirical calculations, or by using standard layouts, this is only acceptable for small substations and is not appropriate for grid and primary substation earthing design.

All new/proposed primary and grid substation earthing layouts shall be modelled using appropriate software and a multi-layer soil model before the design is finalised and accepted.

8.2 Data Requirements

The following information is required to design the earthing system:

- Substation layout drawing.
- Plan of surrounding area (100m radius) with buildings and other utility services shown.
- Supply circuit types and sizes, and construction (e.g. cable, steel tower line, wood pole, etc.)
- For cable connections, source substation EPR and earth resistance (not required if there is any unearthed overhead line in the circuit).
- Outgoing circuit types and presence of overhead sections, if any.
- Geographic plan showing existing bare metal sheathed (or hessian served) or bare wire armoured cables and proposed cable routes within a 500m radius of substation.
- Details of any metal tower lines into/out of the substation.
- Earth fault currents for all voltage levels at the substation (Section 8.3).
- Fault clearance times.

8.3 Fault Levels

The EPR and safety voltage calculations shall be based on the foreseeable worst-case earth fault level. This shall be (at least) the maximum earth fault level at the point of connection including any contribution from generators, plus 10%. Refer to Table 8-1.

For EPR calculations, fault levels and durations should be considered for all voltage levels at the substation (excluding LV).

An example of the PowerFactory fault level format is shown in EDS 06-0012. The RMS break value (Ib) should be used for the EPR calculations.

Note: For 11kV fault levels on ASC systems the solid or bypass earth fault level shall be used, i.e. assuming the ASC is not in circuit. This will also provide some protection against cross-country faults. Refer to ENA TS 41-24 for further details.

Table 8-1 – Fault Levels for EPR and Safety Voltage Calculations

Voltage	Earth Fault Level for EPR and Safety Voltage Calculations
132kV	Maximum Earth Fault Level + 10%, or 13kA, whichever is higher.
33kV	Maximum Earth Fault Level + 10%
11kV or 6.6kV	Maximum Earth Fault Level + 10%

For conductor and electrode sizing calculations, different fault levels and clearance times should be applied; refer to Section 8.9 and Table 8-4.

8.4 Soil Resistivity

An initial estimation of the soil resistivity can often be obtained from the earthing database (EDS 06-0002) or from published geological survey information.

The final design for a primary or grid substation should always be based on a measurement of soil resistivity at the site, where possible, since this will allow for optimal design and best use of electrode materials. Measurements should be carried out according to ECS 06-0024.

8.5 Stage 1: Determine Approximate Resistance of the Earthing System

Determine the earth resistance as follows:

- Obtain soil resistivity (Section 8.4).
- Design the earthing system to optimise resistance in relation to soil structure (Section 9). This first estimate should involve an electrode covering the entire site area (footprint), where possible, unless known constraints exist.
- Calculate the earth grid resistance (R_G) using appropriate computer modelling software.

  Note: The resistance can be estimated using the relevant formulae from ENA EREC S34 but the final arrangement shall be modelled using computer modelling software.

8.6 Stage 2a: Calculate Ground Return Current and EPR

Calculate the EPR as follows:

- Establish the earth fault levels (I_F) for all voltages at the substation. Note that EPR can result from faults at the substation or on circuits feeding from it, e.g. a 33/11kV substation design shall consider 33kV and 11kV fault levels, 132/33kV sites shall consider 132kV and 33kV fault levels, etc.
- Establish the ground return current for each voltage level (I_E *or* I_{GR}). If any circuit into or out of the substation uses 3-wire overhead construction (no earth wire), the full earth fault current may be taken as the ground return current for that voltage level.

Note: The ground return current will generally be less than the full earth fault current for cable fed systems, or for systems with an overhead earth wire, since a proportion of current will return via this metallic pathway and the ground return part is reduced. It will be necessary to calculate the reduced ground return current (I_E *or* I_{gr}) for all voltage levels, since this will be the current that flows into the earthing system under fault conditions. Refer to EDS 06-0012 for further information on the calculation of ground return current. A further reduction is possible for multiple earthed 132kV or 66kV systems (neutral-current-reduction) since the earth fault current will return via two or more star points (refer to EDS 06-0012).

- For systems that are supplied via cable circuits, it is also necessary to calculate the transfer voltage from the source substation(s) (Section 8.7).
- Calculate EPR using the ground return current (EPR = $R_G \times I_{GR}$).
- Summarise the EPR at site for all voltage levels, based on this R_G; an example is shown in Table 8-2 for a rural (overhead fed) 132/33/11kV site.

Table 8-2 – Example EPR Summary Table

Voltage Level	Fault Current (I_F)	Resultant Ground Return Current (I_{GR})	Earth Resistance (R_G)	EPR (I_{GR} x R_G)	Max Fault Duration (from stage 3)
132kV	13kA	8kA (reduction due to overhead line and multiple earthed system)	0.5 Ω	4,000V	0.2 seconds
33kV	2.5kA	2.5kA (overhead system, no reduction)	0.5 Ω	1,250V	0.5 seconds
11kV	10kA	7kA (calculated maximum network ground return, solidly earthed overhead system)	0.5 Ω	3,500V	1 second

Notes:

- These figures are for example purposes only and do not necessarily represent real network conditions. Each application is different and should be calculated as appropriate. Alternative and/or future running arrangements shall also be considered for the worst case.
- In each study it is necessary to identify those faults that will produce the highest EPR. For example, 11kV faults in a 33/11kV substation will not produce a significant ground return current, as current will return (to the 11kV star point, which is on-site) via the main earthing system components. 11kV network faults, on the other hand, will produce a component which flows through the soil back to the star point via the primary/grid substation earthing system. Overhead faults are simplest to visualise and usually produce highest I_{GR}. 11kV faults on cable network are likely to produce much smaller ground return current. The Secondary Substation Earthing Design Tool can assist with this (refer to EDS 06-0014).

8.7 Stage 2b: Calculate Transfer EPR

Transfer voltage should be considered if the source substation has a high EPR, and is cable connected to the new substation. An EPR event at the source could then theoretically cause a voltage rise at the new substation, as illustrated in Figure 8-1.

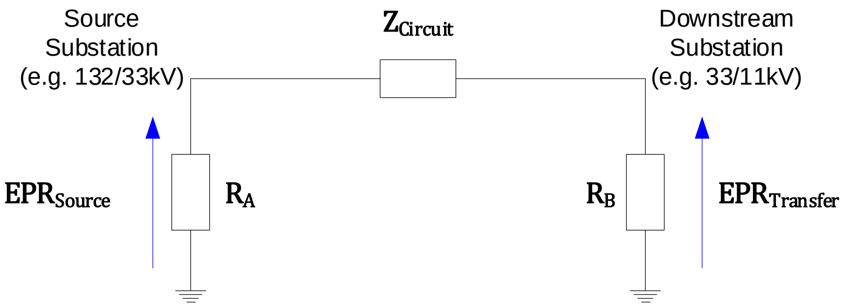


Figure 8-1 – Transfer Voltage

An estimation of the transfer voltage can be calculated using the formula below. It will be necessary to determine the equivalent sheath impedance ($Z_{Circuit}$) between the substations in terms of complex (real and imaginary) components. The new substation earthing impedance (Z_B) can be treated as purely resistive for this purpose, i.e. $Z_B \approx R_G + 0j$.

$$EPR_{Transfer} = EPR_{Source} \times \left(\frac{Z_B}{Z_{Circuit} + Z_B}\right)$$

In most cases, computer-modelling software can assist with this calculation, but the above approximation will highlight if transfer voltage is likely to be an issue. The transfer voltage can be disregarded if the EPR is significantly lower than the EPR for local faults.

The EPR should be kept as low as practicable to avoid impacting surrounding infrastructure in relation to touch and stress voltages caused by the transfer voltage. Where this is not possible specialist advice should be sought, and a more detailed assessment of the risks will be required followed by mitigation where appropriate.

The EPR should also ideally be below 650/430V (COLD site limit). This is not mandatory but EPRs above this level will impose additional requirements (see Stage 5 and Section C.5). If it is not possible to achieve an EPR less than 2kV, specialist advice should be sought.

8.8 Stage 3: Determine Touch Voltage

Determine the acceptable touch and step voltage limits from EDS 06-0012. These are related to the duration of a fault. For grid and primary substation design purposes the values in Table 8-3 may be assumed as worst-case fault clearance times and associated limits for persons standing on chippings/shingle.

Table 8-3 – Normal Fault Clearance Times and Resultant Touch Limits on Chippings

Voltage	Maximum Normal Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
132kV	0.2	1773	> 20000
33kV	0.5	650	> 20000
11kV	1.0	259	> 20000

Notes:

- Lower limits will apply for soil/grass areas, or for outdoor concrete slabs without rebar bonded to the main earthing system.
- The fault clearance times above relate to the worst-case normal (main) protection operation and do not consider backup protection or protection mal-operation. These factors should be considered for conductor sizing (Stage 4) but are not necessary for touch voltage design calculations.
- Some areas will not be able to achieve the clearance times quoted above, particularly for 11kV faults. The advice of a protection engineer should be sought.
- These limits assume normal footwear is being worn and are not valid for barefoot/wet contact scenarios.

It can be seen that (in substations at least), the step voltage limits can be disregarded, as they will almost certainly be satisfied if touch limits are met.

- An assessment should be carried out to ensure that protection will clear earth faults within the times specified above. Revised limits should be used if protection clearance times are longer, or if soil or outdoor concrete (without bonded rebar) is used.
- If the EPR is below these limits, no further work is necessary; move to Stage 4. Otherwise, calculate/model touch voltages and compare to limits. As a first approximation, touch voltages within substation areas will normally be less than 50% of EPR, for a mesh based electrode system, but this should not be assumed in all areas.
- Calculate the touch voltage (see Appendix B) around the substation on all plant, fences, gates, etc. (whether the fence is bonded or separately earthed). This is particularly important, as it is relevant to members of public as well as operational staff. Modified ground coverings (wet/dry soil) and alternative/no footwear may need to be considered in some situations, such as when swimming pools/paddling pools may be in close proximity. The advice of a specialist should be sought in such circumstances.
- Separately earthed fences in general are preferred to bonded fences (since they adopt a lower voltage) and should be installed where possible. See Section 9.2.2.
- If the touch voltages are acceptable, the design is acceptable provided it meets the further requirements listed in Stages 4a and 4b below. Once the design is finalised, a computer printout showing the touch voltages across the substation shall be produced and kept on file.
- If not acceptable, modify the design as necessary to achieve compliance. Typically, EPR (and touch voltages) can be reduced by installation of a larger or deeper electrode system, by reducing the earth resistance. If not practicable, the touch voltages can be reduced around equipment by additional operator mats, grading electrode, or bonded rebar. Return to Stage 1, since modified systems will alter R_G, which in-turn will affect the ground return current, EPR and touch voltage calculations.

- If the site is HOT, but only marginally so, it is worthwhile exploring what might be required to make the site COLD. The cost of installing additional electrode might be outweighed by the cost of additional measures necessary to ensure safety around a HOT site (refer to EDS 06-2108 and Appendix C). A COLD site is generally much easier to integrate into a dense urban network (see Stage 5) or where there is adjacent third party equipment.

8.9 Stage 4a: Conductor and Electrode Sizing

Once the design is safe in terms of touch voltages determine appropriate earth conductor and electrode sizes to satisfy the fault currents and durations given in Table 8-4. Select appropriate sizes from Appendix E whilst adhering to the minimum fault level values and conductor sizes in Table 8-4.

Notes:
- Spur connections to earth electrodes should be based on 60% of the worst-case value.
- Equipment connections with two or more conductors in parallel should be based on 60% of the worst-case value.
- Generally, the same standard conductor and electrode sizes should be used throughout the whole substation installation.
- Sites shared with National Grid shall use of the same conductor/electrode sizes as National Grid if these are larger (refer to ENA TS 41-24 for relevant sizes).

Table 8-4 – Conductor Sizing Parameters

Voltage	Typical Backup Fault Clearance Time	Fault Level for Conductor Sizing	Earth Grid Electrode Minimum Copper Size	Equipment Connections Minimum Copper Size
132kV	3s	Switchgear short-term withstand current or 40kA, whichever is higher	40mm x 6mm	40mm x 6mm (duplicate bolted)
33kV	3s	Switchgear short-term withstand current or 31.5kA, whichever is higher	40mm x 4mm	38mm x 5mm (duplicate bolted)
11kV or 6.6kV	3s	Switchgear short-term withstand current or 26kA, whichever is higher	40mm x 4mm	40mm x 4mm (duplicate bolted)

8.10 Stage 4b: Surface Current Density

Determine the surface current density of the buried bare copper electrode system and check its adequacy (using the calculation methodology in EDS 06-0012).

Note: Only earth electrode buried at a minimum depth of 0.6m (to avoid seasonal variation and soil drying) shall be included in the surface area current density calculations.

8.11 Stage 5: Transfer Voltage Assessment

The EPR shall not create a hazard on adjacent infrastructure as a result of transfer voltage; this may be direct transfer of the EPR via a conductor or indirect transfer by coupling through the soil. An assessment shall be carried out to determine the impact from any transfer voltage.

LV networks shall not be exposed to transfer voltages that create touch or stress voltages that exceed the relevant limits (refer to EDS 06-0002). An initial assessment of compliance can be made by ensuring the EPR is below the relevant touch voltage limit and below the 1200V stress voltage limit. If the EPR exceeds these values, a more detailed assessment is required and where compliance cannot be demonstrated mitigation is required.

Transfer voltage impact onto sensitive sites such as petrochemical, railway, swimming pools, fuel stations or livestock areas shall also be assessed according to the relevant risk thresholds (refer to EDS 06-0002).

Additionally, the site shall be classified as HOT or COLD for the purposes of informing communication network providers or other third parties. This is a requirement of the International Telecoms Union (ITU) since HOT sites can lead to hazards on the wider communications network. A site is HOT if its EPR exceeds 430V (for 33kV or 11kV faults), or 650V (for 132kV faults that will clear within 0.2 seconds).

If external voltage contours are likely to adversely impact third parties it may be necessary to redesign the earthing to avoid third party equipment.

Refer to Appendix C for further information on the additional requirements associated with transfer voltage and HOT sites.

Note: A quantitative risk assessment may be necessary where third party impact outside the substation cannot be avoided at reasonable cost; this is detailed in ENA TS 41-24 but its use is discouraged when risk can be mitigated at the design stage. In general terms all substations shall be safe by design, i.e. the touch voltages in and around the substation shall be below the BS EN 50522 limits. If a new (third party) development adjacent to an existing substation changes this situation, a quantitative risk assessment may be applied if other solutions cannot be found.

8.12 Stage 6: Finalise Design and Produce Reports

On completion of the design, produce an earthing design report and construction drawings. Use the checklist below to ensure all relevant items have been considered.

- All data and sources listed.
- All assumptions stated.
- Latest fault level and fault clearance times used.
- Earth grid and earth rod positions specified.
- Any additional earth conductor specified.
- Connections to the rebar or reinforcement mesh specified.
- Fence earthing specified including use of insulated panels or standoff insulators.
- Earth resistance calculated using correct soil resistivity.
- EPR calculated.
- Transfer EPR calculated.
- Touch and step voltages calculated and within applicable limits.
- Touch and step voltage contour plots included.
- Transfer voltages assessed to an appropriate level and mitigation advised where necessary.
- Site classified as COLD or HOT. If HOT, HOT zone plotted, impact on third parties assessed and required measures/migration specified.
- Earthing electrode and conductor specified and correctly sized.
- Pile connections specified.
- Equipment connections specified.
- Operator earth mats specified.
- Surface covering specified.

9 Detailed Earth Grid Design

9.1 Approach

Start with a basic layout, similar to one described in Section 9.2, and then modify the design as necessary. The standard approach is to ensure the substation is safe and to limit external transfer voltages to acceptable levels. Reducing the EPR to allow a COLD site classification should also be achieved where practicable at reasonable cost.

If it appears that extensive, costly modifications would be required to make the site COLD, an assessment should be made of the costs involved in declaring the site HOT and this compared to the cost of extending the earthing. In most cases a compromise will provide the best solution, i.e. some additional earthing work will be needed to reduce the EPR, but to a level where the site is still HOT.

9.2 Standard Earthing Arrangements

The arrangements described below are a starting point for all earth grid designs, and in some cases will need little or no modification if they can be shown to achieve acceptable EPR and touch voltages. All new build grid and primary substations are based on a standard mesh layout with corner or perimeter rods; this provides duplicate paths for earth fault current.

Standard substation earthing arrangement layout drawings are detailed in EDS 06-0012 and Appendix D provides further details and justification of separately earthed and a bonded fence arrangements.

The separately earthed fence arrangement (Section 9.2.2) is preferred where possible. This requires an above ground spacing of at least 2m between the fence and plant connected to the main earthing system, to prevent hand-to-hand contact.

A bonded fence arrangement (Section 9.2.1) is most appropriate where space is limited, and where touch voltages on the outside of the fence are below the touch voltage limits. It should be noted that the full EPR will appear on a bonded fence, and the design shall ensure this does not pose an unacceptable risk to members of public outside the substation. In a bonded fence arrangement, if touch voltages on the fence exceed limits the electrode system shall extend beyond the fence line to reduce touch voltages on the fence to the tolerable limits. Where this is not practical specialist advice shall be sought.

Note: Barriers or a hybrid bonded/un-bonded fence system can be used in some circumstances, but their use is beyond the scope of this document.

All main items of plant (transformers, switchgear, tap changers, coolers, etc.) shall be bonded to the earth grid with two or more separate connections to provide redundancy in the event of failure or theft.

A standard design will have rod electrodes in addition to buried tape. The rods provide contact with lower soil layers, which may have a lower resistivity than the surface layers. A minimum rod length of 3.6m shall be driven where required; the exact location and numbers of rods may vary depending on modelling results and the soil resistivity layering. Having established a basic layout, establish whether any additional electrode is required (e.g. external rod nests or deep driven rods), to further lower the earth resistance and EPR.

9.2.1 Substation with Bonded Fence

It is imperative that any bonded fence has an electrode ring or similar outside the fence line, to control touch voltages. The standard arrangement shown in Figure 9-1 extends the mesh beyond the fence line to achieve this. This shall not be omitted unless the EPR is below the permissible BS EN 50522 touch voltage limits, and then only if documented with good reasons. Rare events (e.g. cable sheath breakage) can result in EPRs being higher than calculated and the standard designs give some protection against this. Absence of a grading ring may thus expose members of public to danger, and the advice of an earthing specialist should be sought if the ring cannot be installed.

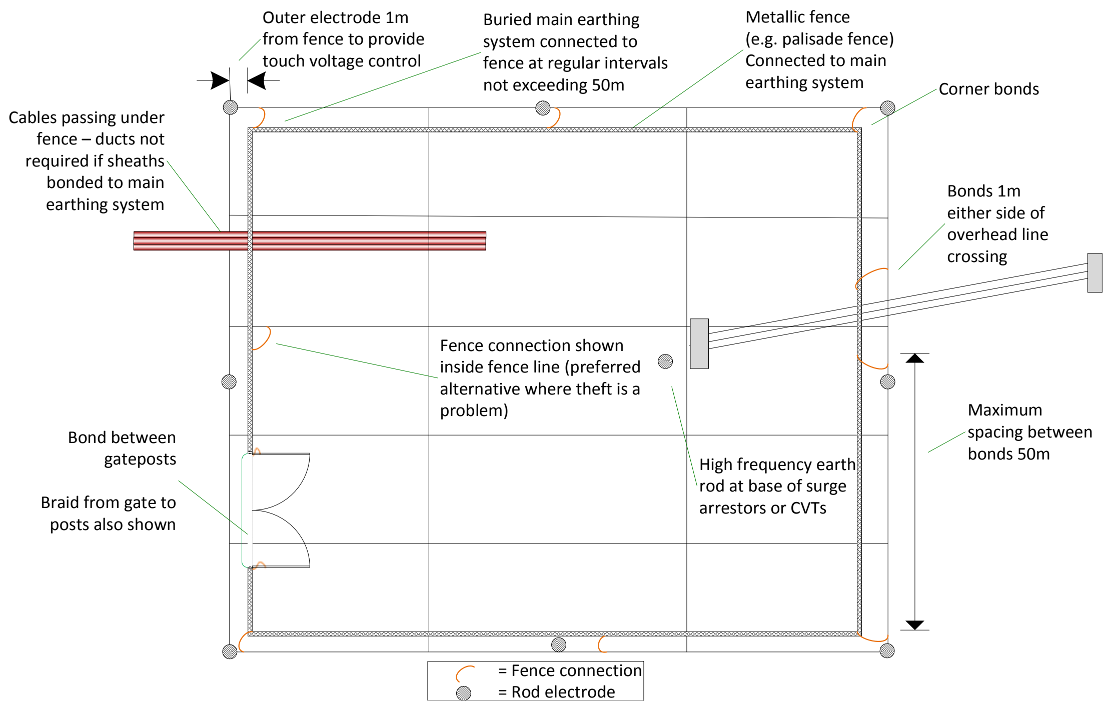


Figure 9-1 – Earthing Layout for Bonded Fence

Ideally all metallic services (such as water pipes) should have standard insulated arrangements, to avoid possible transfer voltages, i.e. voltage rise on the pipe beyond the substation. Metallic services should preferably be replaced with plastic type from 2m beyond the substation perimeter fence. If there is some uncertainty as to whether the site is HOT or not, it is sensible to introduce some of the less costly precautions at the construction stage. For example, insist on a plastic piped water supply and arrange for isolation units on any telecoms circuits (refer to Appendix C for further measures).

On the scale plan of the site, showing the plant arrangement, plot an earth grid to the following specification:

1. An outer (perimeter) loop of standard copper electrode should be installed, 0.5m to 1.0m from the fence line, at a depth of 0.6 to 1.0m. These dimensions may be altered as necessary following a design study/computer modelling, but are a good starting point. The electrode should be copper tape, sized according to Table E-1 or larger if corrosion issues exist.

2. Convert the outer loop to a mesh by positioning standard conductor across the site, in two directions (at 90° to one-other), each conductor being parallel to one of the outer conductors, where practicable. The cross-members should form rectangles, should be spaced a nominal 10m maximum apart on the outer edges of the grid or 12m maximum apart in the central areas and installed to a depth of 600mm. They will be joined to the outer ring and at each crossing point. The conductor routes should be selected to coincide with planned excavations (such as adjacent to transformer bund walls) and run close to equipment/structures that require connection.

3. An inner ring electrode, at the same depth as other electrodes, and bonded to them at crossing points, may be introduced inside the fence line, and can serve as a convenient connection point for plant and ancillary items.

4. At, or close to each corner of the substation, install one 3.6m x 16mm copper clad earth rod. Longer rods may be necessary in some soils or to reduce the grid resistance. The rods may be brought in-board of the fence line if required but ideally should be spaced away from the substation where possible. The rod-tops shall be at least 0.6m from the surface and should be accessible for inspection/testing with a loop to accommodate a clamp-meter. Alternatively, the copper tape to each rod shall be accessible (via inspection pit or similar). Bolted links are not required and offer no value. For further details refer to ECS 06-0022.

5. Additional rods should be installed around the perimeter of the site (in the same way as point 4 above) at intervals not exceeding 10m. Each rod shall be connected to the main earthing ring by an accessible copper tape (i.e. teed rather than looped into the main ring). Where longer rods are used greater spacing between them will be more effective, as a minimum the spacing should not be less than the rod length.

6. The fence shall be connected to the main earthing system at corners, and intervals not exceeding 5m. There shall be additional bonds between gate-posts, and between gate posts and the gate (using flexible braids), to ensure there can be no voltage difference across an individual's hands when opening the gate. If the fence is a powder coated type, or otherwise covered/painted so that continuity between panels is doubtful, each panel shall be connected to the perimeter ring, or a dedicated bond installed between panels to ensure continuity. Such fences shall not be treated as insulating unless specifically designed for the purpose, with a demonstrated withstand voltage and covering that will maintain its integrity throughout the lifetime of the installation. Insulated panels can be used in certain situations and are not described in this document.

7. Transformers, tap changers, coolers, switchgear, fault throwers and critical items (such as neutral connections) in particular, shall have a resilient connection to the main earthing system. This is best achieved by duplicate fully rated connections to the main earthing grid (e.g. to different sides of transformer tank, etc.). The mesh/grid arrangement provides some resilience should there be breakage, theft or loss of buried electrode, as it provides parallel paths for fault current. Care shall be taken when planning the grid layout to ensure that critical components are provided with direct and duplicated routes through to the perimeter loop electrode.

8. Additional electrode loops may be required around plant items, particularly at high EPR sites, as these will reduce the touch voltage. This requirement is subject to design calculations and modelling. Switch mats under operator positions (e.g. open compound earthing switches, isolators, etc.) should be surface laid and bonded to the main earthing system and/or switch handle via dedicated bonds which can be inspected by the operator prior to switching.

A well designed system theoretically renders these switching mats unnecessary since touch voltage is controlled by the earthing system, but the presence of additional bonds between handles and feet which can be visually inspected prior to switching should provide some reassurance to the operator, particularly if there has been any earthing theft/depleted earthing on site.

9. Provision may be necessary in the design of the grid layout to provide connection points for temporary neutral earth resistors or arc-suppression coils (ASC) to replace the normal unit during maintenance, particularly if the unit is shared between two or more transformers.

10. ‘D’ loops should be specified at appropriate points above ground to facilitate connection of temporary (flying) earth leads.

11. At least two copper tapes shall connect the switch room earthing system to the main earth grid. Indoor areas will often benefit from a marshalling bar or wall mounted tape which serves as a distributed busbar for the connection of plant and other items. Internal tapes may be aluminium, provided suitable transition joints are used and protected from water ingress.

12. Rebar in switch room areas shall have duplicate bonds to the substation earth and serves an important function in controlling touch voltage. Rebar should be welded mesh (along at least one side) to provide a resilient connection over the whole floor area. If this is not possible, a shallow screed with embedded mesh should be installed, as described in ECS 06-0022.

13. Use shall be made of sheet piles and reinforcing bars in concrete piles wherever practicable. This will improve the resistance value and reduce installation costs. If vertical piles are to be plastic lined, then some copper tape should be installed on the outer edge of the piles to provide a low cost vertical electrode. These auxiliary electrodes shall be connected to the main earthing system at convenient points, and suitably arranged to accommodate a clamp meter for testing. Refer to ECS 06-0022

14. Switch room rebar for new GIS equipment requires special attention and this will be addressed by the manufacturer or installer. Where the vertical piles have more than 5m of metal reinforcement in them, 20% of them are to be bonded direct to the earthing system. These will be selected at corner locations, on the outer edges of the structure or at locations that will assist with high frequency impulse attenuation. Refer to Appendix A for further details on GIS switchgear earthing.

15. Surge arrestors and CVTs require a dedicated earth electrode to convey high frequency currents. This is normally achieved by a 5m vertical rod installed directly beneath the surge arrestor. The connection from the arrestor/CVT to the electrode shall be as straight as possible, with only shallow bends free from sharp changes in direction. Downleads shall be insulated from, and held clear of the main earthing system (by stand-off insulators or similar). There should be one connection between the downlead and the main earthing system (or structure) just above ground level, this is to carry power frequency fault current. The lower bond to the rod top shall be accessible for testing with a clamp meter.

9.2.2 Substation with Separately Earthed Fence

This separately earthed fence arrangement design is similar to the standard (bonded fence) design above, with the following exceptions:

1. The main earthing grid shall be arranged as shown in Figure 9-2, i.e. with the outer loop 2m inside the fence line. The substation earth electrode system shall not be closer to the fence than 2m, and care is required where doors/gates swing into the substation area.

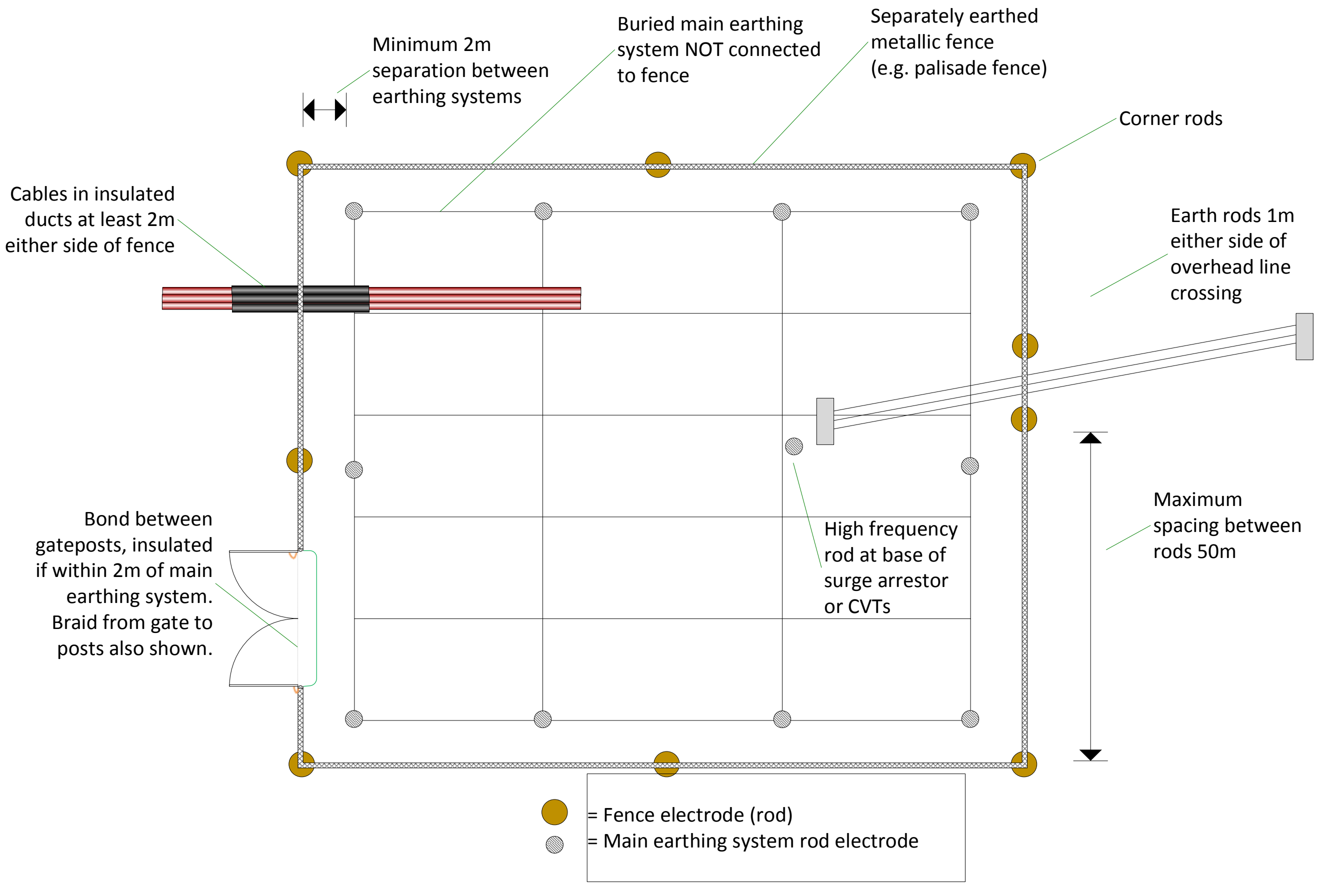


Figure 9-2 – Earthing Layout with Separately Earthed Fence

2. The fence shall have its own electrode system, which shall remain clear of the substation main earthing system.

3. The fence shall have corner electrodes, and electrodes along the sides at intervals not exceeding 50m. The electrodes shall be 3.6m deep rods. Additional electrodes shall be installed 1m either side of all overhead line crossings to protect against fallen conductors.

4. If fence panels are coated/painted or not otherwise electrically continuous, a perimeter electrode should be installed to provide a connection to each panel and to the rods. This should be below ground to prevent theft. Bare copper is preferred to insulated conductor due to the beneficial effect as an electrode. This electrode should be kept close to the fence and away from the substation main earthing system. Alternatively, continuity bonds could be installed between covered metal panels. Any electrode buried at less than 0.6m depth should be excluded from earthing calculations (shallow soil can dry out and give poor connection to earth); deeper horizontal electrode may be considered and could be a substitute for intermediate rod electrodes.

5. The fence shall remain 2m clear of the substation main earthing system and anything connected to it. All cable crossings shall be ducted for 2m either side of the fence. Similarly, earth connections to towers or external structures shall be ducted where they pass under the fence line.

6. Care is required where security lights, card readers, intercoms, etc. are connected to the main earthing system (or take supply from the substation, or are otherwise wired to the substation/switch room/relay room). They can be particularly problematic if installed on or near the fence. They shall either be insulated to withstand the full EPR or adequate separation provided.

   Note: There have been occasions where these installations have flashed over to the fence, combining the two earthing systems under fault conditions.

9.2.3 Indoor (brick-built) Substations and Switch rooms

Indoor substations should, where possible, follow similar design principles to the arrangements described above. Construction considerations are described in detail in ECS 06-0022.

The indoor substation should include the following features:

1. A copper grid should be installed underneath the footprint of the substation, with perimeter ring outside the building line, and rod electrodes.

2. A wall mounted copper (or aluminium) ring shall be installed around the perimeter of switch rooms/transformer rooms to serve as a marshalling bar.

3. This internal ring shall be connected to the copper grid by two or more dedicated and fully rated copper tapes.

4. The floor rebar should be connected to the earthing ring by duplicate connections, and shall be continuously welded mesh, or at least welded along one side to provide a resilient connection to each part of the rebar. The rebar provides tight control of touch voltages and shall be bonded in all switch room and plant areas.

5. If rebar is not accessible, a surface screed should be laid which incorporates a grading mesh, and this bonded to the perimeter ring.

6. If such measures are not possible, the design may be acceptable if the EPR is low. Surface laid operator platforms may also provide a solution; the advice of an earthing specialist should be sought.

7. If the substation is HOT or has a high EPR, care is needed with metallic doors, since these could pose a hazard outside the substation. Where necessary the outer perimeter ring shall be extended around the doors to provide additional protection when the doors are open, or to modify surface coverings (e.g. asphalt) in these areas.

8. Piles/auxiliary electrodes should be connected to the main earthing system via dedicated, accessible and suitably labelled bonds. These should facilitate the use of a clamp meter for testing, using inspection pits where necessary.

9.3 Calculation of the Earth Grid Resistance or Overall Earth Impedance (taking into account parallel paths)

When an earth-fault occurs, the current that returns to the source(s) through the ground will pass through the earth grid together with any connected parallel paths. The contribution from these paths is described in this section.

Before calculating the EPR it is necessary to estimate how much of the fault current flows to earth and how much returns via metallic routes (such as cable sheaths), to avoid over-estimating the EPR. The calculation of ground return current is covered in Section 8.6.

In an urban located substation, the impedance of the parallel paths will often be an order of magnitude lower than the resistance of the substation earth grid, and it is vital that their contribution is accounted for. This will prevent unnecessarily declaring a high EPR or over-designing the grid earth. To be considered, the parallel paths shall be reliable and capable of carrying their proportion of anticipated maximum fault current, without duress, for the duration of any fault up to the worst case (backup) clearance time. A measurement of network contribution can assist if undertaken at an early stage (Section 9.3.4).

9.3.1 Earth Grid Resistance

The earth grid resistance can be obtained by calculation, by computer modelling, or (where there is significant horizontal electrode) by graphical or interpolation methods. In all practical Primary and Grid designs it will be necessary to use computer modelling, although formulae can provide an approximate ‘order of magnitude’ calculation. Relevant equations and figures are presented in ENA EREC S34.

Table 9-1 gives approximate values for a grid in uniform soil, at 0.6m depth, with 2.4m electrodes and one cross.

Table 9-1 – Resistance of Earthing Grids in Different Soils

Soil Rresistivity	15m x 15m	20 x 20m	25 x 25m	30m x 30m
50 Ω·m	1.46 Ω	1.16 Ω	0.965 Ω	0.83 Ω
100 Ω·m	2.92 Ω	2.32 Ω	1.928 Ω	1.65 Ω
150 Ω·m	4.38 Ω	3.48 Ω	2.891 Ω	2.48 Ω
Note: The numbers scale (approximately) linearly with soil resistivity, i.e. the 100 Ω·m value is 2x that at 50 Ω·m, etc.				

9.3.2 Bonded Foundation Structure Steel Reinforcement Bars

If these have been bonded to the earth grid, initially their effect can be ignored unless they increase the horizontal area encompassed by the earth grid or enter low resistivity soil underneath (such as long steel reinforced piles). If the total area is increased, the new total area should be used to recalculate the grid resistance. If steel structures are included in the earth resistance calculations then they shall be of sufficient cross-section to meet the required current rating.

9.3.3 Steel Tower Lines

Each tower has a natural resistance to earth of typically 5Ω to 20Ω, due to the concrete-clad steel legs installed in the soil. The terminal tower at any substation shall be securely connected to the substation earth grid by two dedicated conductors. The total combined resistance to earth of each tower, connected in series/parallel via the overhead earth conductor, is called the chain impedance. The calculated chain impedance relies on the aerial earth conductor being bonded to the tower steelwork at each tower position and the actual value will be significantly higher if this has not been carried out.

The tower line chain impedance has a known reactive (inductive) component due to the overhead earth conductor. On a new circuit, the individual tower footing resistance can be measured (before the earthwire is connected) and this is the preferred method. Alternatively, the resistance can be calculated using the foundation depth, radius, spacing and soil resistivity. Computer modelling is the most accurate calculation method, for which specialist advice may be required. Once the tower footing resistance is known, the chain impedance can be calculated.

ENA EREC S34 provides a simplified graph based on an assumed footing resistance. The graph assumes that there are at least 20 towers in a line, in similar soil conditions.

In the absence of detailed information, a conservative estimate for a 132kV tower line with a minimum of 20 towers would be a chain impedance of 2 ohms at 34 degrees (lag), shown 2Ω $\angle 34°$. This assumes the tower line is not on rocky ground.

If a tower line is shorter than 20 towers, or installed in rocky ground, then individual calculation and/or measurement is necessary and specialist advice may be necessary.

The tower at a line cable interface should be fitted with potential grading and cable surge arresters. These are connected to dedicated ‘high frequency’ earth rods (or radials) directly via copper tape or stranded conductor kept as straight as possible and are also indirectly connected to earth via the tower.

The rationale behind this is that good earthing is necessary at the termination tower for insulation coordination and to prevent voltage doubling. This does not significantly affect the substation earth resistance.

The difference the presence of the tower and earth wires make, is that a relatively low earth impedance will already exist. The high frequency impedance of a tower is much higher than at power frequency such that the impedance of the tower can have a second order effect. A copper connection from the surge arresters is necessary with a few rods at the base. These should achieve 10Ω where possible, or at least driven to a depth of 4.8m. The resistance should be measured during commissioning as it will provide a baseline for comparison of future measurements. Further details for high frequency earthing of surge arresters and capacitor voltage transformers (CVT) can be found in Section 10.3.

9.3.4 Cable Networks

Where these exist, they are likely to be the most important factor governing the earth impedance and the need, or otherwise, to extend the earthing system.

Lead (PILC, PILCSWA, PILCSTA) cable types act as earth electrodes, even if hessian covered, and each cable will serve to reduce the overall earth resistance of the substation(s) to which it connects. Modern polymeric cables provide a lesser contribution, but their substantial sheath cross section provides a valuable connection to remote substations, HV electrodes, LV electrode (where combined to the HV earth) and distributed metalwork in the wider area.

The contribution from both types can be calculated using formulae in ENA EREC S34, although due to uncertainty, these formulae will often underestimate the true contribution from a wider network, particularly a dense network that behaves like a global earthing system. The contribution from such networks is best measured, where possible, or modelled using computer software. Depending on the local soil resistivity and network topology, the relevant network that needs to be considered in any model may vary from 500m to several kilometres, and accurate calculation is not straightforward. EDS 06-0012 provides an indicative figure for network contribution which is valid for preliminary design purposes. Dense urban networks in areas of low soil resistivity can offer significantly less than 0.1Ω in parallel with the substation earth grid.

Where new polymeric cables are used, it may be beneficial to install radial horizontal earth electrodes at the bottom of the cable trench and connect them to the main earth bar in the substation switch room. These can provide an important parallel contribution to the substation earth impedance at relatively low cost where planned cable trenches are utilised. The calculations described above for lead sheathed cables can also be applied for radial electrodes. Where more than one radial electrode is installed their effectiveness will be increased with greater separation between them, e.g. two radials installed at 180° or 90° to each other will be much more effective than installing them along the same route. Calculations should be undertaken to balance any reduction in earth impedance (and EPR) against the extension of ground potentials.

10 Installation Requirements

10.1 Metalwork Bonding

10.1.1 Ancillary Metalwork

All exposed and normally un-energised metalwork inside the substation perimeter, including doors, staircases, ventilation ducts, cable supports etc., shall be bonded to the main earth grid to avoid any potential differences between different items of metalwork.

The appropriate bonding conductor shall be selected from Table E-1.

10.1.2 Metal Trench Covers

Metal trench covers within substation buildings which are not sitting on an earthed metal frame shall be indirectly earthed as follows:

- Install a copper tape strip (25mm x 3mm) along one edge of the trench top edge so that trench covers are in contact with it when in position.
- Connect the copper tape to the switchgear earth bar or internal building earthing system.

10.1.3 Cable Tunnel Metalwork

Metal trays and supports are used within cable tunnels to support power, pilot and communication cables. Where the power cables are of the single core type, there is a risk that during normal or fault conditions voltages or currents may be induced into the metalwork causing damage, cable de-rating or a risk of shock.

To prevent excessive induced or transfer voltages on the tunnel metalwork:

- Cable supports and trays in tunnels shall not be connected to the substation earthing system.
- Cable trays in tunnels shall be broken into sections with a 50mm gap approximately every 50m.
- Cable supports and trays in tunnels shall be separated from any metalwork connected to the substation earthing system by 2m.

Note: The bonding requirements in tunnels differ from those for substations, as it is important to avoid induced currents/voltages and not to inadvertently link substations via tunnel metalwork. In general, metalwork in tunnels shall be separated by 2m from any metalwork connected to the substation earthing system. Any metalwork in the intermediate 2m section shall be unearthed, i.e. a floating section in a manner similar to a floating section of fence, such that hand-to-hand contact between this section and neighbouring steelwork is possible, but hand-to-hand contact between substation and tunnel earthing systems is not possible. A significant voltage rise on the short floating section is considered low risk when supporting earthed cables. This section should be located inside the tunnel bores (i.e. where it is less likely to be touched) to further minimise risk to individuals.

Refer to Section 10.4 for cable earthing.

10.1.4 Basement Cable Support Systems

Cable support structures and cable trays in basements shall be bonded to the substation earthing system using a suitable bonding conductor from Table E-1. Any departure from this shall be justified in the form of supporting calculations or a detailed quantified risk assessment carried out by an earthing specialist.

10.1.5 Adjacent Metal Structures

Where there are earthed metal structures within 2m of the fence (such as a terminal tower), then the preferred fence earthing arrangement may not be achievable. It may be necessary to bond the fence run adjacent to the structure, install a perimeter grading electrode outside, and fit insulated fence panels to separate this part of the fence from the rest. Whether this option is followed or the whole fencing arrangement bonded depends upon the site layout and dimensions, however this shall be considered at the design stage. Fence earthing is described in Appendix D.

10.1.6 Metal Anti-climbing Guards

Where anti-climbing razor wire or similar is fitted to the top of palisade fencing, it shall be bonded to the metallic fence upon which it is situated. Where there is a change in the fence earthing method, there shall be electrical breaks in the anti-climbing wire (e.g. 100mm gaps at either side) co-incident with those of the fencing, or the anti-climbing wire shall be in a situation where it is not realistically possible for someone to touch it and the panel below (the wire shall be supported on insulated mountings as it passes over this section).

Where wire or guard is fitted along a short insulating section of brick wall, this may be left isolated (as for a steel panel on insulators) provided that a 100mm gap is maintained at both ends of the wall. In other situations, wire or guard fitted on a brick type wall shall be earthed either to the adjacent fence or to the earth grid, whichever is the most appropriate and does not introduce a touch voltage risk.

10.1.7 Temporary, Site-Perimeter and Adjacent Landowners' Fencing

Temporary fences inside the substation installed for construction and other purposes are to be earthed in the same manner as permanent fences, i.e. bonded to the main grid within the site, with insulated panels used if necessary to abut them to the external fence when this is separately earthed.

Where galvanised or plastic coated mesh fencing is used, a separate 70mm^2 earth conductor shall be installed along the fence (or buried). This should be connected to the fence at 10m intervals, and to independent earth rods or the earth grid (as appropriate) at a minimum of 50m intervals.

Site outer perimeter fencing, and any other metal fencing belonging to adjacent landowners, presents a transfer voltage hazard if connected to the substation fence. Such fences shall be kept electrically isolated from the substation palisade fencing by means of 2m gaps, insulating spur panels, or brick wall sections as appropriate.

10.1.8 Positioning of Metal Supports for Security Lighting etc. Near Fences

Metal supports for security lighting or cameras require special attention to protect against touch voltages. Ideally these items should be situated within the confines of the earth grid and their electricity supply referenced to the substation earth. This generally means positioning the column about 1m inside the perimeter electrode of the earth grid, or at least 3m from a separately earthed fence. Where this distance cannot be achieved, then a non-metallic support column should be used.

Any metal support within 2m of the fence shall be bonded to it. This may require a different fence earthing arrangement or a modification to the support supply arrangement. In the latter case, the LV cable earth shall be terminated in an insulated connector and only the neutral and phase (or switch) conductor taken up the column. The column and other exposed metalwork are then earthed via the fence and its independent electrodes.

Where the fence is bonded and the earth grid extends outside the substation perimeter fence there is no restriction on the location of the masts in relation to the fence.

Any metal support shall be bonded to the grid, and the low voltage supply shall be derived from the substation supply. Barrier equipment is required in cables or wiring to remote locations to prevent any potential on the substation earthing system being transferred there, if the substation is HOT. Refer to Appendix D for further information on fence earthing.

10.2 Portable Earth Connections

Portable earth connections, e.g. earth loops or spigots, shall be provided on equipment at appropriate locations where portable earth leads need to be applied. Particular, consideration should be given to portable earth connections associated with open terminal busbars, sealing ends etc. if the busbars need to be removed with the portable earths applied.

Refer to ECS 06-0022 for further information.

10.3 Surge Arresters and Capacitor Voltage Transformers

Surge arresters and CVTs can, during lightning/switching events, convey currents containing high frequency components to earth. The inductance of any connections to earth presents a high impedance at these frequencies which can reduce the efficiency of the surge arrester / CVT and lead to problems such as flashovers as current finds alternative paths to earth. To counteract the adverse effects, special earthing arrangements are necessary.

Two connections are required. The first is a standard bond from the support metalwork to the main earth grid. The second is a high frequency earth connection, which should be as straight as possible and connect to an earth rod which is as close as possible to the equipment being protected. A cross connection is made from the down lead or earth rod to the adjacent grid. It is preferable to have a downlead and earth rod for each phase; alternatively a good compromise for twin legged structures is to have two down leads and earth rods connected at the base of each leg. Three phase devices are then bonded together on the top of the pole or structure, minimising bends / right angles as much as possible. Earth rods are normally deep driven single rods to 3.6 metres or more. If this is not possible, additional options are presented in ECS 06-0022.

10.4 Cables

10.4.1 Power Cables

The sheath and armour of all power cables should be earthed at both ends and this arrangement is generally satisfactory for three-core and Triplex type cables. However, bonding the sheath/armour at both ends of single-core cables or very heavily loaded circuits can cause a de-rating effect as large circulating currents may flow in them. There are two alternative methods of installation for single-core cables where the length is sufficient to cause this problem.

- Single-point bonding – where the sheaths are connected to earth at a single point. A parallel earth continuity conductor is generally laid with the cables to provide continuity between items of plant.
- Cross-bonding – where the sheaths are connected to earth at each end, and periodically transposed to cancel circulating currents flowing in the sheaths.

The earthing design for power cables is outside of the scope of this standard. Further guidance can be found in ENA EREC C55.

Specific earthing connection detail is given in ECS 06-0022.

10.4.2 Protection and Control Cables

Provided there is continuous earth bonding between plant and equipment located within the same substation site, protection and control cables shall be earthed at both ends. The only exception is at the RTU which shall only be earthed at one end as specified in the applicable equipment document. Where protection and control cables are run out to remote sites or third party sites then single end earthing shall be adopted. Any necessary precautions against transferred voltage shall also be observed.

10.4.3 Cable Bridges

Refer to ENA EREC C98 for guidance on the earthing and bonding of cable bridges.

10.4.4 Customer Cables

All LV and multicore cables that originate from the customer installation **shall not** be connected to the UK Power Networks substation earthing system (i.e. they shall only be earthed in the customer switch room).

All cable screens, armours etc. shall be insulated and protected in the UK Power Networks substation to prevent shock hazard.

10.5 LVAC Supplies

LVAC supplies shall be provided in accordance with EDS 08-1112.

Where a secondary 11kV (or 6.6kV) substation is installed to provide auxiliary LV site supplies it shall have an earthing system designed in accordance with EDS 06-0014 and be connected to the grid or primary substation earthing system using duplicate connections.

Where the EPR of the overall site is greater than 430V (assuming a 1s clearance time, or other limits for different clearance times) the segregation of HV and LV earthing systems is not usually required provided the secondary substation:

- Is within the 430V surface voltage contour (or applicable limit for clearance times other than 1s).
- Is only supplying the site (and not capable of providing a supply outside the site boundary e.g. back-feeds, etc).
- Has no metallic connection (cable screen or otherwise) outside the site boundary.

Note: If the site has an EPR in excess of 430V (assuming a 1s clearance time or faster) from other HV or EHV supplies, care shall be taken to ensure that dangerous or damaging EPRs are not exported to the 11kV (or 6.6kV/20kV) networks. Refer to EDS 08-2108 for further information.

10.6 Construction and Commissioning

Refer to ECS 06-0022 for construction and commissioning requirements.

11 Design Assessment

11.1 Overview

Where the substation earthing is designed by a third-party (e.g. customer or ICP) they shall provide an earthing design report and earthing arrangement drawing as detailed in Sections 11.2 and 11.3 to enable UK Power Networks to assess the earthing design.

The submitted design should include sufficient information to enable UK Power Networks to understand and assess the design without having to repeat the design process or calculations. If software plots are included they should be clearly explained and any key values summarised in a table.

Earthing designs that do not include sufficient information or that do not meet the minimum requirements specified in this standard may be unsafe and shall not be granted design approval. Connection will be refused, as outlined in Paragraph 26 of the Electricity Safety Quality and Continuity Regulations (ESQC Regulations) 2002, if UK Power Networks deem a substation to be unsafe.

11.2 Earthing Drawing

An earthing arrangement drawing shall include as a minimum:

- Substation layout with earthing arrangement.
- Main earth electrode(s) and depth, earth rods, rebar/reinforcement connections etc.
- Additional earth electrode required to obtain the earth resistance value.
- All bonding to equipment, metalwork etc.
- Type and sizes of earth electrode, earth rods, bonding conductors etc.
- Warning labels.
- Site boundary and the position of any metallic fencing, street furniture or other metallic buildings or structures.

11.3 Earthing Report

The earthing design report shall include as a minimum:

- Standards the design is based on (e.g. National, ENA, UK Power Networks).
- Base data and source.
- Earth resistance.
- Ground return current.
- Earth potential rise (EPR) calculations.
- Touch and step voltage calculations and supporting voltage contour plots.
- Transfer voltage calculations (if applicable).
- ITU limit calculations and plot of HOT zone (if applicable).
- Details of any additional precautions that are required.

12 References

12.1 UK Power Networks Standards

ECS 06-0022	Grid and Primary Substation Earthing Construction
ECS 06-0024	Earthing Testing and Measurements
EDS 06-0012	Earthing Design Criteria, Data and Calculations
EDS 06-0014	Secondary Substation Earthing Design
EDS 06-0017	Customer LV Installation Earthing Design
EDS 08-2108	Supplies to HOT Sites and National Grid Sites
EDS 08-2109	LV supplies to Mobile Phone Base Stations Mounted on 132, 275 and 400kV Towers (internal document only)
EDS 06-0002	HOT Site Requirements (internal document only)

12.2 National and International Standards[2]

ENA TS 41-24	Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations
ENA EREC 41-15	Standard Circuit Diagrams for Equipment in 132kV Substations. Part 9 – AC traction supplies to British Rail
ENA EREC C55	Insulated Sheath Power Cable Systems
ENA EREC C46	Measures Necessary to Minimise Corrosion Damage to Buried Metallic Structures by Neighbouring Cathodic Protection Installations
ENA EREC C98	MV Cables Crossing Bridges – Physical Protection and Current Ratings
ENA EREC G78	Recommendations for Low Voltage Supplies to Mobile Phone Base Stations with Antennae on High Voltage Structures
ENA EREC G99	Requirements for the Connection of Generation Equipment in Parallel with Public Distribution Networks on or after 27 April 2019
ENA EREC P24	AC Traction Supplies to Railway Systems
ENA EREC S34	A Guide for Assessing the Rise of Earth Potential at Substation Sites
ENA EREC S36	Procedure to Identify and Record HOT Substations
ENA EREC S41	Guidance on Transferred Voltages from Earthing Systems
BS 7430:2012	Code of Practice for Protective Earthing of Electrical Installations
BS EN 62305	Protection Against Lightning
BS EN 62305	Protection against Lightning
BS EN 50122-1	Railway Applications-Fixed Installations. Part 1. Protective Provisions Relating to Electrical Safety and earthing
BS EN 50162:2004	Protection against Corrosion by Stray Current from Direct Current Systems

[2] ENA documents available from http://www.dcode.org.uk/annexes.html or www.energynetworks.org.

13 Dependent Documents

The documents below are dependent on the content of this document and may be affected by any changes.

EDS 06-0001	Earthing Standard
EDS 06-0002	Hot Site Management
EDS 06-0012	Earthing Design Criteria, Data and Calculations
EDS 06-0014	Secondary Substation Earthing Design
EDS 06-0017	Customer LV Installation Earthing Design
ECS 06-0022	Grid and Primary Earthing Construction
EDS 07-4030	Grid and Primary Substation Fencing Arrangements
EDS 07-4050	Grid and Primary Switch House Buildings
EDS 07-4055	Customer Buildings for 6.6kV to 33kV Indoor Equipment
EDS 07-4070	Grid and Primary Transformer Bunds and Enclosures
EDS 08-1100	Appendices to ENA EREC G81
EDS 08-1112	Substation LVAC Supplies
EDS 08-4000	EHV Network Design
EDS 08-4101	London 33kV Distribution Network Design and Customer Supplies
EMS 10-0602	Grid and Primary Substation Earthing Assessment Process

Appendix A – Special Situations

A.1 400/275/132kV Substations

In general, earthing conductor should be sized according to the most onerous fault level / duration combination on each site. At large sites however, there can be design economies by using a smaller conductor size in areas where lower fault currents may flow. If this method is to be adopted, calculations/study should be carried out to enable the high fault current routes to be identified. Conductors there will need to be fully rated, but elsewhere the conductor can be sized to account for through current and also for faults that occur there at different voltage levels.

A.2 GIS Substations

Earthing of gas insulated switchgear (GIS) and associated plant and equipment is complex and the manufacturer should be consulted at an early stage. Typically the issues to be considered are:

- High fault current.
- Residual AC current. GIS equipment uses earthed metal ducts around the phase conductors to contain the insulating gas. If single-phase, or when unbalanced currents flow in three-phase equipment, then current is induced in these ducts and a residual AC current is likely to flow continuously via the earthing system. There is presently concern that these AC currents may cause accelerated corrosion, particularly in steel electrodes.
- High frequency currents. The nature of the equipment means that fast switching transients can occur whilst electrical current is being interrupted. These transients include components at very high frequencies which can couple to earth. Some flow within the confines of the local earth grid, whilst others flow into the ground. The electrode system to deal with high frequency current flow into the ground is different to that for 50Hz operation. The most often quoted solution is to increase the density of the earth electrodes in the immediate vicinity, e.g. by using finer meshed grids and vertical rods. This needs to be accompanied by specific screen terminating arrangements and secondary control wiring needs to be routed to minimise inductive interference. The design seeks to ensure that high frequencies are confined to the inside of screened enclosures, but the presence of interfaces (such as at air terminations, insulated CT flanges and transformer bushings) allow some opportunity for these to escape to earth.

It is also important to ensure that the earthing design does not permit circulating currents to flow between plant and connections, which would cause interference. It is normal to provide a significant number of vertical earth rods close to the GIS enclosure, indeed some rods may pass through the floor into underlying soil such that an earth is provided as close as possible to the equipment. It is also common to have a copper or steel mesh electrode embedded in the concrete floor of the building and earth bars either within or buried immediately outside the building walls. All equipment is connected to this via short spur connections. Connections between plant items are run close to and parallel with earth mesh conductors. GIS equipment is generally earthed via vertical connections, which are connected to the internal mesh near the following equipment locations, to disperse externally referenced currents:

- Close to circuit-breakers, cable sealing end or the SF6/air bushing.
- Near to instrument transformers.
- At each end of the busbars, and at intermediate points (for long busbars).

The three enclosures of a single-phase type GIS shall be bonded together and to earth using bonding conductors rated to carry the nominal current of the bays or busbars. Flange joints would not normally require a bonding strap if the contact pressure is high, but these may become a source of interference at high frequency and tests may be required at the factory acceptance stage.

The plant earth connections to an internal grid which has conductors of relatively small cross sectional area should be distributed by additional connections forming a cross or star type arrangement until sufficient grid conductors are bonded to carry the required current. The connection shall not be to one or a few small conductors.

Metallic sheaths of cables (nominal voltage greater than 1kV) should be connected directly to the GIS enclosure. If the connection needs to be separated from equipment under metal enclosures, then voltage surge protection devices are recommended.

Where the soil conditions are suitable for long vertical rods, these can be positioned to cater for high frequency (lightning protection and GIS) and low frequency applications. As they are critical elements of the design, test facilities are to be provided for such rods.

A.3 Sites with Generation

A.3.1 Overview

Conceptual and practical guidance on earthing of generating plant is covered in ENA EREC G99, which should be referred to. it does not cover the design of the earthing electrode systems; ENA TS 41-24 applies to earthing associated with ‘electricity supply systems’ and may also be applied to generating stations.

The earthing design for generators in principle is no different to that of substations, although different standards apply. BS 7430 and ENA EREC G99 provide useful information, in particular to the earthing of star points (system neutrals) under various operating conditions. Some operating conditions can modify earth fault levels and generator contribution should be considered.

The sections that follow provide further guidance on substations associated with wind and solar generation.

A.3.2 Solar Farm

A solar farm typically consists of a UK Power Networks’ intake substation, metering, customer switchgear, inverters and solar panels.

The UK Power Networks substation and the associated earthing system shall be designed in accordance with the relevant part of this document to control the touch and step voltages. The UK Power Networks earthing system should be sufficient to ensure operator safety in the absence of the solar farm earthing system.

The solar farm shall have an electrode system sufficient to limit touch voltage in and around the solar farm. Generally, PV arrays and support structures shall be treated as if they are (or could become) bonded to the earthing system, even if they are separated from the AC system and its earthed components. The main reason for this is that inverters (generally) cannot be relied upon to provide isolation under fault conditions (e.g. insulation failure within an inverter could cause one or both of the DC terminals to become connected to the solar farm earth). Consequently, the metallic array structures shall be bonded to the solar farm main earth terminal and measures taken to establish an equipotential zone by bonding (or barriers) in line with normal best practice. Refer to BS 7430 and BS EN 50522 for more information.

In most situations, the UK Power Networks and solar farm earthing systems will be combined. Provision should be made for testing of each system in isolation prior to commissioning the site. A fall-of-potential measurement over 400 metres or more (depending on site size and constraints) will usually be required to obtain an accurate earth resistance measurement of each earthing system in isolation. Any cable armours (e.g. LV cables or small wiring) between the UK Power Networks and the solar farm substations should remain disconnected until such time as testing is completed. Refer to ECS 06-0024 for further information.

A.3.3 Wind Farms and Wind Turbines

A wind farm typically consists of a UK Power Networks' intake substation, metering, customer switchgear and one or more wind turbines.

The UK Power Networks' substation and the associated earthing system shall be designed in accordance with the relevant part of this document and integrated into the wind turbine earthing system as required to control the touch and step voltages.

Generally each wind turbine will have its own dedicated earthing system, designed to control touch and step voltages and dissipate lightning impulses. The former is achieved by installing potential grading electrodes, whilst the latter is achieved by obtaining a local earth resistance of 10 ohms or less, and providing a direct path to earth free of bends, kinks, and re-entrant loops. Refer to Appendix A.15 for further information on lightning protection.

The electrode system for each wind turbine in practice normally consists of two perimeter earthing rings of copper conductor. The first (inner ring) installed 0.5 to 1m away from the turbine enclosure, at a depth of 0.5 to 1m, and the second (outer ring) just beyond the edge of the concrete base and at greater depth (typically 1-3m deep). Four earth rods (length dependent on soil structure) are installed on the outer perimeter electrode to help further reduce the resistance, together with bonding of the rebar to moderate touch voltages and provide some electrode effect. If further electrode is needed to achieve 10 ohms, then two additional independent radials up 80m long, 180 degrees apart can be installed.

If the site is classified as HOT care is required to prevent dangerous potentials being exported from the site. In some situations, segregated earthing or other measures may be required. Alternatively, interconnecting wind turbines with bare electrode (laid with cables or otherwise) may offer a useful reduction in electrode resistance sufficient to make the site COLD. These design options should be explored with the aid of computer modelling software if necessary to arrive at an economic and practicable solution. Post-construction verification via measurement is also required.

A.4 High-rise Developments

Guidance on substations and the associated earthing in high-rise developments can be found in EDS 06-0013A.

A.5 Communication Towers within or Adjacent to Substations

Because of the increased lightning risk associated with communication masts and the high frequencies involved from this and the equipment itself, special earthing arrangements are necessary. These include earth rods and/or an increased density of electrode in the immediate vicinity of the structure, where it is necessary to minimise the impedance of the earthing system. At a microwave dish or large aerial, it is normal to have a number of parallel earth down leads terminating near the base of the structure, onto earth rods. This arrangement reduces the inductance of the down leads and the earth impedance seen at the mast. Electrodes that run out radially, are relatively close together and arranged symmetrically have traditionally been used in place of rods, where there is underlying rock, to offer a low earth impedance value. In accordance with BS EN 62305 the mast earth resistance should not exceed 10Ω to meet lightning protection requirements.

Where the communication facility shares the same site as a substation, then the two earthing systems should be well interconnected wherever possible. There shall be rods, radial electrodes or other means of reducing the earth impedance at the interface of the two systems. This is to minimise the transfer of high voltage, low energy disturbances from one system to another. The substation earthing system will be especially important in the event of a lightning strike to the communication tower, as it will help disperse the energy associated with this. Good interconnection (at least two standard electrodes) is necessary to restrict any potential difference across the earthing system whilst the lightning energy is being dispersed.

Attention is also required to the bonding/termination of pilot and communication cables and the earthing arrangement for the LV supply.

In dealing with a request for supplies, the following strategy is to be followed:

- If the communication tower is to be situated within the substation earth grid, wherever practicable it should be located away from areas which may be susceptible to high transient voltages (such as SCADA rooms) or locations of expensive equipment (such as power transformers). An earth rod should be installed at each leg and each leg should be reliably connected to the earth grid.
- If the communication tower is situated close (within 10m) to, but outside the substation fence, wherever practicable, the site earthing and fence arrangement should be extended to include this area, using the same earthing philosophy as within the substation. This means the same fence earthing arrangements of both the substation and the cellular facility, in particular at the interface fence sections. Where it is not possible to maintain this, it is usual to introduce insulated fence panels either side of the communication tower fencing. The tower fencing would then be of the bonded type with potential grading electrode outside.
- For both of the above arrangements, wherever possible, the LV supply to the communication tower should be taken from the substation, either from the LV supply busbar or a dedicated 11kV transformer. Caution is necessary where LV supplies are derived from a combined auxiliary/earthing transformer. High secondary voltages occur when remote earth faults occur and have resulted in damage to IT cards and communication equipment.
- If the existing LV supply does not have sufficient capacity, this should be augmented if possible.
- If the LV supply is provided from outside the site, this can only be accomplished using standard arrangements if the substation EPR is low enough to comply with the relevant touch and stress voltage limits. If not, then an isolation transformer (minimum 4kV insulation voltage) or similar facility is required and specialist advice is necessary (refer to EDS 08-2108).

- If it is necessary to extend the site area to accommodate the communication tower and the site has a high EPR, then the associated earthing should be modified if possible such that the EPR is reduced and any pre-existing transfer voltage problems can be improved, e.g. to achieve a COLD site. If this is not possible, specialist advice is necessary as the extent of the HOT zone and any increased impact on third party equipment will need to be considered.
- Sites a significant distance (typically more than 10m away) away from the substation and outside the relevant voltage contours, should be supplied on a standalone basis and not connected in any way to the substation. The LV supply should be provided from the network, not the substation.
- If the tower is of a height and/or location such as to substantially increase the risk of a lightning strike, additional earth rods are to be installed at the base of the communication tower, in particular on the sides which interface with the substation equipment. Risk assessment and lightning protection mitigation methods are covered in BS EN 62305.

A.6 Communication Equipment Fitted to Towers

Communication antennae, dishes and other equipment can often be fitted to towers in an effective manner and avoid the need for planning permission. Transmission towers will experience an extremely high EPR during fault conditions and this shall be considered when providing the base station with an electricity supply. The three main issues are:

- The high stress voltage, which could occur across the distribution transformer when an earth fault occurs on a tower, associated with 132kV and higher voltages.
- Possible high touch and step voltages around the tower and associated equipment.
- Possible extension of the HOT zone and EPR impact.
- Transfer of the very high tower EPR onto the UK Power Networks HV or LV network earthing systems.

Because of the complexity of this work, some special arrangements have been developed at national level and are set out in ENA EREC G78. Specialist advice should be sought for guidance on introducing such installations. In ground earthing designs have been successfully developed for use on 132kV towers where the earth fault current magnitudes are moderately low (i.e. below 10kA) and the soil has relatively low resistivity (below 100Ωm). In other cases, insulated base arrangements are available where the LV supply and base station equipment is located on a steel platform that is insulated from earth.

Refer to EDS 08-2109 for further details on providing supplies to mobile phone base stations on towers.

A.7 Substations Near Railways

Substations close to railway traction supply points impose additional design considerations (particularly for DC railways). Associated Cathodic protection installations can also require additional measures. Any DC systems or 3-rail DC railways within 50m of a proposed UK Power Networks substation require specialist advice.

A.8 AC Railway Supply Substations

This is a highly specialised topic, for any installations, reference shall be made to the relevant railway standards. The subsequent information is provided as an introduction to the topic.

Generally, railway substations are supplied via 132/25kV single-phase transformers. The arrangements should comply with ENA EREC P24. It should be noted that, at these locations, there are very large earth return currents. This is exacerbated by use of single-phase cables where the earthed sheath, in parallel with the soil, acts as the return route. Ideally, the transformers should be situated close to the supply point and share the same electrode system. This will enable earth return currents to flow via metallic routes, rather than through the soil. This, in turn will reduce the EPR on the electrode system which occurs when the railway system is drawing current during normal operation. The main issues are therefore negative phase sequence voltages and transferred voltages. Where the supply point is some distance away, the standing voltage on the transformer earthing system can be significant.

Lower touch and step voltages apply on railway systems, mainly due to the regular exposure of the travelling public to the structures and facilities on which an EPR may occur. The design shall therefore ensure that the BS EN 50122 limits are complied with in areas to which railway staff or the public have access. Irrespective of the fault clearance protection time, it is preferred to limit the EPR to less than 430V, to avoid damage to signalling cables, etc.

As mentioned, the main reference document is ENA EREC P24 and this will apply to the railway supply substation. There are other standards to which reference is necessary and the main ones are:

ENA EREC 41-15 (Standard Circuit Diagrams for Equipment in 132kV Substations. Part 9 – AC traction supplies to British Rail), BS EN 50122-1 (Railway Applications-Fixed Installations. Part 1. Protective provisions relating to electrical safety and earthing) and BS EN 50162 (contains guidance on limiting stray currents by correct earthing and bonding).

Also refer to EDS 06-0017 for the provision of LV supplies to railways.

A.9 Reactors and AC to DC Converters

Reactors and AC to DC converters normally have high electric and magnetic fields, especially air-cored reactors. These can, in turn, induce high currents in any nearby metal structures or earth conductors. Additional precautions are required to prevent induced circulating currents, these include:

- Ensuring that the equipment is only earthed at one point.
- Using non-metallic fencing or supports where they are in close proximity to these devices.
- Where thyristors are used, high frequency harmonic currents may be present and the earth electrode may need to be positioned close to their source to prevent significant potential differences arising.
- Any individual spur parts of the main earth grid (except the reactor earth connection) shall be at least 0.6x the reactor diameter away and any earth grid loops at least 1.2x the reactor diameter away. Care shall be taken that a metal tool of 300mm length cannot cause these distances to be infringed to create a closed loop. Interconnecting leads to other equipment should be run close to earth grid conductors.

A.10 LV Supplies to Third Party Equipment at Substations

To make optimal use of sites, there are more cases of third parties locating their equipment within or adjacent to substations.

Wherever possible, these installations should be installed within the area enclosed by the main earthing system and be provided with an electricity supply derived from within the substation, such as the house/auxiliary supply. If the equipment is located just outside the main earthing system (say within 2m to 5m), if possible the fence and earthing should be extended using the same earthing philosophy as in the main substation, i.e. the earth grid extended and the method of fence earthing continued in the new part, wherever practicable.

There may be a specific type of earth electrode design for the installation and the customer is responsible for designing and installing this part of the earthing system. This shall be bonded to the main substation earth grid, in a manner, which provides the required potential grading, or physical separation against adverse touch voltages.

If the site has a high EPR, then the electrode and fencing arrangement of the extended area should be designed to minimise any detrimental effect on the EPR impact. Particular care is required not to extend transfer voltages into areas where third party mitigation will become an issue.

A.11 Pipeline Interference – Safety and Damage Prevention

Substations, and the associated power cables and earthing system, should ideally be segregated from pipelines by a minimum of 50m in accordance with BS 50443:2011.

If the proposed substation is within 50m of a buried pipeline, the pipeline operator shall be informed and an earthing specialist employed to carry out a detailed earthing study to:

- Calculate the voltage rise on the pipeline closest to the substation.
- Plot the voltage contours around the substation to determine the worst case voltage difference.
- Calculate the current density around the substation and the resultant current ‘collected’ by the pipeline.

These findings should be presented to the pipeline operator to allow them to decide if the voltage rise and collected current require any mitigation on their part.

A.12 Cathodic Protection

The term ‘cathodic protection’ includes different schemes generally employed to prevent corrosion of buried metallic objects. It is most commonly used on buried pipelines and large structures such as bridges. Some cathodic protection schemes use impressed dc current flow which can result in unintended stray current through nearby metallic objects. This process may adversely affect nearby parts of the electricity network such as underground power cables sheaths (bare) or buried earthing systems where accelerated corrosion may occur.

If any parts of the electrical network are planned in the vicinity of a pipeline that has cathodic protection adverse corrosion due to dc stray current should be considered. In this context the vicinity of a pipeline would include the pipeline easement and possibly beyond in the case of an anode bed. In these circumstances, or if there is any doubt, the pipeline operator should be consulted for guidance.

In the event that detailed consideration or testing is required, ENA EREC C46 should be consulted. This provides an agreed procedure for the management of the interactions between the different parties.

A.13 Electrode Routing (e.g. Farms, Caravan Parks etc.)

When routing electrode off site, either to reduce the overall earth resistance or to provide a connection to external equipment such as terminal poles, routes that may be frequented by people with bare feet or animals shall be avoided. These include routes near caravan sites, play areas, nudist colonies, animal drinking troughs and across access gates to stables or milking parlours.

Where electrode crosses land that is to be ploughed, if it cannot be located near to hedgerows, it shall be installed a minimum of 1m deep.

A.14 Guidance for Achieving Electromagnetic Compatibility (EMC)

Typical sources of electromagnetic radiation are given in Table A-1. The guidance provided elsewhere in this document helps ensure practices that should minimise electromagnetic radiation. However, potential solutions to reduce low and high frequency interference are given in Table A-2.

Table A-1 – Sources of Electromagnetic Radiation

Low Frequency Sources	High Frequency Sources
• Short circuits or earth faults. • Fields generated by equipment. • Harmonics.	• Switching on the power system. • Lightning. • Gapped surge arrester operation. • High frequency radio transmitters. • Electrostatic discharges.

Table A-2 – Potential Solutions to Reduce Low and High Frequency Interference

Low Frequency Solutions	High Frequency Solutions
• Separating control cable routes from power cables. • Installing cables in trefoil rather than flat. • Avoiding cable runs in parallel with busbars or power cables. • Control cables to avoid single-phase transformers and inductances. • Avoid cable earth loops. • All wires of the same circuit in one cable or one route. • Auxiliary cable routes to have radial rather than ring configuration. • Use of twisted pair cables.	• Suitable instrument transformers with adequate inter-winding shielding. • Suitable shielding of secondary circuit cables. • Group circuits associated with the same function, wherever possible. • Equipment should be selected and grouped according to its working environment and filters and voltage limiting devices used where necessary.

A.15 Lightning Protection

Lightning protection is covered by BS EN 62305 (protection against lightning). BS EN 62305-3 specifies that the resistance of the lightning protection system (LPS) should not exceed 10Ω and that it is preferable to have a single integrated earthing system.

Therefore provided the LPS does not exceed 10Ω it should be connected to the UK Power Networks earthing system via a removable and clearly labelled link (to facilitate disconnection under controlled conditions should this be necessary).

The LPS will contribute to the overall earthing system but should not be relied upon, therefore the UK Power Networks earthing system shall be designed to operate safely without this contribution.

If the substation is located inside a larger building with lightning protection, the design shall consider the transfer voltage from the substation to other parts of the site via the lightning protection system.

Note:

- There will be an electric shock risk between the two earthing systems if the connection between them is broken.
- If the two earthing systems are not bonded then care is required to ensure that metalwork connected to the two earthing systems cannot be touched simultaneously.
- If the two earthing systems are not bonded, then during lightning strike conditions a flashover may occur between the lightning conductors and any pipework or conductor (including cables within the customer's installation) bonded to the earth terminal.

Appendix B – Calculation of Touch and Step Voltages

B.1 Accurate Calculation

Where the substation earthing system has been analysed using computer modelling, touch and step voltages across the site, expressed as a percentage of the EPR value, will be available. These percentages can be applied to the EPR to calculate the maximum touch and step values.

B.2 Approximate Method

ENA EREC S34 provides formulae for calculating touch and step voltages both within the grid area and around the substation fence.

Approximate values can be obtained by using the earth grid dimensions, soil resistivity and grid current in the formulae.

B.3 Options for Reducing Touch Voltage

If the touch voltage of any exposed metalwork within the grid area exceeds the acceptable limits, the solution is normally to reduce the spacing between cross-members of the grid in that area. The value chosen for the initial design guidance should ensure that there is seldom a problem of excessive touch voltage, especially if the site is covered with crushed rock/gravel.

If the touch voltage on any metallic fencing exceeds the acceptable value, there are a number of options:

1. Provide potential grading protection by laying an electrode 1m beyond and parallel to the fence, buried 0.5 to 1m deep, and connected to it. If the fence is independently earthed, this electrode shall be kept segregated by at least 2m, from the earth grid, otherwise it will be bonded to the earth grid and fence or:

2. Arrange for the affected short section of fence to be insulated and 'earth free', by insetting an insulated fence section with insulated bushes at support positions and at any point where the fence is connected to an earthed section of fence (refer to Appendix D) or:

3. Provide a non-metallic barrier at this point, such as a brick wall.

Appendix C – External EPR Impact – Transfer Voltage

C.1 General

The EPR at a substation can transfer voltages to external areas directly via conductors or indirectly via coupling between different (separated) earthing systems through the soil. The impact of these transfer voltages shall be assessed and mitigation applied where required.

There are different transfer voltage risk thresholds and limits depending on the type of infrastructure that is affected. The risk also depends largely on the EPR and the fault clearance time. Further information can be found in EDS 06-002 and in the following subsections.

C.2 Impact on LV Networks

Transfer voltages shall not cause touch or stress voltage limits to be exceeded on LV networks. Touch voltage limits are fault clearance time dependent, e.g. 233V for 1s. The stress voltage limit on LV equipment is generally 1200V unless higher values can be justified by equipment type test approvals.

An initial comparison of the EPR to the relevant touch and stress voltage limits will determine compliance. For example, based on a 1s clearance time, an EPR below 233V will comply with both limits and no further assessment is required. If the EPR exceeded 233V then further calculations are required to determine the touch voltages at the LV installations.

Where the LV network is a PME arrangement an assumption is made that touch voltages are limited to 50% of the EPR by the multiple LV earth electrodes raising the ground potential. In this case, the EPR may reach twice the touch voltage limit, e.g. for a 1s clearance time the acceptable EPR is 2 x 233V = 466V. For secondary substations a 430V limit is used for simplicity, to align the LV and telecommunication equipment limits.

C.3 Impact to Communication Network Provider (CNP) Equipment

The impact on communication network provider equipment is assessed against the ITU 430V/650V limits and sites with an EPR in excess of these thresholds are classified as HOT.

Where a substation has been classified as HOT, it is necessary to determine the extent and impact of the HOT zone. The HOT zone can affect:

- Communications circuits to and from the site.
- Other secondary substations supplied from the site.
- Dwellings and other buildings sited in the HOT zone.

The HOT zone and appropriate voltage contours (430V, 650V, 1150V, 1700V etc.) can be determined by computer modelling. The relevant plots are included in most earthing design or assessment reports or can be approximated using the formulae in ENA EREC S34 for calculating the voltage profile from the edge of the substation grid under potential rise conditions.

The appropriate voltage contours are shown on a suitably scaled plan of the substation and its surrounding area, in a similar way to that shown in Figure C-1. This can then be used by third parties. Refer to EDS 06-0002 for further details.

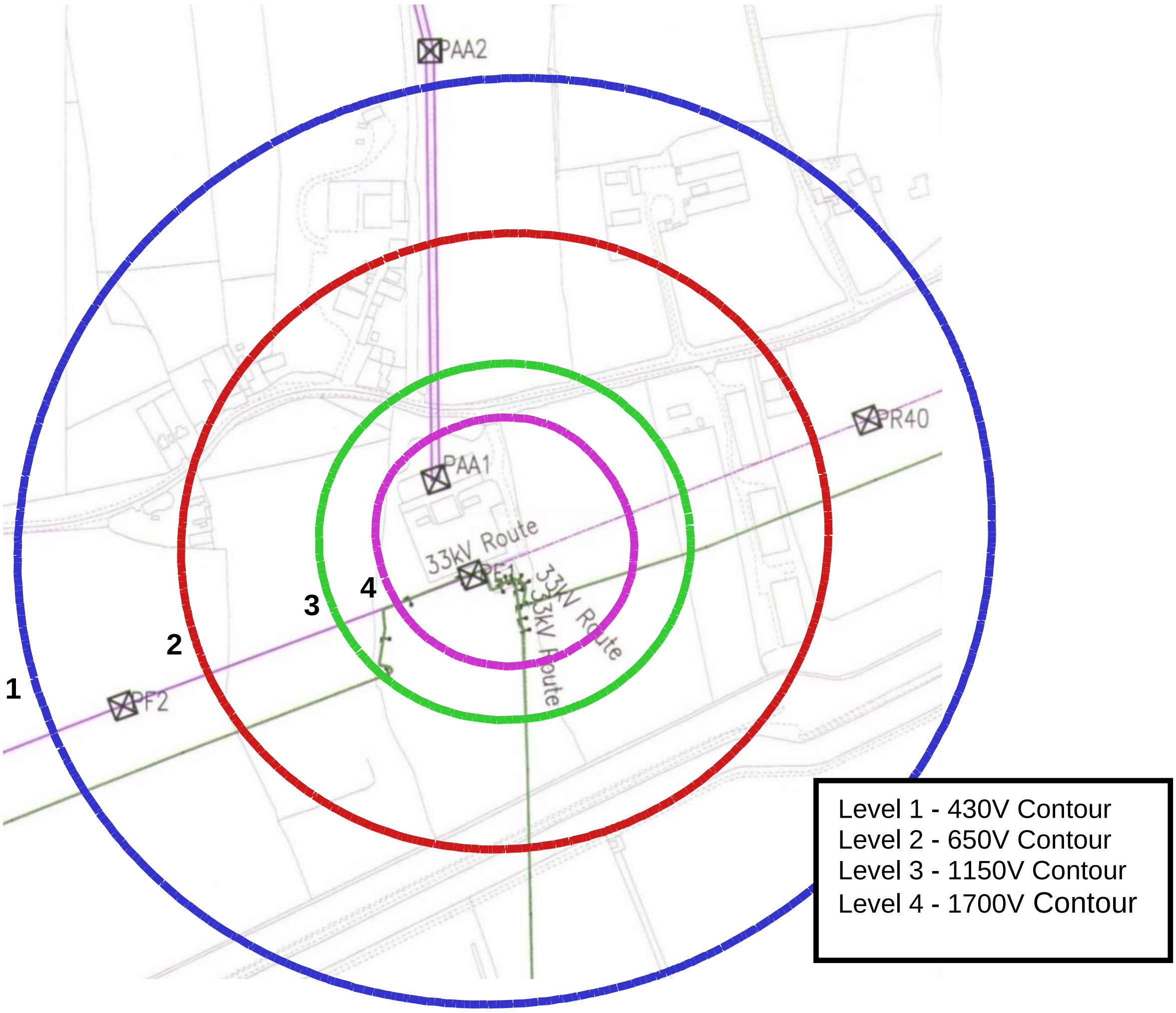


Figure C-1 – Scale Plan of Substation Showing Site Boundary Surface Potential Contours

C.4 Impact on Other Infrastructure

Other infrastructure that may be affected by transfer voltages includes:

- Installations operated by knowledgeable authorities, e.g. petrochemical plants, fuel pipelines, water and gas installations, etc.
- Railways.
- Sites where people may be barefooted, e.g. swimming pools, camping sites, etc.
- Fuel filling stations (where electric vehicle charging equipment may be required).
- Areas where there are livestock and animals, e.g. stables, farms, race courses, etc.

Each of these have different requirements as described in EDS 06-0002.

C.5 Implications if Excessive Transfer Voltages are Identified

The immediate practical requirements are:

- An isolation unit on the termination of the telecommunication cable in the substation.
- All metallic services to the site and building require attention to ensure they do not introduce a transfer voltage risk. This can be prevented by introduction of insulated inserts (normally one inside the substation and another 2m beyond the perimeter fence). Alternatively, say the water supply could be provided by a plastic pipe from 2m outside the perimeter of the substation. Any exposed metal of services within the substation shall be bonded to the substation earth grid if there is any possibility of simultaneous contact.
- There are operational problems associated with work on pilot cables, telecommunication and power circuits. For example, when required to carry out jointing work on a cable between two substations, one of which is HOT. Appropriate operational procedures shall be used to reduce risk.
- The HV and LV electrode systems at the first secondary distribution substation out on each cable fed circuit, or at any distribution substations situated within the HOT zone, shall be considered (for transfer voltage risk), and if necessary earthed separately from one another. The Secondary Substation Earthing Design Tool can assist with this task (refer to EDS 06-0014).

Where the final arrangements mean that a substation will have a zone of influence that extends outside the substation fence, there are a number of steps to be initiated. In general:

- Communication network providers (e.g. Openreach), that use metallic cables, need to be advised and will require the geographic map showing the surface potential contours, as shown in Figure C-1.
- Telecommunication cables within the substation shall be terminated via an isolation transformer and mitigation work on cables passing through the HOT zone may be necessary. Reference should be made to ENA EREC S36/1 to determine who is responsible for costs of telecommunication remedial work.
- Other bodies (gas, water, the petrochemical industry, etc.), having buried metallic pipework within the HOT zone or zone of influence, should be advised so that appropriate operational precautions can be taken by their staff whilst working on any metalwork within the zone and mitigation measures considered.
- There are operational implications when working on telecommunication circuits associated with the substation or within the HOT zone.
- It is necessary to ensure that touch and step voltages are below the appropriate limits.

Where there is equipment belonging to other authorities within the zone of influence, then a number of methods may be adopted to reduce risk. This includes physical diversion, addition of further insulation, adoption of new protection schemes (to increase the relevant limit, e.g. from 430V to 650V or install telecommunication protection devices) and operational procedures.

C.6 Reducing the Impact of Transfer Voltages

It is desirable that a substation should have no external transfer voltage impact and be COLD, but if this is not possible, its impact shall be minimised to an acceptable level. Reducing the substation EPR is an effective way to reduce transfer voltage impact. The EPR is a product of maximum earth fault current and earth return network impedance and some methods to reduce these, and hence the methods to reduce the EPR are listed below.

- Reduce the overall earth fault current;
- Reduce the impedance of the earth electrode or its parallel paths; or
- Divert more of the fault current away from the earth electrode through parallel paths or metallic routes.

It may also be possible to design the earth electrode to create a potential contour (or HOT zone) that avoids sensitive/costly third party equipment. This will almost always require a site specific computer aided design. Sensitive installations might include petrol refineries / stations, gas installations, livestock areas, wet areas, etc.

C.6.1 Reduce the Earth Fault Current

In some cases, and in discussion with Asset Management, it may be practicable to alter the system running arrangement or the method of system neutral earthing in order to reduce the overall rise of earth potential. Caution shall be exercised to ensure that correct protection operation is maintained and customer supply quality is not compromised.

C.6.2 Reducing the Electrode Resistance

The only effective methods of achieving this are to either significantly increase the length of the earth rods (where there is low resistivity soil at deeper levels) or increase the area enclosed by the grid and its electrodes. For example, it may be possible to extend the earth grid out from the fence on one or more sides of the site. This is most economically achieved by bare stranded electrode in each new route used by plastic served cables up to an appropriate distance as shown in ENA EREC S34.

Alternatives, such as using greater cross section conductor or more earth rods of the same length, will only provide a marginal improvement and are rarely economically justified.

Special back-fill materials can sometimes be useful. The most common are Bentonite and Marconite. Bentonite is a clay which, when mixed with water swells to many times its original volume. It absorbs moisture from the soil and can retain it for some time. Marconite is a conductive carbonaceous aggregate which, when mixed with conventional cement, has the effect of increasing the surface area of the earth electrode, thus helping to slightly lower its resistance. These back-fill materials normally only provide a marginal improvement but may be specified for other reasons; for instance to help to maintain the resistance value at a more constant level throughout the year, to provide protection against 3rd party damage, or to protect the electrode from corrosion. They are also useful for surrounding electrodes installed in rock. Where a decision is taken to use Bentonite, Marconite or any other special back-fill material, the design engineer should ensure that this information is passed to the construction staff. These materials can be quite costly, so the construction methods should attempt to limit the amount used. Examples are mixing bentonite with local clay, reducing the hole diameter drilled (for vertical electrodes) and minimising the width and volume of the horizontal trench section into which the electrode will be installed.

Increasing the size of the grid may introduce practical problems (such as maintaining the integrity of long spurs against theft or damage) and difficulty in obtaining the necessary wayleaves.

C.6.3 Reduce the Impedance of Parallel Paths

There are a number of possible alternatives:

- Lay electrode in outgoing mains cable trenches (only useful where the cables have PVC outer sheaths). If calculations show that this will make the substation COLD, it is the most economical solution. However, if the substation remains HOT, the electrode may extend the HOT zone some distance from the substation. Where the electrodes are critical to reduce the EPR and are long, steps shall be taken to maintain their security against damage or corrosion. An ideal arrangement is to route the electrode such that its end may be incorporated into a cable joint or the electrode system of a distribution substation. This means that there are two connections to the electrode, which also helps reduce the longitudinal impedance. If connection of each end is impractical, a test point shall be included in the substation so that the resistance of the spur electrode may be monitored by measurement.
- Make use of abandoned, Hessian served underground cable. Often reinforcement schemes involve replacement of cables. The phase conductors and sheaths may be joined together and connected to the electrode system. Because of the risk of damage, it is essential that multiple connections be provided to such cables. The start ends should ideally be connected via test points, to permit resistance measurements.
- Ensure that maximum benefit will be gained from the impedance of tower footings by ensuring that aerial earth conductors are bonded to the tower steelwork at each tower position. In some cases additional earth electrode (e.g. a loop 1m distance around the tower base or a counterpoise earthwire run along the tower route) can be beneficial.
- It might be possible to take advantage of any deep excavation or piling, to either install some additional earth electrode or incorporate the piles as part of the formal substation earth grid.
- Ensure that effective earthing systems are installed at adjacent substations, where these are directly connected to the site by short cable sections.

Appendix D – Fence Earthing Design

D.1 Design Considerations

The ideal and preferred arrangement is for all external fences to be separately earthed, and for internal fences (i.e. those crossing or subdividing the site) to be bonded to the earth grid. (Section D.3 illustrates in terms of touch-voltage that a separately-earthed fence is the safer option.)

However at some sites it may be necessary to treat separate sections of external fencing differently; or if more practicable, to apply a common earthing method to all compound fencing.

When fencing is separately earthed, adequate separation (minimum 2m) shall be maintained throughout between the fencing and any bonded plant (although at sites with low EPR it may be permissible to reduce the distance from the fence to the buried earth-electrode, only, down to 500mm).

Any bare metal, armoured or sheathed, cable bonded to the substation main earth and running under the separately earthed fence shall be in an insulated duct for 2m either side and perpendicular to the separately earthed fence. This also applies to conductive pipes and any other conductive materials buried below the separately earthed fence.

When fencing is bonded, a detailed calculation is necessary to ensure touch-voltages are safe - unless it is possible to install around the outside either a potential grading electrode or the perimeter electrode itself - typically running 1m outside the fence and buried 1m deep.

Wherever fence-lines with different earthing methods meet, an insulating section of minimum 2m length is required to separate them. This may comprise a brick building, a short section of brick wall, or an insulated fence panel.

An example illustrating these principles and the use of an insulated panel is shown in Figure D-1. The panel may either be non-conductive (e.g. fibreglass), or a conventional steel panel supported on small stand-off insulators. For the latter it is important that suitable insulators are specified, having a voltage withstand of 3kV for 3s and adequate mechanical durability. If the EPR of the substation is likely to exceed 3kV, then higher rated insulators will be required.

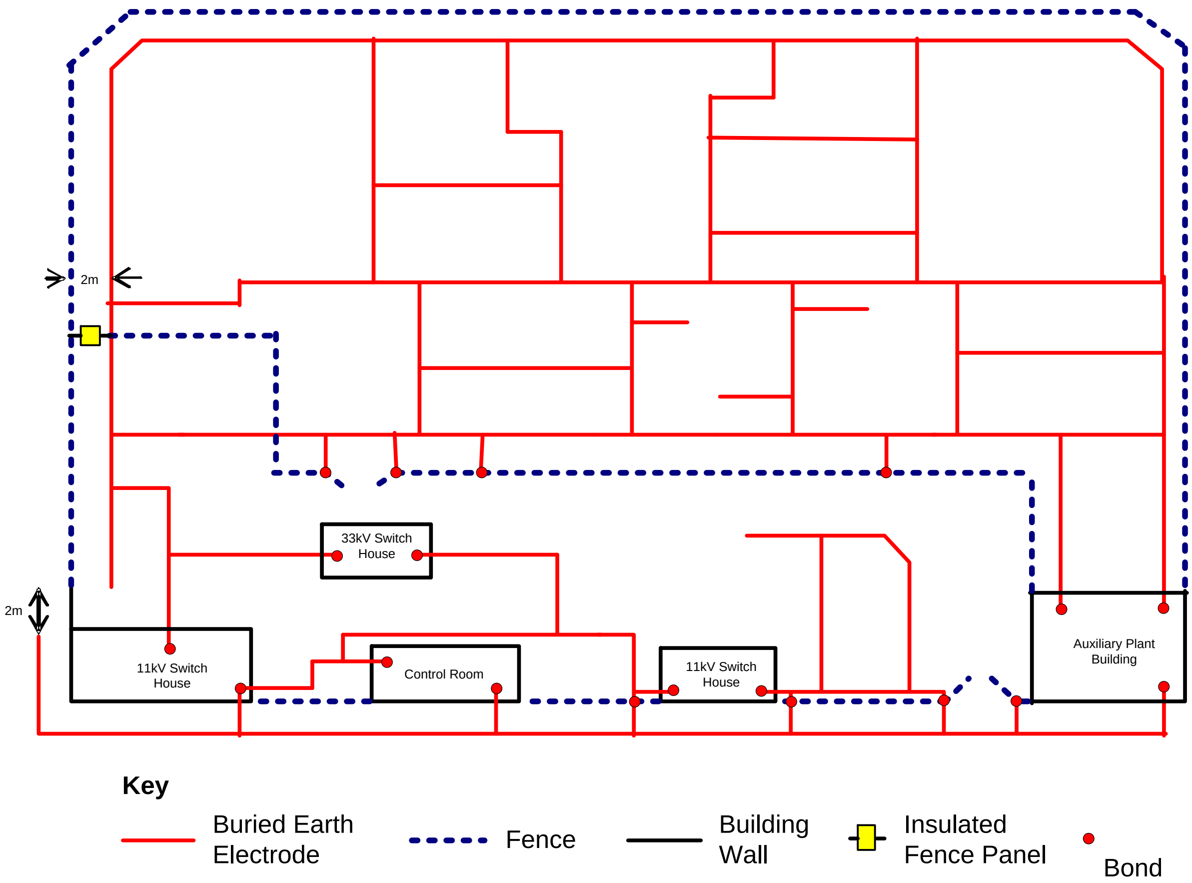


Figure D-1 – Use of Separately Earthed and Bonded Fencing Arrangements at the Same Substation

D.2 Palisade Gates and Removable Fence Panels

Gate openings in a fence-line shall be bonded across between posts, to prevent potential differences arising. Posts supporting removable metal fence panels shall also be bonded across. Gate hinges should also be bonded across, using a flexible braided conductor. Refer to Table E-1 for bonding conductor sizes.

Where gates associated with a separately earthed fence open inwards, it is important that they cannot inadvertently bond this to the grid, or allow personnel to touch the gate and bonded metalwork at the same time. For example, the gate retaining fittings shall not be bonded to the grid, and shall be at least 2m away from other earthed metalwork.

In some cases, it may also be necessary to design the earth mat such that the open gate does not pass over or close to it. A small inset may be formed in the nearby electrode, such that the 2m separation is maintained whilst the gate is open, or else the infringing part of the electrode may be installed in PVC ducts. At existing sites where the earth mat has not been modified, it may be necessary to show by calculation that touch voltages are within the safe limit.

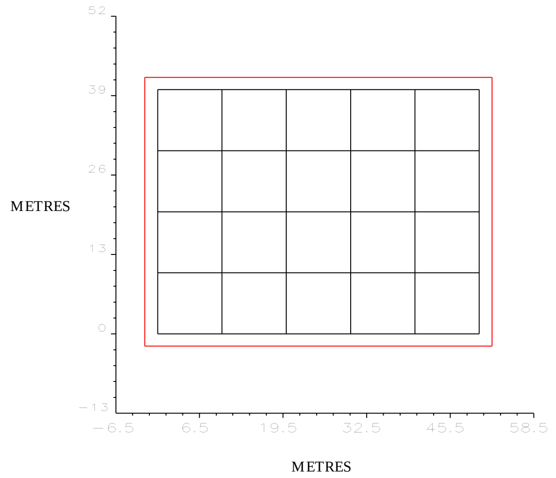
D.3 Safety Advantages of a Separately Earthed Fence

Figure D-2 to Figure D-6 below illustrate why a separately earthed fence is the safer option to use. They show the difference that connecting the fence to the electrode system and then adding a potential grading conductor, makes to the touch voltage on the fence.

Figure D-2 shows that placing the separately earthed fence 2m from the main electrode produces a fence touch voltage of only 3.4% of the EPR. If the fence separation from the grid is reduced to 500mm, the touch voltage only increases to 7.6% (Figure D-3).

Bonding the fence to the grid increases the touch voltages to 44.6% and 37.3% of the EPR, respectively (see Figure D-4 and Figure D-5), which would normally be too high. Adding an external potential grading electrode reduces this back to a maximum of 15.4% of the EPR when the fence is bonded (Figure D-6).

A detailed calculation to ensure touch voltages are safe is necessary if it is not possible to install either a potential grading electrode or the perimeter electrode outside a bonded fence.



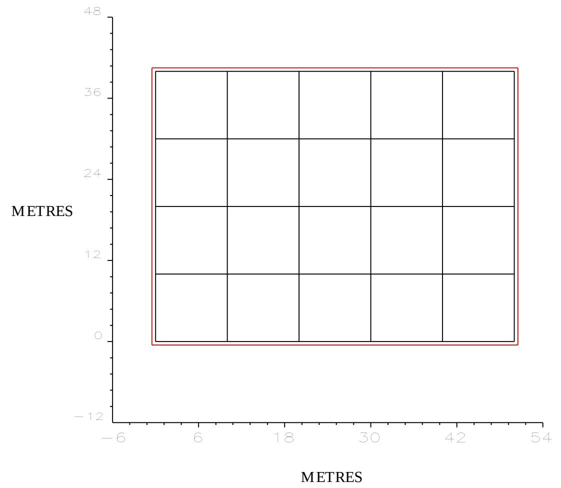
Earth grid dimension – 50m x 40m, with 10m mesh spacing, 600mm deep

Uniform soil resistivity 100Ωm

EPR = 1000V

Maximum touch voltage on fence = 34V

Figure D-2 – Separately Earthed Fence 2m away from Earth Grid



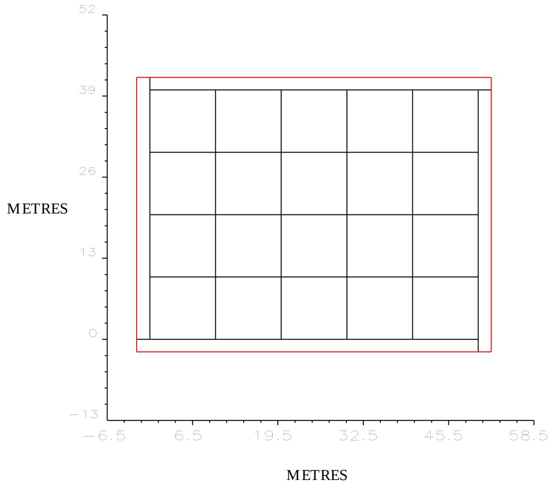
Earth grid dimension – 50m x 40m, with 10m mesh spacing, 600mm deep

Uniform soil resistivity 100Ωm

EPR = 1000V

Maximum touch voltage on fence = 76V

Figure D-3 – Separately Earthed Fence 500mm away from Earth Grid



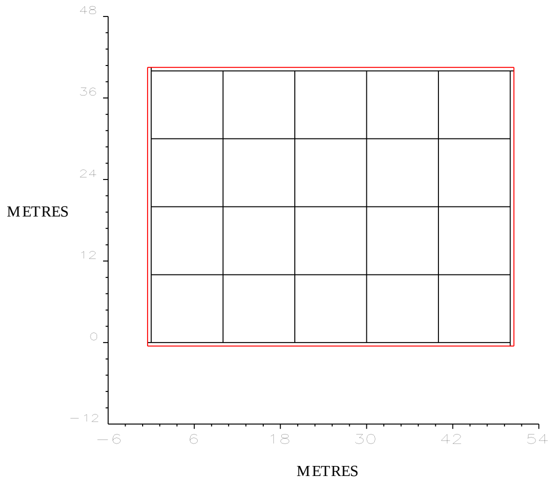
Earth grid dimension – 50m x 40m, with 10m mesh spacing, 600mm deep

Uniform soil resistivity 100Ωm

EPR = 1000V

Maximum touch voltage on fence = 446V

Figure D-4 – Earth Grid Bonded Incorrectly to Fence 2m away from Earth Grid



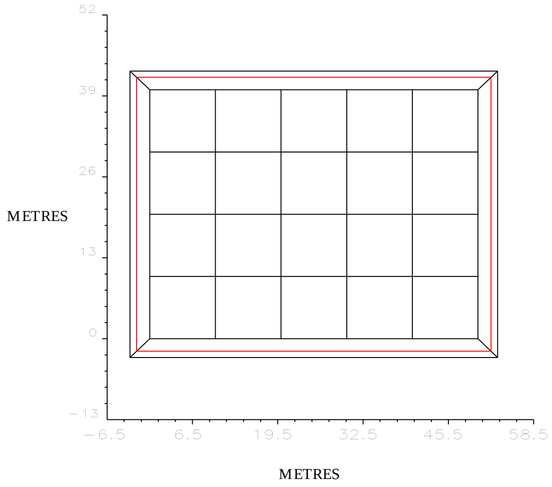
Earth grid dimension – 50m x 40m, with 10m mesh spacing, 600mm deep

Uniform soil resistivity 100Ωm

EPR = 1000V

Maximum touch voltage on fence = 373V

Figure D-5 – Earth Grid Bonded Incorrectly to Fence 500mm away from Earth Grid



Earth grid dimension – 50m x 40m, with 10m mesh spacing, 600mm deep

Uniform soil resistivity 100Ωm

EPR = 1000V

Maximum touch voltage on fence = 154V

Figure D-6 – Fence 2m away from Earth Grid, Fence and Earth Grid Bonded with Potential Grading 1m away

Appendix E – Earthing and Bonding Sizes

Table E-1 – Standard Earthing and Bonding Electrode/Conductor Sizes[3]

Function	Connection[4]	Conductor	Minimum Standard Size (mm or mm^2)			
			12kA/3s	26kA/3s	31.5kA/3s	40kA/3s
Earth grid	Duplicate brazed or welded	Copper tape	25 x 3	40 x 4	40 x 4	40 x 6
Rebar	Single bolted	Copper stranded	70mm^2			
Primary equipment connections[5]	Single brazed or welded	Copper tape	25 x 4	40 x 6	50 x 6	50 x 8
		Copper stranded	120mm^2	240mm^2	300mm^2	400mm^2
	Single bolted	Copper tape	40 x 3	50 x 6	50 x 8	50 x 8
		Copper stranded	120mm^2	300mm^2	400mm^2	400mm^2
	Duplicate brazed or welded	Copper tape	25 x 3	40 x 4	40 x 4	40 x 6
		Copper stranded	70mm^2	185mm^2	185mm^2	240mm^2
	Duplicate bolted	Copper tape	25 x 3	40 x 4	38 x 5	40 x 6
		Copper stranded	120mm^2	185mm^2	240mm^2	240mm^2
Secondary equipment connections[6]	Single bolted	Copper tape	25mm x 4mm			
		Copper stranded	70mm^2			
Above ground equipment connections or internal earth bars	Single bolted	Aluminium tape	40 x 6	n/a	n/a	n/a
	Duplicate bolted		25 x 6	40 x 6	50 x 6	n/a
Equipment connections via structure legs	Single leg	Galvanised steel	327mm^2	707mm^2	856mm^2	1088mm^2
	Duplicate legs		196mm^2	425mm^2	514mm^2	653mm^2
Fence bond	Single bolted	Copper tape or stranded	25 x 3 or 70mm^2			
Gate post bond	Single bolted	Copper tape or stranded	25 x 3 or 70mm^2			

[3] The tape and conductor sizes used in this table are based on standard available sizes and may be oversized. Refer to EDS 06-0012 for actual minimum sizes. Minimum sizes have been calculated assuming a starting temperature of 30°C and final temperatures of 405°C (copper) and 325°C (aluminium).

[4] Connections are either single or duplicate and either bolted or welded/brazed (refer to ECS 06-0022).

[5] Primary equipment connections (e.g. transformers, switchgear, transformer neutrals, busbar supports etc.) are connections that may be required to carry the full fault current.

[6] Secondary equipment connections (e.g. protection/relay panels, link boxes, cubicles, kiosks, building steelwork etc.) are connections that may foreseeably carry a proportion of the HV earth fault current under some failure scenarios (e.g. resulting from failed or poor primary equipment connections).

Function	Connection[4]	Conductor	Minimum Standard Size (mm or mm^2)			
			12kA/3s	26kA/3s	31.5kA/3s	40kA/3s
Gate to gate post bond	Single bolted	Copper stranded	70mm^2			
	Single bolted	Tinned copper braid	25 x 3			
Lighting and security equipment connections	Single bolted	Copper tape or stranded	25 x 3 or 70mm^2			
Other bonding e.g. staircases, cable supports etc.	Single bolted	Copper stranded	16mm^2			