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ENGINEERING DESIGN STANDARD

EDS 06-0012

EARTHING DESIGN CRITERIA, DATA AND CALCULATIONS

Network(s):	EPN, LPN, SPN
Summary:	This standard is a companion document to the earthing design standards and details the design criteria, data and calculations for use in substation earthing design at all voltages.

Author:	Stephen Tucker	**Date:**	31/10/2022
Approver:	Paul Williams	**Date:**	15/11/2022

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Revision Record

Version	7.0	**Review Date**	15/11/2027
Date	31/10/2022	**Author**	Stephen Tucker

Reason for update: Updated to include revised transfer voltage calculation.

What has changed:

- Transfer calculation amended to account for different types of cable construction (Appendix I).
- Cable data updated to include armour resistance for transfer voltage calculation (Appendix J).

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Date	12/05/2022	**Author**	Stephen Tucker

Reason for update: Updated to include new and revised data.

What has changed:

- Tarmac touch and step limits revised in Table 5-1 (Section 5.1).
- Original ENA TS 41-24 Issue 1 touch and step limits removed (Section 5.1).
- Stress and transfer voltage limits included/referenced (Sections 5.2 & 5.4)
- Secondary substation earthing drawing list and data updated. Some touch voltage percentages increased to allow for non-uniform soil model (Appendix A.1).
- Customer switchroom earthing drawing list and data added (Appendix A.2).
- Grid and primary substation earthing drawing list updated (Appendix A.3).
- Network contribution additional methods and data included (Appendix G).
- Transfer voltage additional information included (Appendix I).
- 150 Polylam, 0.04, 240 and 300 PILCSWA cable data amended (Appendix J).
- Document reviewed.

Version	5.0	**Review Date**	09/11/2023
Date	09/11/2018	**Author**	Stephen Tucker

Reason for update: Alignment with other standards.

What has changed:

- Secondary substation list and associated data updated to reflect EDS 07-3102 (Appendix A.1).
- Arrangement 3 equation corrected in Table E-1 (Appendix E.2).
- Minor update to network contribution section (Appendix G).
- Transfer voltage calculation and 11kV cable impedance data added (Appendix I).

Version	4.0	**Review Date**	15/12/2022
Date	30/11/2017	**Author**	Stephen Tucker

Reason for update: Document revised to work as a companion document to the other earthing design standards and align with the latest industry standards ENA TS 41-24 and ENA EREC S34.

What has changed:

- All sections completely revised.
- BS EN 50522 touch and step voltage limits included (Section 5.1).
- Substation standard earthing arrangements and associated data (Appendix A, A.2 and A.3).
- Fault level interpretation (Appendix C) and fault clearance time calculation (Appendix D).
- Ground return current calculation using various methods including C factors (Appendix E).
- Neutral current reduction calculation (Appendix F).
- Network contribution assessment (Appendix G).
- Electrode Surface Area Current Density Calculation (Appendix G).
- Document title changed.

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Version	1.0	**Review Date**	
Date	31/03/2008	**Author**	Stephen Tucker
Original.			

Contents

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1 Introduction

This standard is a companion document to the earthing design standards and details the design criteria, data and calculations for use in substation earthing design at all voltages. The appendices also include supporting and background information on various aspects of substation earthing.

This standard should be used in conjunction with the following:

- EDS 06-0013 – Grid and Primary Substation Earthing Design.
- EDS 06-0014 – Secondary Substation Earthing Design.

2 Scope

This standard applies to the earthing at substations and networks at all voltage levels.

This standard applies to designers and planners involved in substation earthing design.

3 Glossary and Abbreviations

Term	Definition
COLD Site	A COLD site is a substation where the earth potential rise is less than 430V or 650V (for high reliability protection with a fault clearance time less than 0.2 seconds). Note that faults at all relevant voltages should be considered. **Note:** In practice, the 650V limit applies for most 132kV (and higher) earth faults, and 430V for other voltage levels, but exceptions may apply
EI	Extremely inverse (see IDMT)
EPR	Earth potential rise. EPR is the potential (voltage) rise that occurs on any metalwork due to the current that flows through the ground when an earth fault occurs. Historically this has also been known as rise of earth potential (ROEP)
HOT Site	A HOT site is a substation where the earth potential rise is greater than 430V or 650V (for high reliability protection with a fault clearance time less than 0.2 seconds). Note that faults at all relevant voltages should be considered. **Note:** In practice, the 650V limit applies for most 132kV (and higher) earth faults, and 430V for other voltage levels, but exceptions may apply
HV	High Voltage. Refers to voltages at 20kV, 11kV and 6.6kV
IDMT	Inverse Definite Minimum Time. A protection relay characteristic where the operating time of the relay is inversely proportional to the magnitude of the current. IDMT characteristics include standard inverse (SI), extremely inverse (EI) and very inverse (VI) curves.
ITU	International Telecommunication Union. ITU directives prescribe the limits for induced or impressed voltages derived from HV supply networks on telecommunication equipment and are used to define the criteria for COLD and HOT sites
LV	Low Voltage. Refers to voltages up to 1000V AC (typically 400V 3-phase and 230V single-phase) and 1500V DC
PICAS	Paper Insulated Cable Aluminium Screen
PILC	Paper Insulated Lead Cable
PILCSWA	Paper Insulated Lead Cable Steel Wire Armour

Term	Definition
SSEDT	Secondary Substation Earthing Design Tool
SI	Standard Inverse (see IDMT)
Step Voltage	The step voltage is the voltage difference between a person's feet assumed 1 metre apart. **Note:** In practice, in view of revised limits in BS EN 50522 and ENA TS 41-24, step voltage considerations are more of an issue for animal/livestock areas
Touch Voltage	The touch voltage is the hand-to-feet voltage difference experienced by a person standing up to 1 metre away from any earthed metalwork they are touching. **Note:** Hand-to-hand voltage differences within substations are generally not considered as they should be avoided by careful design
Transfer Voltage	The transfer voltage is the potential transferred by means of a conductor between an area with a significant earth potential rise and an area with little or no earth potential rise, and results in a potential difference between the conductor and earth in both locations. Voltage can be carried by any metallic object with significant length, e.g. pilot cable sheath, barbed wire fence, pipeline, telecoms cable etc. and needs consideration for all such feeds into/out of and near substations.
UK Power Networks	UK Power Networks (Operations) Ltd consists of three electricity distribution networks: • Eastern Power Networks plc (EPN). • London Power Network plc (LPN). • South Eastern Power Networks plc (SPN).
VI	Very Inverse (see IDMT)
XPLE	Cross-linked Polyethylene Cable

4 Design Criteria

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

The main objectives are to:

a) Allow sufficient fault current to flow to operate upstream earth fault protection.

b) Ensure the touch and step voltages in and around the substation are within required limits.

c) Reduce the transfer voltage impact on adjacent infrastructure to acceptable levels, and classifying a substation as a COLD site, if reasonably practicable.

d) Allow HV and LV earthing systems to be combined where applicable.

e) Conform to the requirements of UK Power Networks earthing standards, ENA TS 41-24, BS EN 50522 and BS 7430.

f) Ensure the site is safe to energise.

5 Voltage Limits

5.1 Safety Voltages

The maximum touch and step voltage limits based on ENA TS 41-24 Issue 2 and BS EN 50522 are given in Table 5-1 and should be used for all substation earthing design and earthing assessment. In each case standard footwear is assumed with a resistance of 4kΩ per foot.

The safety voltages are further described in Appendix B.

Table 5-1 – BS EN 50522 Maximum Permitted Touch and Step Voltages (ENA TS 41-24 Issue 2)

Fault Clearance Time (s)	Soil		Concrete/Chippings (150mm)		Tarmacadam (75mm)[1]		Tarmacadam (100mm)[1]	
	Touch Voltage (V)	Step Voltage (V)	Touch Voltage (V)	Step Voltage (V)	Touch Voltage (V)	Step Voltage (V)	Touch Voltage (V)	Step Voltage (V)
0.2	1570	>25000	2064	>25000	7194	>25000	7775	>25000
0.3	1179	>25000	1548	>25000	5366	>25000	5799	>25000
0.4	837	>25000	1095	>25000	3770	>25000	4073	>25000
0.5	578	>25000	753	>25000	2569	>25000	2774	>25000
0.6	420	>25000	544	>25000	1833	>25000	1979	>25000
0.7	332	>25000	428	>25000	1425	>25000	1539	>25000
0.8	281	21608	361	>25000	1193	>25000	1287	>25000
0.9	250	19067	321	>25000	1052	>25000	1134	>25000
1.0	233	17571	298	24083	974	>25000	1050	>25000
1.5	188	13826	239	18951	771	>25000	832	>25000
2.0	173	12629	220	17311	705	>25000	760	>25000
3.0	162	11727	205	16074	657	>25000	708	>25000

5.2 Stress Voltage Limits

BS 7671 includes a stress voltage limit of 1200V that is the maximum voltage that should exist across the insulation of LV equipment, e.g. between the local earth and a phase or neutral conductor. A high EPR at a substation shall not result in this stress voltage limit being exceeded in any nearby LV networks.

Secondary distribution substation equipment has higher insulation strength and can tolerate higher stress voltages. In general, the insulation between HV and LV earths at a secondary distribution substation is tested to 3kV and this stress voltage limit is satisfied by restricting the EPR to a maximum of 2kV.

[1] Tarmacadam limits extrapolated from ENA TS 41-24 Issue 2 for a minimum resistivity of 10000 ohm-metres for Tarmacadam 75-100mm thick. The floor covering resistance is calculated using the method from IEEE-80.

5.3 ITU Classification Limits

The limits in Table 5-2 are used to classify a substation as either HOT or COLD and are mainly required for communication network providers to comply with ENA EREC S36 but are also used as the threshold for more detailed assessment of risks in installations operated by a knowledgeable authority such as an oil refinery or gas pipeline.

These limits are not directly relevant to safety of operational personnel or the public, which is determined by touch, step and transfer potential limits and covered in Sections 5.1 and 5.4. Where the EPR exceeds these values, a conductive earth path from the substation to a customer's premises is not permitted unless calculations show that they are lower than the applicable limit, or measures have been taken to control the voltages at those premises. Measures may include the separation of HV and LV neutral earths or provision of an isolation transformer.

Table 5-2 – ITU Classification Limits

<table>
<tr><th>Substation Voltage</th><th>Transfer Voltage</th><th>Comments</th></tr>
<tr><td>400kV, 275kV and 132kV</td><td>650V</td><td></td></tr>
<tr><td rowspan="2">66kV and 33kV</td><td>650V</td><td>High reliability lines with main protection that normally operate within 0.2 seconds and always within 0.5 seconds and has back up protection</td></tr>
<tr><td>430V</td><td>Normal reliability lines or clearance times in excess of 0.2 seconds</td></tr>
<tr><td>20kV, 11kV, 6.6kV</td><td>430V</td><td></td></tr>
</table>

5.4 Other Transfer Voltage Limits

ENA EREC S41 recommends limits that should be used as the threshold to assess transfer voltage risks and where these are exceeded a more detailed assessment is required or mitigation implemented. Examples of sites and situations include:

- Communication network providers.
- LV systems.
- Equipment mounted on transmission towers.
- Railway operators.
- Sensitive sites (knowledgeable authorities).
- Fuel filling stations.
- Sensitive sites (barefooted people).

For further information on the requirements, assessment and mitigation refer to EDS 06-0002.

6 References

6.1 UK Power Networks Standards

EDS 06-0013	Grid and Primary Substation Earthing Design
EDS 06-0014	Secondary Substation Earthing Design
ECS 06-0023	Secondary Distribution Network Earthing Construction
ECS 06-0024	Earthing Testing and Measurements
EDS 07-3102	Secondary Substation Civil Design Standards
EDS 07-4000	Grid and Primary Civil Design
EDS 07-4055	Customer Switchrooms for Indoor Switchgear
EDS 08-1110	Fault Levels

6.2 National and International Standards[2]

BS EN 50522	Earthing of Power Installations Exceeding 1kV AC
BS 7430	Code of Practice for Protective Earthing of Electrical Installations
ENA TS 41-24	Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations
ENA EREC S34	A Guide for Assessing the Rise of Earth Potential at Substation Sites
ENA EREC S36	Procedure to Identify and Record HOT Substations
ENA EREC S41	Guidance on Transferred Voltages from Earthing Systems

7 Dependent Documents

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

EDS 06-0001	Earthing Standard
EDS 06-0013	Grid and Primary Substation Earthing Design
EDS 06-0014	Secondary Substation Earthing Design
EDS 08-0147	Guidance on the use of Arc Suppression Coil Earthing

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

Appendix A – Substation Earthing Arrangements and Data

A.1 Secondary Substation Earthing Arrangements and Data

An overview of the secondary substation drawings is given in Table A-1; refer to EDS 07-3102 for the complete list and the latest drawings. Table A-2 and Table A-3 detail the associated earth resistance and touch voltage percentage values.

Table A-1 – Secondary Substation Standard Drawings with Earthing Arrangements

Drawing Number	Description
EDS 07-3102-01	Unit or Padmount Substation in a GRP Enclosure
EDS 07-3102-02	Unit or Padmount Substation on Bunded Foundation in a GRP Enclosure
EDS 07-3102-03	Elevated Unit or Padmount Substation on Bunded Plinth in a GRP Enclosure
EDS 07-3102-04	Metered Ring Main Unit in a GRP Enclosure
EDS 07-3102-05	Ring Main Unit Plinth Design in a GRP Enclosure
EDS 07-3102.11	Freestanding Brick-built Substation for a Single Metering Ring Main Unit
EDS 07-3102.12	Freestanding Brick-built Substation for Two Metering Ring Main Units
EDS 07-3102-15	Freestanding Brick-Built Substation for a Single Transformer up to 1500kVA
EDS 07-3102-16	Freestanding Brick-Built Substation for a Single Transformer up to 1000kVA with ACB and LV Board
EDS 07-3102-17	Freestanding Brick-Built Substation for Two Transformers up to 1000kVA with ACB and LV Board
EDS 07-3102-20	Integral Substation for a Single Transformer up to 1500kVA
EDS 07-3102-21	Integral Substation for a Single Transformer up to 1000kVA with ACB and LV Board
EDS 07-3102-22	Integral Substation for Two Transformers up to 1000kVA
EDS 07-3102-25	Integral Substation Metering Ring Main Unit
EDS 07-3102-26	Integral Substation for Two Metering Ring Main Units
EDS 07-3102-30	Basement Substation for a Single Transformer up to 1000kVA
EDS 07-3102-31	Basement Substation for a Single Transformer up to 1500kVA
EDS 07-3102-40	Standard Plinth for Micro Substation
EDS 07-3102-41	Standard Plinth for Compact Substation
EDS 07-3102-42	Timber Fence Substation

Table A-2 – EDS 07-3102 Secondary Substation Earthing Arrangements – Earth Resistance[3]

Soil Resistivity (Ωm)		**15**	**25**	**50**	**100**	**150**	**200**	**300**	**400**	**500**	**1000**
Substation Type	**EDS 07-3102 Drawing**	**Resistance (Ω)**									
GRP	01, 02, 04, 05	1.5	2.5	4.9	9.7	14.5	19.3	28.9	38.3	48.2	96.3
GRP Elevated	03	1.2	2.0	4.0	8.0	12.0	16.0	24.0	32.0	40.0	79.9
Brick-built (earth ring)	11, 15, 16, 18	1.2	1.9	3.7	7.4	11.2	14.9	22.3	29.7	37.1	74.1
	12, 17	0.9	1.5	2.9	5.7	8.6	11.4	17.1	22.8	28.5	56.9
Brick-built (earth mesh)	11, 12, 15, 17, 18	3.5	5.8	11.6	23.2	34.8	46.3	69.3	92.6	115.7	231.4
Integral	20, 21, 22, 25, 26	3.5	5.8	11.6	23.2	34.8	46.3	69.3	92.6	115.7	231.4
Basement	30, 31	3.2	5.4	10.7	21.4	32.1	42.7	64.1	85.5	106.8	213.5
Padmount	40, 41	1.6	2.6	5.2	10.4	15.5	20.7	31.0	41.4	51.7	103.5
Outdoor	42	1.5	2.4	4.7	9.4	14.1	18.8	28.2	37.6	47.0	93.9

Table A-3 – EDS 07-3102 Secondary Substation Earthing Arrangements – Touch and Step Voltages[4]

Substation Type	**EDS 07-3102 Drawing**	**Voltages (expressed as % of EPR)**	
		Touch[5]	**Step**
GRP	01, 02, 04, 05	12	28
GRP Elevated	03	28	27
Brick-built	11, 12, 15, 16, 17, 18	12	30
Integral	20, 21, 22, 25, 26	10	45
Basement	30, 31	10	45
Padmount	40, 41	22	16
Outdoor	42	27	16

[3] The earth resistance values are based on computer modelling of the standard earthing arrangements in various values of soil resistivity. The resistance values given are for the standalone substation electrode only.
[4] The touch and step percentages are based on computer modelling of the standard earthing arrangements.
[5] The touch voltages have been increased for earthing arrangements with a buried perimeter electrode to allow for a non-uniform soil model.

A.2 33kV and 11kV Switchroom Earthing Arrangements and Data

An overview of the standard switchroom earthing arrangements for customer supplies at 33kV and 11kV is given in Table A-4. Refer to EDS 07-4055 for further information.

Table A-4 – 33kV and 11kV Switchroom Standard Drawings

Drawing Number	Description
EDS 07-4055.01	33kV Brick-Built Customer Switchroom
EDS 07-4055.04	33kV Metal Cladding Customer Switchroom
EDS 07-4055.03	33kV Elevated Customer Switchroom
EDS 07-4055.05	33kV Modular Customer Switchroom
EDS 07-4055.02	33kV Integral Customer Switchroom
EDS 07-4055.11	11kV Brick-built Customer Switchroom
EDS 07-4055.14	11kV Metal Cladding Customer Switchroom
EDS 07-4055.13	11kV Elevated Customer Switchroom
EDS 07-4055.15	11kV Modular Customer Switchroom
EDS 07-4055.12	11kV Integral Customer Switchroom
EDS 07-4055.16	11kV Basement Customer Switchroom

Table A-5 – 33kV and 11kV Switchroom Earthing Arrangements – Earth Resistance[6]

Soil Resistivity (Ωm)		15	25	50	100	150	200	300	400	500	1000
Substation Type	EDS 07-4055 Drawing	Resistance (Ω)									
Brick-built	01, 11	0.84	1.39	2.78	5.56	8.35	11.13	16.69	22.26	27.82	55.64
Metal-clad	04, 14	0.84	1.39	2.78	5.56	8.35	11.13	16.69	22.26	27.82	55.64
Elevated	03, 13	0.62	1.03	2.06	4.12	6.18	8.24	12.36	16.48	20.60	41.20
Modular	05, 15	0.71	1.19	2.38	4.76	7.14	9.52	14.28	19.04	23.80	47.59
Integral/basement	02, 12, 16	1.22	2.04	4.07	8.14	12.21	16.28	24.42	32.56	40.71	81.41

Table A-6 – 33kV and 11kV Switchroom Earthing Arrangements – Touch and Step Voltages[7]

Substation Type	EDS 07-4055 Drawing	Voltages (expressed as % of EPR)	
		Touch	Step
Brick-built	01, 11	21%	17%
Metal-clad	04, 14	21%	17%
Elevated	03, 13	30%	16%
Modular	05, 15	24%	19%
Integral/basement	02, 12, 16	20%	38%

[6] The earth resistance values are based on computer modelling of the standard earthing arrangements in various values of soil resistivity. The resistance values given are for the standalone substation electrode only.
[7] The touch and step percentages are based on computer modelling of standard earthing arrangements.

A.3 Grid and Primary Substation Earthing Arrangements

An overview of the grid and primary substation standard earthing arrangements is given in Table A-7. Refer to EDS 07-4000 for further information.

Table A-7 – Grid and Primary Substation Typical Earthing Arrangements

Drawing Number	Description
EDS 07-4000.02	132/33kV Substation Earthing Layout
EDS 07-4000.04	33/11kV Substation Earthing Layout

Appendix B – Earthing System Overview

B.1 Introduction

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

Substations and all electrical installations have to be safe in terms of a) shock risk, and b) ability to withstand fault conditions without damage or fire.

In general terms, the installation should be connected to the general mass of earth via a buried electrode system that provides a suitably low earth resistance value. In addition, bonding (low impedance connections) is required between equipment and metalwork to ensure they remain at the same voltage and to safely convey fault current without damage or danger. Conductors and electrodes should by suitably sized for worst-case duty.

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

Earthing does not consider metalwork which is normally live (this will normally be insulated or placed out of reach), but is instead intended to control the voltages on equipment, plant, and other metalwork such as fences in and around the substation or installation.

Every substation is 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.

B.2 Basic Principles

During an earth fault, the voltage of the earthing system and everything connected to it rises briefly until the protection can operate to clear the fault. Effective earthing and bonding minimises the risk to staff and public during this time.

The magnitude of the voltage rise (EPR) is determined by the resistance of the substation’s overall electrode system (R_A) and the fault current that flows into it (I_{ef}). Typically, for systems supplied via overhead systems, almost all of the earth fault current will return to the source via the ground. For cable systems, or for overhead lines with an earth wire, the ground return current will be reduced as there will be a continuous metallic path back to the source substation. The ground return current (see Appendix E), as a percentage of overall earth fault current is termed ($I_{gr}\%$) and can approach 100% for overhead systems and is typically 5% to 30% for cable systems.

The application of Ohm’s Law gives the EPR as follows:

$$EPR = I_{ef}\,(A) \times I_{gr}(\%) \times R_A(\Omega)$$

In designing an electrode system, the value R_A should be low enough to limit the EPR and touch/step voltages to safe values (see Section 5.1). The ultimate overall value for R_A will be lower than the earthing grid resistance (R_G) in isolation, due to contributions from various factors including the wider distribution network (see Section B.5). The standalone value should be sufficient to ensure safety at new build sites if there is any possibility of the additional contribution being lost; in short, the system has to be able to operate safely should there be any foreseeable risk of neighbouring earthing systems or contributions becoming disconnected or compromised.

EPR does not translate directly to a touch voltage. A well-designed earthing system should ensure that the touch voltage is 50% or less of the EPR, as necessary to ensure safety of operators and members of public.

For faults at all relevant voltage levels, the substation should be COLD where practicable. If this is not economically achievable, a HOT substation with an EPR not exceeding 2kV may be acceptable providing the EPR is not problematic for third parties. Whether the site is classified as HOT or COLD the risks of transfer voltages to nearby infrastructure must also be assessed, e.g. onto LV networks, railways, etc.

During fault conditions, significant currents can flow through earthing system components including above ground conductors and below-ground electrodes. This results in heating of these components (and surrounding soil), and therefore they need to be sized accordingly.

Therefore the installation has to be able to pass the maximum current from any fault point back to the system neutral whilst maintaining step, touch, and transfer voltages within permissible limits based on **normal** protection relay and circuit-breaker operating times and without damage based on **backup** protection relay and circuit-breaker operating times.

In addition to conductor sizing calculations, the overall surface area of buried electrode should be sufficient to dissipate fault current without excessive heat/steam generation, since this can compromise the integrity of the system. Additional electrodes may be required to satisfy this.

B.3 Touch, Step and Transfer Voltages

During earth faults, voltage gradients develop in the ground surrounding an electrode system. These gradients are highest adjacent to the substation earth electrode and reduce to zero some distance from it. Voltage gradients around the electrode system, if great enough, can present a hazard to persons or animals and thus effective measures to limit them are required.

The three main design parameters relate to touch, step and transfer voltages. These terms are shown in Figure B-1 and explored in the sections that follow.

Permissible limits are dependent on the duration of the fault, and are influenced by surface covering (e.g. soil, chippings, concrete) and footwear/gloves. Typical design limits are given in Section 5.1. In substations it is normal to assume individuals are wearing safety footwear and are standing on chippings or concrete.

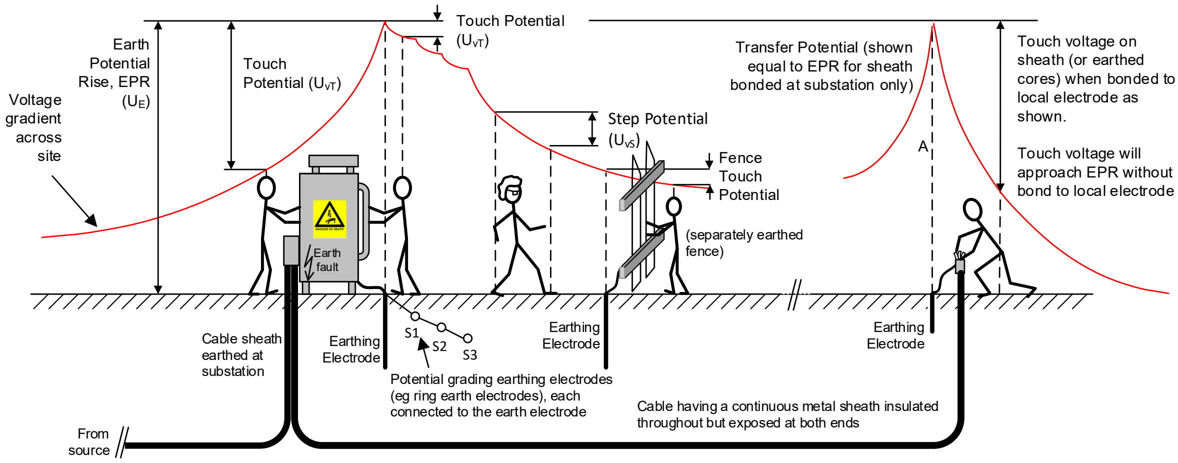


Figure B-1 – Touch, Step and Transfer Voltages Resulting from an Earth Fault

B.3.1 Touch Voltage

Touch voltage is the term used to describe the voltage between a person's hands and feet and is the general term for hand-to-feet voltage. It arises from the fact that the ground surface potential at a person's feet is a different value to that on the buried earth electrode (and any connected metalwork). If an earthed metallic structure is accessible, a person standing on the ground 1m away and touching the structure will be subject to the full touch voltage.

In some situations, the hand-to-hand touch voltage needs to be considered, for example if unbonded parts or different earthing systems are within 2m of each other. The situation should be avoided by design, e.g. by increasing separation or introducing barriers if the systems are designed to be electrically separate, or by bonding items together. The siting of fences is the most likely aspect that needs consideration in this regard.

B.3.2 Step Voltage

Step voltage describes the voltage that could appear between a person's feet and is defined as the voltage between two points on the ground that are 1m apart.

For a given substation, achieving safe touch voltages in the substation will generally achieve compliance with step voltages.

Step voltage can be an issue for animals and should be considered if an electrode system extends into fields or across gateways where horses or livestock may pass. The voltage gradient in these areas should be limited as described in EDS 06-0002. It is generally necessary to avoid these areas or use short insulated/ducted electrode sections where appropriate.

B.3.3 Transfer Voltage

Voltage can be carried into/out of substations by metallic cable sheaths or other metallic conductors such as fences, services etc. In some cases, these will introduce a zero-voltage reference into the substation or carry the full EPR out of the substation. Both scenarios can expose an individual to higher-than-normal shock risk. Pilot cables and telephone cables need particular care.

The limits for permissible transfer voltage relate to shock risk (touch and step voltage), and equipment damage/insulation breakdown (stress voltage) and this should be assessed for high EPR substations near to third party infrastructure. It is also necessary to inform third party telecommunication providers if a site is HOT, so appropriate measures can be adopted to prevent damaging transfer of potential onto the telephone system.

B.4 Features of an Earthing System

Earthing systems typically consist of buried electrode, bare wire, tape or rods buried or driven into soil. The main purpose is to provide a good low resistance contact with the general mass of earth. The earthing system resistance is a measurable quantity that is tested prior to energising the substation (refer to ECS 06-0024 for further information on earthing measurements).

The amount of electrode needed to achieve a given resistance is calculated based on knowledge of the soil type. A low resistance ensures that EPR is limited, and protection operates reliably.

In addition to reducing the earthing system resistance, electrodes are positioned at strategic locations, typically around items of plant/switchgear or fences, and bonded (connected) to that item and to the main earthing system. The ideal location is 0.5 to 1m from the item, such that it will be underneath the feet of any person touching the item. This is sometimes called a grading electrode. In this way, the touch voltage differences are reduced (the extreme example being a surface laid mat, where the operator's hands and feet will be at the same potential). A grading electrode is used to modify the voltage (surface potential contours) appearing on the soil surface in and around substations, and its location can be easily optimised using computer modelling software.

Earthing systems also provide bonding in that they connect together items of plant to ensure they all remain at the same voltage (even if the voltage is elevated under fault conditions). This provides a substantial low resistance path for fault current and minimises the likelihood of dangerous voltages appearing between items that can be simultaneously touched. In general, all significant metallic items in substations are bonded together to form an equipotential zone, unless there is good reason to adopt segregated earthing systems (most commonly associated with fences). It should not be possible for any person to touch two metallic items simultaneously if those two items are not bonded together; for this reason, items which are not bonded together are separated by 2m or more, or separated by barriers or insulation. Fences or some LV system neutrals are examples of earthing systems that may sometimes be deliberately separated from the substation EHV/HV earthing system.

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

B.5 Typical Components of an Earthing System

As well as dedicated electrode systems installed at the substation, an earthing system benefits from connection to buried structures and bare cable sheaths. In many cases the resistance to earth of such systems is much lower than the substation earthing system, and may be considered at design time. If there is a likelihood that such contributions may be lost in future (e.g. decommissioning or demolition work) this should be taken into account and additional electrode installed as appropriate. Figure B-2 shows a typical system.

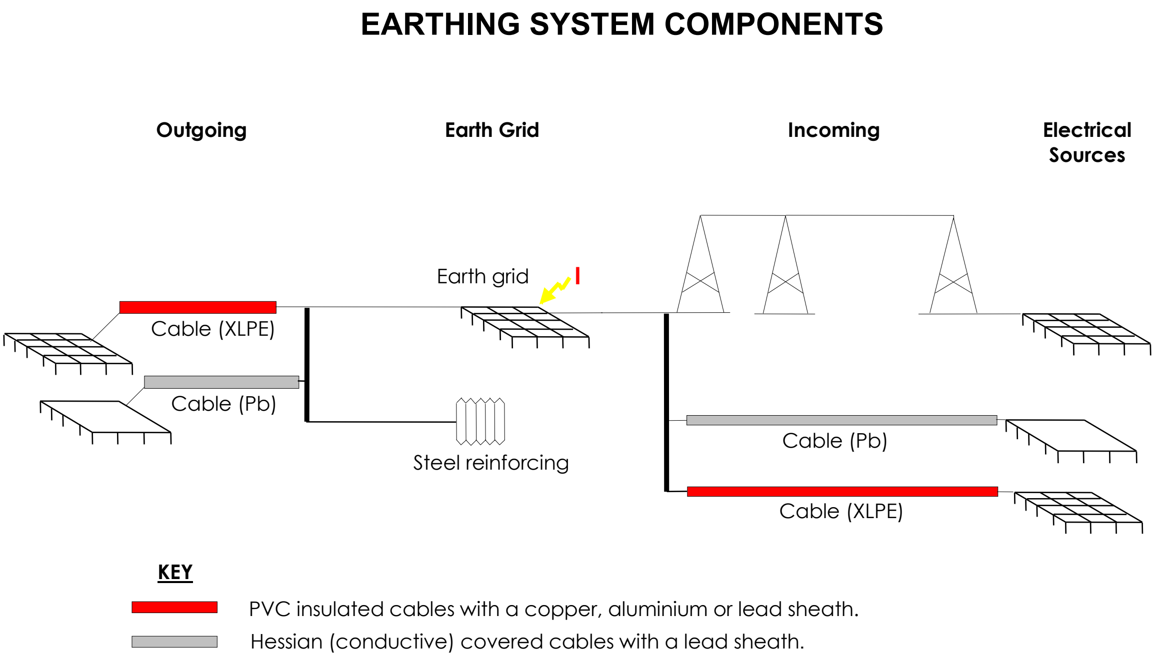


Figure B-2 – Components of an Earthing System

Cable sheaths in particular offer two separate and distinct contributions:

- Electrode effect (contact with soil), for bare lead sheathed or hessian covered cables.
- Metallic interconnection between two points (e.g. insulated PVC cables including Triplex type cables).

The latter provides significant benefits if there is a continuous cable sheath from the source substation, and its integrity can be assured. In this way, earth-fault current returning to the source star-point will flow mostly in the sheath rather than through soil. The reduced ground return component will produce a lower EPR (and touch/step voltages) at the faulted substation.

Note: Triplex type cables, or cables in parallel or looped in/out are assumed to provide a reliable connection because the metallic path is duplicated and it is unlikely that sheath continuity will be lost entirely during a single fault.

Appendix C – Fault Level Interpretation

An example of the PowerFactory fault level format is shown below in Table C-1. The RMS break value (Ib) should be used for earthing calculations.

Refer to EDS 08-1110 for further information on fault levels.

Table C-1 – DigSilent PowerFactory Fault Level Data

Name	Ik" A (kA)	Ik' A (kA)	Ib A (kA)	ip A (kA)	ib (kA)
	Sub-transient	Transient	RMS Break	Peak Make	Peak Break
Busbar	1.539	1.535	1.536	2.221	2.172
Poc	1.390	1.384	1.385	2.007	1.959

Appendix D – Fault Clearance Time Calculation

Table D-1 – Protection Operation Time Formula

Protection Characteristic	Protection Operation Time	
Instantaneous (INST)	0	
Definite Time (DT)	The specified operating time	
IDMT SI	$\frac{0.14}{\left(I_f/I_s\right)^{0.02} - 1} \times tm$	where: I_f = Earth fault current (A) I_s = Earth fault current setting (A) tm = Earth fault time setting
IDMT EI	$\frac{80}{\left(I_f/I_s\right)^{2} - 1} \times tm$	
IDMT VI	$\frac{13.5}{\left(I_f/I_s\right) - 1} \times tm$	

Appendix E – Ground Return Current Calculation

E.1 Overview

The proportion of fault current that will return to the source through the ground is known as the 'ground return current' (I_{gr}).

For an all-cable circuit (Figure E-1), the ground return current will typically be between 5% and 30% of the overall earth fault current and is influenced by the resistance of each electrode system as well as the cable type.

A first estimate of 40% is a reasonable assumption for the ground return current. The actual proportion of current that returns through the ground is based on the cable size, construction, sheath material and length, earth fault current and the earth resistance at either end of the cable network and can be calculated more accurately using various methods:

- C factor method (originally from BS 7354) in ENA EREC S34 (Section E.2).
- Dedicated cable return current or earthing design tool software (Section E.3).

For overhead line systems (or mixed cable/overhead line circuits) without an earth conductor the ground return current is assumed to be 100% of the overall earth fault current, where an earthwire is present reductions can be applied. Refer to ENA EREC S34 for further information and relevant formulae.

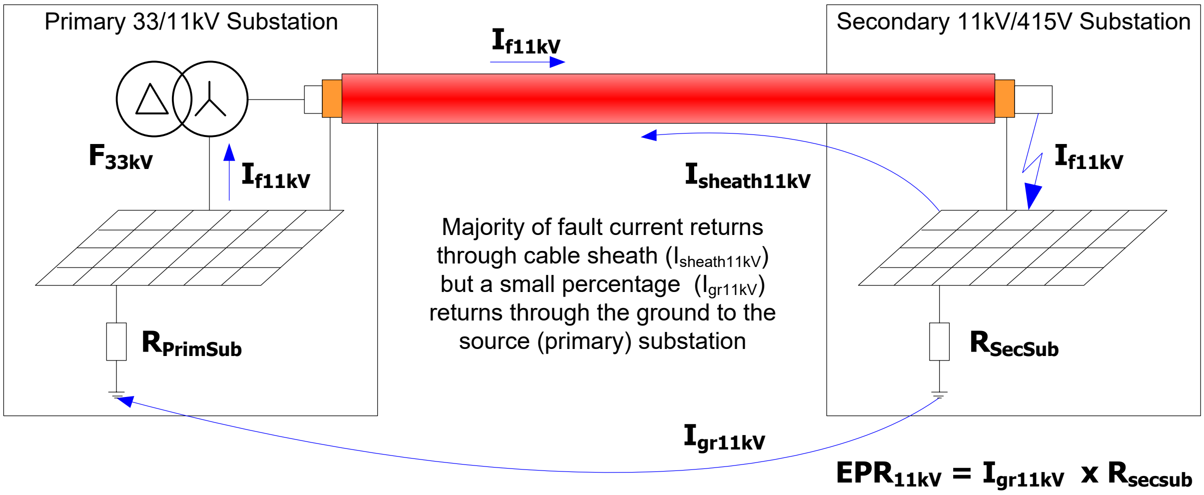


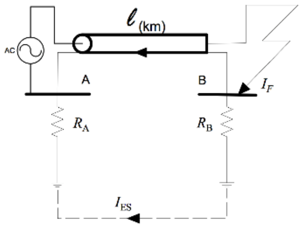
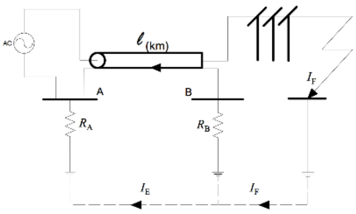
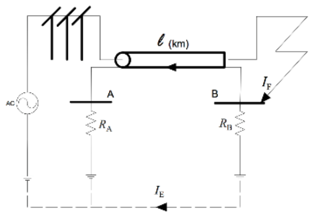
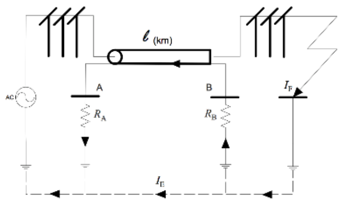
Figure E-1 – Cable Ground Return Current

E.2 C Factor Method

The equations in Table E-1 can be used to calculate the ground return current for various cable systems. The associated C factors are given in Table E-2 (11kV) and Table E-3 (33kV and 132kV). Where a cable is not available the nearest cable with a smaller core cross-sectional area will normally provide a conservative calculation of ground return current.

Note: The values for R_A and R_B should be selected with care. For example, in Arrangement 3 R_A is typically the terminal pole earth and R_B is the substation earth, and the ground return current will be less than 100%. However, the terminal pole earth cannot also be used in parallel with the substation earth as network contribution (refer to Appendix G.4) to reduce the overall value of R_B. If it is used in this way a ground return current of 100% should be used in the earthing calculations.

Table E-1 – Ground Return Current Formula

Arrangement		**Circuit**	**Formula**
1	Cable circuit, local source, fault at cable end		$I_{ES} = I_F \times \frac{\frac{C}{(a+9E)}}{\sqrt{\left\{\left(\frac{C}{a+9E}+\frac{R_{AB}}{\ell}\right)^2+0.6\left(\frac{\rho}{aE}\right)^{0.1}\right\}}}$
2	Cable-line circuit, local source, remote fault		$I_{ES} = I_F \times \frac{\frac{C}{(a+9E)}+\frac{R_B}{\ell}}{\sqrt{\left\{\left(\frac{C}{a+9E}+\frac{R_{AB}}{\ell}\right)^2+0.6\left(\frac{\rho}{aE}\right)^{0.1}\right\}}}$
3	Line-cable circuit, remote source, fault at cable end		$I_{ES} = I_F \times \frac{\frac{C}{(a+9E)}+\frac{R_A}{\ell}}{\sqrt{\left\{\left(\frac{C}{a+9E}+\frac{R_{AB}}{\ell}\right)^2+0.6\left(\frac{\rho}{aE}\right)^{0.1}\right\}}}$
4	Line-cable-line circuit, remote source, remote fault		$I_{ES} = I_F \times \frac{\frac{C}{(a+9E)}+\frac{R_{AB}}{\ell}}{\sqrt{\left\{\left(\frac{C}{a+9E}+\frac{R_{AB}}{\ell}\right)^2+0.6\left(\frac{\rho}{aE}\right)^{0.1}\right\}}}$

Where:

I_{ES} = Ground return current (A)

I_F = Fault current (A)

C = C factor (from Table E-2 or Table E-3)

E = System voltage (kV)

ℓ = Cable length (km)

a = Cross sectional area (mm^2)

$R_{AB} = R_A + R_B$ (resistance of both earthing systems added together)

ρ = Soil resistivity (Ω·m)

Refer to ENA EREC S34 for further information and worked examples.

Table E-2 – 11kV Cable Ground Return Current C Factors

Voltage (kV)	Cable Type	Arrangement (Table E-1)		
		1	2 and 3	4
11	3 x 1c 95mm² XLPE (35mm² Cu wire screen)	32	29	29
11	3 x 1c 185mm² XLPE (70mm² Cu wire screen)	25	20	19
11	3 x 1c 300mm² XLPE (70mm² Cu wire screen)	35	27	25
11	3 x 1c 185mm² XLPE (115mm² Al wire screen)	25	20	19
11	3 x 1c 300mm² XLPE (115mm² Al wire screen)	35	27	25
11	3 x 1c 150mm² XLPE Polylam	137	130	125
11	3 x 1c 240mm² XLPE Polylam	162	152	146
11	3 x 1c 70mm² XLPE EPR (12mm² Cu wire screen)	81	77	76
11	3 x 1c 150mm² XLPE EPR (16mm² Cu wire screen)	87	82	80
11	3 x 1c 240mm² XLPE EPR (16mm² Cu wire screen)	115	107	104
11	3 x 1c 95mm² XLPE EPR (35mm² Cu wire screen)	33	30	30
11	3 x 1c 185mm² XLPE EPR (35mm² Cu wire screen)	47	42	41
11	3 x 1c 300mm² XLPE EPR (35mm² Cu wire screen)	63	56	53
11	3c 95mm² XLPE (35mm² Cu wire screen)	66	63	63
11	3c 185mm² XLPE (50mm² Cu wire screen)	92	87	87
11	3c 300mm² XLPE (50mm² Cu wire screen)	130	122	121
11	3c 95mm² PICAS	34	32	32
11	3c 185mm² PICAS	30	26	26
11	3c 300mm² PICAS	28	23	22
11	3c 0.04 inch² PILCSWA	66	66	68
11	3c 0.06 inch² PILCSWA	57	56	58
11	3c 50mm² PILCSWA	63	62	64
11	3c 0.1 inch² PILCSWA	57	55	56
11	3c 0.15 inch² PILCSWA	61	59	60
11	3c 0.2 inch² PILCSWA	62	60	61
11	3c 0.25 inch² PILCSWA	67	65	65
11	3c 185mm² PILCSWA	78	74	75
11	3c 0.3 inch² PILCSWA	68	65	65
11	3c 0.3 inch² PILCSWA (Al)	68	65	65
11	3c 0.4 inch² PILCSWA	66	66	68
11	3c 240mm² PILCSWA	66	66	68
11	3c 300mm² PILCSWA	97	93	93
An approximate conversion between mm^2 and inch^2 is $mm^2 \approx inch^2 \times 645$.				

Table E-3 – 33kV and 132V Cable Ground Return Current C Factors

Voltage (kV)	Cable Type	Arrangement (Table E-1)		
		1	2 and 3	4
33	3c 0.2in² PILCSWA	80	74	72
33	3 x 1c 185mm² in Triplex (35mm² Cu wire screen)	77	67	63
33	3 x 1c 300mm² in Triplex (35mm² Cu wire screen)	97	79	74
33	3 x 1c 630mm² in Trefoil (35mm² Cu wire screen)	146	121	110
132	3 x 1c 300mm² in Trefoil (135mm² Cu wire screen)	59	25	10

E.3 Dedicated Cable Return Current or Earthing Design Tool Software

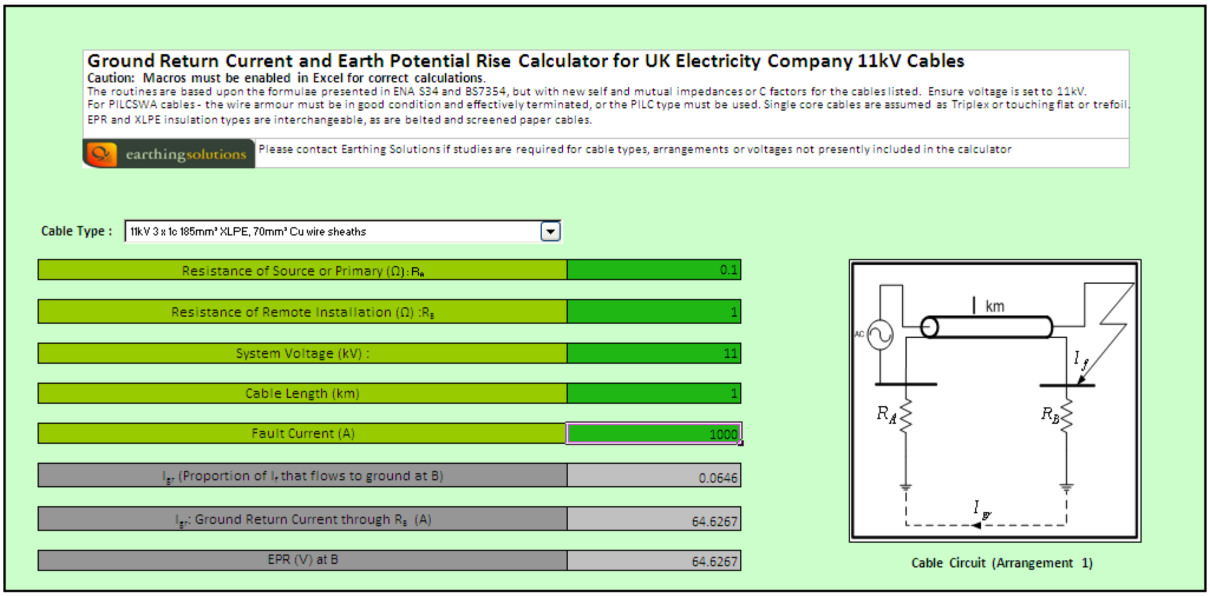


Figure E-2 – Cable Ground Return Current and EPR Calculator

Appendix F – Neutral Current Reduction

F.1 Overview

In the UK, on networks operating at voltages of 132kV and above the system neutral is generally solidly and multiply earthed. This is achieved by providing a low impedance connection between the star point of each transformer (primary) winding and each substation earth electrode. The low impedance neutral connection often provides a parallel path for earth fault current to flow and this reduces the amount of current flowing into the substation earth electrode. For EPR calculations in such systems, the neutral returning component of earth fault current should be considered. An example of the current split between the different return paths is shown by the red arrows in Figure F-1.

Circuits entering a substation are often via a mixture of overhead and underground cables. As explained in Appendix E a high percentage of the earth fault current flowing in an underground cable circuit will return to the source via the cable sheath if bonded at both ends (typically 70% to 95%), whereas in an earthed overhead line circuit the current flowing back via the aerial earthwire is a lower percentage (typically 30% - 40%). It is therefore necessary to apply different reduction factors to the individual currents flowing in each circuit and to achieve this the individual phase currents on each circuit are required.

The detailed fault current data required is normally available from most power systems analysis software packages. Any additional calculation effort at an early stage is usually justified by subsequent savings in design and installation costs that result from a lower calculated EPR.

An example is given in Section F.2 to illustrate:

1. Calculations to subtract the local neutral current in multiply earthed systems.
2. The application of different reduction factors for overhead line and underground cable circuits.
3. A situation where there are fault infeeds from two different sources.

F.2 Example

F.2.1 Arrangement

Figure F-1 shows a simplified line-diagram of an arrangement where a 132kV single-phase to earth fault is assumed at 132/33kV Substation X. Two 132kV circuits are connected to Substation X, the first is via an overhead line from a 400/132kV Substation Y and the second is via an underground cable from a further 132/33kV Substation Z which is a wind farm connection. There is a single transformer at Substation X and its primary winding is shown together with the star point connection to earth.

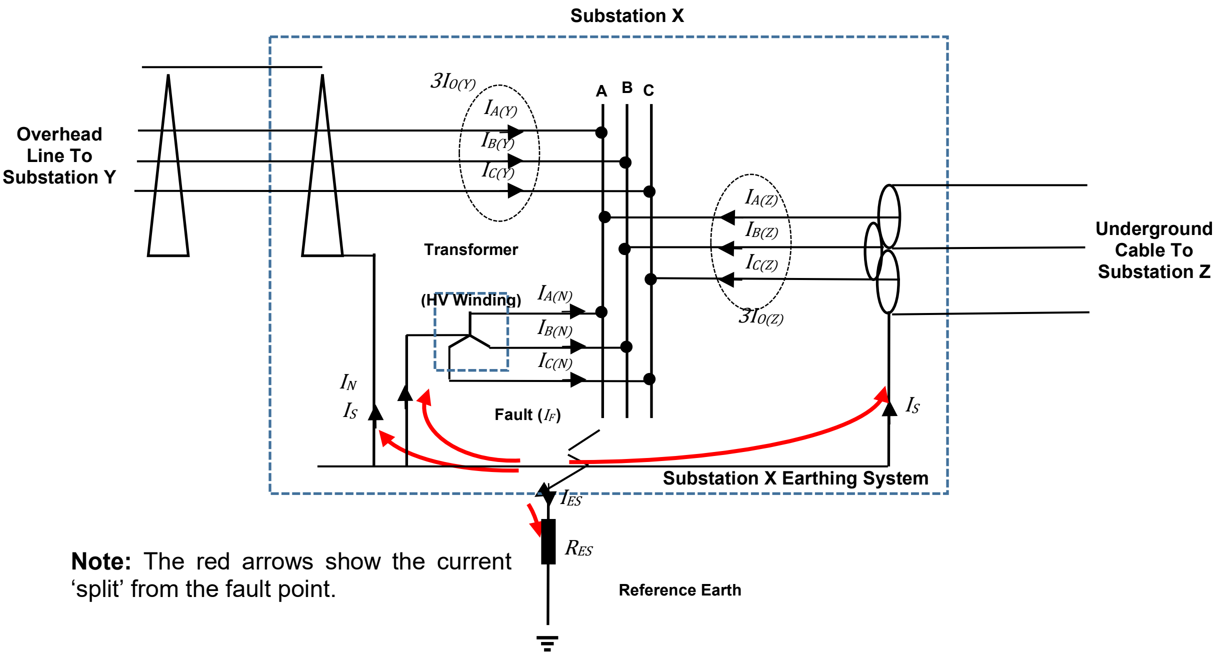


Figure F-1 – Neutral Current Reduction Example Arrangement

F.2.2 Example Data

For the single-phase to earth fault on Phase A illustrated in Figure F-1, the individual currents flowing on each phase of each circuit and in the transformer HV winding are shown in Table F-1. This data is typical of that from a power systems analysis software package.

Table F-1 – Neutral Current Reduction Example – Fault Level Data

Single-phase to ground fault at Substation X							
From	**Ik"A (kA)**	**Ik"A Angle (deg)**	**Ik"B (kA)**	**Ik"B Angle (deg)**	**Ik"C (kA)**	**Ik"C Angle (deg)**	**$3I_0$ (kA)**
Transformer (HV Side)	0.840	62.386	0.291	76.190	0.495	63.802	1.620
Substation Y	4.163	72.533	0.766	-135.761	0.598	-93.980	2.916
Substation Z	8.093	76.072	0.541	27.674	0.233	139.316	8.559
Sum of contributions into	**Ik"A (kA)**	**Ik"A Angle (deg)**	**Ik"B (kA)**	**Ik"B Angle (deg)**	**Ik"C (kA)**	**Ik"C Angle (deg)**	
Substation X	13.071	74.074	0.000	0.000	0.000	0.000	
	UA (kV)	UA (deg)	UB (kV)	UB (deg)	UC (kV)	UC (deg)	
	0.000	0.000	86.916	-146.069	84.262	91.344	

F.2.3 Neutral Current

In Table F-1 the Sum of contributions into Substation X is the vector sum of the faulted 'A' phase contributions from the two lines and the transformer and is defined as the Total Earth Fault Current (I_F). The contribution shown as Transformer (HV Side) represents the transformer star-point or neutral current (I_N).

The current that returns to Substations Y and Z via Substation X earth electrode (I_{ES}) is separate from that flowing back via the transformer neutral (I_N) and metallic paths (neutral and healthy phases). It can be shown that $I_F - I_N = 3I_0$ where $3I_0$ is three times the sum of zero-sequence current on all lines connected to the substation. For each line, $3I_0$ is equal to the vector sum of the individual line phase currents, i.e. $3I_0 = I_A + I_B + I_C$.

Table F-2 provides the calculated $3I_0$ values for each of the two lines and their sum.

Table F-2 – Neutral Current Reduction Example – Sum of Contributions to Earth Fault Current

Contribution from:	$3I_0$ Magnitude (kA)	$3I_0$ Angle (deg)
Substation Y	2.916	76.9
Substation Z	8.559	74.8
Sum of Contributions from Y+Z	11.470	75.3

From Table F-1 and Table F-2 it can be seen that earth fault current magnitude of 13.07kA reduces to 11.47kA once the local neutral current is subtracted.

As a further check of this value the sum of the currents flowing on the transformer (HV side) can be subtracted from the total earth fault current to arrive at the same result, i.e. 13.07∠74° - 1.62∠65.3° = 11.47∠75.3° (kA).

F.2.4 Fault Current Distribution

The circuit from Substation Y is via an overhead line whereas that from Substation Z is via an underground cable. Further calculations are required to calculate the fault current distribution between the substation electrode, tower line earthwire and the underground cable sheaths.

Table F-3 lists the additional information used in this example.

Table F-3 – Neutral Current Reduction Example – Fault Current Distribution Calculation Information

Line construction between Substations X and Y	132kV double circuit tower line, L4 construction. 20 spans long
Reduction factor for line between Substations X and Y	0.708∠-9° (as per ENA EREC S34)
Line construction between Substations X and Z	132kV, 3 x 1c, 300mm^2 aluminium conductor, 135mm^2 copper-wire screen, XLPE insulated, 5km circuit length
Substation Y Earth Resistance	0.1Ω
Substation X Earth Resistance	0.5Ω
Reduction factor for line between Substations X and Z	0.067∠178°

The calculated reduction factors (r_E) for each circuit type from Table F-3 are applied to the three-times zero-sequence currents ($3I_0$) on each circuit and the total ground return current (I_E) calculated as shown in Table F-4.

Table F-4 – Neutral Current Reduction Example – Calculated Ground Return Current

Contribution From:	**$3I_0$ Magnitude (kA)**	**$3I_0$ Angle (deg)**	**r_E Magnitude**	**r_E Angle (deg)**	**I_E Magnitude (kA)**	**I_E Angle (deg)**
Substation Y	2.916	76.9	0.708	-9	2.06	67.9
Substation Z	8.559	74.8	0.067	178	0.565	252.8
Sum of Contributions from Y+Z	11.470	75.3			1.50	66.1

The total ground return current magnitude (I_{ES}) is shown to be only 1.5kA which is significantly lower than the fault current at the fault point (I_F) of 13.07kA.

The earth potential rise (EPR) can be calculated simply as the product of the ground return current I_E and the overall Earth Resistance R_E at Substation X, i.e. 1.5kA x 0.5Ω = 750V.

Appendix G – Network Contribution

G.1 Overview

Figure G-1 shows a typical HV network layout consisting of substations (red circles), HV cables (red), LV cables (yellow) in an urban location. An underground cable network consisting of interconnected substations and metallic sheath cables can provide a low earth resistance that will be in parallel with the resistance of any installed earthing electrode.

Similarly, the terminal pole earth electrodes associated with overhead line networks will also be parallel with the resistance of any installed earthing electrode.

This effect is often termed 'network contribution' and can be used in the earthing design where specified in the specific earthing design standards. The use of network contribution from various sources is explored in more detail in the sections that follow.

Note: Network contribution is only applicable where there is a metallic earth connection (e.g. cable sheath/screen) between the substation and the part of the network providing the contribution and the contribution is typically within 2km. The contribution will be broken by overhead lines or dimmish with excessive distance. Care is also required when substations are directly connected to the source grid/primary substation and there is no other network interconnection, network contribution is typically not applicable in this instance.

Figure G-1 – HV and LV Cable Network

G.2 Urban or Rural Network

The network contribution can be estimated from a map of the network by determining the extent of the network and measuring the approximate network radius. A set of typical values for a number of 11/6.6kV network scenarios are given in Table G-1.

Note: Care is required when applying these values to smaller village or island-type cable networks to ensure that the network contribution would apply and the selected value is not overly optimistic.

A more accurate value of network contribution can be obtained by carrying out an earth resistance measurement from an existing substation (refer to ECS 06-0024).

Table G-1 – Network Contribution Values (based on network type and radius)

Network Type	**Network Radius (m)**	**Network Contribution (Ω) for Various Soil Resistivity (Ωm)**								
		25	**50**	**100**	**150**	**200**	**300**	**400**	**500**	**1000**
Urban Cable Network	100	0.19	0.23	0.46	0.68	0.91	1.36	1.82	2.27	4.53
	200	0.1	0.13	0.25	0.37	0.49	0.73	0.98	1.22	2.43
	500	0.1	0.1	0.13	0.18	0.23	0.34	0.4	0.54	1.07
	1000	0.1	0.1	0.1	0.13	0.15	0.21	0.26	0.32	0.59
Rural Cable Network	100	0.22	0.45	0.89	1.33	1.77	2.65	3.54	4.42	8.83
	200	0.13	0.25	0.49	0.73	0.96	1.44	1.92	2.4	4.79
	500	0.1	0.13	0.24	0.34	0.44	0.65	0.86	1.08	2.13
	1000	0.1	0.12	0.18	0.23	0.28	0.39	0.50	0.61	1.17
1 HV Pole	n/a	10								
2 HV poles	n/a	5								

Figure G-2 shows Horsham in West Sussex and is an example of an urban network with an approx. size of 3500m. The nearest radius is 1000m (from Table G-1), which gives an estimated network contribution of 0.13Ω in 150Ωm soil.

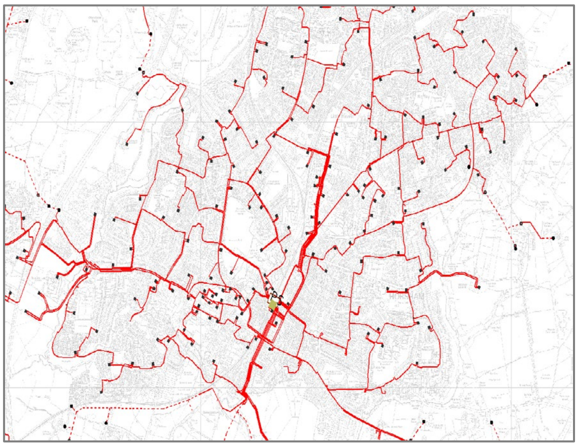


Figure G-2 – Network Contribution Example

G.3 HV Cables

If the substation is not part of a larger network or there is uncertainty about the extent and categorisation of the network, an alternative approach is to consider the length of HV PILC cable or the length polymeric cable and the number of substations directly connected to the substation. These values can be estimated using NetMap or Geospatial Analytics and used to lookup a value of network contribution from Table G-2.

An example is shown over the page.

Table G-2 – Network Contribution from HV PILC and Polymeric Cables

Cable Type	Cable Length (m)	Network Contribution (Ω) for Various Soil Resistivity (Ωm)									
		25	50	100	150	200	250	300	400	500	1000
HV PILC	100	0.5	0.97	1.91	2.85	3.8	4.74	5.68	7.56	9.45	18.87
	200	0.32	0.59	1.11	1.64	2.17	2.69	3.22	4.27	5.32	10.58
	300	0.28	0.47	0.84	1.21	1.58	1.96	2.33	3.07	3.82	7.54
	400	0.26	0.42	0.71	1	1.29	1.58	1.87	2.45	3.03	5.94
	500	0.26	0.39	0.64	0.88	1.12	1.36	1.6	2.08	2.56	4.95
	1000	0.26	0.37	0.55	0.7	0.84	0.98	1.11	1.38	1.64	2.95
	1500	0.26	0.37	0.55	0.68	0.8	0.91	1.02	1.21	1.41	2.34
	2000	0.26	0.37	0.55	0.68	0.8	0.9	1	1.17	1.34	2.09
HV Polymeric 1 Substation per km	1000	3.1	5.91	11.57	17.24	22.91	28.58	34.25	45.57	56.88	113.22
	1500	1.81	3.16	5.96	8.79	11.63	14.47	17.31	22.99	28.67	56.98
	2000	1.88	3.21	5.99	8.81	11.64	14.47	17.31	22.97	28.63	56.83
HV Polymeric 2 Substations per km	500	2.95	5.79	11.46	17.15	22.83	28.51	34.18	45.53	56.88	113.49
	1000	1.6	3	5.83	8.67	11.52	14.37	17.21	22.9	28.59	56.97
	1500	1.23	2.13	3.99	5.88	7.78	9.67	11.57	15.37	19.17	38.12
	2000	1.11	1.75	3.12	4.52	5.93	7.35	8.78	11.62	14.47	28.7
HV Polymeric 4 Substations per km	300	1.52	2.97	5.89	8.81	11.73	14.65	17.57	23.41	29.25	58.43
	400	1.5	2.93	5.79	8.66	11.53	14.4	17.27	23	28.74	57.39
	500	1.5	2.92	5.78	8.63	11.49	14.35	17.21	22.92	28.63	57.16
	1000	0.87	1.56	2.98	4.41	5.85	7.28	8.72	11.59	14.47	28.82
	1500	0.75	1.18	2.1	3.05	4	4.95	5.91	7.83	9.75	19.36
	2000	0.75	1.06	1.72	2.41	3.11	3.82	4.54	5.97	7.41	14.63
HV Polymeric 10 Substations per km	100	2.86	5.7	11.39	17.08	22.76	28.45	34.13	45.51	56.88	113.7
	200	1.46	2.9	5.79	8.67	11.55	14.43	17.32	23.08	28.85	57.66
	300	1	1.97	3.91	5.84	7.78	9.72	11.66	15.54	19.42	38.8
	400	0.78	1.5	2.96	4.43	5.89	7.35	8.82	11.75	14.67	29.31
	500	0.65	1.23	2.4	3.57	4.75	5.93	7.11	9.46	11.82	23.59
	1000	0.46	0.73	1.3	1.89	2.48	3.08	3.68	4.87	6.07	12.05
	1500	0.47	0.65	1.01	1.39	1.78	2.17	2.56	3.36	4.16	8.18
	2000	0.49	0.66	0.93	1.2	1.48	1.76	2.05	2.64	3.24	6.26

Figure G-3 shows the proposed location of a new secondary substation outside a rural village and the extent of the existing HV (red) and LV (green) network. As the substation is outside the existing network the rural network contribution (from Section G.2) is overly optimistic.

However, the substation is being connected into an existing circuit (Figure G-4) which contains approx. 500 metres of PILC cable. In a soil resistivity of 100Ωm the estimated network contribution is 0.64Ω (from Table G-2).

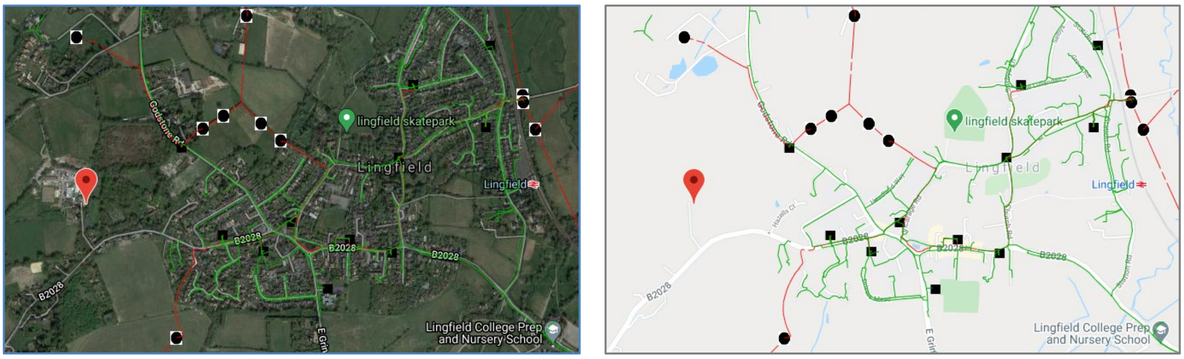


Figure G-3 – Network Contribution PILC Cable Example – Proposed Substation Location

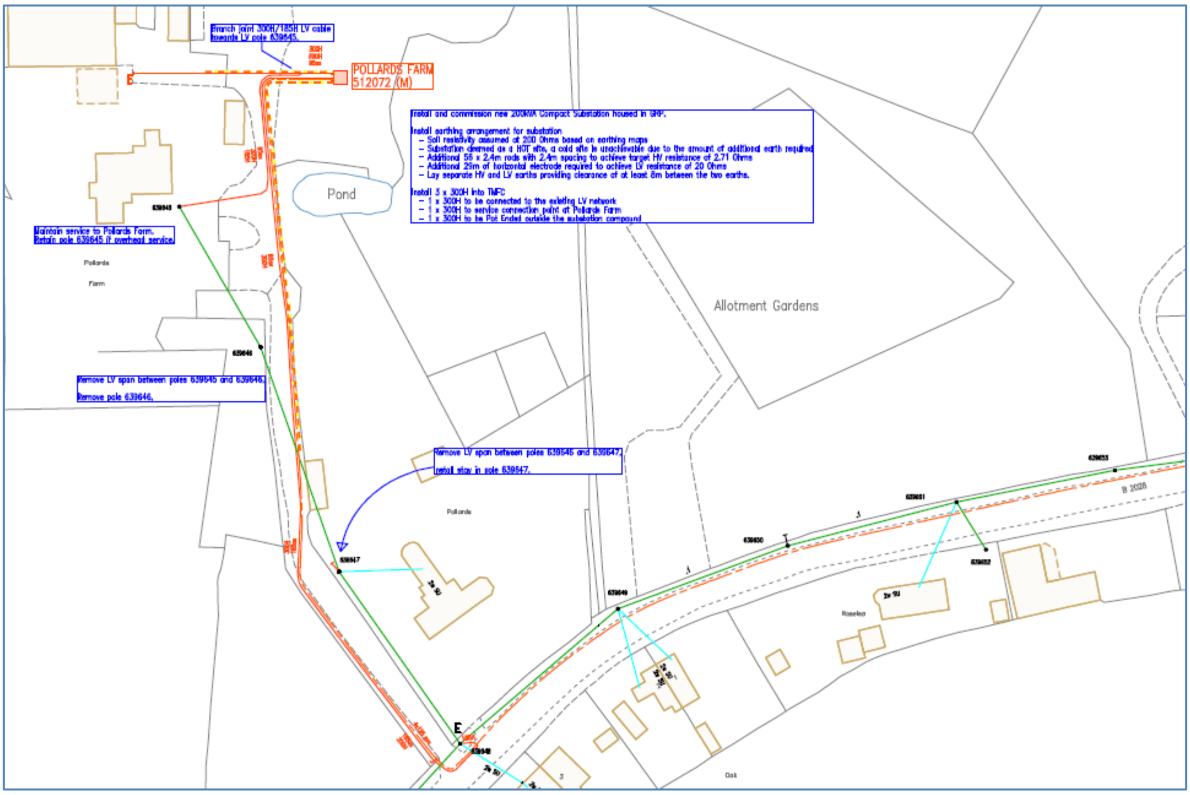


Figure G-4 – Network Contribution PILC Cable Example – Proposed Cable Route

G.4 HV Poles and Substations

If the substation is directly connected to an overhead line network, the HV terminal poles at the end of the cable (Figure G-5) will have a 10 ohm earth electrode which can be considered as network contribution. The network contribution for one and two poles is given in Table G-1.

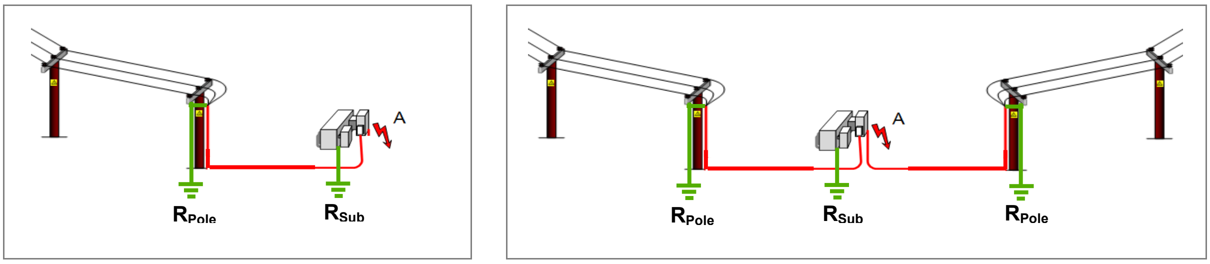


Figure G-5 – HV Overhead Line Network Contribution

This approach can be extended to cover additional poles and substations which form part of a small interconnected network (i.e. they are connected via a common metallic earth connection). Each can be considered to provide a conservative 10Ω parallel contribution. The network contribution can be calculated using the formulae below, for example a network with one HV terminal and 3 secondary substations will provide a typical contribution of 2.5Ω.

$$R_{Network} = \frac{1}{(10^{-1} \times n)}$$

where *n* is the number of pole/substation earths in parallel with each other

Appendix H – Electrode Surface Area Current Density Calculation

H.1 Formula

The surface area of the earth electrode in contact with the ground should be sufficiently large enough to prevent the ground around the electrode drying out and increasing in resistance during a fault.

The minimum electrode surface area can be calculated using the formula in Table H-1 and then compared with the actual surface area of the installed earth conductor, tape and rods.

An example is given in Section H.2.

Table H-1 – Surface Area Formula

Calculation	Formulae	
Minimum Surface Area	$A = \frac{1000 \times I_{gr}}{\sqrt{\frac{57.7}{\rho \cdot t}}}$	A = Required surface area of buried electrode (mm^2) I_{gr} = Ground return current flowing through electrode (A) ρ = Soil resistivity (Ωm) t = Backup fault clearance time i.e. 3 (s)
Conductor Surface Area	$A_{conductor} = 2 \cdot \pi \cdot \sqrt{\frac{\text{CSA}}{\pi}} \cdot l$	$A_{conductor}$ = Total conductor surface area (mm^2) CSA = Conductor cross sectional area (mm^2) l = Total conductor length (mm)
Tape Surface Area	$A_{tape} = 2 \cdot (w + d) \cdot l$	A_{tape} = Total tape surface area (mm^2) w = Tape width (mm^2) d = Tape depth (mm^2) l = Total tape length (mm)
Rod Surface Area	$A_{rod} = \pi \cdot d \cdot l$	A_{rod} = Total earth rod surface area (mm^2) d = Earth rod diameter (mm^2) l = Total earth rod length (mm)

H.2 Example

Consider a standard 3 x 3 secondary substation with a 4m square 70mm^2 ring electrode and two 2.4m 16mm^2 diameter earth rods in 100Ωm soil. The ground return current is 500A and the backup fault clearance time is 3s.

The minimum surface area is:

$$\mathrm{A} = \frac{1000\ \times\ 500}{\sqrt{\frac{57.7}{100 \times 3}}} = 1{,}140{,}099\mathrm{mm}^2$$

The surface area of a 1m length of 70mm^2 copper conductor is:

$$A_{conductor} = 2 \cdot \pi \cdot \sqrt{\frac{\mathrm{CSA}}{\pi}} \cdot l = \ 2 \cdot \pi \cdot \sqrt{\frac{70}{\pi}} \cdot 1000 = 29,659mm^2$$

The surface area of a 1.2m 16mm earth rod is:

$$A_{rod} = \pi \cdot d \cdot l = \ \pi \cdot 16 \cdot 1200 = 60{,}318mm^2$$

Therefore the total surface area of the installed electrode is:

$$(4 \times 4 \times 29{,}659) + (4\ \times 60{,}318) = 715{,}816\mathrm{mm}^2$$

The surface of area of the installed electrode does not meet the minimum surface area requirements is therefore insufficient.

Approximately 15m of additional earth electrode is required to satisfy the surface area requirements. The total surface area with the additional electrode is now:

$$(4 \times 4 \times 29{,}659) + (4\ \times 60{,}318) + (15\ \times 29{,}659) = 1{,}160{,}701\mathrm{mm}^2$$

Appendix I – Transfer Voltage Calculation

I.1 Overview

The voltage transferred from another substation should be considered in the safety voltage calculations and the site classification. An estimation of the transfer voltage from one substation to another can be calculated using the equation below. A sample set of 11kV cable impedance data is included in Appendix J.

Typical modelling software, including UK Power Networks SSEDT, uses a constant current approach which assumes that the earth fault current at the source does not change when the new substation and cable is added. The transfer voltage is calculated using a full matrix determination including cable sheath self and mutual impedances. A reasonable approximation can be obtained by the equivalent circuits in Figure I-1 which represent the situation before and after connection of the new substation leg.

The following sections include the equations for cables with a single sheath (Appendix I.2), cables with three sheaths (Appendix I.3) and cables with a single sheath and armour (Appendix I.4).

Example calculations for each are given in Appendix I.5.

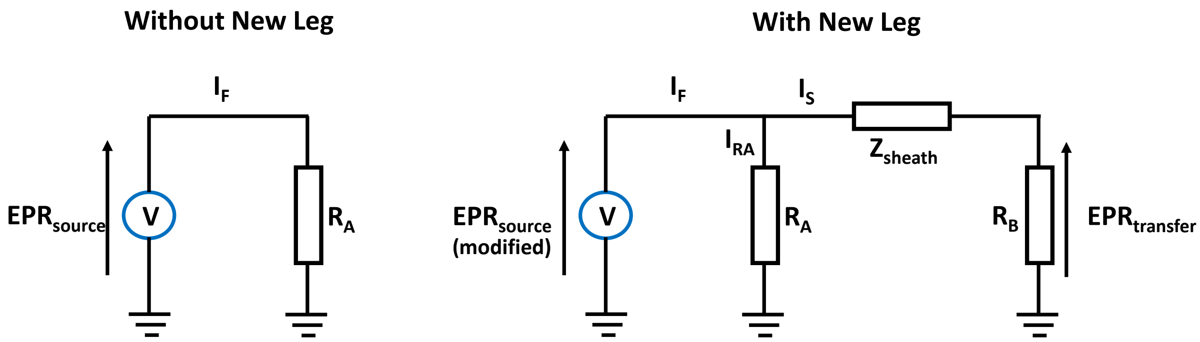


Figure I-1 – Transfer Voltage

I.2 Cables with a Single Sheath

For a cable with a single sheath, e.g. 3c XLPE or PILC, from Figure I-1 the following current divider equation can be derived:

$$\mathrm{EPR_{Transfer}} = \mathrm{EPR_{Source}} \times \left(\frac{\mathrm{R_B}}{\mathrm{R_A} + \mathrm{R_B} + \mathrm{Z_{sheath}}}\right)$$

Where Z_{sheath} is the cable sheath self-impedance of $R_{sheath} + jX_{sheath}$, and the equation becomes:

$$\mathrm{EPR_{Transfer}} = \mathrm{EPR_{Source}} \times \left(\frac{\mathrm{R_B}}{\sqrt{(\mathrm{R_A} + \mathrm{R_B} + \mathrm{R_{Sheath}})^2 + \mathrm{X_{Sheath}}^2}}\right)$$

An example for 2km of 11kV 3c 185 mm² XLPE cable is shown in Table I-1.

I.3 Cables with a Three Sheaths

Where there are three sheaths connected in parallel, e.g. for a 3 x 1c Triplex cable, the equation is modified as follows:

$$\mathrm{EPR_{Transfer}} = \mathrm{EPR_{Source}} \times \left(\frac{\mathrm{R_B}}{\sqrt{\left(\mathrm{R_A} + \mathrm{R_B} + \frac{\mathrm{R_{sheath}}}{3}\right)^2 + \mathrm{X_{sheath}}^2}} \right)$$

An example for 2km of 11kV 3 x 1c 185 mm² EPR cable with three 35mm² copper wire screens is shown in Table I-1.

I.4 Cables with a Single Sheath plus Armour

PILCSWA cables have a lead sheath surrounded by a steel wire armouring (SWA). Where there is a single sheath with an armour connected in parallel an approximation if provided by parallel combination of the sheath and armour real parts only. The imaginary part of the sheath impedance is used. The equation then becomes:

$$\mathrm{EPR_{Transfer}} = \mathrm{EPR_{Source}} \times \left(\frac{\mathrm{R_B}}{\sqrt{\left(\mathrm{R_A} + \mathrm{R_B} + \left(\frac{1}{R_{\mathrm{sheath}}} + \frac{1}{R_{\mathrm{armour}}}\right)^{-1}\right)^2 + \mathrm{X_{sheath}}^2}} \right)$$

An example for 2km of 11kV 3c 0.3inch² PILSWA cable is shown in Table I-1.

I.5 Examples

Table I-1 – Transfer Voltage Calculation Examples

	3c 185mm² XLPE	3 x 1c 185mm² EPR	3c 0.3inch² PILCSWA
Voltage	11kV	11kV	11kV
Source Substation EPR (EPR_{Source})	999V	999V	999V
Cable Sheath Resistance per km ($R_{sheath/km}$)	0.381Ω/km	0.552Ω/km	0.610Ω/km
Cable Sheath Reactance per km ($X_{sheath/km}$)	0.646Ω/km	0.701Ω/km	0.652Ω/km
Armour Resistance per km ($R_{armour/km}$)	n/a	n/a	0.462Ω/km
Circuit Length	2km	2km	2km
Total Cable Sheath Resistance (R_{sheath})	0.762Ω	1.104Ω	1.220Ω
Total Cable Sheath Reactance (X_{sheath})	1.292Ω	1.402Ω	1.304Ω
Total Armour Resistance (R_{armour})	n/a	n/a	0.924Ω
Secondary Substation Impedance (R_B)	0.5Ω	0.5Ω	0.5Ω
Primary (Source) Substation Resistance (R_A)	0.2Ω	0.2Ω	0.2Ω
Transfer Voltage ($EPR_{Transfer}$)	256V	283V	279V

Appendix J – Cable Data

Table J-1 – Typical 11kV Cable Impedance Data[8]

Voltage (kV)	Cable Type	Core R (Ω/Km)	Core X (Ω/Km)	Sheath/ Screen R (Ω/Km)	Sheath/ Screen X (Ω/Km)	Armour R (Ω/Km)
11	3 x 1c 185mm² XLPE (35mm² Cu wire screen)	0.199	0.751	0.550	0.700	n/a
11	3 x 1c 185mm² XLPE (70mm² Cu wire screen)	0.199	0.751	0.294	0.699	n/a
11	3 x 1c 300mm² XLPE (70mm² Cu wire screen)	0.108	0.736	0.296	0.689	n/a
11	3 x 1c 185mm² XLPE (115mm² Al wire screen)	0.199	0.751	0.294	0.699	n/a
11	3 x 1c 300mm² XLPE (115mm² Al wire screen)	0.108	0.736	0.296	0.689	n/a
11	3 x 1c 630mm² XLPE	0.073	0.702	0.241	0.640	n/a
11	3 x 1c 1600mm² XLPE	0.068	0.670	0.178	0.628	n/a
11	3 x 1c 150mm² XLPE Polylam	0.234	0.758	1.771	0.704	n/a
11	3 x 1c 240mm² XLPE Polylam	0.165	0.743	1.548	0.695	n/a
11	3 x 1c 70mm² EPR (12mm² Cu wire screens)	0.444	0.782	1.487	0.717	n/a
11	3 x 1c 150mm² EPR (16mm² Cu wire screens)	0.340	0.772	0.551	0.712	n/a
11	3 x 1c 95mm² EPR (35mm² Cu wire screens)	0.234	0.758	1.131	0.705	n/a
11	3 x 1c 185mm² EPR (35mm² Cu wire screens)	0.199	0.751	0.552	0.701	n/a
11	3 x 1c 300mm² EPR (35mm² Cu wire screens)	0.165	0.743	1.126	0.696	n/a
11	3 x 1c 240mm² EPR (16mm² Cu wire screens)	0.142	0.736	0.532	0.692	n/a
11	3c 95mm² XLPE (35mm² Cu wire screen)	0.343	0.763	0.394	0.658	n/a
11	3c 150mm² XLPE (35mm² Cu wire screen)	0.160	0.751	0.674	0.652	n/a
11	3c 185mm² XLPE (50mm² Cu wire screen)	0.202	0.741	0.381	0.646	n/a
11	3c 300mm² XLPE (50mm² Cu wire screen)	0.145	0.725	0.386	0.637	n/a
11	3c 95mm² PICAS	0.344	0.765	0.231	0.674	n/a
11	3c 185mm² PICAS	0.203	0.742	0.157	0.660	n/a
11	3c 300mm² PICAS	0.144	0.732	0.121	0.648	n/a
11	3c 0.04 inch² PILCSWA	0.739	0.776	1.473	0.681	0.918
11	3c 0.06 inch² PILCSWA	0.480	0.764	1.332	0.677	0.663
11	3c 50 mm² PILCSWA	0.394	0.749	1.321	0.665	0.700
11	3c 0.1 inch² PILCSWA	0.315	0.750	1.021	0.669	0.597
11	3c 0.15 inch² PILCSWA	0.231	0.738	0.944	0.664	0.553
11	3c 0.2 inch² PILCSWA	0.188	0.730	0.771	0.659	0.516
11	3c 0.25 inch² PILCSWA	0.158	0.723	0.723	0.655	0.491
11	3c 185 mm² PILCSWA	0.143	0.712	0.747	0.645	0.517
11	3c 0.3 inch² PILCSWA	0.191	0.719	0.610	0.652	0.462
11	3c 0.4 inch² PILCSWA	0.117	0.710	0.557	0.647	0.431
11	3c 240 mm² PILCSWA	0.117	0.710	0.557	0.647	0.431
11	3c 300 mm² PILCSWA	0.108	0.695	0.557	0.632	0.546

[8] Source: UK Power Networks Secondary Substation Earthing Design Tool.

Appendix K – Conductor and Electrode Sizing

Table K-1 details the minimum conductor sizes based on fault level for use in substation earthing systems. ECS 06-0022 and ECS 06-0023 also list the minimum standard electrode and conductor sizes based on fault current and application.

Note: At sites shared with National Grid the electrode embedded within their area shall comply with the National Grid requirements (typically 400kV - 63kA for 1 second, 275kV - 40kA for 1 second, 132kV - 31.5kA for 3s - in some special cases 40kA). Parts of the site peripheral to National Gird may not need to be sized for this rating provided it can be demonstrated that significant National Grid fault current cannot normally flow in them.

Table K-1 – Minimum Conductor Sizes

Fault Level	Material	Connection Type		Temperature Rise (°C)	Calculated Minimum Conductor Size (mm^2)	Recommended Standard Tape Size (mm)	Recommended Stranded Conductor Size (mm^2)
12kA/3s	Copper	Single (spur)	Bolted	250	119	40 x 3	120
		Single (spur)	Brazed or welded	405	98	25 x 4	120
		Duplicate or loop	Bolted	250	71	25 x 3	120
		Duplicate or loop	Brazed or welded	405	59	25 x 3	70
	Aluminium	Single (spur)	Bolted	250	179	40 x 6	213
		Single (spur)	Brazed or welded	325	161	40 x 6	213
		Duplicate or loop	Bolted	250	108	25 x 6	158
		Duplicate or loop	Brazed or welded	325	97	25 x 6	158
26kA/3s	Copper	Single (spur)	Bolted	250	257	50 x 6	300
		Single (spur)	Brazed or welded	405	213	40 x 6	240
		Duplicate or loop	Bolted	250	154	40 x 4	185
		Duplicate or loop	Brazed or welded	405	128	40 x 4	185
	Aluminium	Single (spur)	Bolted	250	388	n/a	415
		Single (spur)	Brazed or welded	325	349	n/a	415
		Duplicate or loop	Bolted	250	233	40 x 6	266
		Duplicate or loop	Brazed or welded	325	210	40 x 6	266
31.5kA/3s	Copper	Single (spur)	Bolted	250	311	50 x 7	400
		Single (spur)	Brazed or welded	405	257	50 x 6	300
		Duplicate or loop	Bolted	250	187	38 x 5	240
		Duplicate or loop	Brazed or welded	405	155	40 x 4	185
	Aluminium	Single (spur)	Bolted	250	470	n/a	n/a
		Single (spur)	Brazed or welded	325	423	n/a	n/a

Fault Level	Material	Connection Type		Temperature Rise (°C)	Calculated Minimum Conductor Size (mm²)	Recommended Standard Tape Size (mm)	Recommended Stranded Conductor Size (mm²)
		Duplicate or loop	Bolted	250	282	50 x 6	323
		Duplicate or loop	Brazed or welded	325	254	50 x 6	323
40kA/3s	Copper	Single (spur)	Bolted	250	395	50 x 8	400
		Single (spur)	Brazed or welded	405	327	50 x 7	400
		Duplicate or loop	Bolted	250	237	40 x 6	240
		Duplicate or loop	Brazed or welded	405	196	50 x 4	240
	Aluminium	Single (spur)	Bolted	250	597	n/a	n/a
		Single (spur)	Brazed or welded	325	537	n/a	n/a
		Duplicate or loop	Bolted	250	358	n/a	415
		Duplicate or loop	Brazed or welded	325	322	n/a	323