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Guidelines for the design, installation, testing and maintenance of main earthing systems in substations

www.energynetworks.org

Operations Directorate
Energy Networks Association
6th Floor, Dean Bradley House
52 Horseferry Rd
London
SW1P 2AF

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Amendments since publication

Issue	**Date**	**Amendment**
1	1999	Amendment 1 – amendment to formula in Section 8.3.1
1	November 2009	Addendum - Section 15: Earthing associated with HV distribution overhead line networks (excluding tower lines and transformers)
2	8 November 2018	Major revision and re-write. Alignment with latest revisions of BS EN 50522, BS 7430 and ENA TS 41-24. New formulae introduced. Account has been taken of: a) UK Adoption of BS EN 50522:2010, in particular with reference to acceptable touch/step potential limits derived from DD IEC/TS 60479-1:2005. b) changes to earthing practice as outlined in Electrical Safety, Quality, and Continuity Regulations (ESQCR), in particular with regard to smaller distribution or secondary substations. These are described in Sections 9 and 10. c) the requirements for Protective Multiple Earthing systems as outlined in ENA Engineering Recommendation G12. (The relevant items concerning substation earthing in ENA EREC G12/4 have now been transferred to this document). d) the increasing use of plastic sheathed cables. e) the differing requirements of earthing systems at various voltages and for differing types of substation installation.

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Foreword

This Technical Specification (TS) is published by the Energy Networks Association (ENA) and comes into effect from 8 November, 2018. It has been prepared under the authority of the ENA Engineering Policy and Standards Manager and has been approved for publication by the ENA Electricity Networks and Futures Group (ENFG). The approved abbreviated title of this engineering document is “ENA TS 41-24”.

This specification is to be used in conjunction with ENA EREC S34. In this document, account has been taken of:

a) UK Adoption of BS EN 50522:2010, in particular with reference to acceptable touch/step potential limits derived from DD IEC/TS 60479-1:2005.

b) changes to earthing practice as outlined in Electrical Safety, Quality, and Continuity Regulations (ESQCR), in particular with regard to smaller distribution or secondary substations. These are described in Sections 9 and 10 of this specification.

c) the requirements for Protective Multiple Earthing systems as outlined in ENA Engineering Recommendation G12. (The relevant items concerning substation earthing in ENA EREC G12/4 have now been transferred to this document).

d) the increasing use of plastic sheathed cables.

e) the differing requirements of earthing systems at various voltages and for differing types of substation installation.

1 Scope

This Specification applies to fixed earthing systems for all Electricity Supply Industry AC transmission and distribution systems in the UK and equipment earthing within EHV, HV and HV/LV substations.

It also applies to:

- terminal towers adjacent to substations (see NOTE) and cable sealing end compounds.
- pole-mounted transformer or air-break switch disconnector installations.
- pole-mounted reclosers with ground level control.

It does not apply to earthing systems for quarries and railway supply substations.

NOTE: Touch potential control at terminal towers adjacent to substations is covered by BS EN 50341-1:2012.

2 Normative references

The following referenced documents, in whole or part, are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Standards publications

BS EN 50341-1:2012, *Overhead electrical lines exceeding AC 1 kV. General requirements. Common specifications*

BS EN 50522:2010, *Earthing of power installations exceeding 1 kV a.c.*

DD IEC/TS 60479-1:2005, *Effects of current on human beings and livestock, Part 1 – General aspects.*

BS 7430:2011+A1:2015, *Code of practice for protective earthing of electrical installations*.

Other publications

ENA EREC S34, *A guide for assessing the rise of earth potential at electrical installations.*

3 Definitions

ALARP	As low as reasonably practicable. NOTE: This term has a particular legal meaning.
APPROVED EQUIPMENT	Equipment approved in an operational policy document for use in the appropriate circumstances.
ASC	Arc suppression coil. A tuned reactance used to limit earth fault current in the event of a phase-earth fault.
AUXILIARY ELECTRODE	See SUPPLEMENTARY ELECTRODE.
BACKUP PROTECTION	Protection set to operate following failure or slow operation of primary protection – also see NORMAL PROTECTION. For

	design purposes, the backup protection clearance time may be taken as a fixed (worst-case) clearance time appropriate to the network operator's custom and practice.
BONDING CONDUCTOR	A protective conductor providing equipotential bonding.
EARTH	The conductive mass of earth whose electric potential at any point is conventionally taken as zero.
EARTH ELECTRODE	A conductor or group of conductors in direct contact with, and providing an electrical connection to, earth.
EARTH ELECTRODE POTENTIAL	The difference in potential between the EARTH ELECTRODE and a remote EARTH.
EARTH ELECTRODE RESISTANCE	The resistance of an EARTH ELECTRODE with respect to EARTH. NOTE: Where there is a significant inductive component, references to resistance can be construed as references to impedance.
EARTH ELECTRODE RESISTANCE AREA	That area of ground over which the resistance of an EARTH ELECTRODE effectively exists. It is the same area of ground over which the EARTH ELECTRODE POTENTIAL exists.
EARTH FAULT	A fault causing current to flow in one or more earth-return paths. Typically, a single phase to earth fault, but this term may also be used to describe two-phase and three-phase faults involving earth.
EARTH FAULT CURRENT (I_F)	The worst-case steady state (symmetrical) RMS current to earth, i.e. that returning to the system neutral(s) resulting from a single phase to earth fault. This is normally calculated (initially) for the zero-ohm fault condition. Depending on the circumstances, the value can be modified by including earth resistance. NOTE 1: Not to be confused with GROUND RETURN CURRENT (I_E) which relates to the proportion of current returning via the soil.
EARTH POTENTIAL RISE (EPR) (U_E)	The difference in potential which may exist between a point on the ground and a remote EARTH. NOTE 1: Formerly known as RoEP (rise of earth potential). NOTE 2: The term GPR (ground potential rise) is an alternative form, not used in this standard.
EARTHING CONDUCTOR OR EARTHING CONNECTION	A protective conductor connecting a main earth terminal of an installation to an EARTH ELECTRODE or to other means of earthing, or a conductor connecting equipment to a main earth terminal of an installation.
EARTH MAT	A buried or surface laid mesh or other electrode, usually installed at the operator position close to switchgear or other

	plant, intended to control or limit hand-to-feet TOUCH POTENTIAL.
EARTHING SYSTEM	The complete interconnected assembly of EARTHING CONDUCTORS and EARTH ELECTRODES (including cables with uninsulated sheaths).
EHV	Extra high voltage, typically used in the UK to describe a voltage of 33 kV or higher.
ELECTRODE CURRENT (I_{ES})	The current entering the ground through the substation's electrode system under earth fault conditions. For design purposes, the electrode current may be taken as the worst-case current flowing into a substation's electrode system under foreseeable fault conditions including, where relevant, the loss of metallic return paths and/or cross-country faults. NOTE: This term is generally used in the context of electrode sizing calculations and is slightly different to ground return current since the ground return current may flow through alternative paths such as auxiliary electrodes etc.
GLOBAL EARTHING SYSTEM (GES)	An earthing system of sufficiently dense interconnection such that all items are bonded together and rise in potential together under fault conditions. No true earth reference exists and therefore safety voltages are limited.
GRADING ELECTRODE	An electrode installed to reduce a touch potential hazard on equipment.
HOT / COLD SITE	A HOT site is defined as one which exceeds ITU limits for EPR. Typically, these thresholds are 650 V (for reliable fault clearance time <= 0.2 seconds), or 430 V otherwise. NOTE 1:The requirements derive from telecommunication standards relating to voltage withstand on equipment. NOTE 2:These thresholds have formerly been applied as design limits for EPR in some areas. The terms HOT and COLD were often applied as a convenience (on the basis that many COLD sites do achieve safe step/touch limits) but do not relate directly to safe design limits for touch and step potentials in substations.
HIGH EPR / HPR	High earth potential rise resulting from an earth fault. An EPR greater than twice the permissible touch potential limit (e.g. 466 V for faults of 1 s duration on soil).
HIGH VOLTAGE (HV)	A voltage greater than 1 kV and less than 33 kV. Typically used to describe 6.6 kV, 11 kV and 20 kV systems in the UK.
MAIN EARTHING SYSTEM (MES)	A subset of the EARTHING SYSTEM which comprises the interconnected arrangement of the EARTH ELECTRODES and EARTHING CONDUCTORS in a substation. NOTE: formerly termed "substation earthing system" or "main earth grid".

NORMAL PROTECTION OPERATION	Clearance of a fault under normal (usual) circumstances. The normal protection clearance time will include relay operating time and mechanical circuit breaker delays for all foreseeable faults, and may be calculated for design purposes. Alternatively, a network operator may work to the worst-case normal protection clearance time applicable to the network in a given area. This time assumes that faults will be cleared by normal upstream protection and does not allow for e.g. stuck circuit breakers or other protection failures/delays.
NETWORK OPERATOR	Owner or operator of network assets. Includes DNO (Distribution Network Operator), IDNO (Independent or Inset DNO) and Transmission Network Operator (TNO) as defined in the Distribution Code (DCode) or System Operator Transmission Code (STC) as appropriate.
SUPPLEMENTARY ELECTRODE	An electrode that improves the performance of an earthing system, and may increase resilience, but is not critical to the safety of the system.
SAFETY VOLTAGE(S)	Permissible touch, step or transfer potential(s).
STEP POTENTIAL (U_S)	Voltage between two points on the ground surface that are 1 m distant from each other, which is considered to be the stride length of a person. NOTE: U_{vS} is also used for prospective step potential.
STRESS VOLTAGE	Voltage difference between two segregated earthing systems, which may appear across insulators/bushings etc. or cable insulation.
TOUCH POTENTIAL (U_T)	voltage between conductive parts when touched simultaneously. NOTE 1: U_{vT} is also used for prospective touch potential. NOTE 2: For more detail, see Section 4.3.1.

4 Fundamental requirements

4.1 Function of an earthing system

Every substation should 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 installation should be able to pass the maximum current from any fault point back to the system neutral whilst maintaining step, touch, and transfer potentials within the permissible limits defined in Section 4.4 based on normal protection relay and circuit breaker operating times (See definition of normal protection operation in Section 3). In exceptional circumstances where the above parameters may not be economically or practically kept below permissible limits, a probabilistic risk assessment may be carried out. Where this shows the risk to be below accepted ALARP levels, the level of earth potential rise mitigation may be reduced (see Section 5.7).

The earthing system should be designed to avoid damage to equipment due to excessive potential rise, potential differences within the earthing system (stress voltages), and due to excessive currents flowing in auxiliary paths not intended for carrying fault current.

The design should be such that the passage of fault current does not result in any thermal or mechanical damage [for backup protection clearance times] or damage to insulation of connected apparatus. It should be such that protective gear, including surge protection, is able to operate correctly.

Any exposed normally un-energised metalwork within a substation which may be made live by consequence of a system insulation failure can present a safety hazard to personnel. It is a function of the MES to eliminate such hazards by solidly bonding together all such metalwork and to bond this to the earth electrode system in contact with the general mass of earth. Dangerous potential differences between points legitimately accessible to personnel should be eliminated by appropriate design.

The earthing system should maintain its integrity for the expected installation lifetime with due allowance for corrosion and mechanical constraints.

The earthing system performance should contribute to ensuring electromagnetic compatibility (EMC) among electrical and electronic apparatus of the high voltage system in accordance with BS IEC 61000-5-2.

4.2 Typical features of an earthing system

The earthing installation requirements are met principally by providing in each substation an arrangement of electrodes and earthing conductors, which is called the MES. The following are connected to it:

- all equipment housing or supporting high voltage conductors within the substation such as transformer and circuit breaker tanks, arcing rings and horns and metal bases of insulators.
- neutral connection of windings of transformers required for high voltage system earthing. For high voltage systems, the connections may be via earthing resistors or other current limiting devices, as described in Section 4.5.1. The neutral earthing of low voltage systems is separately considered in Section 9.
- electrodes, additional to the MES, which may themselves function as earth electrodes.
- earth connections from overhead line terminal supports and the sheaths / screens of underground cables.
- earth mats, provided as a safety measure, to reduce the potential difference between points on the area of ground adjacent to manually operated plant and the metalwork including handles of that plant (but see also Section 10.6).
- grading electrodes (intended to reduce touch or step potentials), which typically consist of a horizontal ring electrode around all items of earthed plant and the equipment and bonded to it. This is often supplemented by additional grading electrodes inside the ring.
- high-frequency electrodes, conductors and electrodes specifically configured to reduce the impedance to lightning, switching and other surges at applicable locations, e.g. surge arrestors, CVTs and GIS bus interfaces.
- all other exposed and normally un-energised metalwork wholly inside the substation perimeter fence, e.g. panels (excluding floating fence panels), kiosks, lighting masts, oil tanks, etc. Conductive parts not liable to introduce a potential need not be bonded (e.g. metal window frames in brick walls). Items such as fences, cables and water pipes which are not wholly inside the substation are separately considered in Sections 6.6 and 6.7.

- Fences may be bonded to the MES in some situations – see Section 6.6.

Substation surface materials, for example stone chippings which have a high value of resistivity, are chosen to provide a measure of insulation against potential differences occurring in the ground and between ground and adjacent plant. Although effective bonding significantly reduces this problem, the surface insulation provides added security under system fault conditions. Permissible touch/step potentials are higher where an insulated surface layer is provided – see Section 4.4.

4.3 The effects of substation potential rise on persons

During the passage of earth-fault current a substation earth electrode is subjected to an EPR. Potential gradients develop in the surrounding ground area and these are highest adjacent to the substation earth electrode. The EPR reduces to approximately zero (or true earth potential) at some distance from the substation earth electrode.

A person could be at risk if they can simultaneously contact parts at different potential; thus in a well-designed system, the potential differences between metallic items will be kept to safe levels regardless of the EPR.

Ground potential gradients around the electrode system, if great enough, can present a hazard to persons (e.g. Case study in Section 11.1) and so effective measures to limit them should be incorporated in the design.

The three main design parameters relate to touch, step and transfer potentials as defined below. These terms are shown as U_{vT}, U_{vS} and A respectively in Figure 1.

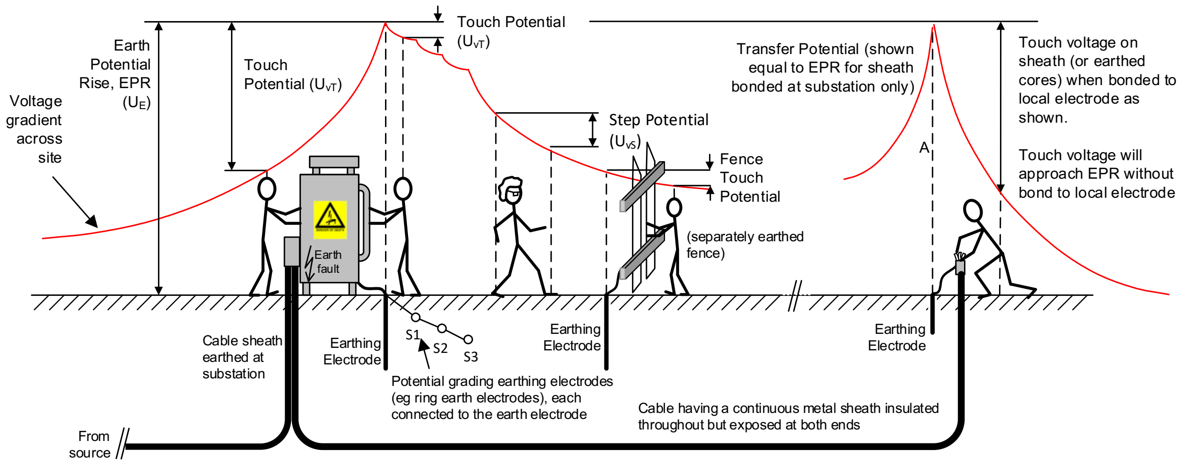

Figure 1 – Touch, step and transfer potentials resulting from an earth fault

4.3.1 Touch potential

This term describes the voltage appearing between a person's hands and feet (see Figure 1), or between a person's hands. Hand to foot touch potential arises from the fact that the EPR at a person's feet can be somewhat lower in value than that present on the buried earth electrode (and any connected metalwork). If an earthed metallic structure is accessible, a person standing on the ground 1 m away and touching the structure will be subject to the touch potential. In addition, the permissible limits for step potential are usually much higher than for touch potential. As a consequence, if a substation is safe against touch potentials, it will normally be safe against step potentials.

In some situations, the hand-to-hand touch potential should be considered, for example if un-bonded parts are within 2 m. The permissible limits for this scenario can be calculated as described in DD IEC/TS 60479-1, using the body impedance not exceeded by 5 % of the population. Typical values for dry conditions and large contact area are shown in Table 1. In general, such situations should be designed out, e.g. by increasing separation or introducing barriers if the systems should be electrically separate, or by bonding items together. The siting of fences needs consideration in this regard.

4.3.2 Step potential

The potential gradient in the ground is greatest immediately adjacent to the substation earth electrode area. Accordingly, the maximum step potential at a time of substation potential rise will be experienced by a person who has one foot on the ground of maximum potential rise and the other foot one step towards true earth. For purposes of assessment the step distance is taken as one metre. (See Figure 1).

4.3.3 Transfer potential

4.3.4 General

A metallic object having length - a fence, a pipe, a cable sheath or a cable core, for example, may be located so as to bring in (import) or carry out (export) a potential to or from the site.

By such means a remote, or true earth (zero) potential can be transferred into an area of high earth potential rise (HPR) or vice-versa. For example, a long wire fence tied to a (bonded) substation fence could export the site EPR to the end of the wire fence, where it may pose an electric shock hazard to somebody standing on soil at true earth potential. Similarly, a metallic water pipe (or telephone cable, or pilot cable, etc.) could import a zero-volt reference into a substation, where local potential differences could be dangerous. Bonding the cable or pipe to the substation system might reduce local risk but could create a problem elsewhere; isolation units or insulated inserts (for pipework) are typical solutions that may need to be considered.

The limits for permissible transfer potential relate to shock risk (touch and step potential), and equipment damage / insulation breakdown (withstand voltage).

4.3.5 Limits for LV networks

Safety criteria (see Section 4.4.1) apply to the voltage that may be transferred to LV networks. Further information is also given in Section 9.5.

4.3.6 Limits for other systems

Voltages carried to pipelines, fences, and other metallic structures during HV fault conditions should not exceed permissible the touch and step potential limits as defined in Section 4.4.1. In some circumstances, for example pipelines connected to gas or oil pumping or storage facilities, lower limits may apply.

4.3.7 Limits for telecommunications equipment (HOT/COLD sites)

Care should be taken to ensure that telecommunications and other systems are not adversely impacted by substation or structure EPR; in general, these systems should be routed so that they are not adversely affected by passing through an area of HPR. Where the EPR on substations or structures exceeds certain levels, the operators of these systems should be notified. See ENA EREC S36 for more information.

ITU Directives[1] presently prescribe limits (for induced or impressed voltages derived from HV supply networks) of 430 V rms or, in the case of high security lines, 650 V rms. (High security lines are those with fast acting protection which, in the majority of cases, limits the fault duration to less than 200 ms.) Voltages above and below these limits are termed HOT and COLD respectively, although it should be noted that these terms do not relate directly to safety voltages.

For telecoms connections to HOT sites, consultation with telecommunications provider may be necessary to arrive at a solution, e.g. isolation transformers or optic fibre links to ensure the telecoms system is segregated from the substation earth.

4.4 Safety criteria

4.4.1 General permissible design limits

An effective earthing system is essential to ensure the safety of persons in, and close to substations, and to minimise the risk of danger on connected systems beyond the substation boundaries. The most significant hazard to humans is that sufficient current will flow through the heart to cause ventricular fibrillation.

The basic criteria adopted in this specification for the safety of personnel are those laid down in BS EN 50522, which in turn derive from DD IEC/TS 60479-1. In addition, ITU-T Directives[1] are considered where relevant, and where their limits might be lower than BS EN 50522.

The relevant limits for touch and step potentials are given in Table 1 and Table 2.

These use the body impedance values not exceeded by 5% of the population, and the C2 current curve as described in Annex NA of BS EN 50522:2010.

In selecting the appropriate limits, the designer should consider the type of surface covering, and if footwear will be worn. Within substations, it should be assumed that footwear will be worn. DD IEC/TS 60479-1 states that these design limits are sufficiently conservative to apply to all humans including children; however, it is recommended that further reference be made to that standard, and relevant (lower) limits adopted as necessary if a substation is in close proximity to, or might otherwise impinge on high risk groups.

Table 1 and Table 2 give permissible touch and step potentials as a function of fault current duration. Note that touch and step potentials are normally a fraction of the total EPR, and therefore if the EPR (for all foreseeable fault conditions) is below the limits above, it follows that the site will be compliant. (The full design assessment procedure is given in Section 5.)

Permissible limits are a function of normal protection clearance times. Figures NA1 and NA2 of BS EN 50522 show curves showing intermediate values of permissible touch potential, if required.

Touch and step potentials are sometimes collectively referred to as safety voltages since they relate directly to the safety of persons or animals.

Substations should be designed so that safety voltages are below the limits given in Table 1 and Table 2. It will be appreciated that there are particular locations in a substation where a person can be subjected to the maximum step or touch potential. Steep potential gradients in particular can exist around individual rod electrodes or at the corner of a meshed grid.

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1 (ITU-T: Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines: Volume VI: Danger, damage and disturbance (2008))

The presence of a surface layer of very high resistivity material provides insulation from these ground potentials and greatly reduces the associated risks. Thus, substations surfaced with stone chippings or concrete are inherently safer than those with grass surfacing, and permissible limits are higher, provided that the integrity of the surface can be maintained.

4.4.2 Effect of electricity on animals

The main focus of this document is human safety. However, horses and cattle are known to be particularly susceptible to potential gradients in soil. There are no safety limits prescribed for animals but technical report IEC/TR 60479-3 provides some limited experimental data. Interpretation of this data suggests that potential gradients (e.g. around remote electrodes or structures placed in fields) not exceeding 25 V/m will generally not result in animal fatality.

4.4.3 Injury or shock to persons and animals outside the installation

Shock risk outside an installation can be introduced by metallic transfer (fence, pipe, cable) or via the soil. Where a hazardous transferred potential can occur due to metallically conductive means, that eventuality should be removed by the introduction of insulation or other protective measures (examples include insulated sections introduced into external metal fences). Where metal fences are bonded to the MES, the touch and step potentials external to them should be controlled by the design, such that they are within the acceptable limits. In other words, most risks should be managed by design such that touch and step potentials are below the safe limits defined in Table 1 and Table 2. Where HV and LV earthing systems are combined, the EPR is transferred from the installation into domestic, commercial or industrial properties and should be at a level that complies with the requirements of Section 9.5.

In many situations, risk to individuals may be beyond the control of the network operator, for example if a building is erected close to an existing substation. In such circumstances, a risk assessment should be carried out to establish the level of risk, and the justifiable spend to mitigate against that risk. Acceptable voltage thresholds will be influenced by activity (e.g. wet/dry), location (e.g. beach-side) and the presence of animals. The risk assessment process is described further in Section 5.7.

Table 1 – Permissible touch potentials for typical fault clearance times

Permissible touch potentials[(A)] (V)	Fault clearance time (s)																			
	0.1	**.15**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**2**	**3**	**5**	**≥10[(B)]**
Bare feet (with contact resistance)	521	462	407	313	231	166	128	106	92	84	80	76	73	71	69	67	63	60	58	57
Shoes on soil or outdoor concrete	2070	1808	1570	1179	837	578	420	332	281	250	233	219	209	200	193	188	173	162	156	153
Shoes on 75 mm chippings	2341	2043	1773	1331	944	650	471	371	314	279	259	244	232	223	215	209	192	180	173	170
Shoes on 150 mm chippings or dry[(C)] concrete	2728	2379	2064	1548	1095	753	544	428	361	321	298	280	266	255	246	239	220	205	198	194
Hand-to-hand dry conditions, large contact area (see 4.3.1)	1114	968	836	639	484	368	276	221	191	172	161	152	146	141	137	134	125	119	115	114

NOTE: These values are based on fibrillation limits. Immobilisation or falls/muscular contractions could occur at lower voltages. Steady state or standing voltages may require additional consideration.

A. Additional resistances apply based on footwear resistance as well as contact patch, as defined in BS EN 50522, i.e. each shoe is 4 kΩ and the contact patch offers 3xρ, where ρ is the resistivity of the substrate in Ω·m. Thus for touch potential, the series resistance offered by both feet is 2150 Ω for shoes on soil/wet concrete (effective ρ=100 Ω·m). For 75 mm chippings, each contact patch adds 1000 Ω to each foot, giving 2500 Ω (effective ρ=333 Ω·m). For 150 mm chippings (and a conservative estimate for dry concrete), the total resistance is 3000 Ω (effective ρ = 670 Ω·m). Concrete resistivity typically will vary between 2,000-10,000 Ω·m (dry) and 30-100 Ω·m (saturated).

B. The >= 10 s column is an asymptotic value which may be applied to longer fault duration. This is a fibrillation limit only; it may be prudent to apply lower limits to longer duration faults or steady state voltages sufficient to limit body current to let-go threshold values.

C. Dry assumes indoors. Outdoor concrete, or that buried in normally wet areas or deep (>0.6 m) below ground level should be treated in the same way as soil.

Table 2 – Permissible step potentials for typical fault clearance times

Permissible step potentials(B) (V)	Fault clearance time (s)																			
	0.1	.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	2	3	5	≥10(C)
Bare feet (with contact resistance)	22753	19763	17077	12715	8905	6044	4290	3320	2770	2434	2249	2098	1992	1897	1823	1771	1616	1503	1442	1412
Shoes on soil or outdoor concrete	A)	A)	A)	A)	A)	A)	A)	A)	21608	19067	17571	16460	15575	14839	14267	13826	12629	11727	11250	11012
Shoes on 75 mm chippings	A)	A)	A)	A)	A)	A)	A)	A)	24906	21976	20253	18971	17951	17103	16445	15936	14557	13517	12967	12692
Shoes on 150 mm chippings or dry concrete	A)	A)	A)	A)	A)	A)	A)	A)	A)	A)	24083	22559	21347	20338	19555	18951	17311	16074	15420	15092

NOTE: As for touch potential, these limits are calculated according to fibrillation thresholds. Immobilisation or falls / involuntary movements could occur at lower voltages. In general, compliance with touch potential limits will achieve safe step potentials.

A. Limits could not be foreseeably exceeded, i.e. 25 kV or greater.

B. Additional footwear / contact resistances appear in series (rather than parallel for the hand-feet case), and are therefore 4x those in equivalent touch potential case.

C. The >= 10 s column is an asymptotic value which may be applied to longer fault duration. This is a fibrillation limit only; it may be prudent to apply lower limits to longer duration faults or steady state voltages sufficient to limit body current to let-go threshold values.

4.5 Electrical requirements

4.5.1 Method of neutral earthing

The method of neutral (or star point) earthing strongly influences the fault current level. The earthing system should be designed appropriate to any normal or alternative neutral earthing arrangements, in a similar way that it will be necessary to consider alternative running arrangements that may affect fault levels or protection clearance times.

If the system uses an ASC connected between the transformer neutral and earth, the magnitude of the current in the earthing system may be small due to the tuning of the coil's reactance against the capacitance to earth of the unfaulted phases. However, other conditions can occur that require a higher current to be considered. For instance, if the tuned reactor can be shorted out (bypassed), e.g. for maintenance or protection purposes whilst the transformer is still on load, it is necessary to design for this (see Sections 5.4.2 and 5.4.5). Furthermore, even if there is no alternative method of system earthing, it may be necessary to consider the possibility of a neutral bushing fault on the tuned reactor effectively shorting out the tuned reactor (eg for thermal design calculations and sizing earth electrode and earthing conductor). Such considerations also apply to all impedance earthed systems if there is a foreseeable risk of the impedance earthing device failing and remaining out for any significant time.

The likelihood of phase-to-earth insulation failure is increased on tuned reactor systems, particularly if earth faults are not automatically disconnected. This is because a first earth fault will cause phase displacement such that the voltage on the two healthy phases will experience an increased voltage relative to earth (approaching line-line voltage). Where justified by operational experience, consideration should also be given to a cross-country fault, where the current can approach phase-to-phase levels if the earth resistance at each fault site is minimal or if there is metallic interconnection between the sites.

4.5.2 Fault current

The passage of fault current into an electrode system causes potential rise (EPR, and touch/step/transfer potentials) and heating. Both are related to the magnitude of fault current flow. Section 5.4 describes the fault currents (and durations) applicable to earthing design.

4.5.3 Thermal effects - general

The earthing system should be sized according to the maximum foreseeable current flow and duration to prevent damage due to excessive temperature rise. For main items of plant in substations (switchgear, transformers, VTs, CTs, surge arrestors, etc.), consideration should be given to the possibility of simultaneous phase-earth faults on different items of plant, which could result in phase-phase current flows through the MES. See also Section 5.4.5.

Any current flowing into an electrode will give rise to heating of the electrode and surrounding soil. If the current magnitude or duration is excessive, local soil can dry out, leading to an increase in the resistance of the electrode system. Section 5.5.2 gives current ratings based on a surface current density limit calculated according to formula C2 in B.2.2 of ENA EREC S34. In some situations, even if target resistance and design EPR values are achieved, it may be necessary to increase the electrode contact surface area to ensure compliance with this requirement (Section 5.4.6).

5 Design

5.1 Design considerations

This section describes general arrangements applicable to all substations. Further discussion relating to those items specific to distribution substations is included in Section 9, and pole-mounted systems are further described in Section 10.

5.1.1 Limiting values for EPR

The design should comply with the safety criteria (touch, step and transfer potentials) and with the earthing conductor and earth electrode conductor current ratings, and should allow sufficient current flow for reliable protection operation.

There is no design requirement which directly limits the overall EPR of a substation to a particular value, however, the design will need to consider insulation withstand between different systems, and voltage contours in surrounding soil. The need to comply with these requirements, and safety limits, will naturally tend to restrict the acceptable EPR. In practice, an upper EPR limit may be applied by different network operators based on equipment specifications and/or proximity to third-party systems.

5.1.2 Touch and step potentials

Touch and step potentials (collectively referred to as safety voltages) are the most important design criteria. Formulae for calculating touch and step potentials are given in Appendix B of EREC S34.

5.1.3 Factors to include in calculation of EPR and safety voltages

For each operating voltage at a substation, two conditions of earth fault should be considered to determine the maximum value of earth electrode current for EPR and safety voltage assessment purposes. In one, the earth fault is external to the substation; here the current of concern is that returning to the neutral(s) of the transformer(s) at the substation under consideration. The other is for an earth fault in the substation; here the current of concern is now that value returning to the neutral(s) of the transformer(s) external to the substation under consideration. If these return currents have available to them other conducting paths directly connected to the earthing system of the substation, for example overhead line earth-wires and cable sheaths, the currents in these paths should be deducted from the appropriate return current to derive the value of current passing through the earth electrode system of the substation. Evaluation of this ground-return current component is described in Section 6 of EREC S34. Also see Section 5.4.2 below.

5.1.4 Transfer potential

A further factor that should be considered is transfer potential that may arise from a fault at the source substation(s), if there is a metallic connection (cable sheath or earth wire) between the substation earthing systems. Methods for calculating the transfer potential are described in Annex I of ENA EREC S34.

A person at a remote location could theoretically receive the full (100 %) EPR as a touch potential since he/she will be in contact with true earth. This may be disregarded if the EPR at the source substation results in acceptable touch potential values at the remote substation. However, particular care is needed if there is a possibility of hand-hand contact between a transfer potential source and other earthed metalwork. This possibility should be excluded by using, where practicable, appropriate barriers (e.g. insulated glands, enclosures) or by bonding. If this cannot be ensured, lower voltage limits will apply to the hand-hand shock case (see DD IEC/TS 60479-1).

5.2 Preliminary arrangement and layout

In order to determine fully the requirements for and adequacy of an earthing system it is necessary to produce a preliminary design arrangement of that earthing system. From a site layout drawing showing the location of the plant to be earthed, a preliminary design arrangement of the earthing system for the substation should be prepared, incorporating the relevant functions of Section 4.1 and the relevant features of Section 4.2. The particular layout arrangement will be unique to each substation but all will have some dependence on, inter alia, a combination of the factors described in Section 5.4, relating to fault level, fault duration, electrode current and soil type.

5.3 Design guidelines

This Section gives an outline of those features of earthing system arrangements which have proved to be most satisfactory in practice.

5.3.1 Outdoor substations

Except for pole-mounted equipment, it is recommended that the earthing arrangement be based on a bare perimeter electrode (peripheral buried horizontal earthing electrode), generally encompassing the plant items to be earthed such that the perimeter earth electrode is at least 1m out from the plant items to provide touch potential control at arm's reach. Internal connections should connect from the perimeter electrode to the items of plant. These internal connections function as an earthing conductor if not in contact with soil, or an electrode otherwise. Where reasonably practicable, the amount run above the surface should be minimized to deter theft. In addition, discrete earth electrodes, e.g. rods or plates, may be connected to this perimeter electrode. These may variously be employed in order to reduce the surface current and/or the electrode resistance of the MES.

The electrode system may be augmented with inter-connected, buried, bare cross-connections to form a grid. Such cross-connections increase the quantity of earth electrode conductor and mesh density of the grid, reduce touch potentials on plant within the grid, and provide local main conductors to keep equipment connections short. Importantly, they also increase security/resilience of connections by introducing multiple paths for fault current.

In all substations, it is recommended that duplicate connections are made from the MES to main items of plant, in order to increase resilience (see Section 5.4.5 for conductor sizing).

Where regular contact of an operator with an earthed structure is anticipated, e.g. at a switch handle, unless the substation has a mesh type earthing system and calculation shows this to be unnecessary, the earthing system should be enhanced. This should be done by providing an earth mat (or, if a mat is impracticable, an appropriate grading electrode) at or just below the surface of the ground and bonded to the metalwork, so arranged that the metalwork can only be touched while standing above the mat (or enhanced area).

Pole-mounted equipment presents a particularly difficult ground potential gradient problem and the special precautions noted in Section 10 should be observed. It may be necessary to apply these precautions in some ground-mounted substations.

Fault current flowing through an earth electrode system to earth uses the outer extremities of the electrode system to a greater extent than the inner parts of the system. Thus, adding more earth electrode, whether as vertical rods or as horizontal tape, to the inner area of a small loop or well integrated grid electrode system, will have little impact in reducing earth resistance or the current density in the outer electrode conductors of the system. However, this can help to control step/touch potentials around specific items of plant.

Such reductions in overall earth resistance as may be desirable are best achieved by extending the electrode system to cover a greater area of ground (e.g. by buried radial electrodes), or by driving rods around the periphery of the system, or by a combination of both.

The vertical rod electrode is most effective for use in small area substations or when low soil resistivity strata, into which the rod can penetrate, lies beneath a layer of high soil resistivity. Rods are least effective where there is a high resistivity layer beneath one of lower resistivity, e.g. where underlying bedrock is near to the surface. In these locations, extended horizontal electrodes in the low resistivity surface layer are more effective.

For large area substations employing a grid electrode system, the addition of vertical rods, even when optimally installed around the periphery of the system, may make only a marginal improvement.

5.3.2 Indoor substations

The plant of indoor substations will normally be erected on a concrete raft, often containing a steel reinforcing mesh (re-bar). To control touch and step potentials around plant, it is common for re-bar to be bonded to the main earthing system, or for a dedicated grading mesh (usually consisting of prefabricated steel or copper) to be buried in the concrete screed in the substation area. These measures are to control potential gradients and are not intended to act as an electrode (they may be employed for example above basement areas); dedicated electrodes will also be required to provide a connection to the mass of earth and achieve the functional requirements. For new substation buildings, a buried peripheral horizontal electrode may be conveniently installed around the building foundation and supplemented with vertical rod electrodes as required. Coordination with the civil engineering design can result in a cost-effective installation.

Where reinforcing mesh in concrete is to function as supplementary earth electrode, it should be designed to carry the current without cracking the concrete, be constructed with mesh panels welded together and be welded to the peripheral buried earth electrode at suitable intervals (e.g. 5 m).

The provision of a buried main earth bonding conductor within the confines of an existing building is often impractical and thus a surface mounted main earthing conductor loop is normally installed with surface-run spur connections to the various items of plant. The earth electrode system employed with this arrangement may differ depending on the magnitude of earth fault current that the electrode system is required to carry. Marshalling earth bars are sometimes used in addition to, or instead of, a surface laid loop and if properly labelled can facilitate measurement/maintenance. The convenience of such an arrangement often brings with it a high reliance on bolted connections and so the resilience aspect should be balanced with convenience.

Substations in buildings may require a buried loop/ring electrode outside the building if any extraneous metalwork (e.g. metal cladding, steel joists, handrails, communications antenna etc.) is bonded to the MES and could otherwise present a touch potential issue to those outside the building. The same considerations apply where a substation is installed in an existing building (for example in the basement of a tower block), even if the building is not recognisable as a substation building; in fact, risks associated with members of the public will often be higher in such installations and warrant additional consideration.

Electrode systems (rod nests, etc.) should not be sited close to main access/egress routes without consideration of step and touch potential in these areas.

Grading electrodes, where required, should be positioned 1 m from metalclad buildings, or at other distances subject to a specific calculation demonstrating that the grading electrode mitigates the identified hazards, and bonded to the building's internal HV or EHV earthing system at two or more separate points.

If the building is to be provided with a lightning protection system (LPS) that will be bonded to the main earthing system, the LPS electrodes may contribute to potential grading. Calculations and/or computer modelling will normally be necessary to demonstrate whether such measures can be used in place of dedicated grading electrodes.

Sparsely positioned rods (e.g. associated with an LPS to BS EN 62305-1) may serve this function if compliance can be demonstrated at the design stage.

An LPS, if purposely designed with regard to power system fault currents and with closely spaced rods (or interconnecting electrode ring), could serve the dual purpose of lightning protection and potential grading. Care is needed to ensure that such a system cannot be disconnected from the building, e.g. by removal of test links.

Conversely, any earthing system designed for power system fault current may be used for an LPS if it is compliant with BS EN 62305-1, particularly with regard to high-frequency components and down-conductor routing (free of tight bends etc.)

5.3.3 Shared sites

Where the customer operates HV (and/or EHV) switchgear, there will be a natural boundary between Network Operator ownership, and customer ownership. Ideally the Network Operator should not rely on the customer's earthing system to ensure electrical safety around the Network Operator's assets, unless maintenance agreements can be made. In practice, the systems may need to be connected together, but each system should where reasonably practicable be designed to be safe in the absence of any (electrode) contribution from the other system.

Neither party should rely on the other's earthing system unless regular maintenance/testing of both systems can be assured.

5.3.4 Distribution (or secondary) substations

Distribution (HV:LV) substation earthing is particularly important given that LV system neutral/earth conductors may be connected to, or close to HV earthing systems and consequently could export transfer potential to customer installations. Specific examples for ground-mounted substations are given in Section 9, and pole-mounted equipment is covered in Section 10.

5.3.5 Metallic fences

Substation fences are typically either separately earthed or bonded to the MES. In general, a separately earthed system will minimise the EPR and the resulting touch potential that may be accessible externally. A bonded design will be required if hand to hand touch potentials between the fence and the equipment connected to the MES exceed permissible limits, and effective measures, eg a 2 m separation, cannot be established to prevent hand to hand contact.

In the case of bonded fences, consideration should be given to touch potentials that appear on the fence under fault conditions; an external peripheral electrode may be required around the outside of the fence at an appropriate depth and distance from the fence to achieve acceptable levels (typically, values are 0.5 m and 1 m respectively). Care should also be taken to ensure that potential rise is not exported via third-party fences etc. that may be in contact with the substation fence.

See Section 6.6 for more details.

5.3.6 Provision of maintenance/test facilities

Facilities for monitoring earth system efficiency (see Section 6.2.5) should be included at the design stage. See Section 7.5 for information on earth resistance measurements.

Test points (e.g. for clamp meter testing) should be shown on earthing drawings.

5.4 Design data

The final design of the earthing system can only be undertaken when sufficient knowledge is available of the proposed physical and electrical arrangements of the substation.

As a minimum, the designer should have knowledge of:

- value of fault current and supply arrangements (overhead and/or underground cable)
- fault duration (or protection settings)
- soil resistivity
- substation dimensions

Any special features about the site, such as subsoil of a corrosive nature and the suitability of the site for driven earth rods or other forms of electrode, should be ascertained. Other relevant features, such as existing earth electrodes, nearby earthed structures, buried pipes or piled foundations should be noted and taken into consideration.

In urban areas in particular, the substation may be served by an underground cable network which, particularly if incorporating non-insulated sheaths/armours, will make a contribution which may be taken into consideration. See Section 9.4.3 for details on the contribution from typical 11 kV networks.

5.4.1 Soil Resistivity

The value of the resistivity of the soil may be ascertained by reference to published data or by direct measurement. Table 3 gives typical values relating to types of soil but these should only be used for very preliminary assessments. Nationally available soil survey data[2] may also be used for this purpose.

Table 3 – Typical soil resistivity values

Soil type	Resistivity (Ω·m)
Loams, garden soils, etc.	5 – 50
Clays	10 – 100
Chalk	30 – 100
Clay, sand and gravel mixture	40 – 250
Marsh, peat	150 – 300
Sand	250 – 500
Slates and slatey shales	300 – 3,000
Rock	1,000 – 10,000

2 e.g. http://mapapps.bgs.ac.uk/geologyofbritain/home.html

Multi-layer soil models and computer modelling may offer more effective/optimal designs than typical or homogeneous soil models. Except for some smaller substations, where the additional expense may not be warranted, direct measurement will normally be necessary prior to detailed design. The recommended method, using the Wenner array, is described in 7.4.2.

It should be noted that the top layers of soil may be subject to a significant seasonal variation due to fluctuating moisture content. Designs should utilise deeper, more stable, strata wherever possible; the depth of this stable layer is variable depending on soil type and weather/climate.

5.4.2 Fault currents and durations - general

The earthing system should remain intact, and safety voltages should be acceptable for all foreseeable fault conditions. BS EN 50522 describes the need to consider single phase to earth, two phase, and three phase to earth fault current flows, as well as cross-country faults in some situations.

The relevant currents for earthing design are summarised in Table 4, and described in detail in the following sections.

Table 4 – Relevant currents for earthing design purposes

Type of system earth supplying fault	Relevant for EPR and safety voltages	Relevant for thermal effects	
		Earth electrode (see Section 5.4.6)	**Earthing conductor** (see Section 5.4.5)
Solid Earthing Impedance Earthing	If known, and if earth return paths are known to be reliable and rated for duty: Ground return current Otherwise: Earth fault current See Section 5.4.4.	Maximum foreseeable electrode current. This should be taken as the ground return current or a value between the ground return current and the earth fault current, taking into account the loss of any metallic return paths (cable sheath or overhead earth wire) where relevant. See also section 5.5.2.	Earth fault currents for all voltage levels at the substation. Three phase (or phase-to-phase) faults should be considered if phase-to-phase fault current can flow through earthing conductors (e.g. separately earthed items of plant, particularly single phase equipment).
ASC earthing	ASCs are generally used in addition to solid or impedance earthing. It is therefore usually appropriate to design to the alternative solid or impedance arrangement (as above) which is termed the bypass arrangement. If there is no automatic disconnection of earth faults, cross-country faults may need to be considered, depending on operational experience.		
NOTE 1: Fault currents associated with all voltage levels in substations should be considered. The appropriate protection clearance times for each voltage level should be applied. NOTE 2: Steady state currents (i.e. the maximum current that can flow in the earthing system without protection operation) may impose additional requirements on the designer. NOTE 3: See also Section 5.4.3.			

See Table 1 in BS EN 50522 for further details.

5.4.3 Fault current growth

Consideration should be given to future network alterations and alternative running arrangements. A margin should be added to allow for future changes without detailed assessment (e.g. typical 15 % increase, unless more accurate information is available).

If fault levels are expected to approach the switchgear rating in the foreseeable future, the switchgear rating should be used as the design figure. In any case, the rating of the earthing system should be reviewed if plant is to be upgraded such that higher fault levels may be possible.

5.4.4 Fault currents for EPR and safety voltage calculations

The fault current applicable to EPR calculation (and therefore safety voltage calculations) is the maximum (symmetrical RMS) current to earth (earth-fault current) that the installation will see under fault conditions.

Normal operating time of protection relays and breakers should be used for safety voltage calculations, rather than worst-case (back-up) protection clearance times.

If there is a metallic return path for earth fault current (e.g. a cable screen or overhead earth wire), this will typically convey a large proportion of the earth fault current. The remainder will return through soil to the system neutral(s). Reduction factors for neutral current flows (multiple earthed systems) and sheath/earth wire return currents may be applied to calculate the ground return current. The ground return current is used in EPR calculations as it flows through the resistance formed by a substation's overall earth electrode system (and that of the wider network) and thus contributes to potential rise of that system. Annex I of BS EN 50522 describes some methods for calculating this component. Further guidance is given in ENA EREC S34.

If specific protection settings are not available, or the Network Operator deems it appropriate, the design should use upper bound (slowest) clearance times associated with normal protection operation, as specified by the network operator.

These considerations apply whether the source substation (i.e. that supplying the fault) is impedance or solidly earthed. EPR should be calculated for all voltage levels at any substation, for faults at the substation and on circuits fed from it. Faults on the LV network can usually be shown to be insignificant in this regard.

For substations with ASCs, the design should be based on the most onerous (in terms of magnitude and/or duration) earth fault or, depending on operational experience, cross-country fault. In addition, the design should consider long duration EPR conditions which may give rise to near steady-state voltages on equipment or fences etc.

NOTE: In many cases, the solid earth fault level is an appropriate design figure for safety voltage assessment on ASC systems, since this is likely to represent a realistic upper-bound. The need to consider alternative fault scenarios / currents is subject to operational experience / risk assessment.

5.4.5 Fault currents and clearance times for conductor size (thermal effects)

Conductor sizing calculations should be based on backup protection clearance time, i.e. the design should allow for failure of primary protection without damage to the earthing system. In the absence of network specific data, the following HV and EHV protection operating times should be assumed:

Over 1 kV, up to and including 132 kV: 3 s

275 kV and higher voltages: 1 s

For earthing conductors and electrodes in substations, it is recommended that the design fault currents detailed in Table 4 are used.

NOTE: The decision of whether to include the missing return path scenario is largely dependent on operational experience and risk assessment. For example, the likelihood of complete failure of the metallic return path will be higher for a single overhead earth wire than it would be for a triplex (3 x bunched single cores) cable network arranged in a ring.

The maximum fault current applies wherever this may be borne by one spur connection, in which case that spur should be sized accordingly. In grid (mesh) earthing designs there will often be parallel paths to share the current; if the current is to flow in two or more paths (e.g. around a ring), each individual path should be sized to no less than 60 % of the fault current.

Installations connected to, or part of the one where the highest fault current occurs, may only be required to carry a portion of that current and the earth conductors may be sized accordingly.

Conductor ratings are given in Section 5.5.1.

5.4.6 Fault currents and clearance times for electrode size calculations (thermal effects)

The discrete earth electrode should at all times retain its functional properties, i.e. both its current carrying capability and its value of resistance to earth. For these reasons, the temperature rise of the electrode conductor and the density of current dissipation from electrode to soil, during the passage of fault current through it, should be limited.

Electrodes are thus subject to thermal requirements of the electrode material due to passage of fault current, and current limits imposed by the electrode-to-soil interface.

Thermal requirements are satisfied by appropriate choice of material and cross-sectional area for each electrode and its connection to the main earthing system (See Section 5.5.1). Surface current density requirements are satisfied by ensuring sufficient electrode surface area. In some cases, it will be necessary to install additional electrode(s) to satisfy this requirement, particularly if the electrode resistance requirements can be met with a relatively small electrode system.

5.4.6.1 Design fault currents and clearance times for electrode ratings

The surface area of the main electrode through which the fault current flows to ground should, as a minimum, be sufficient to disperse the maximum foreseeable electrode current (i.e. the total current flowing into the electrode system).

The ground return current or earth fault current (as appropriate) should be used in calculations if the electrode current(s) are not known. Higher values may be appropriate for ASC systems, as described below.

NOTE 1: The proportion of current flowing into individual electrode groups may be considered in the design.

NOTE 2: Reduction factors for neutral current flows (multiple earthed systems) and sheath/earth wire return currents may be applied in the normal way to calculate ground return current or electrode current.

NOTE 3: Faults at all voltage levels in each substation should be considered.

If there is a metallic return path for earth fault current (e.g. a cable screen or overhead earth wire), this will typically convey a large proportion of the earth fault current. The remainder will return through soil to the system neutral(s). Reduction factors for neutral current flows (multiple earthed systems) and sheath/earth wire return currents may be applied to calculate the ground return current. The ground return current is used in EPR calculations as it flows through the resistance formed by a substation's overall earth electrode system (and that of the wider network) and thus contributes to potential rise of that system. Annex I of BS EN 50522 describes some methods for calculating this component. Further guidance is given in ENA EREC S34.

The possibility of sheath failure or aerial earth wire failure can give rise to higher than normal ground return current (and consequent electrode current) and should be considered where necessary, as described in the previous section.

For ASC systems, the electrode current calculation should consider cross-country faults since these are more likely on such systems. The electrode current in such circumstances can sometimes exceed the normal calculated ground return current. Solid earth-fault level or phase-to-phase fault levels should be used if there is any doubt, even if the bypass is via resistor or reactor. The value to be used is subject to risk assessment and operational experience.

NOTE: This is particularly relevant where earth faults are not automatically disconnected within 3 seconds.

The relevant clearance times are for backup protection operation as described in the previous section, since it is imperative that the earthing system remains intact if faults are slow to clear.

Long term (steady state) current flows can cause drying of soil, and should be considered in addition to normal faults (see below).

Relatively rare faults (e.g. bushing failures or internal faults) which may cause an ASC or impedance to be shorted out should be considered if necessary, based on operational experience.

5.4.6.2 Long term current flows

If significant ground-return current can flow for prolonged duration (i.e. without protection operation), the effect of this current should be considered separately; it can lead to drying at the electrode-soil interface and impose a steady state (or standing) voltage on plant which can require additional measures to ensure safety. This is relevant for ASC systems where earth faults are not automatically disconnected, or where moderate current can return via earth to the system neutral in normal circumstances due to un-balanced network capacitance or leakage. The magnitude of this current should be taken as the ASC coil rating or earth-fault protection relay current settings.

NOTE: A maximum surface current density of 40 A/m^2 is appropriate for long term current flows. This is unlikely to cause drying at the electrode-soil interface.

5.4.6.3 Surface area and current density requirements

The soil surrounding earth electrodes is of a much higher sensitivity than the electrode conductor material and thus the passage of current through the soil will develop, relatively, a much higher temperature rise. The effect of high temperature in the soil causes drying of the surrounding soil, thus further increasing its resistivity, or even the production of steam which can force a separation between the electrode conductor and its interfacing soil.

For this reason, the current rating of an electrode is calculated with reference to its surface current density (A/mm^2) and is dependent on soil resistivity. As a consequence, the current rating of buried electrodes in practical installations is very much less than equivalent sized above-ground earthing conductors. Section 5.5.2 gives ratings of typical buried electrodes.

In many cases, the electrode surface area requirement is satisfied by normal design practice based on achieving a satisfactorily low earth resistance value; care is needed for systems where a small electrode system is otherwise thought to be sufficient.

The appropriate fault current, as described above, should be divided by the surface area of the electrode system to demonstrate that the current density at the electrode-soil interface is within limits. It is permitted to use the surface area of all connected electrodes (main and auxiliary) in this calculation. However, it is good design practice, wherever possible, to ensure that sufficient main electrode meets this requirement.

NOTE: In situations such as substations in urban areas where the overall ground return current is significantly increased by interconnection to a larger network or other auxiliary electrode system, dividing this overall ground return current I_E (returning via a wide area electrode system, as shown as in ENA EREC S34) into the local electrode surface area will provide a safety margin. It is permissible, for design economy, to calculate the local electrode current I_{ES} by evaluation of the ground return current split between the local electrode system and other paths, as shown in Figure 2 of ENA EREC S34), and dividing this resultant electrode current into the local electrode area. This approach should be used with caution, or combined with the risk assessment approach outlined in Section 5.7, as failure of auxiliary electrode connections etc. could result in overheating/failure of the local electrode system under fault conditions.

A formula for calculating the limiting surface current density J_{limit} is given in B.2.2 of ENA EREC S34. Current ratings for some typical electrodes calculated using limiting values of surface current density, are given in Table 8.

5.5 Conductor and electrode ratings

The earthing system should remain intact following a protection failure as described in Section 5.4.5.

5.5.1 Earthing conductors and electrodes

Earthing conductors should normally be selected from standard copper or aluminium sections; this does not exclude the use of other materials if longevity and resilience (especially to corrosion) can be demonstrated. For alkaline or acidic soils (i.e. those where the pH is greater than 10 or less than 4), or in other situations where corrosion is likely, it may be necessary to oversize electrodes, or to apply other measures to give a reasonable lifetime. See BS 7430 for further details.

Based on maximum fault clearance times, the conductor temperature should not exceed 405°C for copper and 325°C for aluminium based on an initial temperature of 30°C. A lower limit of 250°C (absolute) is relevant for bolted connections, since extreme thermal cycling can lead to loosening over time.

Table 5 and Table 6 give declared current ratings for a range of standard conductor sizes for both 1 s and 3 s fault duration times. The short time rating of other conductors can be calculated from formulae given in Appendix B of ENA EREC S34.

NOTE: Table 5 and Table 6 refer to the use of bare conductors. Thermal ratings for insulated conductors can be calculated from data in BS 7454.

Table 5 – Conductor ratings (copper)

(a) 405°C maximum temperature (copper)

These copper sizes are based on a temperature rise of 375°C occurring in 3 seconds and 1 second above an ambient temperature of 30°C (i.e. achieving a maximum temperature of 405°C) with the currents in columns 1(a) and 1(b) respectively applied to the conductors. For each substation, it will be necessary to specify whether column 1(a) or 1(b) should apply.

Fault current (kA) not exceeding		**Copper strip (mm)**		**Stranded copper conductor (mm^2)**	
(a)	**(b)**				
(3 s)	**(1 s)**	**Single (spur) connections**	**Duplicate or loop connections**	**Single (spur) connections**	**Duplicate or loop connections**
4		25 x 4	25 x 4	70	70
8		25 x 4	25 x 4	70	70
12		25 x 4	25 x 4	95	70
13.2		40 x 3	25 x 4	120	70
18.5		40 x 4	25 x 4	150	95
22		50 x 4	31.5 x 4		120
26.8		40 x 6.3	40 x 4		150
40		-	50 x 4		
	40	50 x 4	31.5 x 4 or 40 x 3		
	63	50 x 6	50 x 4		

NOTE 1: Equivalent sizes for stranded conductor include, but are not limited to the following, quoted as number of strands/strand diameter:

70 mm^2=19/2.14 mm or 7/3.55 mm(e.g.HDC); 95 mm^2= 37/1.78 mm; 120 mm^2 = 37/2.03 mm; 150mm^2 = 37/2.25 mm.

NOTE 2: Consideration of corrosion risk may lead to the decision to specify minimum strand diameters (e.g. 1.7 mm or larger as given in BS EN 62561-2). A minimum strand diameter of 3 mm is preferred by some Network Operators for longevity of the electrode system, particularly if corrosive soils exist.

(b) 250°C maximum temperature (copper) – bolted connections

These copper sizes are based on a temperature rise not exceeding 250°C, from an ambient temperature of 30°C with the currents in columns 1(a) and 1(b) respectively applied to the conductors. For each substation, it will be necessary to specify whether column 1(a) or 1(b) should apply. These figures are generally applicable to bolted connections between tapes or lugs etc. which offer a relatively small thermal mass.

Fault current (kA) not exceeding		**Copper strip (mm)**		**Stranded copper conductor (mm^2)**	
(a)	**(b)**				
(3 s)	**(1 s)**	**Single (spur) connections**	**Duplicate or loop connections**	**Single (spur) connections**	**Duplicate or loop connections**
4		25 x 4		70	70
8		25 x 4		95	70
12		25 x 6		120	95
13.2		25 x 6		150	95
18.5		38 x 5			120
22		40 x 6			150
26.8		50 x 6			
40		-	40 x 6		
	40	40 x 6	50 x 3		
	63	-	40 x 6		

NOTE 1: Equivalent sizes for stranded conductor include, but are not limited to the following, quoted as number of strands/strand diameter:

70 mm^2=19/2.14 mm or 7/3.55 mm(e.g. HDC); 95 mm^2= 37/1.78 mm; 120 mm^2 =37/2.03 mm; 150 mm^2 =37/2.25 mm.

NOTE 2: Consideration of corrosion risk may lead to the decision to specify minimum strand diameters (e.g. 1.7 mm or larger as given in BS EN 62561-2). A minimum strand diameter of 3 mm is preferred by some Network Operators for longevity of the electrode system, particularly if corrosive soils exist.

Table 6 – Conductor ratings (aluminium)

(a) 325°C maximum temperature (aluminium)

These aluminium sizes are based on a temperature rise of 295°C occurring in 3 seconds and 1 second above an ambient temperature of 30°C with the currents in columns 1(a) and 1(b) respectively applied to the conductors. For each substation, it will be necessary to specify whether column 1(a) and 1(b) should apply.

Fault current (kA) not exceeding		**Aluminium strip (mm)**		**Stranded aluminium conductor (mm^2)**	
(a)	**(b)**				
(3 s)	**(1 s)**	**Single (spur) connections**	**Duplicate or loop connections** (NOTE 2)	**Single (spur) connections**	**Duplicate or loop connections**
4		20 x 4	20 x 2.5	70	70
7.5		25 x 4	20 x 4	120	70
12		40 x 4	25 x 4		120
13.2		50 x 5	25 x 4		120
18.5		40 x 6	40 x 4		150
22		50 x 6	50 x 4		
26.8		60 x 6	40 x 6		
40		75 x 8	50 x 7		
	40	50 x 7	50 x 4		
	63	75 x 6.5	50 x 6		

NOTE 1: Equivalent sizes for stranded conductor include, but are not limited to the following, quoted as number of strands/strand diameter:

70 mm^2=19/2.14 mm or 7/3.55 mm; 95 mm^2= 37/1.78 mm; 120 mm^2 =37/2.03 mm; 150 mm^2 =37/2.25 mm.

NOTE 2: Duplicate or loop connections have been rated to carry 60 per cent of the full fault current.

(b) 250°C maximum temperature (aluminium) – bolted connections

These aluminium sizes are based on a temperature rise not exceeding 250°C in 3 seconds and 1 second from an ambient (initial) temperature of 30°C with the currents in columns 1(a) and 1(b) respectively applied to the conductors. For each substation, it will be necessary to specify whether column 1(a) and 1(b) should apply. These figures are generally applicable to bolted connections between tapes or lugs etc. which offer a relatively small thermal mass.

Fault current (kA) not exceeding		Aluminium strip (mm)		Stranded aluminium conductor (mm^2)	
(a)	(b)				
(3 s)	(1 s)	Single (spur) connections	Duplicate or loop Connections (NOTE 2)	Single (spur) Connections	Duplicate or Loop Connections
4		20 x 4	20 x 2.5	70	70
7.5		25 x 5	25 x 3	120	70
12		50 x 4	25 x 5	185	120
13.2		50 x 4	25 x 5		120
18.5		50 x 6	50 x 4		185
22		60 x 6	50 x 4		
26.8		70 x 6	40 x 6		
40		-	60 x 6		
	40	50 x 7	40 x 6		
	63	-	60 x 6		

NOTE 1: Equivalent sizes for stranded conductor include, but are not limited to the following, quoted as number of strands/strand diameter:

70 mm^2=19/2.14 mm or 7/3.55 mm; 95 mm^2= 37/1.78 mm; 120 mm^2 =37/2.03 mm; 150 mm^2 =37/2.25 mm.

NOTE 2: Duplicate or loop connections have been rated to carry 60 per cent of the full fault current.

Table 7 - Cross sectional areas (CSA) for steel structures carrying fault current

These sizes are based on the maximum temperature achieved after the passage of fault current for 3 seconds and 1 second from an ambient (initial) temperature of 30°C. For each substation, it will be necessary to specify whether column 1(a) or 1(b) should apply.			
Fault current (kA) not exceeding		**250°C (applicable to bolted structures)**	**400°C (applicable to welded/continuous structures which are galvanised)**
(a)	**(b)**		
(3 s)	**(1 s)**	**CSA (mm^2)**	**CSA (mm^2)**
4		109	91
7.5		204	171
12		327	273
13.2		359	301
18.5		503	421
22		599	501
26.8		729	610
40		1087	910
	40	628	525
	63	989	828

5.5.2 Electrode current ratings

Table 8 gives the current rating of typical electrodes. The limiting factor tends to be heating at the electrode-soil interface, consequently the ratings are dependent on the limit for electrode surface current density and on soil resistivity. The current ratings in Table 8 have been calculated using the formula for limiting current density J_{limit} in B.2.2 of ENA EREC S34.

Table 8 – Maximum current rating of typical rod, tape and plate electrodes

Soil Resistivity (Ω·m)	3 s current rating				1 s current rating			
	Rod 16 mm Dia. (A per metre length)	Plate 915 x 915 mm (A)	Plate 1220 x 1220 mm (A)	25 x 4 mm tape (A per metre length)	Rod 16 mm Dia. (A per metre length)	Plate 915 x 915mm (A)	Plate 1220 x 1220 mm (A)	25 x 4 mm tape (A per metre length)
10	69.7	2322	4128	80.4	120.7	4022	7151	139.3
30	40.2	1341	2384	46.4	69.7	2322	4128	80.4
40	34.9	1161	2064	40.2	60.4	2011	3575	69.7
50	31.2	1039	1846	36	54	1799	3198	62.3
60	28.5	948	1685	32.8	49.3	1642	2919	56.9
70	26.3	878	1560	30.4	45.6	1520	2703	52.7
80	24.6	821	1460	28.4	42.7	1422	2528	49.3
100	22	734	1306	25.4	38.2	1272	2261	44.1
150	18	600	1066	20.8	31.2	1038	1846	36
200	15.6	519	923	18	27	899	1599	31.2
250	13.9	464	826	16.1	24.1	804	1430	27.9
300	12.7	424	754	14.7	22	734	1306	25.4

In most practical installations, the actual values of electrode current density will be considerably less than the limiting values, due to the quantity of bare buried conductor (electrode) employed in the installation to provide effective bonding and in some installations where extra electrodes have been added, to comply with the touch potential limits. Note that the surface current density limit is independent of the electrode material, and therefore the limits can be applied to re-bar, piling or other fortuitous or auxiliary electrodes, providing that the temperature rise in these structures under fault conditions will not cause issues such as cracking/distortion etc.

Where an electrode is encased in a material such as concrete, or material/agent other than surrounding soil, a surface current density calculation should be carried out at the electrode-material interface, using the surface area of the metallic electrode itself and the properties of the agent. In some cases, it will also be necessary to carry out a similar calculation at the interface of the agent with surrounding soil, noting that the larger surface area offered by the agent will apply.

A well-designed earthing system should provide sufficient surface area to satisfy thermal requirements without reliance on re-bar or other fortuitous / auxiliary electrodes.

5.6 Design assessment

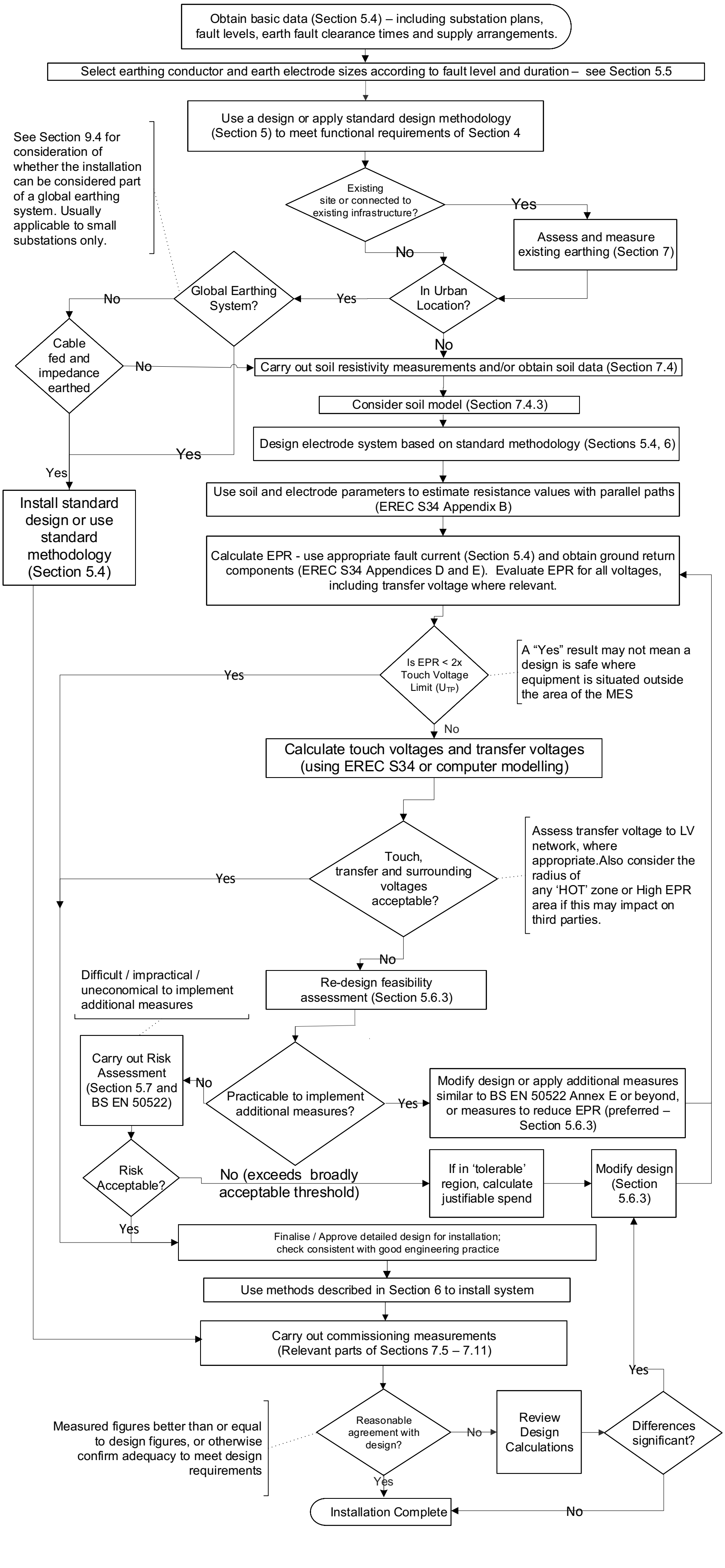
The assessment procedure is outlined in Section 5.6.1. It begins with an approximation which, if giving satisfactory results, avoids the need for a more detailed assessment. If, however, the results indicate that the safety criteria could be exceeded or the EPR is considered to be excessive, the more refined assessment should be employed.

When an entirely theoretical approach is used for assessing the design of an earthing system, doubts on the reliability of the result may arise due to uncertainties as to the correct value of soil resistivity to be used or of the effects that other buried structures may have. In these circumstances, direct measurements may be carried out to obtain a more reliable result.

Recommended methods of measurement are given in Section 7.5. If the earth electrode system is not yet installed, measurements may be made on representative test electrodes and the results extrapolated to the intended final design. Measurement may be delayed until a sufficiently representative part of the intended system is installed to obtain a better prediction of any improvements necessary. In any event, a final check measurement of the completed installation is recommended prior to energisation.

5.6.1 Design flowchart

The general approach is summarised in the flowchart below.


Obtain basic data (Section 5.4) – including substation plans, fault levels, earth fault clearance times and supply arrangements.
Select earthing conductor and earth electrode sizes according to fault level and duration – see Section 5.5
Use a design or apply standard design methodology (Section 5) to meet functional requirements of Section 4
See Section 9.4 for consideration of whether the installation can be considered part of a global earthing system. Usually applicable to small substations only.
Existing site or connected to existing infrastructure?
Yes
Assess and measure existing earthing (Section 7)
No
Global Earthing System?
Yes
In Urban Location?
No
Cable fed and impedance earthed
No
No
Carry out soil resistivity measurements and/or obtain soil data (Section 7.4)
Consider soil model (Section 7.4.3)
Design electrode system based on standard methodology (Sections 5.4, 6)
Yes
Yes
Install standard design or use standard methodology (Section 5.4)
Use soil and electrode parameters to estimate resistance values with parallel paths (EREC S34 Appendix B)
Calculate EPR - use appropriate fault current (Section 5.4) and obtain ground return components (EREC S34 Appendices D and E). Evaluate EPR for all voltages, including transfer voltage where relevant.
Yes
Is EPR < 2x Touch Voltage Limit (UTP)
A "Yes" result may not mean a design is safe where equipment is situated outside the area of the MES
No
Calculate touch voltages and transfer voltages (using EREC S34 or computer modelling)
Yes
Touch, transfer and surrounding voltages acceptable?
Assess transfer voltage to LV network, where appropriate.Also consider the radius of any 'HOT' zone or High EPR area if this may impact on third parties.
No
Difficult / impractical / uneconomical to implement additional measures
Re-design feasibility assessment (Section 5.6.3)
Carry out Risk Assessment (Section 5.7 and BS EN 50522)
No
Practicable to implement additional measures?
Yes
Modify design or apply additional measures similar to BS EN 50522 Annex E or beyond, or measures to reduce EPR (preferred – Section 5.6.3)
Risk Acceptable?
No (exceeds broadly acceptable threshold)
If in 'tolerable' region, calculate justifiable spend
Modify design (Section 5.6.3)
Yes
Finalise / Approve detailed design for installation; check consistent with good engineering practice
Use methods described in Section 6 to install system
Carry out commissioning measurements (Relevant parts of Sections 7.5 – 7.11)
Yes
Measured figures better than or equal to design figures, or otherwise confirm adequacy to meet design requirements
Reasonable agreement with design?
No
Review Design Calculations
Differences significant?
Yes
Installation Complete
No

5.6.2 Assessment procedure

An approximate assessment considers both the internal and external earth fault conditions as explained above but disregards any contribution from external electrodes, e.g. overhead line earth-wires or cable sheaths. This may be all that is required in many cases providing compliance with the safety criteria is demonstrated.

With reference to the flowchart in Section 5.6.1:

1. Establish the soil resistivity (by measurement or enquiry).
2. Estimate the resistance of the site electrode system (using computer modelling or formulae given in Appendix B of ENA EREC S34).
3. Obtain the worst-case fault current flowing through the electrode system, disregarding the effect of fortuitous electrode systems or cable sheath/earthwire return paths.
4. Estimate the EPR, which is the product of resistance (point 2 above) and current (point 3).
5. If the value derived in (4) above does not exceed 2x the permissible touch potential, no further assessment should be done. The finalised design of the earthing system may be prepared taking into account the earthing and electrode conductor ratings.

   If the value derived under (4) above exceeds the appropriate safety voltages by a factor of 2 or more, a more refined assessment should be made as detailed below.

6. Determine the soil resistivity by measurement.
7. Estimate the value of the substation earth electrode system resistance, including the contributions made by any overhead earth wires and/or earthed cable sheaths radiating from the site using the preliminary design assessment layout and the data provided in ENA EREC S34.
8. Obtain the appropriate total values of system earth fault current for both an internal and external earth fault and deduce the greater value of the two following quantities of earth fault current passing through the earth electrode system. See ENA EREC S34 for guidance on this evaluation.
9. For an internal fault, establish the total fault current less that returning to any local transformer neutrals and that returning as induced current in any earth wire or cable sheath/armour.
10. For an external fault, that returning to local transformers less that returning as induced current in any earth wire or cable sheath/armour.
11. Estimate the rise of earth potential (EPR) based on the product of items (7) and (9) or (10) above, whichever is the greater.
12. If the EPR value derived under (11) above exceeds 2x the permissible touch or step potentials, an assessment covering touch, step, and transfer potentials should be made. The design should consider LV, telecoms, and remote systems where relevant.
13. If the earthing system is safe against touch potential, it will almost always be safe against step potential[3], although special consideration may be needed in certain situations such as wet areas, livestock, etc.

Reference should be made to Appendix B of EREC S34 for formulae giving ground surface potential contours; the touch potential is the difference between EPR and ground surface

[3] BS EN 50522 states: "As a general rule meeting the touch potential requirements satisfies the step potential requirements, because the tolerable step potential limits are much higher than touch potential limits due to the different current path through the body."

potential up to 1 m from plant / bonded items. Computer modelling may be necessary for complex systems.

Depending on the results of the evaluation, further improvements in the design of the earth electrode system may be necessary until the appropriate safety criteria for touch, step and transfer potentials are met and any necessary isolation or additional insulation is provided to avoid contact with transferred potentials which exceed the appropriate safety limit.

5.6.3 Methods to improve design (mitigation measures)

Following assessment, if the safety criteria are not met, the designer should consider ways to either reduce overall EPR, or reduce the step/touch potentials.

5.6.3.1 EPR reduction

As described in Section 4.4.1, there is no specified limit to the EPR of the substation and the ultimate design limit is dependent on a number of factors. However, improvements may sometimes be justified to lower this value by reducing the value of the earth electrode resistance. If, for example, the surface potential outside the substation exceeds that which is acceptable to third parties in that area (e.g. telecoms or pipeline operators), lowering the earth electrode resistance may be considered.

Reduction of earth resistance by extending the electrode area may increase transfer potential onto third-party metallic services and this should be considered in the design. It may be more practicable to protect the other authorities' plant by isolation or additional insulation.

EPR (arising from local faults) can generally be reduced by one or more of the following.

- Earth resistance reduction.
- Fault level reduction. This can be achieved by impedance earthing (Section 4.5.1), or changes to running arrangements, or possibly more accurate calculation of earth fault level including earth resistance values, which may be of benefit in marginal situations.
- Ground return current reduction. This can be achieved by lower impedance metallic return paths, e.g. enhanced cable sheaths or earth-wires, or undergrounding a section of overhead line to make a complete cable circuit.

An excessive EPR arising from transfer potential, e.g. carried along the cable sheath from the source substation, can be reduced by lowering earth resistance or by introducing a sheath break into the cable (e.g. by using an insulated gland or unearthed overhead line section). Special care is required in such circumstances to ensure that a person cannot simultaneously make contact with two earthing systems. There may be other considerations which make a sheath break unacceptable or ineffective in some circumstances. Alternatively, measures could be taken to lower the EPR at the source substation. In any case, the design should be re-assessed to consider these revised arrangements.

5.6.3.2 Touch potential reduction

If reduction of EPR is not practicable or economic, touch potential can be reduced by adopting measures to equalise potential between an operator's hands and feet; generally these measures involve additional bonded grading electrode or mesh under the operator's position, or insulated platforms.

Formulae are given in Appendix B of ENA EREC S34 for simple touch potential calculations.

The touch and step potentials should be re-calculated or re-modelled following any changes to the electrode layout. The touch potentials appearing on external parts of a substation (fences/doors/substations) should also be considered as these could cause issues for members of public.

5.7 Risk assessment

As set out in BS EN 50522, risk assessment is one of the acceptable tools for analysis of situations where the cost of removing an identified risk appears to be disproportionately high. A risk-based approach should consider the statistical probability of injury occurring and to weigh this against the cost needed to mitigate against that risk.

Risk assessment should only be used in circumstances where strict compliance with permissible safety voltage limits is not reasonably practicable, and where there are valid and well documented reasons for this. In practice, it is most appropriate outside an installation as it should almost always be possible to achieve safe (deterministic) step and touch potentials within site boundaries.

A worked example is given in Section 11.1.

It is recommended that a risk assessment should be regularly reviewed to take into account any changes which could affect the results.

5.7.1 Methodology

The individual risk of fatality per year (IR) for a hypothetical person is calculated from the mean number of significant EPR events (f_n) per annum, the probability of exposure (P_E) and the probability of fibrillation (P_{FB}). A simplified formula applicable to power system applications is:

$$IR \cong f_n * P_E * P_{FB}$$

This simplified formula is in line with that given in Annex NB of BS EN 50522.

NOTE: A hypothetical person describes an individual who is in some fixed relation to the hazard, e.g. the person most exposed to it, or a person living at some fixed point or with some assumed pattern of life [see HSE document R2P2]. To ensure that all significant risks for a particular hazard are adequately covered, there will usually have to be a number of hypothetical persons considered.

P_E and P_{FB} are dimensionless quantities; P_E relates to the proportion of time that an individual is in contact with the system. P_{FB} can be derived from body current calculations and fault clearance times, with reference to Figure 20 of DD IEC/TS 60479-1. The assessment should in the first instance use the higher P_{FB} for the band (e.g. 5 % for the 0-5 % band AC-4.1 between lines C1 and C2). An interpolated rather than upper-bound P_{FB} may be justifiable in some circumstances.

It is recommended that the large area dry contact impedance model not exceeded for 5 % of the population is used (Table 1 of DD IEC/TS 60479-1) unless specific circumstances apply.

The calculated individual risk is then compared to a broadly acceptable risk of death per person per year as defined in HSE Document R2P2. If the risk is greater than 1 in 1 million (deaths per person per year), but less than 1 in 10,000, this falls into the tolerable region and the cost of reducing risk should be evaluated using ALARP principles taking into account the expected lifetime of the installation and the HSE's present value for the prevention of a fatality (VPF) to determine the justifiable spend for mitigation.

Where the justifiable spend is significantly less than the cost of mitigation, risk assessment may justify the decision whether or not to take mitigating action. Mitigation may include (and is not limited to) new or relocated barriers/fences, insulating paint, earthing redesign, substation relocation, restricted access, appropriate signage, protection enhancements, reliability improvements, EPR reduction, insulated ground coverings or fault level modification.

5.7.2 Typical applications

Typical applications for risk assessment may be those outside an installation, on the basis that it is almost always possible to control step and touch potentials within the confines of a substation by using appropriate buried electrode and/or ground coverings. Risk assessment is not appropriate for situations where the presence of an individual increases the likelihood of an earth fault, e.g. switching operations or work in substations or HV installations.

Case Study 1 in Section 11 gives a typical example of a fence that has been built close to a substation having HEPR. Under substation fault conditions, touch potentials exceeding permissible design limits can appear around the fence due to differences between the elevated soil potential and that of the fence. The risk assessment approach allows the need for mitigation measures to be evaluated.

6 Construction

6.1 General

Above-ground connections may use copper or aluminium conductors. Metal structures may be used to provide connections between equipment and the earthing system where appropriate.

Below-ground earthing systems will normally be installed using copper conductor.

When designing and installing both above and below ground earthing installations, the risk of theft and corrosion should be considered and mitigation measures put in place where necessary.

6.1.1 Materials

The use of copper earthing conductor is preferable due to its electrical and material properties.

Copper tape and (hard drawn) stranded copper conductor (minimum strand diameter 2 mm) are both suitable to be used as a buried electrode.

Bare aluminium conductor or copper rope (fine braided) are not suitable for use underground in any circumstances due to the risk of accelerated corrosion. Aluminium conductor is less prone to theft and may be used provided it is at all points at least 150 mm above the ground.

Galvanised steel may be used as supplementary electrode where it is already installed for other reasons. Consideration should be given to the risk of corrosion over the lifetime of the installation. Galvanised steel has an electro potential different to that of copper and can erode quickly if connected to a system which has copper electrodes.

In very hostile environments, it may occasionally be necessary to use more resilient materials such as stainless steel.

6.1.2 Avoiding theft

At the design stage, all exposed copper electrode should be reduced to a minimum. On new installations above ground, exposed copper and aluminium sections should be fixed using anti-theft fixing techniques. See Section 6.3.1 for conductor fixing detail.

At new and existing high risk sites the use of additional anti-theft precautions should be considered.

Precautions above ground may include:

- application of anti-climb paint on above-ground sections and / or above-ground copper may be painted to look like aluminium or galvanised steel.
- fitting galvanised steel anti-theft capping over the conductor to a height of at least 3 m or the equipment position.
- fitting steel banding around structures and pinning the fixings.
- stamping copper tape electrode with the owner's name.
- earth connections to such items as metal cladding, metal structures, metal door frames or any other metallic panels should be made inside buildings.
- additional site security precautions such as the application of alarms, electric perimeter fences, CCTV etc.
- use of forensic traceable liquids.
- avoiding yellow/green insulated coverings (use e.g. grey instead).

Precautions below ground may include:

- placing concrete or concrete anchor blocks over buried electrode.
- attaching earth rods every few metres to prevent removal of electrode.
- pinning electrode at least every 300 mm where it is installed in concrete trench work or over concrete plinths.
- laying electrode in conductive concrete or similar materials.

Earthing conductors located in pre-formed concrete trenches (or similar) containing power and/or multicore cables should be fixed to the walls near the top (e.g. 100 mm from the top). Where possible, they should be concealed or otherwise protected against theft.

6.2 Jointing conductors and equipment connections

6.2.1 General

Exothermic welded, brazed and compression type joints are acceptable above and below ground and are suitable for all substations. For ground-mounted distribution substations, bolted joints are also permissible, provided they are adequately protected against moisture ingress.

For connections made to equipment, welded joints may be possible, but in the majority of cases bolted joints will be necessary. The provision of bolted earth connections on equipment needs special consideration to achieve a low resistance arrangement which can withstand the maximum earth fault current without deterioration. Purpose designed connections should preferably be provided by the equipment manufacturer.

Bolted connections should preferably be of the double bolt / double hole lug fixing type, however this generally requires drillings to be provided at the equipment procurement stage. Where single bolt / single hole lug fixings are provided, the application of a washer and second (lock) nut gives extra security.

With aluminium conductors in particular, surface preparation is critical to achieving connections with ongoing low resistance.

Nuts, bolts and washers should be of high tensile stainless steel or galvanised steel, except for transition washers used for joining dissimilar metals.

6.2.2 Transition washers

A transition washer may be used to minimise corrosion when joining dissimilar metals with a bolted connection. Transition washers designed for copper-aluminium joints should be surface penetrating, grease protected washers manufactured from corrosion resistant copper alloy to BS EN 2874 (grade CZ121). They are designed to provide a stable corrosion resistant interface between aluminium and copper or tinned copper, and are usually provided as a pack including appropriate matched nuts, bolts and washers.

Different transition washers may be required for connections from copper to galvanised metal.

Transition washers tend not to be widely used for connections between aluminium and zinc coated (galvanised) steel, because zinc and aluminium are very close in the galvanic series. However, such connections are likely to corrode once the zinc coating has been lost, and therefore precautions should be taken to exclude moisture by use of an appropriate grease or paint applied after the joint is made.

6.2.3 Copper to copper joints

Tape to tape connections should be brazed or exothermically welded, except for smaller distribution substations where hot works may not be practicable.

Connections between stranded conductors should be exothermically welded or joined using compression joints.

Stranded conductor to tape connections should be exothermically welded or a lug should be compressed onto the stranded conductor, which for underground use is bolted and then brazed or welded onto the copper tape. For above ground purposes, the lug may be bolted to the tape but should preferably have a double bolt fitting.

Soft soldered joints (e.g. lead-tin or lead-free solder) should not be used.

6.2.4 Copper connections to earth rods

Connections should be brazed or exothermically welded. Bolting and U-bolts should not be used, except for smaller distribution substations where hot works may not be practicable.

6.2.5 Electrode test points

Electrode test points may be required either at the rod top for long single rods or inline between a rod group and the main earthing system. To allow individual rod resistance values to be tested with a clip-on meter and facilitate electrode tracing, all test points should be constructed to allow the test clamp to fit and to avoid corrosion.

Test links are not recommended but where installed, special procedures should be adopted to avoid inadvertent disconnection and to permit safe management/testing techniques.

A test point associated with pile cap connections is useful but only if the design of the re-bar is electrically separated from the rest of the site. At most sites, the re-bar will be connected together and while this provides an excellent earth, testing the individual pile cap earths is impossible. In these cases, separate earth pins should have been provided in the design, perhaps for high-frequency and/or lightning protection, which will allow testing between individual earth rods and the MES.

6.2.6 Copper connections to equipment (steel or galvanised steel)

Connections should wherever possible be in the vertical plane. Remove paint from the metal at joint position on the equipment earth, sand metal smooth and apply neutral jointing compound. Drill the copper tape to accommodate the bolts (normal diameter is 10 mm) and tin the complete contact area. The bolt holes should be less than one-third the width of the tape. Failing this, a copper flag should be jointed to the copper tape and the holes drilled into this. A two-bolt fixing is preferred, unless a suitably rated fixing is provided by the manufacturer. Copper joint surfaces, once drilled, should be cleaned using aluminium oxide cloth (grade 80). Copper is tinned at all bolted connections; the tinning should be thin, and should not exceed an average of 0.5 mm, otherwise it will flow from bolted sections under pressure. Neutral jointing compound should then be applied to the joint faces.

The same procedure should be used when joining to galvanised steel, in which case the zinc coating should be removed from the joint faces.

6.2.7 Aluminium connections to equipment

Aluminium conductor connections to equipment should, where possible be in the vertical plane. In all cases joints should be made in accordance with the procedure for copper connections Section 6.2.6. However, the aluminium tape should not be tinned, and appropriate transition washers should be used at the aluminium to steel interface (but also see Section 6.2.11).

6.2.8 Aluminium to aluminium joints

The preferred method is either inert-gas tungsten-arc (TIG) or inert-gas metal arc (MIG) welding provided that the area of the welded material at least matches that of the tape cross section. Bolted joints are acceptable above ground.

For bolted joints, the following applies:

- All joints require a two bolt fixing.
- Bolts should be of high tensile galvanised steel, fitted with large diameter galvanised steel washers, or (optionally), transition washers designed to penetrate the aluminium oxide coating.
- The surface aluminium should be cleaned using grade 80 aluminium oxide cloth or equivalent and coated with neutral compound grease. This may not be necessary if a transition washer is used, in which case manufacturers guidance should be followed.
- Bolts should be tightened using a torque wrench, to avoid over stressing in accordance with Table 9. It is important not to compress aluminium connectors by excessive tightening, as loss of elasticity by plastic deformation can result in loosening of the connection when subject to thermal cycling.
- All excess grease should be wiped off the finished joint.
- The joint should be sealed against ingress of moisture.

Table 9 – Bolt sizes and torques for use on aluminium

Bar width (mm)	Bar overlap (mm)	Bolt diameter (mm)	Hole diameter (mm)	Recommended torque (Nm)	Washer size (mm)	Washer thickness (mm)
40	80	10	12	35	OD 25 ID 11	2.5
60	100	12	14	50	OD 28 ID 12.5	3.0

6.2.9 Aluminium to copper joints

Connections are to be in the vertical plane, at least 150 mm above the ground or concrete plinth. They should be located in positions where water cannot gather and the aluminium will be above the copper. Bi-metallic joints should not be made on buried sections of conductor.

All connections involving dissimilar metals should be cleaned with abrasive cloth and coated with neutral compound grease, before making a bolted connection. Copper should be pre-tinned. The finished joint should be sealed using bitumastic paint, compound, waterproof tape or a heat shrink tube filled with neutral grease. A transition washer (see Section 6.2.2) may be used to minimise corrosion at bolted joints.

Where joints have been made closer to ground level than 150 mm (usually following theft), a corrosion risk assessment is necessary. If the ground is well-drained and there is little chance of water being retained around the joint, the above arrangement is acceptable. If not, the copper should be extended upwards to reduce risk of corrosion.

6.2.10 Earthing connections to aluminium structures

The following procedures are necessary to ensure that aluminium structures used to support substation equipment do not corrode:

- The bottom surface of the structure base and the top surface where galvanised steel or other equipment is to be fitted, should be painted with two coats of bitumastic paint, prior to bolting into position on the concrete plinth.

  NOTE: This reduces the possibility of bi-metallic action which would corrode the aluminium.

  A conducting strap is required between any steel of the top level equipment support and the aluminium structure.
- Provision should be made for connecting below-ground conductor to the structure via a suitable drilling and bi-metallic connection (see Section 6.2.9).
- Except for fault throwers and high-frequency earths (capacitor voltage transformers and surge arrestors) the aluminium structure leg(s) may be used to provide earth continuity down to the connection to the MES. The following is also necessary:

Any bolted sections of the structure that may be subject to bi-metallic corrosion, and/or may be of insufficient cross section, should be bridged using aluminium earth tape. The bridged joint should be made as any other aluminium to aluminium earth connection. Totally tinned copper straps (see Section 6.2.9) may be used if necessary on connections to insulator supports from the aluminium. The copper and completed connection should be painted to prevent moisture ingress and corrosion.

The aluminium structure should be connected to the MES, using copper tape that is tinned (see Section 6.2.9) at the joint position.

Where the legs of the support structure are greater than 2 m apart or the structure forms a bolted TT (or goal post type) formation, an earth connection should be made on two legs of the structure.

6.2.11 Steel structures

The legs of steel structures should be used wherever practicable to provide the connection between the earthing system and supported equipment, except for fault-throwing switches and earth switches. For equipment requiring high-frequency earths (e.g. CVTs and surge arrestors), see Section 6.14.

Ideally, the structure should be of the welded type or have one or more legs formed with a continuous section from ground to equipment level.

If a steel structure is used to convey fault current, it should be reliable, and of sufficient current carrying capacity to avoid excessive temperature rise. If there is reliance on a single joint or leg, bolted shunts should be considered. Where bolted shunts are used, the temperature rise of bolted connections should be limited to 250 ºC. See Section 5.5.1.

Joints should be reliable. Galvanising (zinc coating) of the steel forms an oxide which increases in thickness with age and could create a high resistance at joint surfaces.

Where aluminium tape is connected to a galvanised steel structure, a transition washer is not required, provided the joint surfaces have been adequately prepared and the joint is protected from water ingress.

6.3 Above-ground earthing installations

6.3.1 Fixing above-ground conductor to supports

Bare copper or aluminium tapes should not be in direct contact with steel (or galvanised steel) structures, since electrolytic corrosion will result at the contact areas. The tapes should be held clear of the structures using non-metallic spacers, or corrosion prevented using sleeving or paint/greases to exclude moisture.

To prevent theft, the following methods of fixing should be used:

- Pinning at least every 300 mm for higher security using stainless steel pins. The pins should have plastic spacers to separate the pin from the conductor. Plastic spacers should separate uncoated aluminium or copper tape from galvanised steelwork.
- Drilling and screwing with tamper proof screw heads. This method is more appropriate if the concrete support may be damaged by use of percussion driven pins. A plastic spacer is required to separate the screw from the metal. The screws should be stainless steel.

It is important that the pins or screws are fitted such that water cannot gather and cause corrosion. Aluminium should preferably not be in direct contact with concrete, so if practicable, the back of the conductor should be coated with a high temperature aluminium grease or other heat-proof coating.

Consideration should be given to the reduction of conductor cross-sectional area and current carrying capability due to drilling. Any holes introduced into the earth conductor should not exceed 10 mm in diameter and one third of the width.

The design final temperature of any bolted connection is 250 ºC, compared to that of 405 ºC (copper) and 325 ºC (aluminium). Consequently, earthing conductors with bolted connections have a rating that is between 80 % and 90 % of their normal value.

6.3.2 Prevention of corrosion of above-ground conductors

Copper strip conductor in contact with, galvanised steel should either be tinned or coated in a high temperature grease to prevent electrolytic action.

Unless it is protected, aluminium earthing conductor should not be laid within 150 mm of ground level.

6.3.3 Metal trench covers

Within substation buildings, metal trench covers need to be indirectly earthed. This is best achieved by installing a copper strip (25 mm x 3 mm) along one edge of the trench top edge. The covers will be in contact with this when in position. The copper strip should be bonded to the switchgear earth bar or internal earthing system.

6.3.4 Loops for portable earth connections

Earth loops of aluminium or copper strip conductor connected to the structure earth connection, should be provided at appropriate locations where portable earth leads need to be applied. The loops, if not provided as part of the structure, should preferably be formed separately and jointed to the aluminium or copper tape. The loop should be not less than 230 mm long and 75 mm high and suitable for connection of portable earths complying with ENA TS 41-21.

Loops should not be installed in the run of high-frequency earths associated with CVTs and surge arrestors since these will introduce a high impedance to high-frequency/steep fronted surges. A loop for portable earths may be added in parallel to the straight earthing conductor rather than as a loop formed in the earthing conductor itself. D loops should only be installed on fully rated conductors.

6.4 Below-ground earthing installations

6.4.1 Installation of buried electrode within a substation

The electrode should be installed at a depth of at least 600 mm to give physical protection to the electrode and connections. This also tends to place the electrode in moist soil below the frost line so helping ensure its resistance is stable. The resistivity of ice is in the region 10,000 to 100,000 Ω.m (compared with 10-1000 Ω.m for most soils) and therefore the resistance of an earthing system will increase significantly if it is not clear of frost.

Buried earth electrode should be surrounded by 150 mm of fine texture non-corrosive soil, firmly consolidated. The use of pulverised fuel ash (PFA) or coke breeze as backfill is not recommended as it may induce rapid corrosion of buried electrode and metallic cable sheaths.

Where there is a risk of corrosion, the electrode size may need to be increased.

If the indigenous soil is hostile to copper, i.e. acidic with a pH value of less than 6 or alkaline with a pH value of more than 10, suitable surrounding soil should be imported. However, if groundwater is present (which may serve to remove the imported soil), other methods may be necessary to protect the electrode. More regular testing or inspection may be required.

When laying stranded conductor, care should be taken to avoid distorting and opening the individual strands because this increases the probability of accelerated corrosion.

6.4.2 Positioning of buried electrode

Earth electrode should not be laid close and parallel to hessian-served power cables, multicore cables, or bare metal pipes. This is to reduce the risk of puncture due to high currents or voltage transients on the electrode.

Electrode should be at laid at least 300 mm away from hessian-served power cables and bare metal pipes and 150 mm away from plastic sheathed cables. Where a crossing is necessary, PVC tape or a split plastic duct should be applied around the cable or pipe for 0.5 m either side of a position where the cable or pipe crosses an earth electrode, or for the distance over which the 0.3 m separation cannot be maintained.

Where copper tape within the site is to be buried under proposed cable routes care should be taken to ensure it is buried deep enough or otherwise protected in a duct so that it is not damaged during cable installation.

Where electrode connected to the earthing system is laid under metal fencing, and the fencing is independently earthed, the electrode should be insulated for at least 2 m each side of the fence.

Earthing conductors laid near drainage pits or other civil works should maintain a separation of at least 500 mm to avoid mechanical damage during subsequent works.

Where bare electrode has to cross permanent trench routes:

- short lengths of electrode may be laid under the trench for later connection to the grid;
- a short duct may be laid under the trench to accommodate the electrode.

Subsidiary connections to equipment may be laid at shallower depth. Due to variation of soil resistivity near the surface, their contribution to the overall earth resistance should be ignored in the design. Their contribution towards reducing touch and step potentials should be included.

In cases where a concrete plinth covers the whole substation site, (e.g. 11 kV/LV unit type or urban 33 kV substations) earth electrodes should be installed prior to construction of the plinth. Provision should be made to bring multiple connections out through the concrete. The extent of the electrode mesh required will be influenced by whether steel reinforcing is used and bonded, within the foundation.

When routing bare 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 should be avoided.

If this is not possible, calculations or computer modelling should be used to confirm that the step potentials in these areas are acceptable (a design figure of 25 V/m may be used for livestock areas as described in Section 4.4.2). Where electrode crosses land that is ploughed it should be installed a minimum of 1 m deep.

When re-bar is installed in building and equipment foundations, duplicate connections may be made from the re-bar to the grid for touch potential control. (See Section 6.5).

Burying copper in concrete below ground level, and at a depth such that the moisture content remains reasonably stable, does not reduce the effectiveness of the earthing (except where damp-proof membranes are installed).

6.4.3 Other earth electrodes

6.4.3.1 Earth rods

These are generally convenient to install where the subsoil is free from boulders and rock. Rod electrodes and their connections should be in accordance with ENA TS 43-94. The earth resistance of a rod or group of rod electrodes may be calculated from formulae given in Appendix B of ENA EREC S34.

A number of rods may be connected in parallel but they should be installed with sufficient spacing such that each is essentially outside the resistance area of any other. For worthwhile results, the mutual separation should be not less than the depth of the rod.

The rods may be connected to the earthing system via a test chamber which is capable of accepting a clip-on resistance meter.

Deep earth electrodes should, as far as possible, be driven into the earth vertically. If rods are installed in drilled holes, they may be backfilled with a proprietary low resistance backfill material.

Rods may be particularly advantageous if the earth resistivity falls with depth. If several deep earth electrodes are necessary in order to achieve a required parallel resistance, where space is available the mutual minimum separation could usefully be double that of the effective length of an individual earth electrode.

Substations in large urban developments are often located below ground level in tanked structures. In such situations, special facilities for installing earth electrodes are required.

6.4.3.2 Earth plates

Earth plates have been used in older earthing system designs when they were often situated in groups or “nests” near the main transformers. Modern designs make little use of plates, except where the soil is such that it is difficult to drive in earth rods or at the corners of the earthing system perimeter electrode. In this case a plate will be installed in the vertical plane and acts as a replacement for a rod.

In older sites, should an earth plate require replacement, it is likely that the earthing system itself will require redesign and this may render the plate obsolete. Where there is any doubt, the plate can be replaced on a like-for-like basis, or by several 2.4 m rods in parallel, close together. Plates are typically 1220 mm or 915 mm square in size, of ribbed cast iron and approximately 12 mm thick.

6.5 Use of structural earths including steel piles and re-bar

Structural metalwork (piles and foundations) can make a valuable contribution to an earthing system, specifically providing parallel paths for earth fault current, reducing overall earth resistance and increasing resilience. Such contributions should be viewed as additional to, rather than instead of, a dedicated earthing system, unless they have been designed for that purpose.

Horizontal (meshed) re-bar installed in concrete or in a screed below plant can provide good control of touch potentials. Use of re-bar should be primarily viewed in terms of touch potential control, rather than as an electrode system.

6.5.1 Sheet steel piles

Sheets that are more than 3 m long and 2 m wide should be bonded to the earthing system. Stainless steel studs are to be exothermically welded to each second sheet at a suitable height (normally 600 mm below finished ground level) and a strip of 40 mm x 4 mm copper tape will be bolted to these. The strip will in turn be connected to the MES. If the piles form a separate electrode connected to the earthing system at one point, the connection should be via a test chamber such that the contribution of the piles may be monitored. Bolted connections should be avoided where possible.

6.5.2 Horizontal steel-reinforced foundations

For transformer and switch rooms, the most significant benefit of shallow re-bar mesh is in potential grading (touch potential control). Where this is necessary to ensure operator safety (i.e. in situations where the EPR exceeds safe touch potential limits), it is important to ensure the integrity of any connections.

For touch potential control, re-bar will be installed normally at shallow depth (i.e. with the re-bar strips bound with soft steel wire, or as a prefabricated mesh), but with two or more re-bar connections left protruding from the concrete for approximately 150 mm sufficient to allow connection to copper or aluminium conductors. Alternatively, connections may be provided before concrete is poured using a re-bar clamp with flexible earth conductor. In either case any inaccessible re -bar extension used for the final connections should be welded to the main re-bar assembly.

Ideally the re-bar should be arranged with welded connections along at least two orthogonal edges such that welded joints connect each bar.

If the re-bar is to function as an auxiliary earth electrode (e.g. it is installed at sufficient depth to make a contribution), current rating considerations may mean that exothermic welding is necessary for connections to the re-bar and between re-bar meshes.

NOTE: Protruding re-bar may not be acceptable in some circumstances due to concerns with water ingress etc.

6.5.3 Vertical steel-reinforced concrete columns

Where these columns have steel reinforcing that extends further into the ground than it is possible to bury a conventional earthing system, the design may require these to be bonded to the earthing system. The easiest method is to leave a section of bonded re-bar 150 mm out of the concrete for a connection to be made later by the earth installers. This should have its electrical continuity maintained at joint positions by welding the connections. Some designs require electrical connections between the piles made with re-bar. In this case, supervision of the civil works will be required before concrete is poured.

NOTE: Protruding re-bar may not be acceptable in some circumstances due to concerns with water ingress etc.

6.6 Metallic fences

This Section mainly applies to EHV outdoor substations; however, the principles in this Section may also be applied at HV where necessary in order to ensure that touch potentials are within permissible limits.

Two alternative earthing arrangements may be applied to metallic substation fences. These are:

- an independently earthed (or segregated) fence arrangement where the fence is kept electrically isolated from the substation MES (Figure 2).

  or

- a bonded fence arrangement where the fence is bonded to the substation MES (Figure 3).

Occasionally it may be appropriate to employ both methods on different fence sections at the same site. In this case insulated sections are used to physically link the fences with different earthing arrangements.

Where the fence panels are supported by steel posts that are at least 1 m deep in the ground, the posts can be considered as earth electrodes.

Where it is important to provide electrical continuity between adjacent panels (e.g. where overhead lines cross, or run in parallel with the fence or in proximity to magnetic fields), this can be provided by attention to the bolt/fixing connections or by providing a separate continuity conductor which may be buried or supported on the fence.

6.6.1 Independently earthed fences

Where the MES is effectively within the substation perimeter fence, the fence should be separately earthed with rods approximately 2.4 m long located at:

- all fence corners.
- 1 m either side of each point where HV overhead conductors cross the fence.
- additional locations such that the interval between rods sites should not exceed 50 m.

Gate posts should be bonded together with below-ground connections to ensure that potential differences do not arise when the two parts are bridged by a person opening the gates. Flexible bonds (minimum CSA 16 mm^2 cu or equivalent) should also be used to bond the gates to the posts as an additional safety measure.

6.6.2 Segregation between independently earthed fence and earthing system

A segregation distance above ground of at least 2 m should be maintained between the substation fence and the MES including all items connected to it. This is based on personnel avoiding simultaneous contact with the independently earthed fence and equipment connected to the earthing system. A similar distance should be maintained below ground, where practicable, taking into account the location of substation perimeter electrodes etc.

The 2 m segregation between the independently earthed fence and the earthing system should be maintained on an ongoing basis. This should not be compromised by alterations such as the addition of lighting or security installations, where e.g. cable armours can compromise the segregation of the systems.

Where the required segregation cannot be achieved, mitigation measures should be considered e.g. insulating paint or barriers that do not compromise security. Alternatively, the risk assessment approach outlined in Section 5.7 may be applied.

A formula for calculation of the touch potential on a fence is given in Formula P7 in Appendix B of ENA EREC S34.

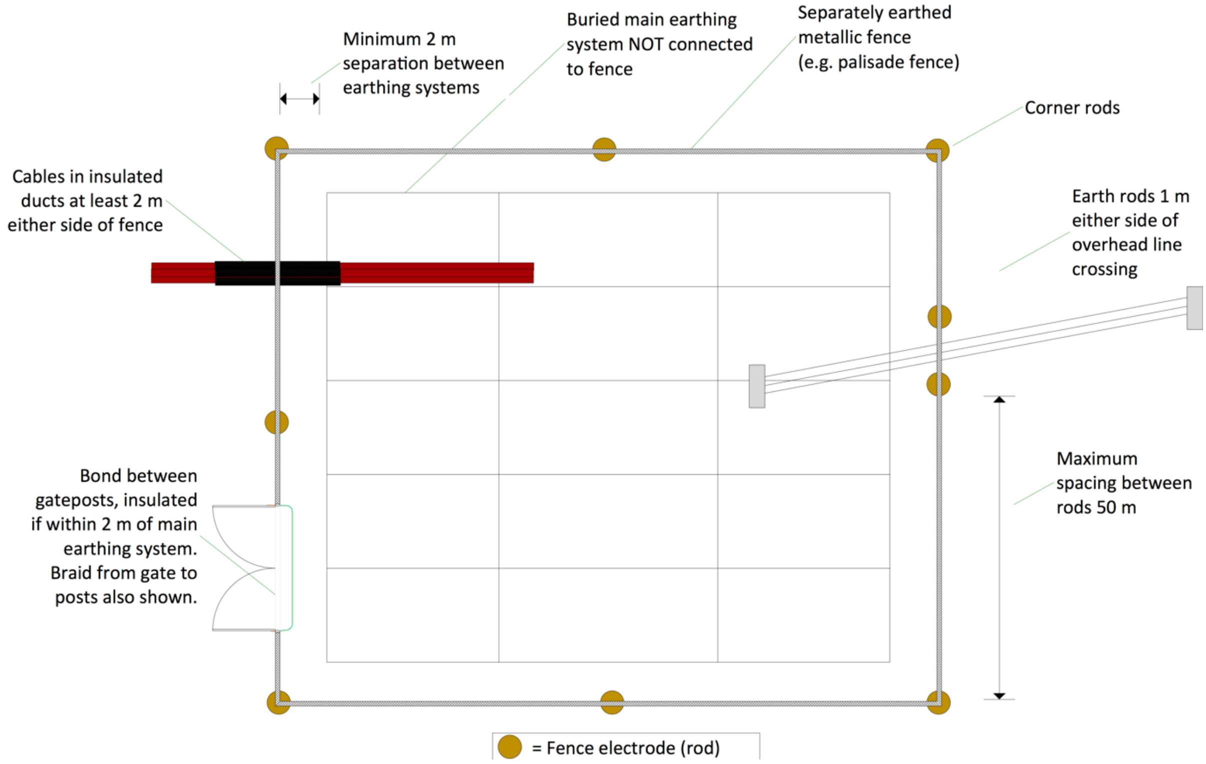


Figure 2 – Arrangement of separately earthed fence

6.6.3 Fences bonded to the substation MES

This arrangement is used where substation plant and equipment is located within 2 m of a metallic fence and where internal fences which are located within the area encompassed by the MES. The fences should be connected to the MES using discrete but visible connections located at:

- all fence corners.
- 1 m either side of each point where HV overhead conductors cross the fence.
- additional locations such that the interval between connections does not exceed 50 m.

Where the fence which is connected to the substation MES is the perimeter fence, and where the touch potential external to the fence could exceed the safety voltage limits set out in Table 1, the following requirements apply:

- A bare electrode conductor should be buried in the ground external to the perimeter fence at approximately a distance of 1 m and at a depth of 0.5 m. In agricultural locations, risk of disturbance due to ploughing should be addressed;
- The conductor should be connected to the fence and to the earthing system at intervals of 50 metres or less such that it becomes an integral part of the MES. One method to achieve this is to expand the substation grid such that the fence is located within the area of this grid. (Figure 3)
- Chippings around the substation perimeter will provide additional protection to animals/persons outside the substation.

At locations where fencing connected to the substation MES abuts with independently earthed fencing and this presents a touch hazard, there should be electrical isolation between the two fence systems. See Section 6.6.5 for methods of achieving electrical isolation between fences using insulated fence sections.

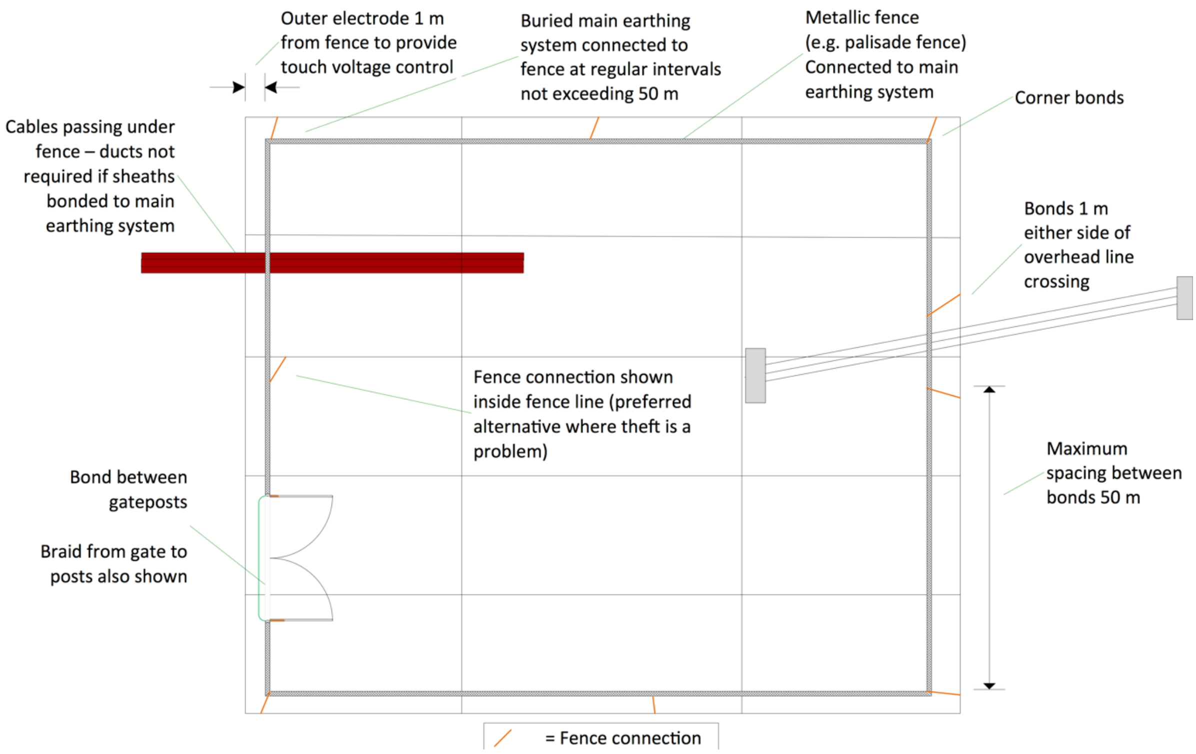


Figure 3 – Arrangement of bonded fence

6.6.4 Third-party metallic fences

Third parties should not directly connect their metal fences to a metallic substation fence, as this may introduce a transfer potential risk. Where such third-party fences are present or are likely to be present within 2 m of the substation, one of the options listed below should be implemented to maintain electrical isolation between the two fence systems.

Note: Security considerations may preclude this if the third-party fence could act as a climbing aid.

6.6.5 Insulated fence sections.

Insulated fence sections to segregate lengths of fencing which are bonded to the substation MES from those which are independently earthed or connected to third-party fences may be used. The insulated sections may be formed by:

- Installing a 2 m (or longer) insulated fence panel made wholly of insulating material.
- Installing a 2 m (or longer) metal fence panel mounted on insulated supports / standoff insulators. The insulators need a voltage withstand capability in excess of the highest EPR at the perimeter of the site whilst at least maintaining the equivalent physical strength of the fence.

Coated fences (see Section 6.6.7) should not be treated as insulated sections unless specifically designed and tested for such purposes.

6.6.6 Chain link fencing (galvanised or plastic coated)

Such fencing should be earthed by bonding the support posts, fence and straining wires and any anti-climbing devices to the independent or bonded fence earth electrode system as appropriate. This may conveniently be achieved by the addition of an electrode run with the fence to aid bonding/earthing. The fence should be treated as if it were bare metal, i.e. no insulation withstand should normally be assumed.

If a touch potential issue exists with a plastic coated chain link fence this should be addressed by installing a grading electrode rather than by relying on the integrity of the plastic fence coating which may not be comprehensive and is also likely to deteriorate.

6.6.7 Coated fence panels

These typically consist of galvanised steel support posts and galvanised steel mesh panels, all of which are coated. When used for enclosing electrical apparatus or a substation, they should be earthed and precautions are necessary to cater against damage or erosion of the coating. The support posts should be earthed via a bolted connection and ideally the metal of each panel should in turn be similarly connected to the post. Ideally these should be via manufacturer provided facilities. The overall fence is connected to earth in a similar manner to a separately earthed or bonded metal palisade fence.

Such fences should not be treated as insulating, unless the covering is specifically designed for this purpose and its longevity can be assured.

If a touch potential issue exists with a coated fence this should be addressed by installing a grading electrode.

6.6.8 Electric security fences

When electric security fencing is installed on independently earthed fence installations, the isolation of segregated fence sections from the substation MES should be maintained. This may require independent electric fence zones and special consideration of electric fence earth connections.

6.6.9 Anti-climbing precautions

Where barbed wire or other metal anti-climbing devices are erected along the top of brick walls or other non-metallic barriers they may be connected to earth using the same procedure as with fencing. Metallic parts not liable to introduce a potential, e.g. short lengths of barbed wire or spikes, need not be bonded.

Care should be taken to ensure that anti climbing guards do not bridge fencing sections that are designed to be separately earthed or isolated. This includes e.g. the metal centre rods of plastic vane guards.

6.7 Specific items

6.7.1 Water services to substations

Water supplies to substations should be run in non-metallic pipes. This avoids the substation potential rise being transferred outside so endangering other users of the water supply system. This is now largely a legacy issue at older sites as insulated pipes are used for new construction. When such an existing site is being refurbished or upgraded, a section of insulated plastic pipe should be inserted in the incoming metallic water service.

Any metallic pipe used within the substation site should be bonded to the MES and adequately segregated from separately earthed fence sections.

6.7.2 Non-current carrying metalwork

Most non-current carrying metalwork of all kinds within the perimeter fence should be securely bonded to the main earthing system to ensure that all such items are held to the same potential and, if called upon to do so, will carry fault currents without damage. Conductive parts not liable to introduce a potential need not be bonded.

The cross section of any bonding conductors should be as described in Table 5 and Table 6. If there is no likelihood of current flow or corrosion/erosion, equipotential bonding conductors should be no smaller than 16 mm^2 copper or equivalent.

NOTE: Small metallic items (extraneous metalwork) that are unlikely to introduce or carry a significant potential, need not be bonded to the main earthing system (see Section 4.2). Such items may include, but are not limited to, window frames, signposts, wall brackets, small access steps/handrails etc. However, if there is any foreseeable likelihood of them acquiring a potential in service sufficient to cause a touch potential hazard, such items should be bonded to the main earthing system.

Larger items, even if some distance from current carrying metalwork, may acquire a stray voltage due to inductive or capacitive coupling and should always be bonded.

6.7.3 Items normally bonded to the substation MES

These include:

- overhead line termination structures including towers, gantries and earthed wood pole structures within or adjacent to the substation.
- power cable sheaths and armours (at one or more points).
- transformer and reactor tanks, coolers and radiators, tap changers, earthing resistors, earthing reactors, high voltage transformer neutral connections.

- metal clad switchgear assemblies and cases, isolators and earth switch bases.
- metal gantries and structures and metalwork mounted on wood structures.
- metallic building structures including steel frames (bonded at each corner), re-bar and piles.
- miscellaneous metalwork associated with oil and air tanks, screens, steel structures of all kinds.
- all panels, cubicles, kiosks, LV AC equipment, lighting and security masts.

Critical items such as transformer tanks and terminal towers should have duplicate connections to the MES.

6.7.4 Items not normally bonded to the substation MES

The following list is not exhaustive, and includes some typical items that a designer may specify to remain unbonded.

- The perimeter fence is only bonded to the MES if all or part if it cannot be kept at least 2 m clear of earthed structures and the MES. (see Section 6.6).
- Screens of telephone cables where they are taken into HOT sites. (see Section 4.3.7).
- Extraneous non-current carrying metalwork (see Section 6.7.2).
- Parts intended to be isolated from earth, e.g. floating fence panels, some stay wires.

6.7.5 Non-standard bonding arrangements

Sometimes it may be necessary to isolate cable sheaths and screens from the substation MES to avoid transfer potential issues. Such arrangements should be the subject of a bespoke design and precautions taken at the earth isolation point to avoid touch potential issues.

NOTE: There may be other considerations which make a sheath break unacceptable or ineffective in some circumstances. ENA EREC C55 provides further related information.

6.8 Overhead line terminations

6.8.1 Tower terminations adjacent to substation

Where the aerial earth wire of an incoming overhead line terminates on a steel tower / terminal support adjacent to a substation, continuity should be provided for current in the earth wire to flow into the main earthing system by:

- bonding the aerial earth wire to the top of the line gantry, and bonding the base of the gantry to the MES.

  or

- bonding the aerial earth wire to the top of the tower, and bonding the base of the tower to the substation MES.

The current rating of the bonds should at least be equal to that of the aerial earth wire.

If not bonded via an aerial earth wire, the tower should be bonded to the MES via two continuous conductors which run from different tower legs via separate routes and connect to two different points on the MES. Each below-ground conductor should be fully rated. The bonds should be buried and be installed so as to minimise risk of theft. If the bonds run under an independently earthed fence, they should be insulated for a 2 m distance on either side of the fence.

If the tower legs are located within 2 m of an independently earthed metal fence, the section of fence adjacent to the tower should be bonded to the tower and electrically isolated from the rest of the fence. Alternatively, the relevant metal fence panels may be replaced by insulated panels, or suitable insulating coating applied (see Sections 4.4.3 and 6.6.7). If this is not practicable, a risk assessment should be carried out (see Section 5.7).

6.8.2 Steel tower termination with cable sealing ends

Where an aerial earth wire terminates on a tower with a sealing end platform or an associated cable sealing end compound that is well outside the substation, continuity between the base of the tower and the substation MES will be provided by either the sheaths of the power cables or by an earth continuity conductor laid and installed in accordance with ENA EREC C55.

6.8.3 Terminal poles with stays adjacent to substation fence

Stay wires that are external to the site and more than 2 m from the fence or earthed metalwork may be left unearthed, if this is in accordance with normal practice. They should be earthed within the substation compound where possible to minimise risk from current leakage across the stay insulator.

Earthed stay wires can present a touch potential risk if the stay is in very close proximity to an independently earthed fence, and may form an inadvertent connection between the independently earthed fence and the substation MES. To address this, in addition to installing the normal upper stay insulator a second stay insulator should be installed as close to ground level as possible leaving the centre section of the stay unearthed. 2 m segregation should be achieved between the lower earthed section of the stay including the rod and the fence.

Unless the earthed stay rod is inside the earthing system, a loop of buried electrode should be laid around the rod at a 1 m radius, and bonded to the rod/main earthing system to control touch potential.

6.8.4 Down drop anchorage arrangement with arcing horns

Where it is necessary to have an assembly of ferrous fittings such as turn buckles, links, shackles etc. between the insulators and an earthed structure or ground anchor point, precautions may be required if the earth fault current is very large.

The earthed-end arc-ring (or horn) anchorage arrangement may be attached to the main earth connection by means of a flexible copper shunt, in order to limit earth fault current flowing through the discontinuous ferrous fittings. This prevents mechanical damage due to arcing.

6.8.5 Loss of aerial earth wires

If alterations are carried out to overhead lines which break an otherwise continuous aerial earth wire between substation sites, consideration should be given to the increase in ground return current and consequent increase in EPR.

There may also be a further increase in EPR due to reduction of the chain impedance contribution. It may be necessary to consider the installation of an overhead or buried earth conductor to provide continuity of the aerial earth wire.

6.9 HV cable metallic sheath / armour earthing

This section covers all HV cables contained within or entering HV substations but excludes those HV cables which feed HV/LV transformers located in the substation where the LV supply is exclusively for use in the substation. The requirements for the latter are dealt with under Section 9.

6.9.1 Insulated sheath cables

The metallic sheath/armour of cables can, due to their inductive coupling properties, provide a very low impedance return path for earth fault current flowing in the cable phase conductors.

This can greatly reduce the current that returns to source though the ground and, subject to the sheath being continuous, significantly reduce the EPR at associated terminal substations.

To achieve this, the sheath/armour should be earthed at least at both ends. This arrangement of earthing is generally satisfactory for three-core and TRIPLEX type HV cables forming part of general distribution system circuits.

Simply bonding sheaths/armours at both ends of single-core cables or very heavily loaded circuits such as transformer interplant cables can cause de-rating as large circulating currents may flow in the sheath/armours, causing additional heating and risking damage.

Consequently, two methods of installation have been developed 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 may be 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.

Single-point bonding preserves the rating of the cables, but permits a potential to develop between the sheaths/armours and earth at the unearthed ends of the cables which could, on long cable runs, require shrouding or other measures to ensure safety.

Cross-bonding provides a return path for earth fault current in the sheaths without permitting significant circulating de-rating current to flow or exceeding the sheath voltage rise limit. Care is needed at link boxes/transposition points.

Both methods, together with their merits and disadvantages, are described in detail in ENA EREC C55 together with solutions to the problems described above. A bespoke cable and earthing / bonding design is usually required for very heavily loaded circuits (e.g. interplant cables) or circuits operating above 33 kV.

Methods for calculating the ground return current (for systems with sheaths earthed at both ends) are given in Appendix D of ENA EREC S34.

6.9.2 Cables entering substations

The sheath/armour at the substation end of the cable should be earthed to the substation MES.

Triplex, three-core, and fully cross-bonded cables will, in addition, be earthed at their remote ends. This provides both a conductive and inductive path for fault current. With cross-bonded single-core cables, it is the usual practice to install further additional sheath earths along the route of the cable. The additional sheath earths will normally produce an insignificant benefit, and can be ignored in the assessment of the substation earth resistance.

6.9.3 Cables within substations

Three-core cables will have their sheath/armour earthed at both ends.

Single-core cables will usually be short enough to allow single-point sheath/armour earthing, without causing serious sheath voltage rise problems. The single sheath/armour bond to earth should be located where personnel are most frequently present, for example at switchgear. Screens should be shrouded at the unearthed end. An earth continuity conductor may be required. See ENA EREC C55 for further details.

For the higher voltage systems, sheath voltage limiting devices (SVLs) may be installed between the sheath and earth at the unearthed end of the cable to protect the integrity of the sheath and its terminating point insulation against transient voltage surges on the sheath.

6.9.4 Outdoor cable sealing ends

Where cables terminate at outdoor sealing ends, pedestal-type insulators are fitted to insulate the sealing-end base and gland from its support structure. If sheath earthing is made at this location, special earthing bonds are required in accordance with ENA TS 09-15 or ENA EREC C55 as appropriate.

When the standing sheath voltage at a termination can exceed 10 V to earth, the base metalwork of the sealing-end should be screened against accidental contact by means of an insulating shroud of the type illustrated in ENA EREC C55.

Sealing end support insulators should be used only for short single-core cable tails with an earth bond made at the trifurcating point of any three-core cable.

6.9.5 Use of disconnected, non-insulated sheath/armour cables as an electrode

Metallic sheathed/armoured hessian served cables are often decommissioned or replaced with insulated sheath cables. Where these are laid direct in soil, they can provide a valuable electrode contribution. Where practicable, (particularly if the buried length exceeds 200 m) these redundant cables should be retained as earth electrodes to maintain their contribution towards lowering overall substation earth resistance and EPR.

If such sections are retained, the phase conductors and sheaths/armours of these cables, once disconnected, should be joined together to maintain their contribution to the electrode system. The start ends should ideally be connected to the substation MES via test chambers to permit continuity or resistance measurements. The remote ends should, if practicable, be connected to the electrode system at a joint or distribution substation. Cable and earthing records should be annotated to show such cables are being used as substation earth electrode.

Constant-force springs (CFS) or plumbed joints may be appropriate for connecting stranded copper conductor to lead sheathed cables; other types of connection may loosen in service as the lead continues to flow or creep under contact pressure. In any case, moisture should be excluded from such joints using heat shrink boots or similar. Manufacturers guidance should be sought if connecting to sheaths of other cable types.

6.10 Light current equipment associated with external cabling

All exposed conductive parts of light current equipment should be earthed to the main earthing system as required. Where pilot or communication cables operate between two remote points and the rise of earth potential at each end of the circuit does not exceed the appropriate ITU-T limit, any required circuit earth may be made at either end. If the rise of earth potential at either end exceeds the appropriate ITU-T limit, protective measures should be applied to those circuits. See ENA EREC S36 and Section 4.3.7.

6.11 Metalclad and gas insulated substations

6.11.1 Metalclad substations

Metal clad substations will normally be erected on a concrete raft. The provisions for an earth electrode system in these circumstances will be similar to those described in Section 6.4. Where touch potential is an issue, consideration should be given to using an enclosure made of insulating material and to using surface-laid earth mat/grating.

6.11.2 Gas insulated switchgear (GIS)

GIS employing single-phase busbar enclosures requires additional earthing precautions incorporated into the design of the substation MES.

Due to close coupling with individual phase conductors, busbar enclosures can experience high levels of induction. Steelwork used to support the enclosures and adjoining items of plant may form closed paths in which induced inter-phase and earth currents flow under both steady-state and fault conditions. These currents can be undesirably high and may approach the phase conductor current. The flow of circulating current renders secondary wiring more vulnerable to inductive interference.

A further issue with GIS is the creation of surge voltages on the enclosures and associated steelwork during switching or other transient/high-frequency system disturbances.

To help minimise the above effects it is recommended that an earthing system, well integrated and with locally enhanced electrode (e.g. increased mesh density and vertical rods) in the regions close to the plant, be laid over the raft from which short spur connections can be taken to the specific earthing points on the equipment. Typical arrangements are described in CIGRE Paper 044/151.

To retain current in the busbar enclosures, short circuit bonds, together with a connection to the earthing system, should be made between the phase enclosures at all line, cable and transformer terminations, at busbar terminations and, for long busbar runs, at approximately 20 m intervals. Switchboards over 20 m in length will require intermediate connections. Except where adjacent enclosures are insulated from each other, the interface flanges of the enclosures should have bonds across them and the integrity of bolted joints of all bonds should be checked.

As a guide, the resistance of the bonded flanges should not exceed 5 $\mu\Omega$. At insulated flanges, consideration should be given to the installation of non-linear resistive devices to prevent transient flashover.

6.12 Fault-throwing switches, earth switches and disconnectors

6.12.1 Background

Fault-throwing switches, earth switches and disconnectors are normally mounted on steel, aluminium, steel reinforced concrete or wood pole structures.

Metallic structures may be of electrically continuous all-welded construction or assembled using several large pre-welded sections or individual bolted members. In some cases, although the structure is of bolted construction, there may be a continuous metallic section from ground to equipment level. Where there is more than one metallic section in series in a fault current path, continuity between sections should be considered.

Fault-throwing switches should have a dedicated earth connection in addition to any structure earth. See Section 6.12.2.

Where steel or aluminium support structures are used to support disconnectors and / or earth switches, it is desirable to use the structure itself to carry earth fault current in order to reduce the need for above-ground earth conductors vulnerable to theft. This arrangement is only acceptable where the metallic structure can provide a reliable earth connection with adequate current carrying capacity.

NOTE: Some Network Operators may not permit the use support structures in lieu of a dedicated earthing conductor.

When installing earth connections to earth switches and disconnectors, the design should take into account the magnitude and duration of the prospective earth fault currents involved.

The main earth connection to these devices carries earth fault current under the following conditions:

Table 10 – Conditions for the passage of earth fault current

Device	Condition for passage of earth fault current
Fault-throwing switch	By design when protection operates
Earth switch	When there is an equipment failure or switching error. May also carry lightning induced current when closed.
Disconnector	When the disconnector or its connections fault, or when the disconnector is used in a sacrificial mode if main protection fails.

The main options for connecting earth switches and disconnectors are to use:

- a fully rated earth conductor fixed to the structure. This method is most applicable to higher fault current applications (e.g. systems operating at 90 kV and above) or where the support structure cannot provide an adequate earth fault current path. See Table 5 and Table 6 for conductor ratings.
- the metallic structure to conduct earth fault current from the top of the structure equipment to the grid. This is subject to the structure being electrically continuous and having sufficient current carrying capability. The method is more applicable to lower fault current applications (e.g. 33 kV systems) which use welded or continuous metallic structures.

The following earthing arrangements apply to fault-throwing switches, earth switches and disconnectors located within secured substation sites fitted with earthing systems.

Different arrangements (e.g. insulated downleads) may be required for equipment located outside substations in areas accessible to the public.

6.12.2 Fault-throwing switches (phase to earth)

A direct earth connection should be made from the switch earth contact to the substation MES using a conductor fixed to the structure.

6.12.3 Earth switches

Connections from earth switches to the substation MES may be made by either:

- an earth conductor, fixed to the structure

  or
- by using the metallic support structure as a conductor subject to the structure being electrically continuous and having sufficient current carrying capability.

6.12.4 Disconnectors

Connections from disconnector support metalwork to the substation MES may be made by either:

- a fully rated earth conductor, fixed to the structure.

  or

- by using the metallic support structure as a conductor, subject to the structure being electrically continuous and having sufficient current carrying capability.

6.13 Operating handles, mechanisms and control kiosks

6.13.1 Background

Earthing arrangements for operating handles of disconnectors, circuit breakers, earth and fault-throwing switches should provide touch and step potential control for the operator.

These are critical locations which require careful consideration and sound construction.

A full earthing system may not always be present at some older sites and additional precautions may be required when operational work and/or minor alterations are being carried out to ensure safe touch and step potentials. Generally, with exceptions outlined below, stance earths should be provided at all locations where operators may stand to operate high voltage equipment handles, mechanisms and control equipment.

6.13.2 Earth mats (stance earths)

New installations will have touch and step potential control provided by a purpose designed earthing system. If it can be demonstrated that such measures are adequate to ensure operator safety, and if a network operators operational policy allows, an additional stance earth may not be required. In making this assessment, the likelihood of deterioration due to theft or corrosion should be considered. Portable or visible (surface laid) stance earths may be required in addition to any buried grading electrode as a risk reduction measure.

NOTE: Surface-laid earth mats are generally preferred over buried earth mats; they give much better touch potential control and their presence can readily be checked. The size and position of the mat should match the operator stance position(s) for the given equipment. Galvanised steel grating earth mats can be readily extended to cover the operator path followed with horizontal operation handles. Buried earth mats may be a suitable alternative to surface-laid earth mats where the resulting touch potential is sufficiently low.

6.13.3 Connection of handles to the earthing system and stance earths

The earth connection from the handle to the earthing system should always be separate to that for the switch metalwork and be as short as possible.

The earth connection should use standard copper conductor connected direct to the earthing system.

In some cases, an insulated insert may be fitted between the operating handle and the switch metalwork to help prevent any fault current flowing down the handle and mechanism into the earthing system.

See also Section 10.6.

6.14 Surge arrestors and capacitor voltage transformers (CVTs)

Plant connected between line and earth, including surge arrestors and CVTs, presents relatively low impedance to steep-fronted surges and permits high-frequency currents to flow through it to earth.

Unless a low impedance earth connection to the MES is provided, the effectiveness of a surge arrestor could be impaired and high transient potentials appear on the earthing connections local to the equipment. The following installation earthing arrangements are recommended:

Two connections to earth are required for both surge arrestors and CVTs:

- The first connection (for power-frequency earthing) will use the structure to connect to the MES.

- The second (high-frequency) connection should be direct to an earth rod, installed vertically in the ground as near to the surge arrestor base as possible, with a tee connection to the support structure if metal. High-frequency earth rods should be driven vertically into the ground to a depth of approximately 4.8m. Where this is not achievable, a high density earth mesh arrangement or four (or more) long horizontally buried conductors (nominally 10 m in length, minimum depth 600 mm) dispersed at 90° (or less, equally spaced across the full 360º) may be used in place of the rod. Calculations should be provided to demonstrate that any proposal is equivalent to the 4.8 m long earth rods. The high-frequency connection should be made to the centre of the alternative high-frequency earthing designs. Dedicated earth mats or similar may be considered in difficult circumstances.

NOTE: See BS EN 62305-1, BS EN 62561-2 and ENA ETR 134 for more information.

The benefit of surge arrestors over arc gaps is greatest when the resistance to earth is less than 20 Ω. When a surge arrestor is provided at a cable termination, the earth side of the arrestor should be connected to the cable crucifix and thereby to the cable sheath. Surge arrestors should be sited as close as practical to the terminals of the plant, (e.g. transformer bushings or cable sealing ends) which they are protecting.

The support structure and plinth will be designed to allow the high-frequency earth connection to either pass through its centre, or through an angled slot to ensure that the connection is as short and straight as possible. This will aid performance and deter theft. It is particularly important to avoid sharp bends. This connection should not be enclosed within a steel support tube or box.

Fully rated conductors should be used for both high-frequency and power-frequency connections. High-frequency downleads should be insulated from the support structure (except where bonded to the structure at low level) to accommodate surge counters, and also to facilitate testing of the electrode with a clamp meter (see Section 7.6.2(b)).

7 Measurements

7.1 General

This section describes some of the most common measurements which may be required during the design, commissioning or maintenance of an earthing system at an electrical installation. An overview of the important measurement and interpretation methods is provided together with some guidance on avoiding sources of error. More detailed guidance and method statements would be expected to be available in company manuals and operational documentation.

7.2 Safety

The earthing related measurements described in this section are potentially hazardous. They should be carried out by competent staff using safe procedures following a thorough assessment of the risks. The risk assessment should include, but not be limited to, consideration of the following aspects and the necessary control measures implemented, e.g. personal protective equipment, special procedures or other operational controls.

- Potential differences that may occur during earth fault conditions between the MES and test leads connected to remote test probes. The likelihood of an earth fault occurring should be part of this assessment, e.g. not allowing testing to proceed during lightning conditions or planned switching operations.
- Potential differences that may occur between different earthing systems or different parts of the same earthing system. In particular, approved safe methods should be used when disconnecting earth electrodes for testing and making or breaking any connections to earth conductors which have not been proven to be effectively connected to earth.

NOTE: Disconnection from earth can cause potential differences to arise in the case of the path from tower line-earthing system due to induction. As it is related to current in the tower line, and therefore continuously present, it represents a particularly serious hazard.

- Potential differences occurring as a result of induced voltage across test leads which are in parallel with an HV overhead line or underground cable.
- Environmental hazards of working in a live substation or a construction site as governed by the applicable safety rules and/or other regulations.
- Injury when running out test leads for large distances in surrounding land.

7.3 Instrumentation and ancillary equipment

It is imperative that measurements are taken using the most suitable instrumentation for the required task which is in good working order and has a valid calibration certificate. The instrumentation will be used for field measurements in all weather conditions. It should therefore be robust, have a sufficient level of water resistance and be suitably protected from electrical transients (e.g. by fuses) and shielded for use in high voltage installations. Further advice on this may be sought from instrument manufacturers.

Instruments should be calibrated regularly (e.g. annually) to a traceable national standard. Heavily used instruments should be checked more frequently, e.g. against other calibrated instruments or standard resistors, between formal calibration periods. Instruments should be periodically serviced/safety tested and any identified damage or faults should be rectified before re-use.

Many of the measurements require ancillary equipment such as test leads, earth rods, connection clamps, etc. and it is equally important that these are also fit for purpose and well-maintained.

7.4 Soil resistivity measurements

7.4.1 Objective

To determine the resistivity of the materials (soil, rock, etc.) that make up the ground where an earth electrode is installed, site-specific measurements are required. The results obtained can be interpreted to provide a uniform equivalent resistivity for use in standard design equations (See ENA EREC S34) or a multi-layer soil model which can be used in commercially available computer simulation tools. Important design parameters such as the earth resistance and EPR are strongly dependent on the soil resistivity, so it is essential for the accuracy of the design that proper attention is given to these measurements and their interpretation as early as possible in the design process.

7.4.2 Wenner method

A four-terminal earth tester is used for these measurements. A number of measurement techniques are available which involve passing current through an array of small probes inserted into the surface of the soil and measuring the resulting potentials at specified points. Using Ohm’s Law a resistance value can be calculated which can then be related to the apparent resistivity using suitable formulae. Varying the positions of the probes, and hence forcing the current to flow along different paths, allows the resistivity at different depths to be measured. The most commonly used arrangement for earthing purposes is the Wenner Array. This is described in more detail in NC 7.2 of BS EN 50522.

NOTE: There are variations on the Wenner Array method using uneven electrode spacing. These include the Schlumberger Array method.

For substations, it is important to take measurements at a number of different locations around the site. In areas with significant buried metallic structures (eg urban areas and industrial sites/power stations), meaningful measurements may only be obtained from the nearest parks or open ground and so results from several locations around the substation are essential.

7.4.3 Interpretation of results

It is difficult to interpret measurement results by inspection other than for a uniform soil model. Formulae for interpretation of data for soils with two or more layers are cumbersome and in practice this requires the use of software. A number of suitable software tools are commercially available. Because most of these are based on a curve-fitting approach, geotechnical information such as borehole records is useful to reduce uncertainty in the soil resistivity model by indicating layer boundary depths, materials, water table height, bedrock depth, etc. and should be used where available.

Knowledge of the soil resistivity at different depths is important when designing the most effective electrode to reduce the substation earth resistance. For example, vertical rods are better suited to a soil with a lower resistivity material beneath. Conversely, where there is lower resistivity material at the surface with underlying rock, extended horizontal electrodes will be more effective.

7.4.4 Sources of measurement error

A number of sources of error should be considered when planning and carrying out these measurements. These include, but are not limited to:

- influence of buried metallic structures such as bare cable armouring/sheaths, earth electrodes, pipes, etc. Measurements taken above or near buried metallic services will indicate lower resistivity values than actually exist. This can lead to under-designed earthing systems which may be costly to rectify at the commissioning stage. Measurement locations should be carefully planned to avoid interference from metallic structures by consulting service records and, where there remains uncertainty, on-site scanning may be required. It is also important that measurements are taken at a number of different locations (a minimum of two) around the site of interest so that any influenced results become apparent in comparison to unaffected results. Two orthogonal sets of measurements can also help to indicate an error.
- interference from stray voltages in the soil or induction from nearby electrical systems may adversely affect measurement results, normally evident as an unstable reading on the instrument or unexpectedly high readings. This may be reduced by avoiding test leads running in parallel with high voltage power lines/cables or near other potential sources of interference, e.g. electric traction systems.
- the Wenner spacings used should be appropriate for the size of the earthing system and recommended spacings are provided in Annex NC of BS EN 50522. Spacings that are too short may not identify the lower layer resistivities which can introduce large positive or negative error into design calculations.
- low resistivity soils, especially at long Wenner spacings, require relatively small resistances to be measured at the surface. Instrumentation with an inadequate lower range may reach its limit and incorrectly indicate higher resistivity values than exist.
- care should be taken in interpreting the measurement data. If using computer software tools, it should be remembered that the result is a model of the soil conditions which is largely determined by automatic curve-fitting routines or user judgement. To increase confidence, it is good practice to test the model by comparing it to other geological data available for the site and the expected range of resistivity values for the materials known to be present. Measured earth resistances of vertical rods (of known length) installed at the site can also be compared to calculated values obtained using the soil model. It should be

recognised that the soil resistivity model may need to be refined throughout the project as more supporting information becomes available.

7.4.5 Driven rod method

The driven rod method is an alternative to the Wenner Method which is particularly useful in built-up urban areas where there is inadequate open land to run out test leads. This method should be used with caution and measures should be taken to avoid the possibility of damage to buried services, in particular HV cables. Where the absence of buried services cannot be established, rods should not be driven. An earth rod is driven vertically into the ground and its earth resistance measured as each section is installed using either of the methods from Section 7.6.2. Using a simple equation (for uniform soil equivalence – see Appendix B of ENA EREC S34) or computer simulation (for multi-layer analysis) the soil resistivity may be deduced from the measured rod resistance and its length in contact with the soil. This method can be cost-effective as the rods can be used as part of the earthing installation. Where possible, the results from driven rods at a number of locations around the site should be used together with any available Wenner Method data to improve confidence in the derived soil resistivity model.

7.5 Earth resistance/impedance measurements

7.5.1 Objective

To measure (where practicable) the substation earth resistance or impedance on commissioning of a new substation and subsequently at maintenance intervals. The measurement will include all earthing components connected at the time of the test and the result represents the value which is normally multiplied by the ground return current to determine the EPR. This method may also be used to measure the earth resistance or impedance of individual electrodes, tower footings or tower line chain impedances. (See Appendix G of ENA EREC S34 for details of chain impedance and relevant calculations).

7.5.2 Method

The most commonly used method of measuring substation earth resistance or impedance is the fall-of-potential method and this is described in NC 5.1 of BS EN 50522. It requires temporary electrodes to be installed in the ground some distance from the substation and connected back via trailing leads. A standard four-pole earth tester should be used (as opposed to a three-pole tester – see Section 7.5.4(e)) to inject a small test current into the earth electrode and returned via a remote probe. A potential gradient is set up around the electrode and a second probe is used to measure this with respect to the electrode potential rise. The resistance is calculated and results are normally presented as a curve of resistance versus distance from the substation along a particular route. Voltage measurements may be taken along any route, but traverses which are parallel or orthogonal to the current lead are most commonly used and are more readily interpreted using standard methods.

Most commercially available earth testers use a switched DC square wave signal. Where it is possible to select a very low switching frequency (below 5 Hz) the measured values will approach the DC resistance which will be accurate for small earth electrode systems in medium to high soil resistivity. When higher switching frequencies are used (128 Hz is common) inductive effects may be evident in the results. Where an appreciable inductive component is expected and long parallel test leads are used, it is advisable to use an AC waveform so that mutual coupling between the test lead may be subtracted and a true AC impedance obtained. Because of the appreciable standing voltage commonly found on live substation earth electrodes, AC test signals are normally selected to avoid the fundamental and harmonic frequencies. For the most accurate results, measurements should be taken using frequencies either side of the power-frequency to allow interpolation. Additional guidance may be found in IEEE 81.

It may not be possible to use the fall-of-potential method where no suitable routes exist for the test lead / probe set up, e.g. in urban or industrial areas. Alternative methods should be used in these locations. See Section 7.6.

The substation earth resistance or impedance can also be measured by injecting a current from a generator connected to a remote earthing system via a de-energised power line. The rise in electrode potential is measured with respect to another remote earth electrode such as a telecommunication circuit earth. This method is more costly in terms of equipment resources and circuit outages and it is rarely used in the UK. Experience has shown that care should be taken to ensure that there are no unwanted metallic paths between the substation electrode and either of the reference electrodes as this will divert current and introduce errors, unless the diverted current can be measured and a correction applied. This is especially difficult to achieve in urban environments, otherwise this technique would be a good option where no suitable area for a fall-of-potential measurement exists.

7.5.3 Interpretation of results

Earth resistance or impedance measurement results are normally in the form of a series of points on a curve which should be interpreted using a mathematical rule or procedure. Care should be taken in selecting a suitable method and their limitations should be understood. More detail on the methods available is given in Annex NC of BS EN 50522.

7.5.4 Sources of measurement error

There are a number of sources of error which should be considered when planning and carrying out these measurements. These include, but are not limited to:

a) influence of buried metallic structures such as bare cable armouring/sheaths, earth electrodes, pipes, etc. Measurements taken above or near buried metallic services will generally underestimate the substation resistance. Measurement locations should be carefully planned to avoid interference from metallic structures by consulting service records and, where there remains uncertainty, the use of scanning methods on site. Measurement results that have been influenced by a parallel buried metallic structure will typically be lower than expected and the resistance curve will be flat. A metallic structure crossing the measurement traverse at right-angles will result in a depression in the resistance curve. If interference is suspected the measurement should be repeated along a different route or an alternative method used.

b) the distance between the substation and the remote current probe is important to the accuracy of the measurement. The theoretical recommended distance is between five and ten times the maximum dimension of the earth electrode with the larger separations required where there is underlying rock. In practice, where there is insufficient land to achieve this, the current probe should be located as far away from the substation as possible. Measurements taken using relatively short distances between the substation and return electrode may not be accurately interpreted using standard methods and require analysis using more advanced methods. Typical distances used range from 400 m for standard 33/11 kV substations up to 1000 m or greater for large transmission substations or large combined systems.

c) interference caused by standing voltage (noise) on a substation MES may result in standard earth testers failing to produce satisfactory results. This is normally evident as fluctuating readings, reduced resolution or via a warning/error message. Typical environments where this may be experienced include transmission substations (275 kV and 400 kV), railway supply substations or substations supplying large industrial processes such as arc furnaces or smelters;

d) results should be interpreted using an appropriate method and compared to calculations. Where there is significant difference further investigation is required. Interpretation using the 61.8% rule or slope method may not be appropriate in all circumstances as they are based on simple assumptions. Detailed analysis using computer software may give greater accuracy where:

- the soil resistivity is non-uniform, i.e. multi layered soils.
- where the current return electrode is relatively near to the electrode under test, e.g. less than five times the size of the earth electrode being tested.
- for a large and irregular-shaped electrode where the test is taken far away from the centre of the electrode.
- where there are known nearby buried metallic objects that may have influenced the measurements.

e) use of a three-pole earth tester is acceptable where the resistance of the single lead connecting the instrument to the electrode is insignificant compared to the electrode resistance. These instruments are generally suitable only for measuring small electrode components such as rods or a small group of rods in medium to high resistivity soils. For larger substations or low resistance electrodes, a four-pole instrument is essential to eliminate the connecting lead resistances which would otherwise introduce a significant error.

7.6 Comparative method of measuring earth resistance

7.6.1 Objective

To measure the earth resistance of small individual electrode components within a large interconnected earthing system. It is most effective where a relatively high resistance electrode is measured in comparison to a reference earthing system which has a much lower resistance.

7.6.2 Method

Two different approaches may be used:

a) The first method, illustrated in Figure 4, requires that the electrode being tested is disconnected from the remainder of the substation MES, e.g. immediately after installation prior to the connection being made or via opening of a test link at existing sites. A standard four-pole earth tester may be used with terminals C1 and P1 connected to the electrode component being tested. Terminals C2 and P2 are connected to the reference earth. Current is circulated around the earth loop containing the electrode and the reference earth resistances and the voltage developed across them is measured. Using Ohm's Law the series loop resistance is calculated and if the reference earth resistance is sufficiently low relative to the electrode resistance the measured value will approach the electrode resistance.

b) The second method, illustrated in Figure 5, uses a similar principle but does not require disconnection of the electrode. A clamp type meter is placed around the connection to the electrode which generates and measures current and voltage in the electrode loop and displays the loop resistance. The advantage of this method is that the earth electrodes may be tested without disconnection hence avoiding the associated safety risks and the need to apply earth disconnection procedures. This is the preferred method for safety and facilities should be included in the design to allow access to rods for testing with a clamp meter.

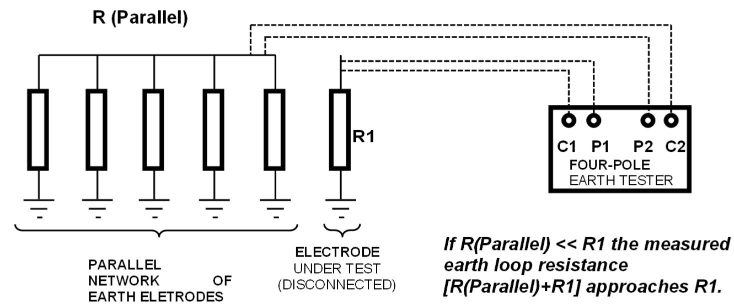


Figure 4 - Earth resistance measurement using the comparative method and a four-pole earth tester (test electrode disconnected)

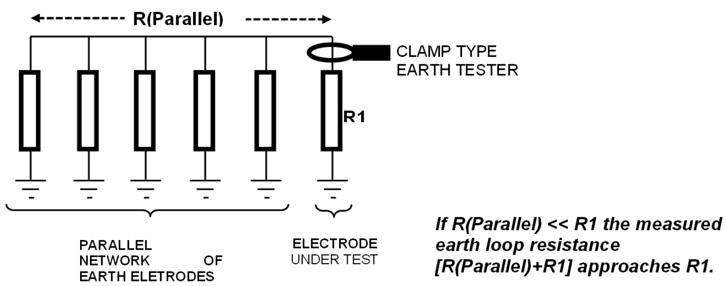


Figure 5 - Earth resistance measurement using the comparative method and a clamp type resistance meter (test electrode connected)

7.6.3 Interpretation of results

In order to accurately measure an electrode resistance via this method it is necessary to have a very low reference earthing system resistance compared to the electrode resistance (10 % or lower is recommended). It is also necessary to have a reasonable physical separation between the electrode and reference earth to reduce mutual coupling through the soil.

If the reference earth resistance is too high, the measured result will be significantly higher than the electrode resistance (if this is known, it can be subtracted). If the electrode and reference earths are too close together, a value lower than the electrode resistance may be measured. These errors may be acceptable if the purpose of the measurement is a maintenance check where it is only necessary to compare periodic readings with historical results to identify unexpected increases, e.g. due to corrosion or theft.

If several different electrodes can be tested with respect to the same reference earth, more detailed interpretation methods may be developed to increase confidence in the individual electrode resistances and, in some circumstances, allow the reference earth resistance to be deduced.

7.6.4 Sources of measurement error

a) If the reference earth resistance is too high relative to the electrode resistance, the measured value may be significantly higher than the electrode resistance. An approximate assessment of this may be made by comparing the physical area covered by the respective earthing systems, e.g. a rod electrode measured with respect to a large MES would be expected to provide a reasonably accurate resistance value for the rod electrode.

b) Where the test electrode and reference earth are in close proximity to each other there will be significant mutual coupling via the soil which may result in an apparently lower reading than the true electrode resistance.

c) The electrode under test may be inadvertently in contact with the reference electrode below ground level, or otherwise connected to it. If so, the test current is circulated around a loop and the resistance value obtained does not represent the intended earth electrode resistance.

d) This method cannot be directly used to measure the overall substation earth resistance which requires the use of the fall-of-potential method given in Section 7.5.2.

7.7 Earth connection resistance measurements (equipment bonding tests)

7.7.1 Objective

To measure the resistance between a plant item and the main substation earth electrode to check bonding adequacy. This is essential during commissioning of a new substation to confirm that each item of plant is effectively connected to the earth electrode system. It is also useful as an on-going maintenance check and for operational procedures, e.g. post-theft surveys.

7.7.2 Method

The procedure is based upon the principle of measuring the resistance between a set point (or points) on the main electrode system and individual items of earthed equipment. A micro-ohmmeter is used and the connection arrangement is illustrated in Figure 6. Measurements can be taken from one central point (such as the switchgear earth bar) or, to avoid the use of unduly long leads, once a point is confirmed as being adequately connected, it can be used as a reference point for the next test and so on.

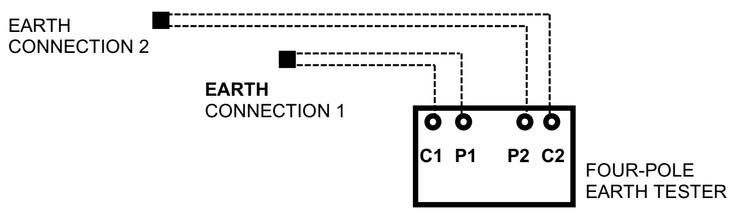


Figure 6 - Connections for earth bonding conductor resistance measurements

To establish that a satisfactory connection exists between the grid and any exposed metalwork it is necessary to measure in the micro-ohms or milli-ohms range. An injection current of at least 100 mA is recommended.

The probable path of the injected current should be considered and, where the substation uses a bus-zone protection scheme, care should be taken to ensure that any test current does not produce enough current to operate protection systems.

Special procedures should be adopted when checking bonding between a substation earthing electrode and a terminal transmission tower. If the bond is ineffective or missing, a potential difference may exist which may pose a shock hazard or damage to a test instrument. Normally these methods will include checking current flow in the terminal tower legs prior to testing, as a higher proportion of current will flow in a leg with an effective connection to the substation. This would be supplemented by voltage measurements using suitably insulated probes and meters and buried electrode location techniques.

7.7.3 Interpretation of results

The measured resistance between the two connection points will depend on the length, cross-sectional area, material and number of earth conductors between them. Based on a maximum distance of 50 m between connection points, a threshold value of 20 mΩ will provide a good indication of when further investigation is required.

7.8 Earth conductor joint resistance measurements

7.8.1 Objective

To measure the resistance across an earth conductor joint to check its electrical integrity. This is normally performed for every joint created at a new substation prior to backfilling. It is also carried out during periodic maintenance assessments.

7.8.2 Method

The method described uses a micro-ohmmeter to measure electrical resistance and is suitable for bolted, compression, brazed and welded joints. It does not check the mechanical integrity of welds or check for voids inside a joint.

Most micro-ohmmeters are supplied with standard leads with two sharp pins that can penetrate through paint or surface corrosion to reach the metal underneath. The first set of leads is connected to one side of the joint and the second set to the other as illustrated in Figure 7. Ideally, the connectors should be no more than 25 mm either side of the joint. A suitable scale should be selected on the instrument (normally a minimum current of 10 A is required to measure in the micro-ohm range) and an average value recorded after the test polarity has been reversed.

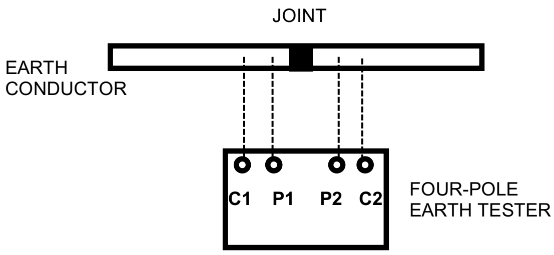


Figure 7 - Connections for earth conductor joint resistance measurements

Joints should also be mechanically robust and survive a firm tap with a steel hammer.

7.8.3 Interpretation of results

The measured resistance should not significantly exceed that of an equivalent length of conductor without a joint. Joints which exceed this by more than 50 % should be remade. Where different sized tapes are involved the threshold value used should be that of the smaller tape.

At new installations, it is recommended that a few sample joints are made under controlled conditions (e.g. in a workshop), their resistance measured and the median of these values used as the benchmark for all other similar joints made at the installation.

7.9 Earth potential measurements

7.9.1 Objective

To measure touch, step and transfer potentials (e.g. in HPR zones) for comparison with calculated values. These measurements may be required to confirm that the installed design complies with the main safety limits (see Section 4.4). Advanced techniques and equipment are required to perform these measurements at live substations and guidance on the different methods available can be found in IEEE 81.

7.9.2 Method

Earth potential measurements may be measured by injecting a current into the substation electrode and returning through a remote electrode via a connecting conductor. The return electrode may be another substation electrode connected via a de-energised power line or a temporary test lead and set of probes. Providing the return electrode is located at a large distance from the substation relative to the size of the substation electrode, a potential profile will be set up around the substation proportional to that which would exist during fault conditions. The potential between the substation electrode and different points on the surface can be measured and related to touch potential. Step potential can also be determined from measurements of the potential difference between points on the surface which are 1 m apart. In both cases, the actual touch potential can be found by scaling in the ratio of the test current and fault current.

In a similar way, the potential gradients may be measured around the substation, for example emanating out from each corner, and equipotential contours derived. Measurements may also be carried out to determine the voltage transferred from a substation electrode to a nearby metallic structure, e.g. a steel pipe or the earthing system associated with a different electrical system.

7.9.3 Interpretation of results

The measurement results should be interpreted by competent engineers and compared to calculated values. It is recommended that a series of measurements are taken at a number of locations around the substation where high touch or step potentials are expected (normally at the corners or in areas where the electrode mesh is less dense). This will enable the trends in the potential gradients to be assessed to identify spurious data points. Where the return electrode is not located sufficiently far away from the test electrode, large errors may be introduced. These errors may be corrected using a detailed computer model or by averaging the measurements obtained using different current return electrode locations.

7.10 Earth electrode separation test

7.10.1 Objective

To assess the electrical separation of two electrodes in the soil by measurement, e.g. segregated HV and LV electrodes at an 11 kV distribution substation or a substation earth electrode and a separately earthed fence.

7.10.2 Method

This method requires that the earth resistances of the two electrodes (R_1 and R_2) have been measured separately using the fall-of-potential method described in Section 7.5.2 and Annex NC of BS EN 50522.

Similar connections are made as for the bonding integrity checks (Figure 6) and the earth loop resistance (R_3) of the two electrodes via the ground is measured.

7.10.3 Interpretation of results

If the two electrodes are separated by a large distance, R_3 will approach the series resistance of $R_1 + R_2$. Lower measured values of R_3 indicate a degree of conductive coupling through the soil. Generally, for the purposes of checking satisfactory segregation of earth electrodes the following test is used: $R_3 > 0.9*(R_1 + R_2)$. Values lower than $0.9*(R_1 + R_2)$ may indicate inadequate separation and further investigation is required (see Section 9.7.3).

7.11 Buried earth electrode location

7.11.1 Objective

At older substation sites, whilst an earthing system is in place, a record of its design may not exist or may be out of date. An earthing record is desirable to ensure that the design is satisfactory and to assist in the planning of new construction work. The record should include the position of the electrode, its burial depth, material, size and installation method (e.g. above ground, in ducts, or buried directly).

Where existing electrode should be located within live substations, surface detection methods are usually the lowest cost option.

7.11.2 Method

The most effective surface detection techniques, found by experience are documented below. This includes commercially available low to medium frequency systems and ground penetrating radar (high-frequency) systems. It should be noted that these methods are subject to interference from other buried services and often need to be supplemented by trial excavations.

A low to medium frequency system comprises a transmitter and receiver, working at frequencies from 50 Hz (detection of live mains cables) to nearly 100 kHz. The transmitter injects a signal into the earthing system which is to be traced (the “target line”). As this signal passes through the earth electrodes, it radiates an electric and magnetic field, one or both of which can be detected and interpreted by coils in the receiver. Basic receivers simply emit an audio tone as they are passed over the target line. More advanced receivers give information, such as burial depth and test current magnitude. This feature can sometimes enable the target line to be distinguished from others which have erroneously picked up the transmitter’s signal through coupling.

A ground penetrating radar system, used in conjunction with appropriate analysis software, can also be used to produce a reasonable graphical image of structures below the surface. Radar systems detect the dielectric contrast between a target and its surroundings and so are well suited for detecting conductive, metallic electrodes against soil which is relatively resistive. They are well suited to drained, high soil resistivity locations. The radar system is usually guided over the trace area in a grid pattern, with detection results being stored for later analysis by the computer.

Where neither of the above methods is conclusive, e.g. in areas with a high density of buried services, selected trial holes may be required.

8 Maintenance

8.1 Introduction

Earthing systems should be inspected, maintained and repaired so as to ensure they will operate in the manner required on an ongoing basis.

8.1.1 Inspection

Inspection falls into two main categories:

a) Visual Inspection

b) Detailed physical examination and testing

When setting inspection, testing and maintenance regimes for a substation consideration should be given to identifying and where necessary rectifying issues arising from:

- physical deterioration and damage/theft;
- inappropriate installation alterations or third-party actions which prejudice the principal of operation of the earthing system;
- inappropriate installation / design;
- changes to system operating regimes or construction which alter the magnitude, flow and / or duration of earth fault current to values outside the original earthing system design parameters;
- magnitude of EPR and how close touch and step potentials are to safety limits.
- Impact of EPR on third parties.

The frequency of inspection and testing should be set according to EPR, risk of theft, damage, and deterioration. It may be revised from time to time if circumstances change.

If an extraordinary event occurs (e.g. delayed fault clearance), additional ad-hoc inspection and testing may be required.

8.1.2 Maintenance and repairs

When undertaking repairs or minor alterations to damaged earth conductor and buried electrode, the procedures adopted should take into account:

- Broken conductors may operate at elevated voltages even when the rest of the associated network is operating normally.
- The possibility of transient or sustained system earths fault occurring while repairs are being undertaken.

Inspection, testing and maintenance work should be undertaken in accordance with company operational and safety procedures. Where required, risk assessments and method statements will be prepared. Inspectors should wear company specified personal protective equipment and only approach plant and equipment when it is safe to do so.

See Sections 8.3 and 8.4 for further issues.

8.2 Types of inspection

8.2.1 Introduction

The three main types of inspection are covered in Sections 8.2.2, 8.2.3 and 8.2.4 and may be summarised as:

- a frequent basic visual inspection to check there is no visible damage, theft or obvious impairment of the earthing system;
- a less frequent and more detailed visual inspection to review the standard of construction and condition as well as checking for damage, theft and impairment;
- an infrequent, more thorough, visual inspection combined with testing, measurement and analysis.

For an open busbar substation, typical areas to be inspected include earth connections associated with:

- aluminium, steel, concrete and wood structures;
- towers, earthed poles and above-ground cable connections within or adjacent to the substation site.
- isolator mechanisms, fault-throwing switches, earth switches and control kiosks including associated surface and buried earth mats;
- transformers, reactors, VTs, CVTs, CTs, surge arrestors and arcing horns;
- transformer neutral links and switches and associated connections to earth either direct or via earthing resistors, reactors or earthing transformers;
- metallic fencing and gates;
- indoor switchgear (if present) including connections to plant, cables, structural steel work and earth bars.

8.2.2 Frequent visual inspection

This can form part of a normal routine substation inspection procedure or be a part of the procedures operational staff conduct when entering a substation. The objective is to frequently and quickly check for visible damage, theft or obvious impairment of the earthing system.

During routine visual inspections, accessible earth connections associated with key items of electrical plant in the substation should be checked. Procedures such as lifting trench covers will normally be avoided unless the initial inspection gives cause for concern.

8.2.3 Infrequent detailed visual inspection

Before commencing a detailed examination, the substation earthing records should be checked to confirm they correspond to the actual layout. The inspector should be aware of the fence earthing arrangement and whether it is independently earthed or bonded to the earthing system or a mixture of both.

The key items covered in the frequent inspection plus all other accessible connections to plant, circuits and civil infrastructure should be inspected thoroughly. As well as condition, the standard of construction should be reviewed against present practices and any inadequacies reported. Checks for damage, theft and impairment of the earthing system should also be carried out. Visual checks should be carried out on less accessible earthing conductors not covered in the frequent inspection such as those located under trench covers or located in basements.

The results of all inspections should be documented in accordance with company procedures.

A pre-prepared check list for each site will assist consistent reporting and record keeping.

8.2.4 Detailed visual inspection, testing and analysis

This consists of four related parts:

- A thorough detailed visual inspection and review of the earth connections to all electrical plant, circuits and civil infrastructure
- Carrying out specific testing and measurement of the earthing installation.
- Selecting portions of the buried electrode system for examination via trial holes.
- Analysis and recording of results including review of EPR related issues.

8.2.4.1 Testing

See Section 7 for specific measurement and analysis techniques.

Testing may include:

- Measurement of the overall substation earth resistance/impedance value.
- Measurement of the resistance of:
  a) Individual earth electrodes.
  b) Rod and plate groups.
  c) Fence earth rods.
  d) Test electrodes (where fitted).
  e) Surge arrestor, CVT and GIS high-frequency earths.
- Measurement of soil resistivity.
- Resistance tests across a representative sample of important joints using a micro-ohmmeter. The value should be recorded and compared with the values recommended by the manufacturer, or taken for similar joints elsewhere. Any joint where the resistance value is excessive should be broken down, cleaned and re-made, or replaced.
- Confirmation of continuity between key items such as transformers, switchgear, terminal tower(s) etc. and the substation MES using a micro-ohmmeter. This is especially important for items where corrosion, theft or damage is considered to have prejudiced the integrity of the connection.
- Confirmation of continuity between adjacent site earthing systems.
- Confirmation of whether metallic fences are isolated from or bonded to the MES by carrying out a separation test.
- For substations fitted with frame leakage earth fault protection checking the integrity of the segregation between earth zones by testing and/or visual inspection and also testing across cable terminations where island glands are fitted.
- Measurement of soil pH.
- Tracing of buried electrode if required to update the substation earthing drawing;
- Separation tests and review of separation between distribution substation HV and LV earths. (See Sections 7.10 and 9.7);

8.2.4.2 Selected excavation and examination of buried earth electrode

Since the earth electrode system is largely buried, it is impracticable to carry out a detailed examination of the whole installation. However, it cannot be assumed that the buried electrode system, once installed, will remain in good condition.

Particularly where a substation site is associated with former industrial use such as a coal power station or foundry which may have produced corrosive material used as landfill, there is enhanced risk of corrosion of buried copper conductor. A similar risk may arise if material from such sites is imported to construct a substation. It is recommended that representative locations be chosen to excavate and expose the buried electrode in order to check its condition.

These should include some below-ground connections, e.g. an earth rod connection position, or other locations where the electrode is jointed. Several connections from above-ground plant should be uncovered back to the connection to the buried earth tape/grid, to check their condition through the layers of chippings and soil. Conductor size should be compared with records.

Whilst carrying out excavation, the soil pH value should be checked. This should lie between 6.0 and 10.0. For pH values outside these limits, it is probable that corrosion of the copper conductors/connectors will be evident. In the past, power station ash has been used as bedding for earth electrodes. This is known to be acidic and is likely to cause corrosion of the conductors.

Where tests show the pH value of the soil to be outside the limits, if the copper electrode is corroded, repairs or a new electrode system and either some imported soil or an inert backfill (such as bentonite) is required. If the electrode has limited corrosion, a soil / corrosion investigation is necessary to assess the risk of future corrosion and any precautions necessary. Normally the corrosion rate will be uneven, with severe corrosion in some areas and none in others. Severely corroded electrodes should be replaced, whilst that elsewhere should be monitored and measures taken to limit corrosion in all important areas.

Should examination of the exposed conductors or connections give cause for concern, additional excavations elsewhere on site may be necessary to assess the extent of the problem.

8.2.4.3 Analysis and recording of test results

Resistance values for the substation, individual electrode groups and for joints should be recorded and where previous values are available compared to indicate any trend.

The earthing drawing should be updated if required with revised electrode sizes and positions.

Once a new substation earth resistance is obtained, it should be used to recalculate the substation EPR using up-to-date earth fault current data and earth fault current return paths (earth wires/cable sheaths etc.). Safety voltages and conductor current ratings should be recalculated and any deficiencies identified.

The presence (or otherwise), values and configuration of any resistances / impedances placed in high voltage transformer neutrals should be recorded and aligned with those contained in the company power system model.

Defects should be listed and prioritised for remedial action.

8.3 Maintenance and repair of earthing systems

In some cases, earthing related maintenance and repair work will be reactive, following theft or damage revealed by an inspection.

Before undertaking earthing system repair or measurement work, the responsible person in charge of the work should familiarise themselves with the site-specific risks and consequences of:

- Working on or touching unsound earthing systems;
- Open circuiting (even for a short time) earth conductor circuits;
- Extending (even temporarily) earthing systems from sites where touch and step potentials are controlled;
- Working on broken earthing conductors;
- An earth fault occurring on the system being worked on. For primary substations supplying extended HV rural overhead line networks this can be a relatively frequent occurrence (e.g. at least once a week). Supervisors should avoid work or testing being carried out in high risk periods such as during storms or fault switching.

There is risk of serious or fatal electric shock when working on intact and depleted/damaged earthing systems. The responsible person in charge of any remedial work should be suitably qualified to undertake this area of work. Network Operators should develop their own policies/procedures for dealing with depleted earthing systems.

Specialised equipment including insulated rods, shorting leads and conductor clamps are required to make repairs. PPE including insulated footwear and gloves should be available if required.

High voltages can appear on earth system conductors even under normal running conditions. Items requiring particular caution include connections associated with CVTs, transformer neutrals, underground cable bonding arrangements and connections between earthing systems and overhead line towers.

Examples of situations requiring remedial work include:

- broken or damaged below-ground earthing conductors which have been exposed in the course of excavation work;
- broken or damaged bonding conductors on underground cable systems (such as cross-bonding connections that can be expected to carry significant current under normal operating conditions);
- repairs to/replacement of high resistance earth connections (see Section 8.4);
- minor alterations to/diversions of earthing systems for construction work;
- repairs after theft of earthing conductors (Remedial work on depleted earthing systems is normally the subject of a bespoke company instruction and is outside the scope of this document).

8.4 Procedure for re-making defective joints or repairing conductor breaks

8.4.1 Introduction

It may be necessary to re-make a joint or repair a break on the earth electrode system at a substation for a number of reasons:

- The joint is obviously damaged.
- The joint has failed a micro-ohmmeter test.
- An earth electrode has been severed.
- A minor diversion of the electrode system or other repair work may be proposed.

Should a fault occur during the period when a repair is being carried out, to prevent danger from a high voltage which could appear across the joint, precautions should be taken.

The design of the earthing system (if present) may or may not be adequate to eliminate danger to personnel when touching a bare broken conductor even after a temporary earth continuity conductor has been applied.

Before carrying out any repairs, the joint or break to be repaired should be short-circuited by connecting a fully rated conductor to positions either side of the break or defective joint. This short should be applied using an approved procedure involving insulated rods.

If company policy so states or any doubt exists, the operator should wear insulating footwear and gloves designed for electrical application when handling earth conductor to make a permanent repair.

Whilst carrying out work, the operator should stand within the boundaries of the earthing system, or immediately above a bare buried earth conductor.

For example, if a terminal tower earth connection is broken, a significant potential difference may be present between the tower and earthing system. Arcing and current flow will occur when trying to remake the connection. Insulated rods and approved connectors are required to apply the initial short-circuit. The repairs, as detailed in Section 8.4.2, can then be carried out.

Similarly, high voltages may appear across open circuited cross bonding conductors on HV underground cable circuits.

8.4.2 Joint repair methods

- Compression joint – cannot be repaired, should be replaced.
- Mechanical connector - disconnect, clean all contact surfaces, apply a company approved contact lubricant, reconnect and re-tighten.
- Cold-weld/exothermic weld joint - if defective, this type of joint should be replaced.

On completion of repair of any joint, having first connected the instrument across the joint, the temporary earth continuity conductor or shorting strap should be removed. A micro-ohmmeter resistance test should then be carried out across the joint.

8.4.3 Flexible braids

Flexible bonding braids or laminations should be inspected for signs of fracture and corrosion and changed as required. A protective compound may be applied to flexible braids where corrosive conditions exist.

9 Ground-mounted distribution substation earthing

9.1 Introduction

Whilst the general principles of earthing can be applied to all voltage levels, small (distribution) substations providing supply to LV networks can present their own additional challenges. The key earthing related differences between distribution (or secondary) substations, and larger (primary, or grid substations) include:

- HV distribution apparatus is often located in densely populated areas in close proximity to the public.
- earth fault clearance times on distribution systems are usually longer.
- many older legacy installations do not have the benefit of a comprehensive earthing system environment, as they rely on metallic sheath cable systems to control touch and step potentials.
- LV earth connections may be combined with HV earthing systems, or in close proximity to them.
- connections from the LV distribution system are taken into almost every property.
- for new connections, Network Operators have a legal obligation to provide an LV earth terminal to their customers as long as it is safe to do so;
- the low voltage system should be earthed such that earth potential rise due to high voltage earth faults does not cause shock or injury (to installation users, public or staff) or damage to internal electrical installations, distribution equipment or telecommunication systems.

The design issues, therefore, can be summarised as:

a) achieving safety in and around the HV/LV substation, and

b) ensuring that danger does not arise on the LV system as a consequence of HV faults.

The design approach given in Section 5.6.1 applies equally to distribution substations, and special considerations are described below.

9.2 Relocation of pole-mounted equipment to ground level

Due to the high EPR that can appear on pole-mounted equipment, metallic items should not be relocated at ground level (e.g. replacing a pole transformer with a small pad-mount substation) without appropriate modifications to the earthing system.

Ground-mounted substations will introduce a touch potential risk that is absent from pole-mounted installations, and consequently require an electrode system that not only limits EPR, but controls touch and step potentials to safe limits.

Similarly, care should be exercised if other earthed equipment on the pole (e.g. auto-reclose relay cabinet) is within reach of persons on the ground.

The decision to operate with combined HV and LV, or otherwise, should consider the voltage that will be impressed on the LV system under HV fault conditions (Section 9.5).

Section 10 describes pole-mounted installations in detail.

9.3 General design requirements

In common with any earthing system, the design of any new-build substation should satisfy requirements for EPR, touch/step potentials, transfer potentials, and stress voltages. If major changes are to be made to an existing substation, the effects of these proposed changes on the existing earthing system need to be considered. A significant consideration in all cases is the transfer potential that will be impressed on the LV network under HV fault conditions. See Section 9.5.

9.3.1 Design data requirements

The data required is similar to that described in Section 5.4, as necessary to determine the current flow into the electrode system, and the fault duration. These include:

a) fault level at the new substation, or at the source (primary);
b) resistance of the earthing system at the primary substation (R_A), and at the new distribution substation (R_B);
c) circuit length and cable type(s);
d) whether there is any overhead line in the circuit.

For worst-case studies, if there is any overhead line, the ground return current (I_E) can be assumed equal to the earth fault current at the distribution substation (i.e. I_E% = 100 % I_F).

9.3.2 Conductor and electrode sizing

Earth conductors at distribution substations will usually connect key items of plant such as transformer(s), ring main unit / switchgear, and low voltage cabinets. In many unit substations these items may be supplied with bonding connections in place. These bonds should be sized as described in Section 5.5.1; in general they should be sized for the maximum foreseeable earth fault level. For ASC systems, the limited ASC current should not be used (see Section 5.4.2). Network Operators may wish to use the earth fault level at the primary substation, or a higher value allowing for growth (See Section 5.4.3) and uncertainty, up to the 3-phase fault current.

Electrodes should have sufficient surface area to meet the requirements of Sections 5.4.6 and 5.5.2. The worst-case foreseeable electrode current should be used for design purposes. This may be taken as the maximum earth fault current at the substation or its source, or the cross-country fault current or bypass fault current, whichever is the greater, on ASC systems.

Note: If detailed modelling of current distribution is carried out, it will be seen that the ground return current I_E, if calculated using a contribution from a wide area network, will be significantly higher than the local electrode current I_{ES}. Either may be used for electrode design purposes providing that connection to the wider network contribution is reliable. If any doubt exists as to the prolonged integrity of sheath return paths and/or auxiliary electrode connections, the (larger) earth fault current level I_F(calculated for a zero ohm fault) should be used.

9.3.3 Target resistance

A HV electrode system should be established for the substation that is of sufficiently low resistance to ensure reliable protection operation and to limit EPR (and touch/step potentials) to acceptable levels. The design process in this respect is the same as that given in Section 5.3. The resistance that should be achieved is termed the target resistance, and may be specified with and without contribution from parallel systems. Use of a target earth resistance for the substation MES, which ensures compliance with the safety criteria, is useful as it is a more readily understood parameter that can be achieved and tested by installers. Network contribution is discussed in Section 9.4.3.

For ground-mounted substations, traditional custom and practice (permitted by previous versions of this TS) was to apply a target resistance (before connection to the network) of 1 Ω (including contributions from the wider network). If this could be achieved, it was permissible to combine the HV and LV earthing systems. No perimeter or grading electrodes were installed in such legacy systems, and often only one vertical rod or horizontal electrode would be installed. This approach relied heavily on contributions from lead-sheathed cables radiating away from the substation, often passing under the operator's position. These cables provided a degree of potential grading (thus reducing touch potentials) as well as reducing the overall (combined) earth resistance of the substation. Experience has shown that this approach is no longer applicable, particularly given the now widespread use of insulated sheath cables.

Network Operators may find that different target values for earth resistance are generally applicable in different geographical areas, and for overhead or underground networks, and thus may choose to adopt a rule of thumb to assist designers and other connections providers. In any case, calculations or measurements sufficient to demonstrate that the installed system will be safe should be carried out at the design stage. See Section 9.3.7.

Target resistance values should consider all foreseeable running arrangements or network configurations, especially if the network is automated or remote controlled. See Section 9.9.

9.3.4 EPR design limit

A natural EPR design limit is imposed by a) consideration of transfer potential onto the LV systems for combined HV/LV systems, and b) insulation withstand voltage between the HV and LV systems for segregated systems. See Section 9.7for more detail regarding separation distances. These considerations may for example, lead to typical design EPR limits of 2 kV (or higher, depending on equipment withstand voltage) for segregated systems, and 466 V for combined systems.

9.3.5 Calculation of EPR

The EPR for a distribution substation, for faults at that substation, is calculated in the conventional manner, i.e. by multiplying the ground return current by the overall (combined) substation earth resistance.

9.3.5.1 Factors to consider

The ground return current value is influenced by the earth fault current split between the soil return path and the cable sheath.

The earth fault current is influenced by the resistance of the earthing system and the impedance of the cable sheath. The source impedance (primary substation), the resistance of the primary substation MES, and in particular the method of neutral earthing will have an effect.

For most accuracy, some form of iterative calculation or computer model will be required to explore the relationship between fault current, EPR, and substation resistance. However, in any such design there are often other factors or unknowns / variables which may be of more significance. For this reason, it may be sufficient for a design to err on the side of caution by using a zero-ohm earth fault level (the maximum theoretical fault level at the distribution substation calculated using zero sequence impedances for the circuit). Fault impedance can then be introduced only if necessary to achieve an economic or practicable solution.

ENA EREC S34 provides a detailed discussion of EPR calculations and includes worked examples to assist with the calculation of ground return current.

9.3.5.2 Transfer potential from source

A second contribution to EPR comes from transfer potential exported from the source substation, since any EPR at the source will be conveyed along the cable sheath and will appear (in part) at the new substation.

Transfer potential need not been considered if there is any unearthed overhead line in the circuit, or if the new substation is not the first on the feeder and transfer potential is known to be of no significance at previous distribution substations.

In determining the acceptable transfer potential from source, the relevant protection clearance time at the source should be used in touch/step potential calculations.

9.3.6 Step/touch potentials at the substation

Many Network Operators or connection providers opt for a standard design of distribution substation, and it is possible to establish, by modelling or calculation, the step and touch potentials as a % of EPR for each standard layout. These values are influenced to a small degree by the depth of earth rods and the proximity of other earthed metalwork, but for design purposes can be taken as fixed for each layout. Typical values for touch potential within a 3x3 m unit substation that has a perimeter grading ring and corner electrodes are 20-40 % of EPR. A substation built on a fine (and bonded) re-bar mesh might present a touch potential in the region of 10% or less of EPR.

Substations that employ a single rod electrode, or similar legacy design, are unlikely to limit touch potentials to less than 75 % of EPR away from the electrode, and may have unacceptably high step potentials (gradients) in the vicinity of the electrode, depending on its depth of burial. Computer modelling using an appropriate package and soil model will normally be necessary to demonstrate safety unless the system is simple enough to permit first principle calculations such as those presented in ENA EREC S34 or other relevant standards.

The appropriate design limits for touch and step potential are given in Table 1 and Table 2 and are dependent on normal (calculated or worst-case) protection operation.

9.3.7 Simplified approach

In some cases, a safe system can be achieved without detailed design calculations. Network Operators may wish to instead adopt simple rules in certain geographic areas, provided these rules can be shown to produce a site with acceptable touch, step and transfer potentials. For example, a standard layout (perhaps consisting of a perimeter electrode and corner rods) might be appropriate if:

a) 11 kV fault current is limited by a reactor or resistor, and;
b) there is a continuous cable connection to the primary substation, and;
c) there is interconnection to the wider (HV and LV) network, and;
d) the transfer potential from the Primary Substation is below the permissible touch potential (taking into consideration clearance times at the primary);
e) there is some potential grading to limit step/touch to 50% or less of EPR (this assumes that site EPR will not exceed 2x permissible touch potential limits).

This approach is broadly consistent with that outlined in the design flowchart (Section 5.6.1).

9.3.8 Circumstances where the simplified approach is not appropriate

More detailed assessments might be needed if one or more of the following apply:

a) there is any overhead line in circuit, or other break in the earth-return path;
b) the substation is not interconnected to the HV or LV network;
c) the secondary winding of the main transformer at the primary substation is solidly earthed.
d) dedicated earth fault protection is not installed;

e) In difficult circumstances a HPR but safe (step/touch potential) design is allowable by appropriate use of grading electrode/mesh to control step and touch potentials. Alternatively, the EPR may be reduced by appropriate means (see Section 5.6.3).

9.4 Network and other contributions

Distribution substations are commonly connected to larger metallic systems which can serve as an electrode. The following Sections describe typical contributions which may be included in design calculations.

9.4.1 Additional electrode

In many cases it will be possible to supplement the substation's electrode system by laying bare copper, or a long rod nest beneath incoming or outgoing cables (subject to separation/segregation where required), although when there are several parties involved in a project it may not be possible for the substation installer to do so without agreement with cable installers and landowners at the design stage. Test facilities e.g. an accessible loop may be provided so that the integrity of buried horizontal electrode can be tested periodically.

Electrode contribution such as this may be considered in calculations for EPR, touch/step potentials, and surface current density. It should not be included in design calculations if it is vulnerable to theft and/or damage. Suitable precautions should be taken to ensure the integrity of any such connections if they are safety-critical.

9.4.2 Parallel contributions from interconnected HV and LV networks

If it is not practicable to achieve a safe (compliant) design based on HV electrode (and additional electrode) contribution alone, a reasonable parallel contribution from the HV network may be included in the design (Section 9.4.3). However, this network contribution should not be the sole means of earthing and it is recommended that the local (HV) electrode contribution does not exceed a value sufficient to ensure reliable protection operation. In this way, there is some protection against failure of cable sheath/glands.

The LV network contribution may also be used if it can be shown that it is safe to combine the HV and LV networks. Consideration should be given to the magnitude of fault current that will flow into other (parallel) systems, particularly in the case of solidly earthed HV systems, to ensure that the thermal ratings of any conductor or cable sheath are not exceeded.

The thermal rating and surface current density requirements of Sections 5.5.1 and 5.5.2 should be met.

9.4.3 Ascertaining network contribution

The HV network or LV network, (if applicable), can serve as an effective electrode system, and will provide a reduction in earth resistance when combined with the substation earth.

The network contribution element is difficult to establish accurately at the design stage, and measurements of the LV and HV network may be necessary to inform the design. However, due to the relatively routine nature of most small HV (11 kV or 6.6 kV) connections, a conservative estimate is often made to expedite the design process.

The contribution from the network is (for older networks) made up of horizontal electrodes (un-insulated cable sheaths) and point electrodes at distribution substations.

The cable connected distribution substations, whether connected with polymeric HV cables or otherwise, can be modelled as a ladder network, with cable sheath impedances forming the series elements, and earth electrode resistances forming the parallel parts. This is termed the chain impedance, and is akin to the treatment of metal EHV towers in ENA EREC S34. The chain impedance contribution from the HV network substations falls as distance increases from the new substation. In practice, the substations within a 1-2 km radius are those which need to be considered.

The horizontal electrode contribution from any lead-sheathed or hessian-served HV cable sheaths can be treated in the same way as a buried horizontal conductor. In practice, each conductor will have an effective length, beyond which no additional contribution can be assumed. (See Appendix F of ENA EREC S34). A practical HV network will radiate from a substation in more than one direction and a contribution can be assumed from each leg provided their areas of influence do not overlap. In cases of doubt, these systems should be modelled using appropriate computer software, or measurements carried out, taking care to use a method appropriate to the size of the network.

Calculated values for network contribution are often pessimistic in dense urban areas, where numerous parallel contributions (such as water and gas pipes, building foundations, etc.) may exist. If this is so, the designer may commission a measurement of network contribution (if possible), or may use an estimated value for network contribution, or may be able to demonstrate that the area is a global earthing system (GES).

9.4.4 Global earthing systems (GES)

A GES is a system where all equipment is bonded together, and the ground is saturated with metallic electrode contributions in the form of metallic cable sheaths or bare conductors laid direct in soil. In such a system, the soil surface potential will rise in sympathy with that of bonded HV steelwork under fault conditions, and the potential differences (leading to touch potential risk) are minimal. The term is often used to describe dense urban networks where measurements or detailed calculation of network contribution is not practical. See Annex O of BS EN 50522 for more detail.

Network operators may wish to designate certain geographic areas as a GES, in which case they will need to carry out measurements or analysis to demonstrate that the designation is appropriate. In addition, they should carry out calculations to assess the target resistance required in these areas; this is most easily achieved by assuming a low value of network contribution and designing an electrode system that is sufficient to satisfy protection operation, current density and thermal ratings in the absence of this network contribution. A standard design using perimeter electrode/re-bar mesh etc. is usually still warranted for these reasons, using an appropriate resistance value to ensure safety.

Networks within a GES by definition operate with combined HV/LV earthing. Islands of higher potential, and consequently touch and step potentials, within a GES can arise from transferred sources that may not be locally bonded, e.g. cable sheaths bonded to remote systems, metallic gas/water pipes with insulated covering, pilot/communications cables, and HV or LV insulated sheathed cables connected to metallic plant that is not locally bonded to the GES. In these cases, the benefits of a GES do not apply.

9.5 Transfer potential onto LV network

9.5.1 General

ESQC Regulations require that danger will not arise on the LV system as a consequence of HV faults. In practice, this means that the HV and LV earthing systems should be separated if the HV EPR exceeds the applicable limit.

NOTE: Previously, a design limit of 430 V has been applied, i.e. the HV and LV systems could be combined if the HV EPR was <=430 V; in practice, this EPR would be impressed on the LV neutral/earth (distribution transformer star point). The voltage ultimately transferred to a consumer's LV earth terminal would be less than this, and the touch potential appearing within an installation would be even lower.

9.5.2 Touch potential on LV system as a result of an HV fault

Table 2 of BS EN 50522 introduces the concept of an *F*-factor for TN LV systems. In order to combine HV and LV earthing systems, the HV EPR should not exceed $F \times U_{Tp}$, where U_{Tp} is the permissible touch potential related to the appropriate HV fault clearance time.

The *F*-factor relates to the percentage of EPR that will appear as a touch potential on the LV network; it also relates to the potential grading that will occur within an installation and the decay in exported potential along a multiple earthed neutral conductor. The resultant touch potential within the consumer's installation is necessarily subject to a number of factors beyond the control of any Network Operator.

It is recommended that in the UK, a value of $F = 2$ is used unless:

- The LV neutral/earth conductor is earthed at only one point, or
- The LV supplies only a small system that is isolated from the general mass of earth (e.g. a metal pillar on a concrete plinth without outgoing circuits).

In such circumstances, Note (d) to Table 2 of BS EN 50522 applies, which states: "*If the PEN or neutral conductor of the low voltage system is connected to earth only at the HV earthing system, the value of F should be 1.*" A reduced EPR limit is applicable (e.g. 233 volts for a 1 second fault, see Table 1), because it should be assumed that the full EPR could appear as a touch potential.

In practice, for typical arrangements in the UK where $F = 2$, and assuming a 1 s fault clearance time, the HV EPR should not exceed 466 volts if the systems are to be combined. Lower limits will apply for longer fault durations.

9.5.3 Stress voltage

The stress voltage is the voltage across any two points in a substation or connected circuits. The stress voltage limit relates to the insulation withstand requirement of cables and equipment.

If HV and LV systems are combined, the stress voltage limits are unlikely to be exceeded in the substation.

For segregated HV and LV systems, stress voltage includes the difference in potential between the HV and LV earths, and may be assumed equal to the EPR of the substation. Typically, this should be considered in the insulation withstand of the LV neutral bushing, LV neutral busbar supports, and LV cable screen where these are in close proximity to HV steelwork (a value of 2 kV or more is often quoted for modern equipment).

Care is needed if bringing (remotely earthed) LV supplies into such sites, particularly if feeding into metal equipment cabinets that are earthed to HV steelwork. In such circumstances, the insulation withstand within the equipment should be verified to ensure that that breakdown between LV phase/neutral/earth and HV steelwork cannot occur internally. Isolation transformers may be required to ensure that HV and LV systems do not flash across under HV fault conditions.

Where these criteria are met, the requirements of Table 2 of BS EN 50522 will be achieved.

9.6 Combined HV and LV earthing

HV and LV earthing systems will generally be combined if the EPR on HV steelwork does not exceed LV transfer potential limits described in Section 9.5.

In general:

- combine HV & LV earths if the potential rise due to an HV or EHV earth fault is safe to apply to the transformer LV earth;
- segregate HV & LV earths if the potential rise on the transformer LV earth is unacceptable.

A substation with EPR limited to 466 V will usually be suitable for combined earthing if supplying a PME network[4] and the HV fault clearance time does not exceed 1 s. This limit is subject to the caveats given in Section 9.5.2.

9.7 Segregated HV and LV earthing

For segregated earth systems, it is necessary to ensure that the LV electrode system is sited at sufficient distance from the HV electrode so that the potential rise on the LV network is acceptable.

9.7.1 Separation distance

Table 11 and Table 12 give an approximate minimum separation distance based on the EPR and acceptable LV transfer limits. The values are not significantly dependent on soil resistivity once the EPR is known, although a uniform soil model is assumed.

NOTE: Where the earth design is not based on a simple peripheral electrode the use of multi-layer soil models and computer modelling may be required to determine the optimal separation distance.

The tables are calculated for 3x3 m substations and 5x5 m substations, assuming both have a perimeter electrode. These are calculated values as given by formula P3 in Appendix B of ENA EREC S34. They have been compared with modelled results for uniform soil and the most conservative values are presented here; this represents the voltage contour furthest from the substation, such that any LV electrode beyond this distance from the substation boundary will be at or below the stated V_x figure under HV fault conditions.

These figures relate to the distance of the voltage contour at its furthest point from the substation. In some cases (multiple earthed systems) the first LV neutral/earth electrode may be sited inside the appropriate contour. See Section 9.7.4 and worked examples in ENA EREC S34.

NOTE: The following limits are tabulated. For other values, see Table 1.

233 V = touch potential limit on soil for 1 s fault duration (or EPR limit with *F*=1);
324 V = 162 V x 2, EPR limit applicable to 3 s fault duration with *F*=2;
376 V = 188 V x 2, EPR limit applicable to 1.5 s fault duration with *F*=2;
466 V = 233 V x 2, EPR limit applicable to 1 s fault duration with *F*=1.

Table 11 – Separation distance (m) from 3x3 m substation

EPR(V) / V_x (V)	1000	2000	3000	5000
233	3.0	7.6	12.2	21.5
324	1.8	5.0	8.3	15.0
376	1.4	4.2	7.0	12.7
466	0.8	3.0	5.3	9.9

[4] An *F*-factor of 2 can be assumed for PME networks compliant with ENA EREC G12/4, i.e. the voltage appearing at the customer's earth terminal is expected to be no more than 50 % of the substation EPR. This paragraph also assumes that HV faults will clear within 1 s.

Table 12 – Separation distance (m) from 5x5 m substation

EPR (V) / V_x (V)	1000	2000	3000	5000
233	5.0	12.7	20.4	35.8
324	3.0	8.4	13.9	25.0
376	2.3	6.9	11.7	21.2
466	1.4	5.1	8.9	16.6

9.7.2 Transfer potential to third parties

For substations that are close to third parties, consideration should be given to railways, pipelines, telecommunications, cable TV, etc. if such utilities pass through an area of high potential. The formulae in Appendix I of ENA EREC S34 may be used to provide an indication of the EPR that may be transferred to nearby objects.

9.7.3 Further considerations

The precise separation distance to be maintained between the HV and LV earthing systems is dependent on the EPR, the soil layer structure, and the physical layout of the earth electrodes. If necessary, it should be calculated during the design phase using the methods given in ENA EREC S34 or via detailed simulation and should include the effect of electrodes located away from the substation (See Section 9.7.4).

For existing substations or during commissioning of a new installation, the transfer potential should be determined by measurement where practicable to confirm the calculated value. A separation factor of 0.9 or greater should be achieved (see Section 7.10).

9.7.4 Multiple LV electrodes on segregated systems

The separation distances above are those relating to the potential contour, such that the LV electrode or electrodes are sited beyond this. In practice, if these distances cannot be maintained, one or more electrodes on a multiple earthed neutral (e.g. a PME system) may be sited within a higher voltage contour (but no closer than 3 m) provided that the majority of the PME LV electrodes are sited beyond this. An above-ground separation of 2 m or more should be maintained to prevent simultaneous (hand-hand) contact between the systems.

This assumes that the remainder of the LV system as a whole will have a resistance lower than that of the LV neutral electrode. The LV earthing system will have a centre of gravity that lies outside the relevant contour, i.e. the transfer potential will be the weighted average of that appearing at all LV electrodes. Any design based on these assumptions should be backed up by a measurement of separation factor for the installed arrangement.

See also ENA EREC S34 for calculations / worked examples.

This relaxation does not apply to SNE systems, or PNB systems where the neutral/earth is earthed at only one point.

Where calculations based on the local LV electrode (i.e. the electrode closest to the substation) indicate impractical separation distances or excessive transfer potentials, the design should be reviewed and further LV electrodes installed at the end of LV feeder cables, connected via the PEN conductor. To maximise this beneficial effect, they should be located as far away from the HV electrode as possible and have a lower resistance than the LV electrode at the substation.

9.8 Situations where HV/LV systems cannot be segregated

In some situations, it is not possible to segregate HV and LV systems safely without additional measures. One example is where an LV system exists within a HV system, or there are other similar physical constraints meaning that systems cannot reasonably be kept apart. See BS EN 50522.

In such circumstances, consideration should be given to combining the HV and LV systems and augmenting the electrode system(s) such that EPR and HV-LV transfer potential is acceptable. If this is not practical, insulated mats/barriers could be considered in relevant areas.

If necessary, the building or area could operate with a combined HV/LV system safely yet with a high EPR, provided all sources of transfer potential into and out of the HPR area can be excluded, and touch potentials are managed in and around the building. See guidance on stress voltage given in Section 9.5.3.

9.9 Practical considerations

HV networks are usually capable of being manually or automatically reconfigured. The change in running arrangements will affect various parameters including fault level, protection clearance time, and the sheath return current as a percentage of fault current I_F.

This complication means that a bespoke design for a distribution substation may not be valid if the running arrangement changes, and therefore the value of detailed design calculations on a dynamic network is questionable. It is recommended that the design considers all foreseeable running arrangements, or for simplicity makes worst-case assumptions regarding fault level, protection clearance time, and ground return current I_E.

A network operator may wish to adopt or provide a target resistance value (tailored to different geographic areas and different system earthing/protection scenarios), or other simplification of these design rules, for these reasons.

9.10 LV installations near HPR sites

LV electrodes (segregated systems) as described above should be clear of the relevant voltage contour. The consideration also applies to any customer's TT system earth electrode. If necessary the electrode(s) should be relocated or the shape of the HPR zone altered by careful positioning of HV electrodes. In addition, where possible, LV electrode locations should place them clear of any fallen HV or EHV conductors.

The siting of LV earths should consider zones with elevated potential e.g. some properties close to HPR substations or EHV towers may themselves be in an area of HPR, in which case provision of an LV earth derived from outside that zone may introduce a touch potential risk at the installation, due to the LV earth being a remote earth reference. The arrangement can also pose a risk to other customers on the LV network if it will permit dangerous voltages to be impressed on the LV neutral/earth.

Detailed modelling of HV/LV networks may demonstrate that potential differences are not significant, due to the influence of the network on the shape of the contours; however, such modelling may not be practicable. If any doubt exists, customers should not be offered an earth terminal, and no LV network earths should be located in the area of HPR. Cables passing through the area should be ducted or otherwise insulated to limit stress voltage to permissible limits. Typically a customer will use their own TT system earth electrode; however if properties are in an area where EPR exceeds 1200 V, it is possible that they will experience L-E or N-E insulation failures under HV or EHV fault conditions and isolation transformers or careful siting of HV:LV transformers and electrode systems may be required. See Section 9.11 and the case studies in Section 11.

For PME electrode locations, see ENA EREC G12.

9.11 Supplies to/from HPR sites

Network supplies into HPR sites invariably need care if the network earth is to remain segregated from the HPR site earth. In remaining separate, this can introduce touch potential risk within the site. It is normally necessary to use a careful combination of bonding and segregation to ensure that danger does not arise within the site, or on the wider network. Sheath breaks, insulated glands or unearthed overhead line sections are often convenient mechanisms to segregate the earthing systems.

Similar considerations are required for LV supplies derived from HPR sites if these are to export to a wider area. Typically, the LV neutral will be earthed outside the contours of highest potential and will be kept separate from all HPR steelwork in accordance with normal best practice. It may be necessary to apply ducting or additional insulation to prevent insulation breakdown and resultant fault current diversion from the HPR site into the wider network.

See ENA EREC S34 for specific examples, and the case studies in Section 11 below.

9.11.1 Special arrangements

Where a standard substation earthing arrangement is not applicable, other options may include:

- combining HV and LV earths and managing touch and step potentials by installing an earthing system to enclose the installation supplied, i.e. effectively producing a large equipotential safe zone, irrespective of EPR. The design should take into account any metallic services such as Telecoms entering or leaving the installation, and is most useful in rural areas.
- using an isolation transformer with a separate earthing system where an LV supply has to be taken outside a HPR substation site with a bonded HV/LV earth system;
- using isolation transformers to provide small capacity LV supplies to HPR ground-mounted substations, e.g. LV supplies to telecontrol equipment located within substations with segregated HV/LV earths (see 9.5.3). The alternative use of TT supplies (derived outside the High EPR zone) in such circumstances does not protect against insulation failure/flashover between the LV phase/neutral conductors and HV steelwork and could lead to the systems becoming inadvertently combined.
- For supplies to mobile phone base stations see ENA EREC G78.

See Section 11.2 for examples of LV supplies into HPR sites.

10 Earthing of pole-mounted substations and associated equipment

This section describes earthing associated with HV distribution overhead line networks (excluding tower lines).

10.1 General

Extreme care should be taken when replacing pole-mounted equipment with ground-mounted equipment, since any existing earthing system is unlikely to be adequate to limit touch potentials to safe levels on the new installation.

10.2 Pole-mounted transformers

Pole-mounted transformers (PMTs) typically operate with a segregated HV and LV earthing system (see Section 9.7) and, since the metalwork is out of reach, a high EPR can be tolerated on the HV steelwork, provided that the LV electrode system is suitably separated from the HV system. Figure 8 shows a typical arrangement where the main LV electrode is at the first pole, i.e. one span away, from the HV pole.

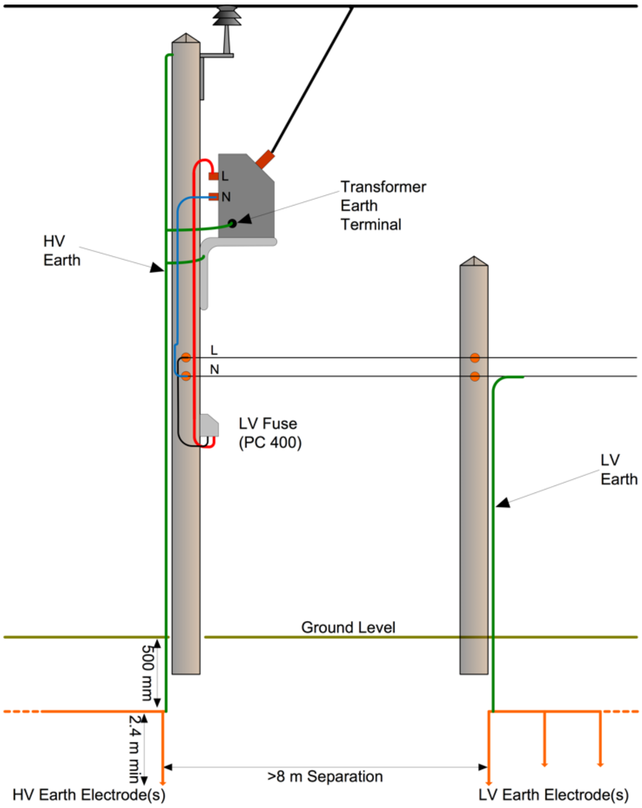


Figure 8 - Typical PMT earthing arrangement

The limiting factor for EPR is usually insulation withstand voltage of the LV cables, insulators and bushings at the pole-top; often a design value of 2 kV to 5 kV is assumed, depending on equipment specifications. A high EPR (with a small electrode system) is often inevitable on systems supplied by unearthed overhead lines as these do not enjoy the return path offered by a metallic cable sheath/armour.

The HV electrode should be sited and designed so that it will not present a danger in terms of hazardous step potentials (potential gradient) around it. In this respect, it is no different to that of ground-mounted systems described above, except that PMTs are often in fields, close to livestock/animals, and with high ground return currents. See Section 10.3.

10.3 Electrode configuration for pole-mounted equipment

The following earth electrode designs assume that the overhead network does not have a return earth conductor. With this type of system, the EPR of the local earth electrode typically will exceed tolerable touch, step and transfer potentials under earth fault conditions.

Due to the possible hazardous touch potentials, earth conductors above ground should be suitably insulated and provided with mechanical protection for a minimum height of 3 m or above the height of the anti-climbing device, whichever is greater. In addition, the main earth conductor should be suitably insulated for a minimum of 500 mm below ground level. Where the separation of electrodes is required, guidance is given below.

It is not always reasonably practicable to ensure in all situations that step potentials directly above an installed earth electrode system remain below permissible limits under earth fault conditions[5]. It is generally considered that the probability of an earth fault occurring whilst an individual happens, by chance, to be walking across the earth electrode at the same time, is extremely small. Therefore, in most circumstances no special precautions are required. However, at sensitive locations that are often frequented[6] by people, particularly children, and concentrations of livestock in stables or pens for example, precautions may be justified to eliminate or minimise the risk. This can usually be achieved by careful site selection or at the time of installation by installing the earth electrode in a direction away from the area of concern, burying the electrode as deep as practicable, and/or fencing the electrode off to prevent access.

A similar situation also applies to personnel carrying out live operations such as HV drop-out fuse replacement, live-line tapping at earthed locations or ABSD switching using hook stick (hot-stick or insulated rods) techniques on earthed poles.

10.4 HV earth electrode value

The HV electrode is usually the only return path for HV fault current, except for relatively rare instances of cable fed PMTs, or cable terminations, and its resistance should generally be sufficiently low to operate HV protection within design limits for the network (typically 1 to 1.5 s maximum); electrode resistance values between 10 Ω and 40 Ω are often quoted for design purposes, with lower values providing increased resilience to lightning strikes. Lower resistance values will limit the potential rise on HV steelwork, and can prevent back flashover across LV bushings resulting from lightning surges, which would otherwise destroy the transformer winding.

In general, the lower the earth electrode resistance, the more earth fault current will flow, resulting in more reliable operation of the circuit protection. Where surge arrestors are used it is generally accepted that 10 Ω is the preferred maximum value of earth electrode resistance for satisfactory operation of the arrestor. This is in line with the preferred 10 Ω value in BS EN 62305-1 for high-frequency lightning earth electrodes.

10.5 Electrode arrangement selection method

A common arrangement of rods used for earth electrodes associated with overhead line equipment is a run of parallel rods interconnected with a horizontal conductor.

Resistance values may be calculated using formulae in Appendix B of ENA EREC S34. The calculated values are considered to be conservative and are based on uniform soil resistivity.

Calculated resistance values for the same rod and soil arrangements, using earthing design software are approximately 30% lower. Where the ground conditions are difficult, i.e. of high resistivity and/or rocky, the cost of obtaining the required earth electrode resistance value may warrant carrying out a site-specific design.

10.6 Earthed operating mechanisms accessible from ground level

This section deals with pole-mounted auto-reclosers (PMAR), sectionalisers, and air break switch disconnectors, all of which are capable of being manually operated via an earthed metallic control box or switch mechanism. It is important to note that where an LV supply is

5 This is now less of an issue as step potential limits have been considerably relaxed compared with previous versions of this specification.

6 See BS EN 50341-1 clause 6.2.4.2 for definition

required for control circuits, the supply should be derived from a dedicated transformer whose LV neutral is earthed directly to the installation's main HV earth conductor.

There are several methods of minimising the risk from any hazardous touch and step potentials at such installations. In selecting the most appropriate method, due account should be taken of the nature of the site, the accessibility of the equipment to third parties and the EPR under fault conditions.

a) Use of wireless remote control for a unit mounted on the pole out of reach from ground level. With this method, an HV earth electrode system may be required where surge arrestors are fitted or where the manufacturer of the equipment specifies. Where equipment is unearthed its mounting height should comply with the relevant regulations.
b) Place the control box out of reach from ground level, access being via an insulated ladder. Again, with this method an HV earth electrode system may be required where surge arrestors are fitted or where the manufacturer of the equipment specifies. Where equipment is unearthed its mounting height should comply with the relevant regulations.
c) Install an operator's earth mat and grading conductors to help provide an equipotential zone for the operator. Figure 9 and Figure 10 show an example of how this may be achieved. Whilst this minimises the hazards for the operator, it requires that the installation be carried out with great diligence. It is also important that the future integrity of the earth electrode is ensured. Misplacement of the earth electrode conductors can result in the operator being exposed to hazardous touch and step potentials. Consideration should be given to the selection of the site prior to installation to ensure that the required earth electrode configuration can be installed correctly and maintained adequately into the future. Use of suitable personal protective equipment for switching operations may also be considered as an additional risk control measure; dielectric (insulated) footwear rated at >7 kV is now commonly used to protect operators against step potentials when stepping on/off the platform.

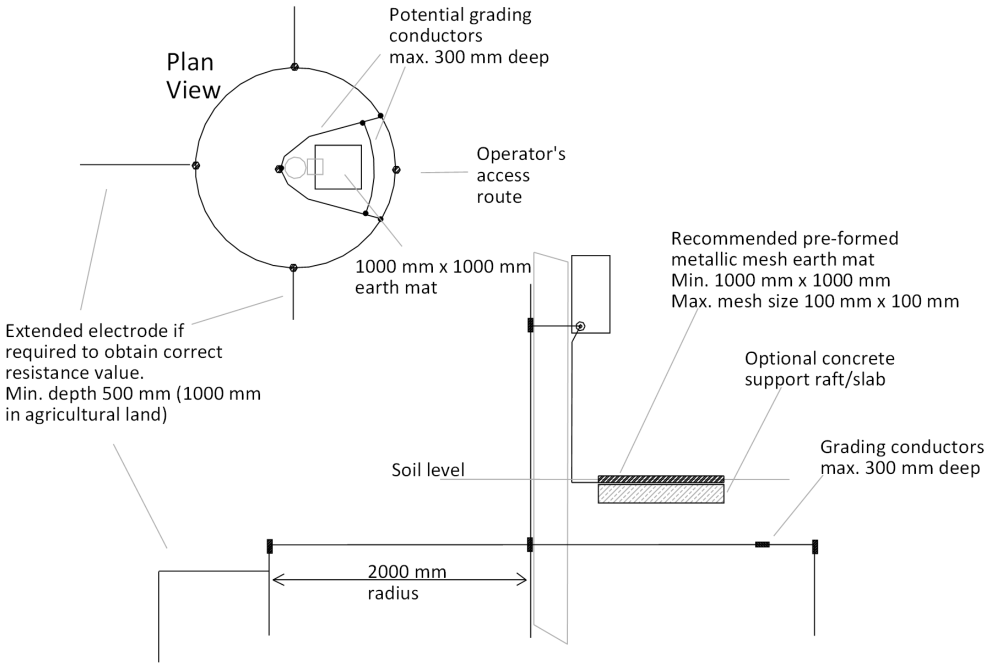
Where mechanical damage is likely, for example in farmland, protective measures need to be considered to ensure the integrity of the earth electrode and the earth mat. An example would be to install and fix the earth mat on or in a raft of concrete or fence off the area surrounding the earth mat.

The use of grading conductors to minimise step potentials in the immediate vicinity of the operator's earth mat may prove impractical in some circumstances, particularly where there is a danger of them being damaged by ploughing. Burying the grading conductors at a greater depth will significantly reduce their effectiveness. Keeping step potentials within tolerable limits can be extremely difficult and in some case impracticable. In such circumstances, alternative mitigation should be considered.

Soil structure, operating voltage, type of HV system earthing (solid or resistance) and system impedance all have an effect on the value of step and touch potentials created around the earth electrode, whereas protection clearance times will have a bearing in determining the tolerable touch and step potential limits. At some sites, it may be prudent to restrict access to the control box, for example by use of insulating barriers or fences, so that it is not possible for third parties to touch the control box and where operators can only touch the control box when standing on the earth mat.

It should be noted that burying the operator's earth mat will increase the touch potential between the control box and the surface of the ground above the earth mat; the greater the depth of the mat, the greater the potential difference between the soil surface above the mat and the control box. The hazard this presents can be managed by covering the mat with a high resistivity material which will increase the impedance path between the hands and feet. Burying the mat will also have the effect of reducing the step potentials for an operator stepping off the mat. However, the prime concern is to minimise the touch potentials, as these are considered to be more hazardous than step potentials. Where the mat is buried, the touch potential and the hazard it presents will be site-specific, being dependent upon the actual EPR and the protection clearance times for the given site, therefore a site-specific design is recommended. The surface mat shown in Figure 9 results in negligible touch potentials for the operator standing on the mat, irrespective of the EPR.

In all cases it is an option to use control measures to mitigate risk if a company deems this is the most appropriate solution in the circumstances.



NOTE: This arrangement does not exclude the use of a portable earth mat.

Figure 9 - Earthing arrangement for a PMAR with ground-level control box

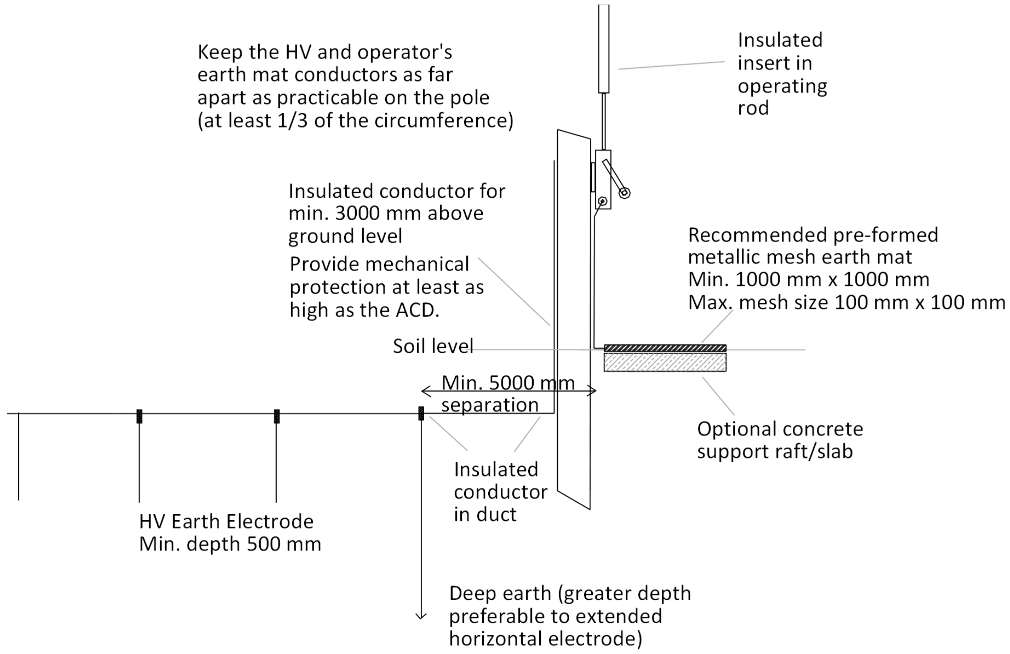


Figure 10 - Alternative earthing arrangement for a PMAR with ground level control box

10.7 Air break switch disconnector (ABSD) with an isolated operating mechanism

There are several methods of controlling hazardous touch and step potentials, at pole-mounted ABSDs.

a) Method 1 - Install an insulated rod-operated ABSD at high level that does not require an earth electrode. Where equipment is unearthed, its mounting height should comply with the relevant regulations. This option removes the risk of the operator being exposed to the hazard of touch and step potentials that could occur under certain earth fault conditions when adopting method 2 below.

b) Method 2 - Install an ABSD that is operated manually from ground level with a separate HV earth electrode and operators earth mat. This approach relies on effective separation of the HV earth electrode that connects the HV steelwork to earth, and the operator's earth mat connected to the operating handle. This arrangement is typical of existing earthed ABSD equipment found on rural overhead line distribution networks.

Separation is achieved by placing the HV earth electrode a minimum of 5 m away from the base of the operator's earth mat using insulated earth conductor from the electrode to the HV steelwork, and by insulating the operating handle from the switch mechanism using an insulating insert in the operating rod. The top of the insert should be a minimum of 3 m from ground level when in its lowest position. The operating handle should be connected to an earth mat positioned where the operator will stand to operate the handle. If the earth mat is installed such that it is visible, the operator can verify its existence and its connection to the handle prior to operating the handle. The continuing effective segregation of the HV earth electrode and the operator's earth mat is the most important aspect of the way in which this arrangement seeks to control the touch and step potentials around the operator's earth mat position. To minimise the possibility of contact between the buried insulated earth conductor and the surrounding soil, should the insulation of the earth conductor fail, the conductor could be installed in plastic ducting.

Where mechanical damage is possible, for example in farmland, protective measures may need to be considered to ensure the integrity of the earth electrode and the earth mat. An example would be to install and fix the earth mat on or in a raft of concrete or to fence off the area surrounding the earth mat using non-conducting fencing.

Under earth fault conditions the HV earth electrode will rise in potential with respect to remote earth. A potential gradient will be produced around the electrode, the potentials being highest immediately above the electrode and reducing rapidly with distance. The earth mat will be located within the potential gradient surrounding the HV earth electrode, but due to the separation distance of 5 m the potential at that point with respect to remote earth will be relatively small. The surface level earth mat for the operating handle and the handle itself will rise in potential but there will be effectively no potential difference between the mat and handle.

Under earth fault conditions, assuming the correct separation distance between the HV earth electrode and the operating handle earth mat, should the operator have one foot on the mat and one off the mat, touch and step potentials surrounding the earth mat should not exceed tolerable limits. However, there is a risk of hazardous touch and step potentials arising if the HV earth electrode short-circuits to the operating handle earth mat. The risk of such a short circuit occurring is extremely small provided that the earth installation is correctly installed, inspected and maintained.

The actual size and shape of the earth mat should be such as to ensure that the operator will be standing towards its centre whilst operating the handle. Notwithstanding this requirement, the minimum size of earth mat should be 1 m by 1 m. Due consideration should be taken of the type of handle, whether it is a two-handed or single-handed operation and whether the operator may be left or right handed. A purpose-made mat is recommended in preference to a mat formed on site out of bare conductor, as this eliminates problems of variation in shape and size that can occur with the latter. Where a buried earth mat is used, the maximum depth of the mat should be no greater than 300 mm.

Under normal earth fault conditions the touch potential for both buried and surface mounted scenarios will be negligible. When deciding between the use of a buried earth mat and a surface mounted mat the following issues should be considered:

- A surface mounted mat will allow the operator to visually confirm both the position of the earth mat relative to the handle and also the integrity of the connection between the earth mat and the handle.
- A surface mounted mat will minimise any touch potentials between the soil surface on the mat and the handle, both under normal earth fault conditions and under second fault conditions where the handle and the earth mat become energised, although this scenario should be less likely because effective segregation can be visually confirmed before operation.
- Conversely, a surface mounted mat will maximise the step potential around the mat, although this will only be an issue if the mat and handle become energised under a second fault scenario.
- A buried earth mat will not allow the operator to visually confirm either its position relative to the handle, or the integrity of its physical connection to the handle before operation.
- Burying the earth mat will increase the value of any touch potential between the handle and the soil above the earth mat, and this potential will increase with depth.
- To maintain the same effective soil surface area with a buried earth mat for the operator to stand on and minimise any resulting touch potentials requires a significantly larger mat than for a surface mounted mat.
- Where a second fault occurs that energises the operating handle and earth mat, with a buried earth mat the touch potential could exceed tolerable levels.

- Conversely, burying the mat will have the effect of reducing the step potentials under such conditions for an operator stepping off the mat.

The use of suitably rated PPE in these situations would assist in minimising the risk of exposure to possibly hazardous potentials.

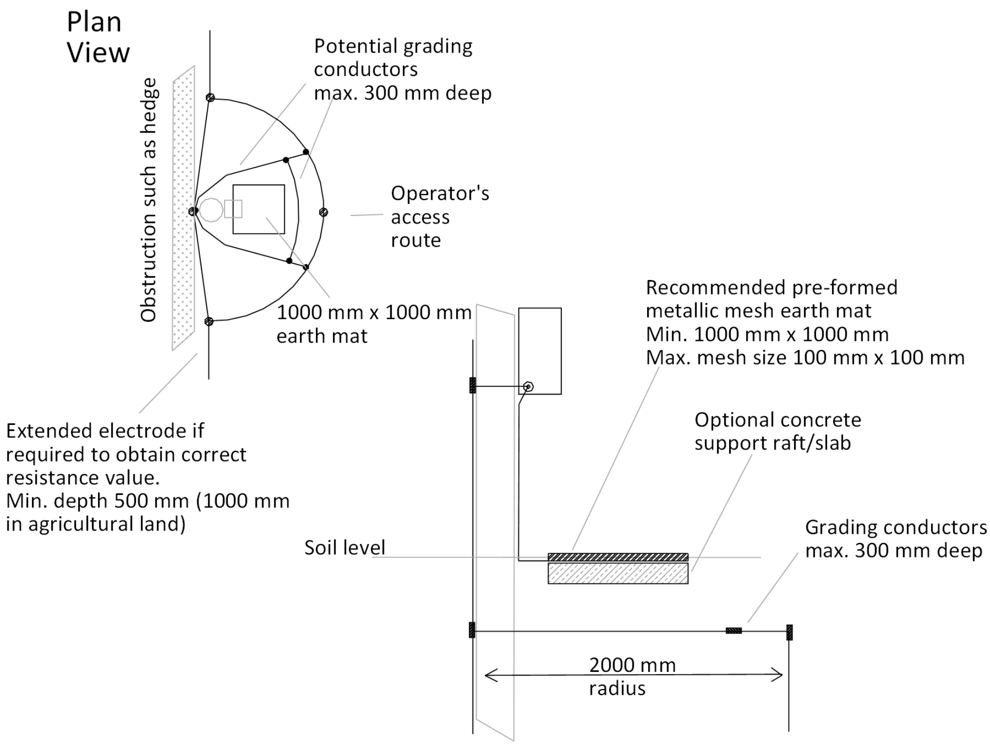


Figure 11 - Recommended earthing arrangement for an ABSD

10.8 Surge arrestors

The preferred value for the surge arrestor earth electrode resistance is 10 Ω or less. Ideally this electrode system should be installed as close to the base of the pole as possible. However, for some locations where it may be necessary for an operator to carry out switching operations on the HV networks at that pole this may create unacceptable step potential hazards. In such cases the HV earth electrode should be installed away from the pole at a location where the step potential is calculated to be safe (typically 5 m) for the operator to stand when carrying out any switching operations, see Section 6.14. It is preferable to have a small number of deep earth rods rather than many shallow rods or plain horizontal conductor. The earth conductor connecting the base of the surge arrestors to the earth electrode system should be as straight as possible, having as few bends in as is practicable.

Where other HV equipment is situated on the same pole and requires an earth electrode, only one HV earth electrode should be installed.

NOTE: This practice differs for that in substations as given in Section 6.14, where separate power-frequency and high-frequency earths are required.

The preference is to install an earth conductor directly from the surge arrestors to the buried HV earth electrode, and then connect the earths of the other items of HV equipment to it on the pole. At sites where switching may take place the earth lead should be insulated to the first earth rod which should be a minimum of 5 m from the operating mat for an ABSD or 5 m from the operating position for equipment that requires the use of hot-sticks or insulated rods. Additional protection may be achieved by placing the earth lead in ducting to that point.

10.9 Cable terminations

Typically, cable terminations on poles are associated with surge arrestors or other HV equipment, in which case the cable sheath or screen is connected directly to the surge arrestor or HV equipment main earth conductor. In the absence of surge arrestors or other earthed HV equipment, the cable will require the installation of an earth electrode.

10.10 Operations at earthed equipment locations

At earthed installations fed via overhead line systems, it is essential to have robust operational procedures to minimise the risk from the possible hazards associated with HPR under earth fault conditions. It should be noted that the risk increases during live fault switching operations. It is beyond the scope of this document to detail such procedures but consideration should be given to the following points:

- Earth systems are usually designed to minimise hazards under main protection operation. They are not designed, unless specifically required, to minimise hazards under secondary or backup protection conditions. This is an important point to note when developing fault switching operational procedures. Temporarily disabling parts of the protection system, reconfiguring the network, or raising protection settings to aid in fault location during fault switching can give rise to touch, step and transfer potentials of a duration that the associated earth systems have not been designed to take account of.
- Precautions should be taken, by virtue of the equipment design and earthing arrangements, to minimise any touch and step potential hazards. For example, where rod-operated (insulated hot-stick) equipment is used, the simplest way of minimising hazards from touch and step potentials is by, where practicable, placing the earthing electrode, not serving as grading conductors, away from the position where the operator will be standing. Where several people are present during operations, any person not actively carrying out operations should stand well clear of the installed earth electrode.

10.11 Installation

The following points should be considered when installing an earth electrode system for overhead line equipment:

- Materials and jointing methods should comply with the requirements of BS 7430.
- Installation teams should have a basic understanding of the functions of an earth system, and should carry out installations to a detailed specification.
- Typically, installing a horizontal earth electrode system at a greater depth than 500 mm will not have any significant effect on reducing the value of earth electrode resistance. However, it is recommended that the electrode is buried as deep as is practically possible to minimise surface potentials and the possibility of mechanical damage. Where ploughing is a concern, the electrode should be buried at a minimum depth of 1 m.
- Ensure maximum separation is achieved on the pole between HV earth conductors and ABSD handle earth mat conductors.
- It is recommended that a test point is made available for future connection of an earth tester above ground so that the earth electrode resistance can be measured. This test point should be installed and constructed so as to prevent unauthorised access, and on ABSDs prevent possible flashover to the operators handle and associated earth mat.
- Welded, brazed or compression connections are preferable to bolted connections for underground joints.
- Corrosive materials and high resistivity materials such as sand should not be used as a backfill immediately around the electrode.

- The earth resistance of the installed electrode should be measured and recorded.
- Where a buried operator's earth mat has been installed, the mat should have two connections made to the operating handle.

10.12 Inspection and maintenance of earthing installations

10.12.1 Items to inspect

During routine line inspections, it is recommended that the following items are visually inspected and their condition recorded, with any defects being rectified in a timely manner:

- ABSD earth mat and connection to operating handle.
- Separation of HV and operator's handle earth on an ABSD.
- Separation of HV and LV earth conductors on the pole.
- Check that the anti-climbing device does not compromise the separation between the HV earth conductor and the operating handle.
- Insulation of HV and LV earth conductors.
- Mechanical protection of HV and LV earth conductors.
- Bonding of plant and equipment.
- State of connections, including any test point.
- Signs of possible mechanical damage to earth electrode and buried earth mats.

10.12.2 Items to examine

Periodically, examine a random sample of buried earth electrodes and buried ABSD handle earth mats, and rectify any defects found. The examination should check for the following:

- position of earth mat and electrode locations relative to ABSD handle and operator's position.
- insulating insert in the ABSD operating rod.
- state of underground connections.
- state of earth electrode components, particularly galvanised steel rods.
- state of insulation on underground earth conductors where separation of electrodes is required.

NOTE: When carrying out this work, protective measures should be taken to ensure the safety of personnel during fault conditions.

The results of the examinations can be used to assist in developing ongoing inspection and maintenance policy, and procedures.

10.12.3 Items to test

- Periodically test the earth electrode resistance. For the relatively small earth systems typically associated with overhead line equipment, a small 3-terminal earth tester is adequate. The test should be carried out in accordance with the manufacturer's instructions.
- Regularly test the continuity between operating handle and the operator's earth mat.
- Regularly test the continuity of buried earth mats.
- Periodically test a random sample of insulating inserts used in ABSD operating mechanisms.

IMPORTANT: When carrying out these measurements, the equipment should be made dead or where this is not practicable a risk assessment should be carried out and suitable test procedures should be adopted which safeguard the operator from any rise of earth potential. Such procedures may, for example, include the use of insulating gloves and boots, mats and / or fully insulated test equipment.

11 Case studies / examples

11.1 Risk assessment – third-party metallic fence near substation

This case study concerns a third-party metallic fence that has been erected close to (within 4 metres of) a primary substation. The EPR at the substation in this case is 3 kV, and generic fault data suggests that EPR events may occur up to 2.1 times per year on average (due to a combination of local and remote faults).

In this example, the substation measures 30 x 30 m. The slowest (normal) fault clearance time is 0.5 s.

In this case, hand-to-hand touch potential is not an issue between the substation fence and the third-party fence (because the above-ground separation exceeds 2 m). However, a hand-to-feet touch potential can exist at the third-party fence during substation fault conditions, and this is assessed below.

This case study is representative of various scenarios where a transfer potential is introduced from a remote source; in this case the metallic fence will adopt a potential that may differ from the ground potential, particularly if the fence is on insulated supports and in contact with a remote earthy structure. Similar principles can be applied to any telecoms circuits, LV cables, etc. which encroach on an area of high potential rise.

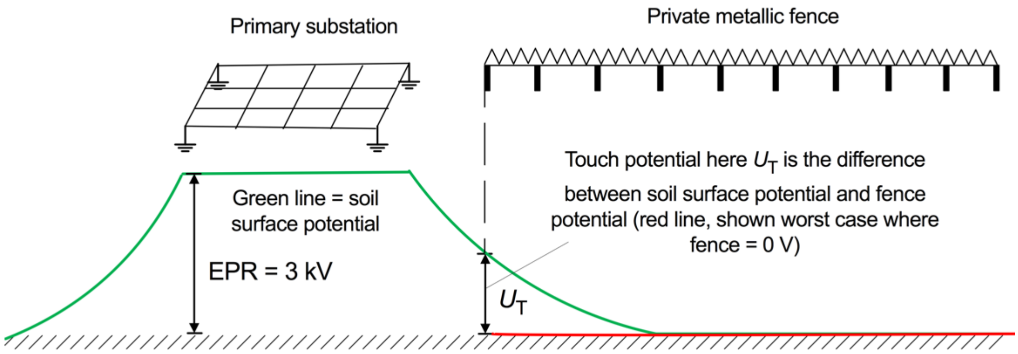


Figure 12 - Third-party fence close to substation

In Figure 12, U_T represents the highest touch potential that may be assumed to be present; as shown it represents the difference between the ground potential at the point nearest to the substation, compared with a remote (zero-volt) reference on the fence.

In practice, the touch potential will be lower, however, this is sufficient for an initial worst-case estimate.

Simplified calculations (rearranging formula P7 in appendix B of ENA EREC S34) give the surface potential rise V_x at a point x 4 m from the substation boundary:

$$x = \sqrt{\frac{A}{\pi}\left[\left(sin\frac{V_x\pi}{2U_\mathrm{E}}\right)^{-1} - 1\right]}$$

where U_E= 3 kV and A = 900 m^2. This rearranges to:

$$V_x = \frac{2U_E}{\pi}.arcsin\left(\left(\frac{x}{\sqrt{A/\pi}} + 1\right)^{-1}\right)$$

Thus the surface potential at a distance 4 m from the substation, V_x = 1799 V.

This could be taken as the hand-to-feet touch potential at the point where the fence is closest to the substation, assuming the fence will adopt zero-volts during the fault. Alternatively, due to the close proximity to the substation and the non-circular contours at that point, computer modelling of the soil surface potential should be more accurate; this shows that the ground potential rise at the closest point of the fence is 1720 V.

Using either value for 0.5 s, and comparing to Table 1, shows that this touch potential is above acceptable deterministic limits for soil (578 V), chippings (650 V), or concrete coverings (753 V)· Having carried out this first estimate, it is apparent that a quantified risk assessment (QRA) is appropriate to quantify the level of risk to members of public.

A QRA can proceed on the basis of worst-case estimated data, provided these estimates are justifiable and proven not to underestimate the overall risk. It is preferable, however, where possible, to collect further information to inform studies. This data could include measurements, modelling, mapping/cable plans, collection of fault statistics, fault level analysis, EPR calculation/checks, interrogation of protection relay data or power quality monitors (historic fault rates and/or fault levels), aerial imagery / satellite imagery or other online sources. Video, or other data sources may assist with an estimate of likely human exposure.

In this case, the third-party fence is a metal palisade type with metal uprights that may be assumed to be buried at a depth of up to 0.5 m. The panels are 2.5 m wide and supported clear of the ground. The local soil resistivity is 100 Ω·m. The fence is 50 m in length and effectively runs radially from the substation.

The fence is on the edge of an industrial area with a footpath nearby, but not adjacent to the fence. Individuals contacting the fence can be assumed to be wearing normal footwear (4 kΩ per shoe) whilst (in this example) standing on soil/grass (i.e. a shoe-to-soil contact resistance of 300 Ω per foot), giving an additional circuit resistance of 2150 Ω to the body and hand-to-feet contact impedances.

Because of the coupling between the fence and the soil along its length, the fence will not adopt a true zero potential during EPR events at the substation but will instead adopt a weighted average value over its length. Figure 13 shows the result of computer modelling of touch potential along the fence, i.e. the difference in potential between the fence and the soil 1 m from it. It can be seen that 18 m along the fence, the touch potential falls to a null point where the fence and soil potentials are equal. The maximum touch potential appears (in this case) at the end of the fence closest to the substation; a person standing 1 m from the end of the fence could be subject to a touch potential of 970 V; this value, which is still worst-case, should be used in the assessment together with an appropriate probability for the exposure.

NOTE: More accurate assessment could use a probability distribution function for the potential along the fence; this is beyond the scope of this example.

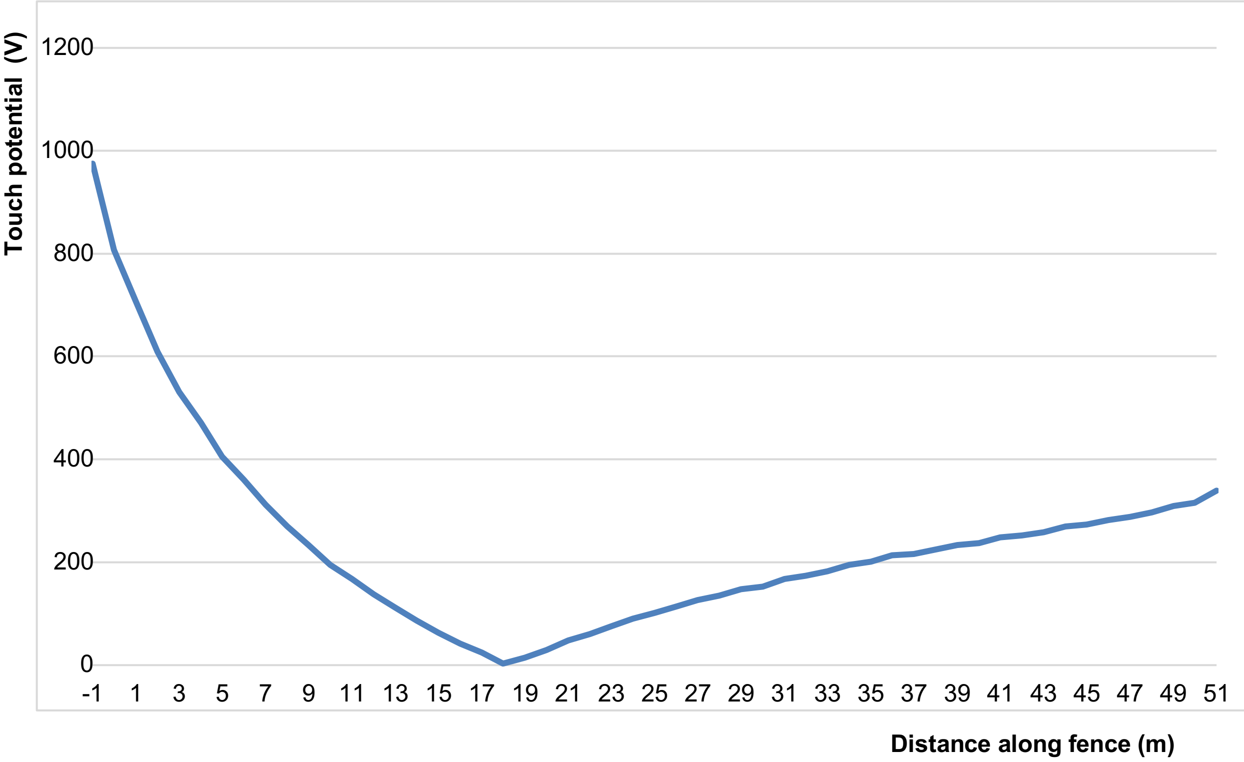


Figure 13 - Touch potential along fence

For shoes on soil conditions, the maximum permissible touch potential (0.5 s) is 578 V. This deterministic limit is based on the C2 curve from DD IEC/TS 60479-1 and the body impedance model for 95 % of the population, i.e. the same criteria used in the examples in the UK National Annexes in BS EN 50522.

The touch potential (hand-to-feet) of 970 V is therefore still above the C2 curve and fails the deterministic test. Having established this, order of magnitude analysis can proceed with an assumed P_{FB} = 1; more detailed analysis shows the body current to be around 354 mA, which is in the AC-4.2 region of Figure 20 of DD IEC/TS 60479-1, i.e. "Probability of ventricular fibrillation above 5 % and below 50 %". Interpolation of the value gives P_{FB} = 43.4 %, although due to uncertainties it is more appropriate to adopt the upper threshold for the region.

Thus: P_{FB} = 0.5.

Note: Fibrillation current calculations use the same assumptions as outlined in Annex NA of BS EN 50522, i.e. using Table 1 from DD IEC/TS 60479-1 for values of human body impedance not exceeded by 95 % of population, and an additional 2150 Ω for the accidental circuit (shoes + soil contact patch). The body impedance is a function of voltage across the body, therefore it becomes necessary to go through some form of iterative loop to estimate the voltage drop across the body (and thus body impedance) in order to converge on the solution for final body current. An impedance factor of 0.75 is used to convert hand-to-hand impedances to hand-to-feet values. It is not normally necessary to consider wet values except in permanently wet locations.

The statistical fault rate (estimated significant EPR events per year) based on historical fault data is 2.1 faults/year.

f_n= 2.1

The probability of exposure (P_E) relates to the time that an individual may be exposed to risk. The most significant, and obvious risk relates to contact with the fence. The fence is in a relatively remote location on an industrial area, with little footfall and only occasional contact with the fence. An initial estimate of 2 minutes contact with the fence, per individual, per day is based on anecdotal observations from the landowner:

P_E = 2 (minutes) /(24 * 60 minutes per day) = 1.39 x 10^{-3}

The individual risk (IR) is calculated using the formula:

$$IR = f_n * P_E * P_{FB}$$

where:

f_n = number of significant EPR events, on average per year.

P_{FB} = probability of heart fibrillation.

P_E = probability of exposure.

HSE guidance [R2P2] defines an individual risk of 1 in 1,000,000 per person per year (pppy) as broadly acceptable, for which no further work is warranted. A risk between 1 in 10,000, and 1 in 1,000,000 is tolerable for members of the public. A risk greater than 1 in 10,000 (or 1 in 1000 for workers) is deemed unacceptable, and should be addressed regardless of cost.

The overall individual risk in this case, using the assumptions above is 1.46 x 10^{-3}, i.e. 1.46/1000 fatalities pppy. This risk level is UNACCEPTABLE and should be addressed.

The assessment at this stage is based on very conservative estimates. Having established that the risk may be significant, it becomes necessary to either carry out mitigation work, or reassess the risk with more accurate data.

Given that mitigation work will in most cases be relatively expensive, this initial assessment provides justification for further analysis.

In this example, the network operator opted to carry out a more detailed site survey and investigation. The following findings were noted:

- Whilst earth faults were observed on average 2 to 8 times a year (based on historical data), it was found that significant EPR events (i.e. those producing EPR over the deterministic threshold) at this substation occurred, on average 0.9 times per year.

NOTE: In addition, the Network Operator also established that the full EPR for this site was 2400 V rather than 3 kV as assumed; however the decision was taken to work with an assumed upper limit of 3 kV to allow for fault level growth. It was also found that only a small percentage of faults gave an EPR approaching 3 kV, but the data was not statistically significant. For this reason, the count of EPR events greater than deterministic limits is used in the analysis below.

- Over a 1 month video survey period, individual contact with any area of the fence was noted, on average twice per week, by the same individual, for a maximum of 10 s per occasion. Of these contacts, one third involved the portion of fence where touch potential exceeds the deterministic limit of 578 V. To simplify analysis, it has been assumed that all contacts with this portion will give a touch potential of 970 V. The alternative is to assess the exposure and touch potential for each 1 m of the fence separately.

Finally, some parts of the fence were found to be surrounded by concrete rather than soil. Calculation of P_{FB} for these areas shows a reduced risk of fibrillation (21 % for 970 V), which is still in region AC-4.2. There is no difference if the upper bound (50 %) is used and this fact is ignored as of no consequence.

Using this updated data set:

Defect	f_n	P_{FB}	P_E	Individual risk (IR)	Risk Band
Close proximity to substation with HPR	0.9	0.5	1.099x10^{-5}	4.95x10^{-6} per person per year	Tolerable; requires ALARP assessment

The risk is not broadly acceptable, in that it exceeds 1 in 1,000,000 per person per year. It is tolerable for members of the public. An assessment is required to justify expenditure to reduce or mitigate this risk.

The ALARP principle should be applied, which means that the justifiable cost of mitigation should be calculated based on current HSE guidance [R2P2] for the value of preventing a fatality, or VPF. In 2001, this figure stood at £1,000,000 per life saved. The justifiable spend is calculated according to the loss of life that could occur during the lifetime of the installation, which for a substation may be taken as 100 years:

Expected lifetime of installation: 100 years (assumed)

Fatalities in 100 years: 4.95 x 10^{-6} x 100 = 0.000495

Number of individuals exposed to same risk: 1 (this value is informed by observations / data)

Justifiable spend (per individual exposed) = £1,000,000 x 0.000495 x 1 = £495

Therefore, if the cost of reducing risk to broadly acceptable levels is less than this, mitigation of the hazard should be carried out. If the risk cannot be significantly reduced for this amount, the Network Operator may be able to justify the decision to do nothing.

Risk reduction measures could include hazard warning signs (which may cause some reduction in P_E), insulated paint (reduction in body current and P_{FB}), modifications to the fence / addition of a grading electrode, use of asphalt ground coverings and so on. However, due to ownership / access issues, such measures may not be possible, in which case alterations to the substation MES / voltage contours, EPR / fault levels, protection clearance times or fault rates should be considered.

Modifications to customer property (if permissible) should also consider the likelihood that they may become altered or compromised as they are beyond the control of the Network Operator.

Before calculating the justifiable spend, any worst-case assumptions should be revisited.

If there is robust data to justify it, a further reduction factor can be applied by looking at the relationship between exposure and fault. If for example, fence contact occurs only on dry sunny days, it may be that the fault rate is lower on those days. A correlation factor may be applied to account for this. In the example above, if the fault rate on dry days is one tenth of that for the rest of the year, a factor of 0.1 may be applied to $P_E * P_{FB}$, giving an overall risk (in this example) that becomes broadly acceptable.

This case study considers only one aspect of overall risk, i.e. hand-to-feet touch potential on a relatively small section of a 50 m fence. All similar scenarios and related risks should be considered (e.g. hand-to-hand contact if appropriate, or transfer potential to/from other sources. Also, the possibility of bare feet / step potential and/or horse-riding accidents (if near a riding school) should be considered and an overall risk calculated by summing the individual risks from each scenario. In this case, there is no additional foreseeable likelihood of fibrillation or falls / injuries close to the substation or third-party fence but this could change and should be reviewed periodically as part of substation inspections.

This study considers only fibrillation risk. Injuries from minor shocks (e.g. falls etc.) have not been considered. A tailored approach may be required for different circumstances or for vulnerable individuals, e.g. nurseries / playgrounds (especially those with pools or wet areas), nursing homes, riding schools, hospitals, etc.

11.2 LV supply into HPR site

This case study considers the provision of an LV supply into a transmission substation with an EPR which cannot safely be carried outside the substation boundary (i.e.the EPR exceeds 2 x safe step and touch potential thresholds).

The following parameters apply:

EPR	3 kV
Protection clearance time	0.2 seconds

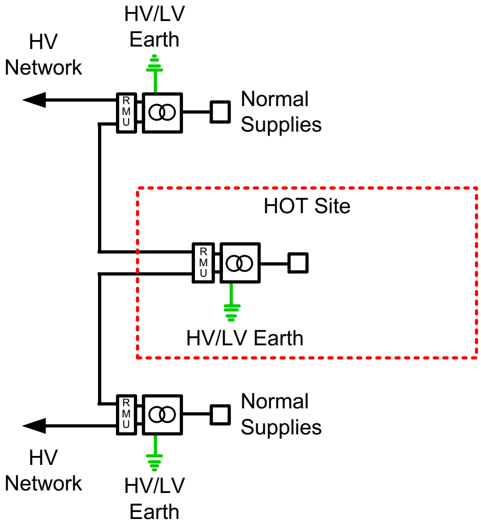
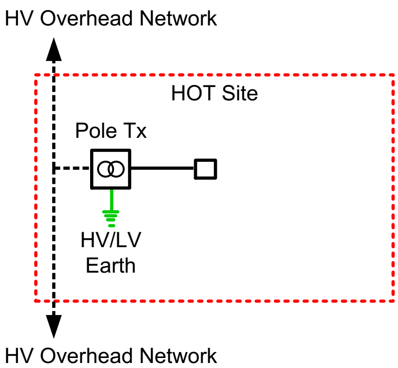
The substation is in a suburban location with a local underground LV network and mixed overhead / underground 11 kV cable system. The LV network supplies nearby properties and remains outside the HOT zone (650 V) which is calculated to extend 150 m from the site.

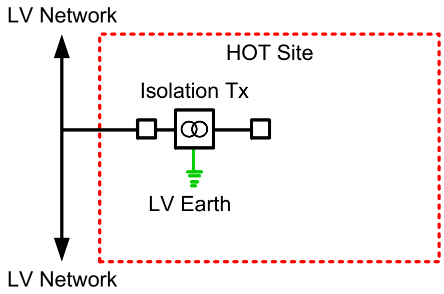
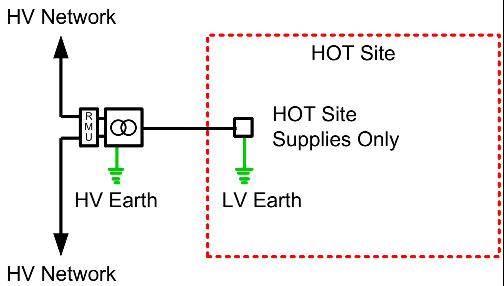
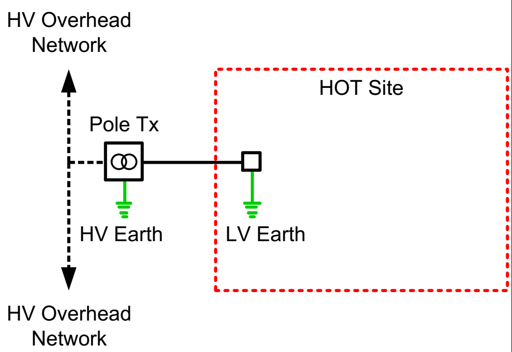
A 100 A, 3-phase LV supply has been requested by the substation operator, to provide a backup to local site supply transformers.

The EPR exceeds that which can safely be imposed on the LV network under fault conditions. Therefore, taking a standard LV supply into the site from the nearby network is not an option as the LV neutral/earth would invariably become combined with the substation earthing.

The available options, and the advantages/disadvantages of each, are given in Table 13.

Table 13 - Arrangements for LV supply into HPR site

Arrangements	Advantages / Disadvantages
11 kV cable to local transformer located in the transmission substation 	The 11 kV system can be assumed to be remotely earthed and may therefore adopt a close-to-zero-potential rise under transmission EPR events. If the cable is taken into the site, its sheath insulation could puncture and a high EPR could be exported to the 11 kV system. To avoid this, the cable should be ducted within the highest voltage contours (dependent on its sheath withstand voltage). Extending ducting to the 2 kV contour is a relatively common practice to avoid this. Any such cable connection into a HOT site requires extreme care with the earthing of the switchgear/transformer, as the earthing systems for the 11 kV cable should not be combined with site earths. It is often most practical to earth the transformer HV and LV earths to the site earth, but to introduce an insulated gland (sheath break) in the 11 kV cable(s) where they enter the plant. However, this can cause: a) touch potentials between cable sheath and local steelwork, b) no metallic return for 11 kV faults beyond the break, requiring the substation earth to be able to limit 11 kV EPR and of sufficiently low resistance to operate 11 kV protection, and c) operational issues if the switchgear earth is applied, since the 11 kV cable cores will become connected to the local site earth. This could create a hazard for staff working on the cable or elsewhere on the 11 kV network unless specific operational practices are adopted.
11 kV overhead line supply to transmission substation with a pole-mounted or ground-mounted transformer 	An 11 kV supply to the substation, if via 3-wire (unearthed) overhead construction, is a simple and effective solution to the issues described above. The overhead line can effectively be carried direct into the site, where it can supply a ground-mounted or pole-mounted transformer. For both arrangements, the transformer HV and LV earths can be combined and connected to the site earth. A 3 kV EPR on the site earth is unlikely to initiate flashover between the 11 kV phases and steelwork, or between any short 11 kV cable sheath-to-cores, although this possibility should be considered in extreme EPR situations. (Similar insulation breakdown could occur internal to the transformer if the casing is elevated above phase voltages). Care should be taken with operational earth positions and procedures. The disadvantage of this method is that the supply may be more vulnerable than underground supplies and consequently might be unacceptable where a highly resilient supply is necessary.

Arrangements	Advantages / Disadvantages
LV supply from network into the transmission substation 	As previously stated, it is not possible to take a standard LV supply, as there is a real risk that the high EPR could be transferred to other customers. Similarly, providing an LV supply without an earth terminal (i.e. TT arrangement) also poses a significant risk of insulation breakdown / flashover to the LV system during transmission EPR events as the LV neutral/earth will remain at close-to-zero volts. An LV supply may be provided via an isolation transformer, though care is required with the siting and protection of the isolating unit itself.
Dedicated off-site transformer and LV supply into transmission substation  	A dedicated off-site transformer offers no benefit over the previous solutions, and introduces the risk of exporting transmission EPR to the transformer.

The pole-mounted transformer and overhead 11 kV line solution (Figure 14) has been adopted as it is the minimum cost solution and (because it is a back-up supply) the reliability is acceptable to the transmission network operator. For operational reasons, an ABSD is best located outside the site boundary and will serve as a point of isolation and earthing point for the 11 kV network beyond that point.

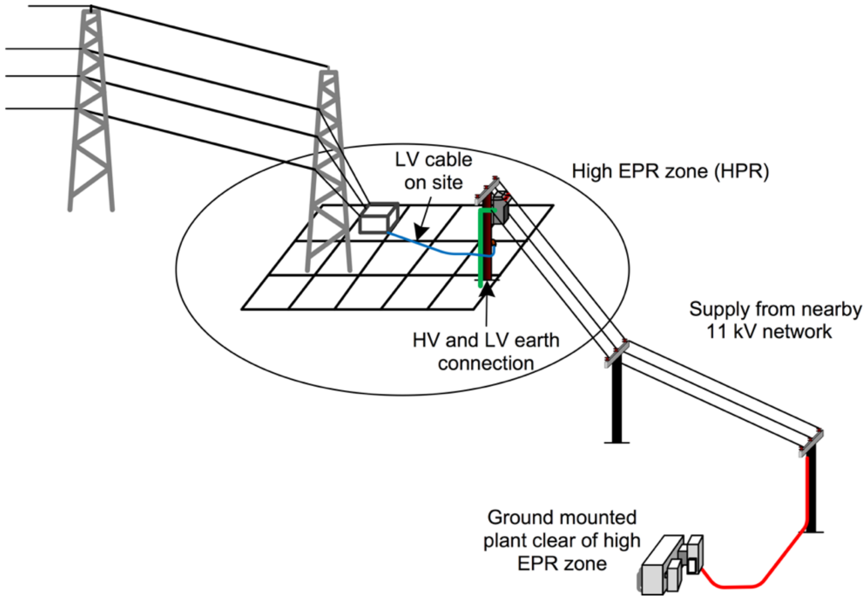


Figure 14 - Overhead supply into HPR site

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