Eskom	Standard	Technology

Title: **SUBSTATION EARTH GRID DESIGN STANDARD**

Unique Identifier:	**240-134369472**
Alternative Reference Number:	**34-1245; 41-877**
Area of Applicability:	**Engineering**
Documentation Type:	**Standard**
Revision:	**2**
Total Pages:	**67**
Next Review Date:	**September 2026**
Disclosure Classification:	**Controlled Disclosure**

Compiled by	Approved by	Authorized by
Theunus Marais	Braam Groenewald	Naresh Hari
Chief Engineer – Substation Engineering	Corporate Specialist – Substation Engineering	General Manager – Transmission Engineering
Date: 10 September 2021	Date: 10 September 2021	Date: 2021-09-15
		Supported by SCOT/SC
		Subhas Maharaj
		Substation SC Chairperson
		Date: 14/9/2021

PCM Reference: **Substation Design**

SCOT Study Committee Number/Name: **Substation**

Content

Figures

Tables

1. Introduction

Effective earthing is of the utmost importance for the protection of equipment and for safety purposes. Simultaneously increasing emphasis on safety and reliability of supply dictates careful design, implementation and maintenance of earthing systems. The objective of earthing is to provide a means to dissipate electric currents into the earth under normal and fault conditions without exceeding any operating and/or equipment limits or adversely affecting continuity of supply.

This Eskom Standard has been prepared to establish the requirements for the design and installation of earth electrodes in AC medium voltage (MV), high-voltage (HV) and extra-high-voltage (EHV) substations throughout all Divisions within Eskom. It shall be used by all Eskom appointed design engineers, testing service providers, project managers, clerk of works, operators, and maintenance teams to ensure the implementation of substation earth electrodes are compliant to Eskom requirements.

This document replaces all previous revisions of DST 34-1245 and TST 41-877 and to ensure alignment with national and international best practices for the design, installation, testing, commissioning, operation and maintenance of earth electrodes in Eskom AC substations.

2. Supporting clauses

2.1 Scope

This standard is applicable to outdoor AC substation earthing, both conventional and gas-insulated. Distribution, Transmission, and Generating Plant substations are included. The earthing of DC substations is not covered in this document, nor is the analysis of the effects of lightning surges.

2.1.1 Purpose

The intent of this standard is to provide guidance on the design of AC substation earth electrodes to meet equipment and safety requirements.

2.1.2 Applicability

This document shall apply throughout all Eskom Holdings Limited Divisions for AC substation earth electrode design, installation, testing, commissioning, operation and maintenance requirements.

The specific effects of lightning surges are beyond the scope of this standard, although an earthing system designed as described herein will, nonetheless, provide protection against steep wave front surges entering the substation and passing to earth through its earth electrodes.

2.1.3 Effective date

The standard is effective from date of authorisation and implementation of this standard shall be monitored after a period of six months from the authorisation date.

2.2 Normative/informative references

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs.

2.2.1 Normative

[1] ISO 9001, Quality Management Systems

[2] Carman WD & Woodhouse DJ, Performance Evaluation of Series Impedance Insulation Used as Earthing System Safety Mitigation Measures (IEEE Powercon 2000, Perth WA)

[3] Christy Thomas, Seasonal Variation of Soil Resistivity and the Correction Factor (8th Cigre Southern Africa Regional Conference, November 2017)

[4] Christy Thomas, Seasonal Variation of Soil Resistivity and the Correction Factor (Earthing Africa Inaugural Symposium & Exhibition, June 2017)

[5] IEEE Std 80, IEEE Guide for Safety in AC Substation Grounding

[6] Occupational Health and Safety Act 85 of 1993: Electrical Machinery Regulations

[7] Report ST 95/12, Guide for the Design of a Substation Earthing System, WC vd Merwe and CS Engelbrecht

[8] SANS 10142-1, The wiring of premises Part 1: Low-voltage installations

[9] SANS 10142-2, The wiring of premises Part 2: Medium-voltage installations above 1 kV a.c. not exceeding 22 kV a.c. and up to and including 3 MVA installed capacity

[10] SANS 10199:2012, South African National Standard, The Design and Installation of Earth Electrodes

[11] The South African Distribution Code, Network Code

[12] The South African Grid Code, The Network Code

[13] TJ Marais, Investigation into the electrical properties of crusher stone used in substation earthing systems (Cigre IEC International Symposium – South Africa 2015)

[14] 02TB-017, Back-up Overcurrent Protection Philosophy: A Probabilistic Approach

[15] 240-55922824, Substation Layout Design Guide

[16] 240-56030640, General Information and Requirements for High Voltage Cable Systems Standard

[17] 240-56063710, MV Cabling in Substations Standard

[18] 240-64100247, Standard for Earthing of Secondary Plant Equipment in Substations

[19] 240-56356396, Earthing and Lightning Protection Standard *(Generation Division Standard applicable to power stations)*

[20] 240-71062174, Generic Substation Design

[21] 240-75880946, Earthing Standard *(covering the earthing of sub-transmission line structures)*

[22] 240-76624507, Standard for Neutral Earthing of Transmission and Distribution Networks

[23] 240-84854974, Continuity Measurement of Substation Earth Grid Systems

[24] 240-95773230, Transmission Substation Earth Fault Application Guide

[25] 240-96393507, Soil Resistivity Testing For Substation Applications

[26] 240-101940513, Substation Earth Electrode Resistance Measurement

[27] 240-108982466, Standard for HV Yard Stones in Eskom Substations

[28] 240-130615862, Earthing of Transmission Line Towers

[29] 240-170000153, Copper Conductors Used for Earthing in Substations

[30] 240-170000349, Copper-Cladded Steel Conductors used for Earthing

[31] 240-170000535 - Copper Clad Steel Exothermic Connections

2.2.2 Informative

[32] Ausgrid NS 222, Major Substation Earthing Layout Design

[33] CIGRE, 1984 Session, Paper 36-02, Corrosion Behaviour of Earthing Materials

[34] CIGRE, Application Guide 44, Earthing of GIS

[35] CIGRE, Electra 204, Engineering Guide on Earthing Systems (in Power Stations)

[36] CIGRE, Technical Brochure 213, Engineering Guide on Earthing Systems in Power Stations

[37] CIGRE, Technical Brochure 535, EMC within Power Plants and Substations

[38] CIGRE Technical Brochure 749, Substation earthing system design optimisation through the application of quantified risk analysis

[39] D-DT-5240, Earthing Standard

[40] D-DT-6044, BAR:ROUND;DIA 10 MM;CU;ANNEALED

[41] D-DT-6045, STRIP:FLAT;WD 50 MM;THK 3.15 MM;CU

[42] D-DT-6365, BAR:ROUND;DIA 8.5 MM;40 PCT CCS;DSA

[43] ENA EG1, Substation Earthing Guide

[44] IEEE 81, IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Grounding System

[45] IEEE Std 837, IEEE Standard for Qualifying Permanent Connections used in Substation Grounding

[46] NRS 076, Earthing of Distribution Substations with Nominal Voltages up to and Including 132kV

[47] 0.54/393, Earthing Standards

[48] 32-9, Definition of Eskom Documents

[49] 32-644, Eskom Documentation Management Standard

[50] 240-56356668, Maintenance of Power Station Earthing and Earth Mats Guideline

[51] 240-65216546, Standard for Portable Earthing Gear

[52] 240-105197930, Variable Frequency Earth Electrode Resistance Measurement Result Sheet

[53] 240-105197932, Tagg Slope Earth Electrode Resistance Measurement Result Sheet

[54] 240-105221530, Soil Resistivity Measurement Result Sheet

[55] 240-109589380, Direct Lightning Stroke Protection of Substations

[56] 240-170000402, Copper and Copper-Clad Steel Substation Earth Grid Conductor Capacity Investigation

2.3 Definitions

2.3.1 General

Definition	Description
Anneal	To subject to great heat and then slow cooling, and sometimes reheating and further cooling, for the purpose of rendering the material less brittle, to temper or to toughen.
Apparent soil resistivity	The equivalent, overall resistivity of a volume of soil with varying properties, expressed in ohm meter.
Bond (-ing conductor)	Low impedance connection.
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis software package developed by SES Technologies.
CDEGS MALT (module)	Analyse preliminary earth grid system based on the specified soil model, not considering additional connected sources and assume all conductors are lossless
Copper-clad steel	Bimetallic conductor that is manufactured by a mechanical bonding process that produces a metallurgical bond between a solid oxygen-free copper layer and a steel core.

Definition	Description
Counterpoise	Conductor or system of conductors, buried in the ground, and electrically connected to the earth grid.
Dead Soft Annealed	Metal is heated to above the critical range and appropriately cooled to develop the greatest possible commercial softness or ductility.
Decrement factor	An adjustment factor used in conjunction with the symmetrical ground fault current parameter in safety-oriented earthing calculations. It determines the RMS equivalent of the asymmetrical current wave for a given fault duration, t_f, accounting for the effect of initial DC offset and its attenuation during the fault.
Earth	Conducting mass of the earth whose electrical potential at any point is conventionally taken as zero.
Earth connection	Terminal or clamp at earth potential, to which all the equipment earth wires are connected and to which an earth electrode is connected externally.
Earth electrode impedance	The vector sum of resistance and reactance between the earth electrode, grid or system and remote earth.
Earth electrode resistance	The impedance, excluding reactance, between the earth electrode, grid or system and remote earth. Note that some sections of this document refer to impedance as resistance if the reactive portion of the impedance is deemed negligible.
Earth electrode/grid/mat	A system of interconnected earth (or ground) electrodes arranged in a pattern over a specified area and buried below the surface of the earth.
Earth fault current	The maximum of the calculated single phase-to-earth, double phase-to-earth or three phase-to-earth fault current levels associated with a specific voltage level in the substation.
Earthing isolator/switch	Mechanical switching device for earthing parts of an electric circuit, capable of withstanding for a specified duration electric currents under abnormal conditions such as those of short-circuit, but not required to carry electric current under normal conditions of the electric circuit, or In a substation, a special disconnector which is intended to connect phase conductors to earth for safety purposes.
Earth lead/tail	A conductor including any clamp or terminal, by which connection of equipment's earth terminal or conductor to an earth electrode is made. This is typically the connection between the structures and the earth grid.
Earthed/earthing	The electrical connection between an apparatus and the general mass of earth in such a way that it will ensure a safe discharge of electrical energy at all times.
Earthing arrangement/system	A system intended to provide at all times, by means of one or more earth electrodes in a specific area, a low impedance path for the immediate discharge of electrical energy, without danger, into the general mass of the earth.
Exothermic weld or connection	Also known as exothermic bonding, thermite or thermit welding, is a welding method that employs molten metal to mechanically and electrically fuse two earth rods, or an earth conductor to an earth rod, or conductor to conductor. The process employs an exothermic reaction of a thermite composition to heat the metal, and requires no external source of heat or current.

Definition	Description
Fault current division factor	A factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the earth grid and surrounding earth.
Grid current	The portion of the earth fault current that flows between the earth grid and surrounding earth.
Grid resistance	Refer to the definition of earth electrode resistance above.
Ground potential rise (GPR)	The maximum electrical potential that a ground electrode may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current multiplied by the grid resistance.
HV yard	Enclosure that contains exposed overhead medium voltage, high-voltage; extra-high voltage or ultra-high voltage components.
N – 1	N refers to the base case application in performing the required function, with no added redundancy. If any component fails the system cannot perform its function. N – 1 refers to the inclusion of extra components which are not strictly necessary for it to function, in case of failure in other components. With one portion of the system out of service (N – 1), it must be possible to fulfil the intended operation under all credible system operating conditions.
Order of magnitude	A level in a system used for measuring something in which each level is ten times larger than the one before.
Other metal structures (in the context of this document)	This will include all metal structures bonded to the earth grid not specifically listed, i.e. metal supports for fire barriers, equipment label supports, etc.
Peri-urban	Denoting to or located in an area immediately adjacent to a city or urban area.
Potential gradient	Potential difference per unit length (usually expressed in volts per metre, V/m), measured in the direction in which the potential difference is at a maximum.
Prohibited area	An enclosed area in which live conductors or live parts of electrical apparatus working at high-voltage are accessible, but situated in such a position that inadvertent human contact therewith is not possible from ground/floor level.
Remote earth	A theoretical concept that refers to an earth electrode of zero impedance placed an infinite distance away from the ground under test. In practice, remote earth is approached when the mutual resistance between the ground under test and the test electrode becomes negligible. Remote earth is normally considered to be at zero potential.
Rural	In, relating to, or characteristic of the countryside rather than a town or city.
Soil resistivity	The resistance between opposite faces of a cube of soil having sides of length 1 m. This value is expressed in ohm meter.
Step potential/voltage	The difference in surface potential over a distance of 1m that can be bridged by a person from foot to foot without contacting any other earthed object.
Touch potential/voltage	The voltage difference between an earthed metallic object and a point on the earth's surface 1m away.

Definition	Description
Transferred potential	Potential rise of an earthing system caused by a current to earth transferred by means of a connected conductor (for example a metallic cable sheath, Protective Earth and Neutral (PEN) conductor, fence, pipeline, rail, etc.) into areas with low or no potential rise relative to reference earth, resulting in a potential difference occurring between the conductor and its surroundings.
Urban	Of, living in, or situated in a town or city.

2.3.2 Disclosure classification

Controlled disclosure: controlled disclosure to external parties (either enforced by law, or discretionary).

2.4 Abbreviations

Abbreviation	Description
AASHTO	American Association of State Highway and Transportation Officials
AC	Alternating current
CIGRÉ	International Council on Large Electric Systems
CCS	Copper-Clad Steel
CT	Current transformer
CVT	Capacitive voltage Transformer
DC	Direct current
DSA	Dead Soft Annealed
Dx	Distribution
EHV	Extra-high voltage
GPR	Ground potential rise
HV	High Voltage
I_c	Maximum expected RMS current in the grid conductor
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I_F	Design fault current
I_G	Current in the earth grid after time t_f
LV	Low Voltage
ME	Medium equipment
MV	Medium Voltage
OHS	Occupational Health and Safety
RMS	Root Mean Square
SCOT	Steering Committee of Technologies
t_f	Fault clearing time
TNSP	Transmission Network Service Provider

Abbreviation	Description
Tx	Transmission
UHV	Ultra-high voltage
URS	User requirement specification
VT	Voltage transformer

2.5 Roles and responsibilities

All design engineers shall comply with the requirements as set out in this standard when designing new substation earth electrodes, do design work affecting substations as a result of network strengthening and when doing substation refurbishment designs.

The respective Engineering Design Lead (Senior/Chief Engineer as the case may be) shall ensure that the requirements of this standard are implemented and adhered to for all AC related substation designs.

2.6 Process for monitoring

The applicability and validity of the document content shall be monitored continuous and updated as and when required

2.7 Related/supporting documents

This document prescribes the principles as found in [5] (IEEE Std 80-2013) with inputs from the other sources referenced.

This document supersedes Distribution Standard 34-1245 and Transmission Standard 41-877.

Revision 2 and subsequent revisions of this standard also supersedes Technical Instruction 240-103693534 (Use of Copper-Clad Steel as Earth Tails in Distribution Substations).

3. Substation earth grid design

The design principles prescribed in this document are based on [5] (IEEE Std 80-2013, IEEE Guide for Safety in AC Substation Grounding).

An earthing system should be designed and installed in a manner that will limit the effect of ground potential gradients to such voltage and current levels that it will not endanger the safety of people or equipment under normal and fault conditions.

In addition, all substation earth grids shall comply with the applicable codes and safety regulations. It is the design engineer’s responsibility to ensure that due care is taken during the design and implementation phases that this is the case.

3.1 South African Grid and Distribution Code requirements

3.1.1 Grid Code

The following earthing and surge protection requirements are stipulated in section 4.6 of [12] and shall be complied with in Transmission substations:

1) The TNSP shall ensure adequacy of all earthing installations to provide for
   - the safety of personnel and the public
   - the correct operation of all protection systems
   - agreed design and performance levels.

2) Earthing isolators shall be provided at new substations where the fault level is designed for 20kA and above.

3) The TNSP shall provide adequate protection to limit lightning surges at the connection point to the limits listed (in the South African Grid Code, The Network Code, Table 2) using the best technology methods. Note that protection has to be placed as close as possible to the point of connection. The protection shall be adequate to protect the generator unit to the rating levels specified in Table 2 of the South African Grid Code, The Network Code. Adequate safety margins shall be provided.

3.1.2 Distribution Code

The following earthing requirements are stipulated in section 6.4 of [11] and shall be complied with in Sub-transmission and Distribution substations:

1) The Distributor shall advise Customers about the neutral earthing methods used in the Distribution System.

2) The method of neutral earthing used on those portions of Customer's installations that are physically connected to the Distribution System shall comply with the Distributor's applicable earthing standards for loads and for embedded generators.

3) Protective earthing of equipment must be done in accordance with the applicable national standard.

4) In cases where the calculated Ground Potential Rise exceeds 5kV as per NRS 076, the responsible party shall inform the affected participants.

5) Approved designed lightning protection requirements shall be applied to the Distribution System and switching yards.

6) Substation earthing requirement shall be in accordance with NRS 076.

3.2 Design objectives

Considering the above, the aim of designing a safe earthing system in a substation is therefore to accomplish the following:

- Provide a means to conduct and dissipate electric currents into the ground under normal and fault conditions without exceeding any operating and equipment limits, or adversely affecting continuity of supply.
- Ensure an adequate degree of human safety, such that a person in the vicinity of earthed facilities is not exposed to the danger of electric shock.

The major design constraints therefore are:

- Step and touch potentials in and around the substation shall be within safe limits,
- With reference to section 3.1.2 point (4) the GPR shall be limited to 5kV if at all possible.
- The 5kV is especially important in urban, peri-urban and rural areas where communities reside or work near an electrical system. It must however be noted that there are instances where the 5kV cannot be met by the earth grid installation on its own. In such cases the electrical installation must not pose a danger to public in surrounding areas during fault conditions otherwise remedial actions "outside" the substation must be applied.

When high fault currents flow in the earth, voltage gradients are established within and around the substation which can be lethal to a person standing nearby. Although completely accurate pre-calculation of the gradients is seldom practical because of the variables involved, sufficient general data is available on which to base a design that should be acceptably safe.

3.3 Information required for earth grid design purposes

The following minimum information is required as inputs to the earth grid design.

3.3.1 Planning information

From the planning department the following is required as a minimum:

- The maximum of the calculated single phase-to-earth, double phase-to-earth or three phase-to-earth fault current levels associated with all voltage levels in the substation.
- The fault current duration of applicability, i.e. implementation of the current project only, 15 years from the date of the report, or the substation expected end of life, etc.
- Network X/R ratio per voltage level applicable to the substation under investigation.

3.3.2 Protection information

The maximum N – 1 protection fault clearing time is required:

- For installations with only Main and Backup protection (typically Dx applications) this will be the backup protection fault clearing time.
- For installations with Main 1, Main 2 and Backup protection (typically Tx applications) this will be the Main 2 protection fault clearing time as a minimum and has been indicated to be 0.5s.
- As a starting point 0.5s is used but has to be verified as adequate. If this does not satisfy the N – 1 fault clearing time requirements it shall be increased to the duration required.
- For Dx substations the slowest backup protection time is when being supplied from a Tx substation and the Tx substation provides the backup protection, in which case it should not exceed 800ms as stated in [14].
- Should the fault clearing time used prove to be too long and not render a safe earth grid design solution it will have to be reduced. This shall be done in consultation with the applicable Protection Coordination and Configuration Engineer.

3.3.3 Line/cable information

The following is required for all lines with shield wires and power cables connected to the earth grid:

- Number of lines with a single shield wire that will be connected to the earth grid.
- Number of lines with multiple shield wires that will be connected to the earth grid.

Should finite element analysis software be used to evaluate the design the following additional information will be required:

- Average structure geometry and structure footing resistance per line.
- Phase and shield wire conductor properties.
- Length per line and the fault level of the remotely connected substations.
- Applicable cable information as required for simulation purposes.

3.3.4 Substation layout information

In order to determine the size of the earth grid the following is required:

- The substation layout, including fence positions, fence types and earth grid maximum size and dimensions.
- Earth conductor material type.
- Type of connections to be used on the earth grid and to connect earth tails to the structures.

3.4 Design earth fault current (I_F)

In order to do the substation earth grid safety design and to determine the number of earth tails needed per structure it is necessary to know, among other factors, what the expected highest future earth fault current in the substation is likely to be. Ideally this future value should be the expected substation end-of-life earth fault current. This required value is hardly ever available so it becomes necessary for the design engineer to assume (or guess) some future value based on the values supplied in the planning report.

The fault current to be used when designing the substation earth grid must be based on the highest future earth fault current stated in the planning report or URS for all voltage levels in the substation. To ensure that the earth grid will still render the substation safe (with regard to expected step and touch potentials) beyond the period stated in the planning report or URS refer to the subsections below for the respective Distribution and Transmission earth fault currents to be used for design purposes. These proposed values take into account the existing low fault current base as well as the fact that the planning proposal indicates a future value already, although the applicable timeframe might be very short or even unknown.

The design earth fault current value chosen shall be used to determine the number of earth tails to be applied per structure, as well as for the substation safety design (refer to the applicable sections to follow). The safety design relates to the dimensions of the meshes (or blocks) forming the earth grid to ensure that step and touch potentials are within safe limits.

3.4.1 Distribution substation design earth fault current

For distribution the values given in Table 1 shall be used as a guide. It is important to note that there is no single correct or optimal value to be used, but of importance is to apply sound engineering judgement in choosing the value to be used. It is advisable to choose a value to allow for substantial increase in earth fault current when the planning report does not give a definite time frame. Conversely, if the planning report indicates a value far into the future the margin of increase can be reduced.

Table 1: Distribution substation design earth fault current guide

Future earth fault current (URS of planning report)	Design earth fault current (kA)	Applicable to
Below 5kA	10	All voltage levels
Between 5kA and 10kA	15	All voltage levels
Between 10kA and 15kA	20	All voltage levels
Between 15kA and 20kA	25	Maximum for 11kV and 22kV equipment All remaining voltage levels
Between 20kA and 25kA	30	All remaining voltage levels
Between 25kA and 30kA	(31.5) 35	31.5kA is the maximum for 33kV, 44kV and 66kV equipment All remaining voltage levels
Between 30kA and 40kA	40	Maximum for 88kV and 132kV equipment

For MV/MV substations where the earth fault current is limited at upstream substations by neutral earthing resistors these expected maximum values should be considered instead of the values proposed in Table 1.

3.4.2 Transmission substation design earth fault current

Refer to [24] (240-95773230) for an indication of the maximum earth fault current to be used as input in calculating the required number of earth tails per structure, the earth conductor size and the grid current.

3.5 Quantity of earth tails per structure

Each earth tail between the structure and main earth grid shall be either 2x10mm diameter annealed soft drawn round copper rods in parallel (standard Tx practice), 2x8.5mm diameter dead soft annealed round 40% CCS rods in parallel or a single 50x3.15mm copper bar (standard Dx practice).

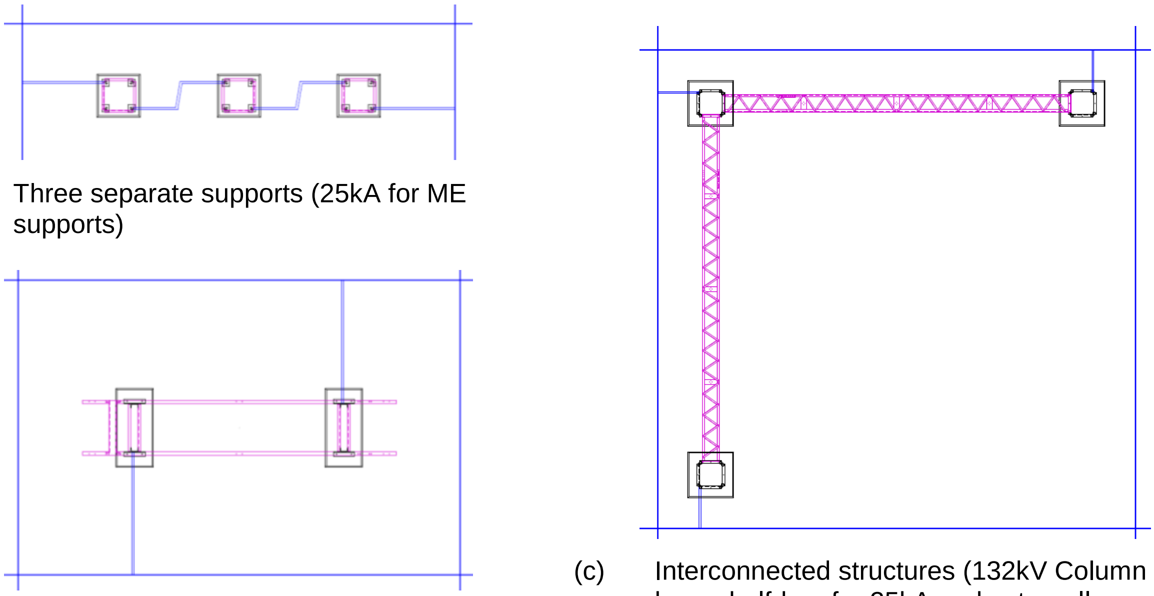
All equipment and busbar support structures shall be bonded to the earth grid via the number of earth tails specified in Table 2, based on the chosen design earth fault current I_F per applicable voltage level. The earth tails shall run in opposite directions from the structure to eliminate common mode failure of the earth grid conductor.

Table 2: Number of earth tail connections per structure

Design earth fault current	Number of earth tails per structure
25kA and below	2
Between 25kA and 40kA	4 (Dx connection through foundation)
	3 (Dx and Tx external connection to structure, including CCS)
Above 40kA	4

Notes:

1) The minimum number of earth tails as stated shall not be deviated from. More earth tails can be applied but are not necessary.
2) The Distribution practice is to apply 4 earth tails per structure through the foundation for design earth fault currents between 25kA and 40kA because of the higher theft risk in Dx substations.
3) The quantities given in this table is applicable to earth tails made up out of 2x10mm diameter annealed soft drawn round copper rods in parallel, 2x8.5mm diameter dead soft annealed round 40% CCS rods in parallel or a single 50x3.15mm copper bar.
4) Should any conductor other than as stated in note (3) above be used for the earth tails or main earth grid all conductor parameters shall be properly calculated and documented in the design document, irrespective of whether the material used is copper, CCS or any other material.



(a) Three separate supports (25kA for ME supports)

(b) Individual interconnected support (25kA for 132kV isolator)

(c) Interconnected structures (132kV Column and beam half-box for 25kA and externally connected 40kA)

Figure 1: Typical arrangement for 2 earth tail connections per structure

Typical structure earth tail configurations are given in Figures 1 and 2. Earth tails can be routed through adjacent structures to the earth grid as indicated in Figure 1 (a) for three individual ME support structures each with two earth tails connected in opposite directions to the earth grid conductors as required for 25kA. For interconnected structures the number of earth tails shall be divided between all support structures with a minimum of at least one earth tail per individual structure, refer to Figures 1 (b) and (c).

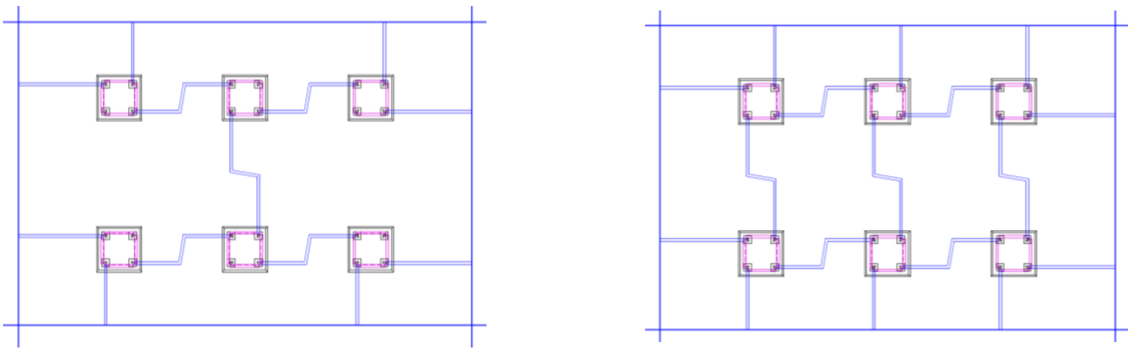
Figure 1 (b) depicts an interconnected structure with two legs or separate supports and foundations (in this case a 132kV isolator support) with its two earth tail connections to the main grid. Lastly, Figure 1 (c) indicates the minimum earth tail requirements associated with 25kA for a half-box column and beam installation. Figure 1 (c) will also be applicable when three earth tails are required, resulting in one earth tail per column for the example shown.

Figure 2 gives an indication of how three and four earth tails per structure should be connected to other structures and the earth grid.

As indicated in Figures 1 and 2, earth tails shall run in opposite directions from the structures to eliminate common mode failure of the main earth grid conductor.

All lighting and lightning masts shall be bonded to the earth grid via at least two earth tails.

Loose standing structures (JB's, equipment pedestals, etc.) shall be bonded to the earth grid via at least one earth tail as discussed in section 11.8.3.



(a) 3 earth tails per structure associated with externally connected 40kA maximum

(b) 4 earth tails per structure associated with in foundation 40kA and Tx > 40kA

Figure 2: Typical arrangement for 3 and 4 earth tails per structure

3.6 Earth grid design process and constraints

It must be noted that an earthing system based on a low earth (grid) resistance only will not necessarily guarantee safety because of the various factors impacting the design. No single standard layout can be adopted and it is therefore necessary to custom design the earth grid associated with every substation.

The basic design process flow to be followed is given in Figure 3. This process flow is applicable irrespective of the design method being used, i.e. calculating all parameters by hand in accordance with IEEE 80 or by making use of appropriate finite element analysis software.

In general the earth grid shall consist of a grid of horizontal buried conductors supplemented by a number of vertical earth-rods connected to the grid if required. It must be noted that vertical earth-rods only add value for homogenous or high-over-low soil structures. Refer to section 3.6.2 on the soil models for more on this.

3.6.1 Standard practices

As a standard the following shall be applied:

- Safety parameters as stipulated in IEEE 80 will be applied for a body weight of 50kg and a body resistance of 1000Ω shall be used.

- 1x10mm diameter annealed soft drawn round copper rod or 1x8.5mm diameter dead soft annealed round 40% CCS rod shall be used as main earth grid conductor. Should other conductor material types be considered all care shall be taken in determining the minimum conductor diameter required based on the material properties and connection types.

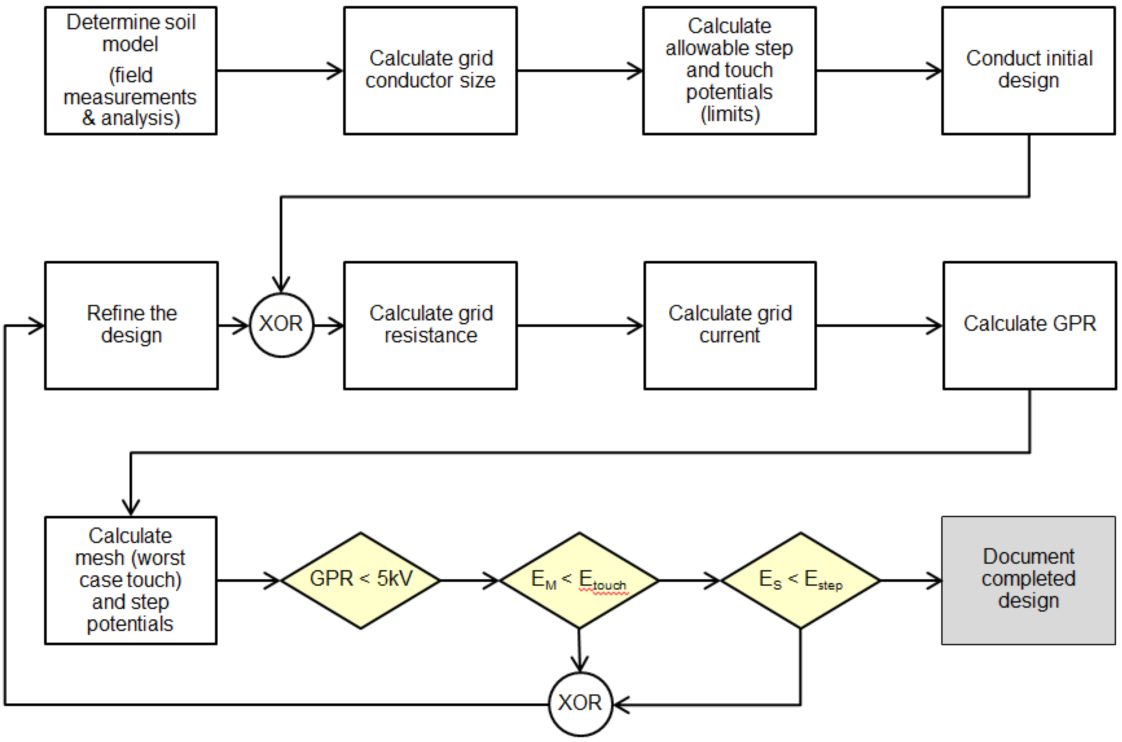


Figure 3: Earth electrode basic design process flow

- As a standard the grid shall be buried at a depth of 1000mm. This is however a design decision and can be increased or decreased by the design engineer based on project specific requirements.
  - Where it is not possible to maintain this depth for whatever reason it can be reduced to a minimum of 600mm as long as all safety requirements are adhered to as stipulated in section 3.2 (Design objectives). In addition this reduction in depth shall not compromise the physical safety of the earth grid, i.e. increase the risk of copper earth grid conductor theft or damage.
  - Although not prohibited it is not advised that the grid depth is increased beyond 1000mm because it will introduce practical/implementation constraints. If the depth is increased all safety requirements shall be adhered to as stipulated in section 3.2 (Design objectives).
- The grid shall extend over the whole area occupied by the substation and depending on the type of fence (metal or non-metal) shall either extend outside the yard by 600mm to 1000mm or stop on the inside. For non-metallic fences or walls the earth grid normally does not extend outside the perimeter enclosure, whereas for metal fences the earth grid should extend beyond the fence to create an equipotential zone on the outside of the fence if required.
- For applications where the grid extend beyond the fenced area crushed stone or other surface material coverings shall extend at least 1200mm outside the fence. If crushed stone is used the kerb shall be installed at 1200mm outside the fence.
- All metal structures and objects in the substation shall be connected to the earth grid to ensure all of it is at the same reference potential to prevent a touch potential risk.
- In Dx substation no visible copper shall be present, including for structure earth tails. Structures shall be earthed through the foundation holding down bolts as per D-DT-5240 Sheets 3 and 6.

- It must be noted that the connection type has an impact on the conductor's transfer capacity, refer to table 5. On the main earth grid all conductor to conductor connections shall be done as follows:
  - When CCS is used only exothermically welded connections are acceptable.
  - For Dx substation applications in accordance with D-DT-5240 Sheet 2. For Dx only brazed and exothermically welded connections are acceptable.
  - For Tx substation in accordance with 0.54/393 Sheets C2 note 6 and Sheet C5. Crimped, brazed or exothermically welded connections can be used for Tx applications.

3.6.2 Soil model

The soil model is an electrical representation of the soil in which the earth electrode will be installed and is one of the important input parameters in the design. It must be stressed that the soil model is only an approximation of the actual soil conditions and that a perfect match is unlikely.

3.6.2.1 Determining the soil model

Soil resistivity measurements shall be done in accordance with [25] (240-96393507, Soil Resistivity Testing for Substation Applications). Depending on the season (time of year) that the measurements are done it will be necessary to apply a correction factor to the measured results to ensure the worst case soil conditions are used during the design, refer to Annex B, [3] and [4] for more detail on this.

Based on the corrected test results the soil model shall be determined in accordance to the method described in Annex A, or by making use of finite element analysis software that can perform this function. Also refer to [10] (SANS 10199:2012, The Design and Installation of Earth Electrodes) for further information on determining the soil model by hand.

Two-layer soil models are often a good approximation of many soil structures and shall be used as a minimum for the design. The two-layer model consists of an upper layer of finite thickness and with different resistivity than the lower layer of infinite thickness, refer to Figure 4 for a typical representation of a two-layer soil model. If the soil however has a complex structure it will be necessary to apply a multi-layer model which can be determined by making use of finite element analysis software.

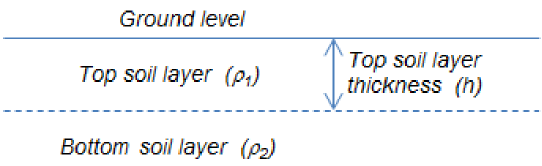


Figure 4: Typical two-layer soil model

For Greenfield substations soil measurements shall be done at least twice per site during the project design and construction phases.

- The first time shall be during the detail design phase on the virgin site to obtain a baseline for the initial design. The results from this measurement together with inputs from the civil designer shall be used in determining the soil model to be used for design purposes.
- The second test shall be done once the substation platform has been completed and before any trenching or foundation work is done. These results will represent the "as constructed" soil condition and shall be used as input in the design that was done during the design phase to verify the adequacy of the design. If necessary the grid layout shall be modified to ensure all safety requirements are met, irrespective of whether unsafe conditions exist or if it is an "over design".

For existing substations the process as described in [25] (240-96393507, Soil Resistivity Testing for Substation Applications) shall be followed for the measurement. Refer to the section titled "Process to be followed for strengthening and refurbishment projects" to determine the soil model for these applications.

3.6.2.2 Soil treatment to lower soil resistivity

In certain cases where high soil resistivities are prevalent, adding additional grid conductors and vertical earth-rods will not necessarily result in the desired design solution. In such cases increasing the overall electrode diameter by modifying the soil properties might solve the problem because the inner shell of soil closest to the electrode normally comprises the bulk of the electrode ground resistance to remote earth. For that reason modifying the soil properties surrounding the grid conductor can be very effective.

Various materials are available for use in this regard, namely:

- In areas where it is necessary to excavate surface or subsurface rock and backfill with imported material, this excavated rock can possibly be reused. If a suitable backfill material can be obtained the rock can be run through a mobile crusher plant and then blended with the imported material before being reused. The blending ratios should be calculated in such a way to ensure the resistivity of the backfilled layer support the earthing design requirements as well as the terrace required bearing pressures. This initiative should be led by the civil design engineer responsible for the terrace design.
- Sodium chloride, magnesium, copper sulphates, or calcium chloride, can be used to increase the conductivity of the soil immediately surrounding an electrode. <u>This is however not a supported solution</u> as these substances will speed up the corrosion of the earth conductors. It will also tend to leach into surrounding areas over time which can be in contravention of environmental requirements. For the same reason the soil treatment will have to be renewed periodically.
- Concrete being hygroscopic attracts moisture, therefore buried in soil, a concrete block behaves as a semiconducting medium with a resistivity typically ranging between 30Ωm – 200 Ωm depending on the soil moisture level. In medium and highly resistive soils a wire or metallic rod encased in concrete therefore has a lower resistance than a similar electrode buried directly in the soil. This encasement reduces the resistivity of the most critical portion of material surrounding the metal element in much the same manner as a chemical treatment of soils. The disadvantage of this practice as a solution is that the temperature of the conductor associated high currents would vaporise the moisture in the concrete causing it to crack.
- Bentonite is a natural clay containing the mineral montmorillionite. It is non-corrosive, stable, and has a resistivity of 2.5Ωm at 300% moisture content. Due to its hydroscopic nature, it acts as a drying agent drawing any available moisture from the surrounding environment. Bentonite needs water to obtain and maintain its beneficial characteristics. Its initial moisture content is obtained at installation when the slurry is prepared and once installed bentonite relies on the presence of ground moisture to maintain its characteristics. Most soils have sufficient ground moisture so that drying out is not a concern. The hygroscopic nature of bentonite will take advantage of the available water to maintain it's as installed condition. If exposed to direct sunlight, it tends to seal itself off, preventing the drying process from penetrating deeper than its surface. It may not function well in a very dry environment, because it may shrink away from the electrode, increasing the electrode resistance.
- Other commercial earth enhancement materials are available, some with resistivities of less than 0.12Ωm. These are typically placed around the vertical earth-rod in the hole or around the earth grid conductors in a trench. Depending on the type it can either be in a dry form or premixed into a slurry. Some of these enhancement materials are permanent and will not leach any chemicals into the ground. Other available earth enhancement materials are mixed with local soil in varying amounts and will slowly leach into the surrounding soil, lowering the earth resistivity over time.

Bentonite or other commercial non-abrasive materials can therefore be used. The total solution must however be simulated with finite element analysis software to ensure the desired effect is obtained.

3.6.3 Grid conductor types and sizes

Eskom has standardised on three conductors for use in substation earthing, i.e.:

- 10mm diameter annealed soft drawn round copper rod in accordance with [29] and [40] used for the main earth grid and the earth tails,

- 8.5mm diameter DSA 40% CCS rod in accordance with [30] and [42] used for the main earth grid and the earth tails,
- 50x3.15mm annealed copper strip in accordance with [29] and [41] used for earth tails and bonding on equipment, i.e. on earth switches and transformers in some cases.

It is important to note that if CCS is used the only accepted connection type is exothermic welding complying with [31] (240-170000535). Any other connection type shall degrade the conductor current transfer capacity to a level that the "system" under consideration cannot accommodate the required current load.

The conductor has to be sized appropriately to ensure it will be able to transfer the maximum expected fault current for the time required without fusing. Not only is it necessary to size the main earth grid conductor correctly, but the earth tails also have to be adequately sized. Equation (37) from IEEE 80-2013 is used to calculate the minimum acceptable conductor cross sectional area.

Although not necessary to calculate the minimum required conductor size if the Eskom standard 10mm diameter annealed soft drawn round copper rod or 8.5mm diameter DSA 40% DSA CCS rod is used for the main earth grid conductor, it is always good practice to do so as verification. It will be essential to verify the chosen conductor material and diameter as being adequate should any other material and/or conductor cross sectional area be used. As stated, the system transfer capacity is also dependent on the connection type used.

In determining the maximum current that is expected to be flowing in the earth grid conductor (I_c) the current split factor as explained in [15] (240-55922824, Substation Layout Design Guide) section 19-1 shall be applied as reproduced in Table 3 below. This has been confirmed as applicable as reported in [56] (240-170000402).

Table 3: Fault current split in structure earth tails

Number of earth tails per structure	Percentage current per earth tail	Maximum expected RMS current in the grid conductor (I_c)
2	80% : 20%	(80% / 2)I_F = (40%)I_F
3	66% : 17% : 17%	(66% / 2)I_F = (33%)I_F
4	55% : 15% : 15% : 15% :	(55% / 2)I_F = (27.5%)I_F

The highest percentage value for the selected number of earth tails shall be used to determine I_c. As an example, if the design earth fault current I_F is 25kA, two earth tails shall be used in accordance with Table 2 and as stipulated in Table 3 the maximum percentage of current in any earth tail can be up to 80%. I_c shall then be (25kA·80%)/2 = 10kA because it is assumed that the current in the earth tail split into two directions where it connects to the main earth grid conductor.

$$A_c = I_c \cdot \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_f \cdot \alpha_r \cdot \rho_r}\right) ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} \qquad \text{Eq. (1)}$$

$$d_c = 2 \cdot \sqrt{\frac{A_c}{\pi}} \qquad \text{Eq. (2)}$$

with					
	I_F	-	Design earth fault current	-	kA
	A_c	-	minimum conductor cross sectional area	-	mm^2
	I_c	-	maximum expected RMS current in the grid conductor	-	kA
	TCAP	-	thermal capacity per unit volume	-	J/(cm3·°C)
	t_f	-	fault clearing time	-	s
	α_r	-	thermal coefficient of resistivity at reference temperature Tr	-	1/°C

ρ_r	-	resistivity of the earth conductor at reference temperature Tr	-	µΩ-cm
K_0	-	1/αo with αo the thermal coefficient of resistivity at 0 °C	-	°C
T_m	-	maximum allowable temperature	-	°C
T_a	-	conductor ambient temperature	-	°C
d_c	-	minimum conductor diameter	-	mm

The grid conductor diameter to be used, referred to as *d* later in this document, shall be a diameter larger than the minimum calculated diameter d_c and shall typically be the accepted standard conductor, i.e. 10mm round copper or 8.5mm round CCS.

The material constants to be used are reproduced from IEEE 80-2013 Table 1 in Table 4 below. The maximum allowable temperature is a function of the conductor connection method applied and the location of the conductor. The maximum allowable temperature limits for the different connection types are given in Table 5 and the permissible final conductor temperatures in Table 6 reproduced from [15] Table 19-1.4. It is important to note that the lowest temperature between the values given in Tables 5 and 6 must be used to determine the transfer capacity of the “system” under investigation.

In the case of exothermic welds, the joint fuses the two components together at the connection. For design purposes the maximum temperature chosen shall be lower than the lowest of the two material fusing temperatures to prevent damage to the materials when in operation.

Table 4: Conductor material constants

Description	Material conductivity (% IACS)	α_r factor at 20°C (1/°C)	K_0 at 0°C (°C)	Fusing temperature (°C)	Resistivity at 20°C ρ_r (µΩ-cm)	Thermal capacity TCAP J/(cm³·°C)
Copper, annealed soft-drawn	100	0.00393	234	1083	1.72	3.4
Copper, commercial hard-drawn	97	0.00381	242	1084	1.78	3.4
Copper-clad steel wire	40	0.00378	245	1084	4.40	3.8
Copper-clad steel wire	30	0.00378	245	1084	5.86	3.8
Copper-clad steel rod	17	0.00378	245	1084	10.10	3.8
Aluminium-clad steel wire	20.3	0.00360	258	657	8.48	3.561
Steel, 1020	10.8	0.00377	245	1510	15.90	3.8
Stainless-clad steel rod	9.8	0.00377	245	1400	17.50	4.4
Zinc-coated steel rod	8.6	0.00320	293	419	20.10	3.9
Stainless steel, 304	2.4	0.00130	749	1400	72.00	4.0

Table 5: Maximum allowable temperature per connection type

Connection type	Allowable temperature rise	Recommended application
Bolted	250ºC	Gates, fences and structure to earth tail connections. Regular maintenance is required to maintain intended connection integrity.
Crimped	450ºC	Main earth grid cross connections, but is skill and tool dependent to ensure intended connection integrity.

Connection type	Allowable temperature rise	Recommended application
Brazed	650ºC (Only if 3mm Silver Copper Phosphorus Brazing Filler Metal welding rods are used, otherwise 600ºC)	Earth-tails to main grid, but is skill and material dependent.
Exothermic Weld	Cu or CCS: 1050ºC All other materials: Material specific	Connections between dissimilar materials, especially earth-tail connections to equipment steelwork. Connection quality is skill and mould condition dependent.

Note: In the case of exothermic welds, the joint fuses the two components at the connection. Consequently the permissible temperature rise shall be lower than the conductor with the lowest fusing temperature as indicated in Table 4 above. The value chosen should also be in line with the limits given in Table 6 below.

Table 6: Maximum allowable temperature per conductor type and application

Material	Permissible final temperature (ºC)
Aluminium (Al) Bare	600(1)
	150(2)
	90(3)
Copper (Cu) Bare and Copper-Clad Steel (CCS) Bare	1050(1)
	150(2)
	90(3)
Steel, Bare or Galvanised	1300(1)
	150(2)
	90(3)

Notes:

1) For exothermic connections only.
2) Where hazards are greater:
   - For non-visible conductors in locations with increased fire risk.
   - For earthing conductors laid together with PVC cables.
3) For earth conductors encased in concrete, i.e. inside foundations as applied by Dx.

3.6.4 Allowable step and touch potential limits

The practice as per IEEE 80-2013 is applied, including Equations (8), (27), (29) and (32) in calculating the safe step and touch potential exposure limits. Body resistance is taken as a 1000Ω and the body current associated with a person weighing 50kg or more. The following equations are used to calculate the allowable (safe) step and touch potential limits:

$$I_b = \frac{0.116}{\sqrt{t_f}} \qquad \text{Eq. (3)}$$

$$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho}{\rho_s}\right)}{2 \cdot h_s + 0.09} \qquad \text{Eq. (4)}$$

$$E_{step} = I_b \cdot (R_b + 6 \cdot \rho_s \cdot C_s) \qquad \text{Eq. (5)}$$

$$E_{touch} = I_b \cdot (R_b + 1.5 \cdot \rho_s \cdot C_s) \qquad \text{Eq. (6)}$$

with	E_{step}	-	maximum allowable step voltage	-	V
	E_{touch}	-	maximum allowable touch voltage	-	V
	I_b	-	maximum expected RMS current in the grid conductor	-	A
	R_b	-	body resistance	=	1000Ω
	ρ_s	-	resistivity of the surface material	-	Ωm
	C_s	-	surface layer de-rating factor		
	t_f	-	fault clearing time	-	s
	ρ	-	soil resistivity in which the earth grid is buried	-	Ωm
	h_s	-	thickness of the surface layer	-	m

3.6.4.1 Surface layer material

Crushed stone or surface material coverings are very useful in retarding the evaporation of moisture and thus in limiting the drying of topsoil layers during prolonged dry weather periods. Also, covering the surface with a material of high resistivity is very valuable in reducing the body current.

In basing calculations on the use of a layer of clean surface material or crushed stone, consideration should be given to the possibility that insulation may become impaired in part through filling of voids, by compression of the lowest ballast layers into the soil beneath, by material from subsequent excavations, if not carefully removed, and in some areas by settlement of airborne dust over time.

The range of resistivity values for the surface material layer depends on many factors, some of which are kinds of stone, size, condition of the stone (clean or contaminated with fines), amount and type of moisture content, atmospheric contamination, etc. The resistivity of the water with which the rock is wetted has considerable influence on the measured resistivity of the surface material layer. Thus surface material subjected to sea spray may have a substantially lower resistivity compared to surface materials utilized in arid environments. It is therefore important that the resistivity of rock samples typical of the type being used in a given area be measured.

As a standard crushed stone as specified in [27] (240-108982466, Standard for HV Yard Stones in Eskom Substations) shall be used. Aggregate size shall be between 26,5mm and 37,5mm nominal size and shall have a wet resistivity value of at least 3000Ωm. The wet resistivity of the crushed stone should be verified by testing, refer to [13]. When testing the following should be considered:

- As a norm wetting water shall be normalised to the resistivity of rainwater as stipulated in [13].
- As stated above, the crushed stone might be subjected to sea spray when the substation is close to the coast. For these applications the wetting water resistivity associated to the sea spray water shall be used.
- The tested resistivity value should not be used for design purposes because of a reduction in this resistivity over time as a result of environmental contamination, compaction of the stone layer, etc. It is proposed that the value used in the design does not exceed 75% of the measured value to allow for environmental contamination and compaction over time.

Laying of stone: The stone shall be spread over the compacted surface of the yard, levelled and lightly rolled to a finished thickness of at least 100 mm or as otherwise specified in the design document and/or drawings.

Other materials can be considered for specific applications but the resistivity of the intended material to be used will have to be measured before the design is done to ensure that the correct parameters are applied. Typical resistivity values are given in Table 7 of IEEE 80-2013, forming the basis of Table 7 below.

Table 7: Typical surface material resistivities

Description of material	Dry resistivity (Ωm)	Wet resistivity (Ωm)
Crusher run granite with fines, size unknown	$140 \cdot 10^6$	1300 (ground water, 45Ωm)
Crusher run granite with fines, 40mm	4000	1200 (rain water, 100Ωm)
Crusher run granite with fines, 20 – 25 mm	–	6513 (10 minutes after 45Ωm water drained)
Washed granite, 25 – 50 mm	$1.5 \cdot 10^6$ to $4.5 \cdot 10^6$	5000 (rain water, 100Ωm)
Washed granite, 50 – 100 mm	$2.6 \cdot 10^6$ to $3 \cdot 10^6$	10000 (rain water, 100Ωm)
Washed limestone, size unknown	$7 \cdot 10^6$	2000 – 3000 (rain water, 45Ωm)
Washed granite, similar to 20mm gravel	$2 \cdot 10^6$	10000
Washed granite, similar to pea gravel	$40 \cdot 10^6$	5000
Washed granite, 20mm	$190 \cdot 10^6$	8000 (rain water, 45Ωm)
Paving brick, industrial strength, 75mm thick	$700 \cdot 10^3$	2500
Asphalt	$2 \cdot 10^6$ to $30 \cdot 10^6$	10000 to 6×10^6
Concrete	$1 \cdot 10^6$ to $1 \cdot 10^9$	21 – 200

3.6.4.2 Surface layer thickness

The thickness required will depend on the material's wet resistivity and the requirements identified in the design. Of importance is the long term surface layer quality consideration, i.e. how the resistivity will "degrade" over time. Added to this is the practical consideration of walking and driving over it, with thicker layers resulting in more damage caused when driven on resulting in an uneven stone layer level that will have an impact on allowable step and touch limits.

The stone shall be spread over the compacted surface of the yard, levelled and lightly rolled to a finished thickness as specified in the design document and drawings. For practical reasons the layer thickness after installation should be kept to between 80mm and 150mm in depth for practical reasons and shall not be higher than the top of foundation level.

3.6.4.3 Addition of insulating materials, i.e. safety shoes

The allowable step and touch potential limits can be increased by including the contact resistance of the mandatory safety shoes to be worn in substations. It must however be noted that [5] (IEEE Std 80-2013) assumes this safety shoe resistance to be zero. Other publications report that the resistance of new dry shoes varies a lot from that of older wet shoes complicating the issue.

According to [2] it is important to keep in mind that damaged shoes typically with cracks or holes in it will cause a low impedance path for current. Shoes in this condition will not provide the required added safety margin. Because the type of shoe, the material used and the condition thereof cannot be guaranteed it is advised to not add an additional shoe impedance. Refer to Table 8 for typical values taken from [2], the shoe type chosen must be confirmed as corresponding to the footwear used by maintenance staff.

Table 8: Example of footwear impedance and voltage withstand characteristics

Description of shoe	Impedance (Ω)	Typical voltage withstand (V)
Wet used black rubber	500	750
Wet used leather	5000	500
Wet used elastomer	50000	4000

Should it be necessary to include the resistance of shoes when calculating the allowable step and touch potential limits Equations 5 and 6 can be rewritten as follows:

$$E_{step} = I_b \cdot (R_b + 6 \cdot \rho_s \cdot C_s + 2 \cdot R_s) \qquad \text{Eq. (5-1)}$$

$$E_{touch} = I_b \cdot \left(R_b + 1.5 \cdot \rho_s \cdot C_s + \frac{R_s}{2}\right) \qquad \text{Eq. (6-1)}$$

with R_s - resistance of a single safety shoe (≤ 500Ω) - Ω

3.6.5 Grid layout design considerations

The earth grid layout shall be based on the substation layout plan which shows all major equipment and structures. The following shall be considered as a starting point for the initial design:

- A continuous conductor loop should surround the perimeter of the substation to enclose as much area as practical. This measure helps to avoid high current concentration and hence high potential gradients both in the grid area and near the grid edges. Enclosing more area also reduces the grid resistance.
- Within the loop, conductors should be laid in parallel lines to form a grid and where practical, along the structures or rows of equipment, to provide for short earth tail connections.
- The ratio of the mesh sides should be between 1:1 and 1:3. Frequent cross-connections have a relatively small effect on lowering the grid resistance. Their primary role is to assure adequate control of the surface potentials.

When several electrodes, such as earth-rods are connected to each other and to all equipment neutrals and structures that are to be earthed, the result is essentially a grid arrangement of earth electrodes, regardless of the original objective.

The soil model has an impact on deciding whether to include vertical earth-rods as part of the layout or not. When the top soil layer in which the earth grid is buried has a resistivity much lower than the bottom layer (i.e. low-over-high soil model) vertical earth-rods will not add much value as very little fault current will be shunted into the higher resistivity bottom soil layer. The converse is applicable for a high-over-low soil model, where vertical earth-rods will help shunt current out of the grid into the lower resistivity bottom soil layer. If the rods are installed predominantly along the grid perimeter in high-over-low or uniform soil conditions, the rods will considerably moderate the steep increase of the surface gradient near the peripheral meshes.

All required parameters shall be calculated making use of this initial layout and will be used as the baseline for further design optimisation.

3.6.6 Grid resistance (R_g)

The grid resistance is not the material resistance of the earth grid, but rather the "interface" resistance between the earth grid and remote earth, or put differently the resistance of the earth grid and surrounding earth as measured between the earth grid and remote earth.

The grid resistance to remote earth is required to calculate the grid current as well as the GPR. The grid resistance depends primarily on the area covered by the earth grid and adding additional conductor will have a limited impact in reducing the resistance. Equation (57) from IEEE 80-2013 is used to calculate the grid resistance:

$$R_g = \rho \cdot \left[\frac{1}{L_T} + \frac{1}{\sqrt{20 \cdot A}} \cdot \left(1 + \frac{1}{1 + h \cdot \sqrt{20/A}}\right)\right] \qquad \text{Eq. (7)}$$

with R_g - grid resistance - Ω

ρ - soil resistivity in which the earth grid is buried - Ωm

L_T - total buried length of conductors including vertical earth-rods - m

A	-	area occupied by the earth grid	-	m^2
h	-	depth of the earth grid	-	m

3.6.7 Grid current (I_G)

This is the current expected to be in the grid at the time the fault is cleared (at time t_f) and is based on equations (68) and (69) from IEEE 80-2013.

$$I_G = D_f \cdot S_f \cdot I_F \qquad \text{Eq. (8)}$$

$$S_f = \frac{R_{rest}}{R_{rest} + R_g} \qquad \text{Eq. (9)}$$

with	I_G	-	grid current = current flowing in the grid at the time the fault it cleared	-	A
	D_f	-	decrement factor for the entire duration of the fault		
	S_f	-	current division factor		
	I_F	-	symmetrical design earth fault current	-	A
	R_g	-	grid resistance	-	Ω
	R_{rest}	-	equivalent resistance associated with all connected external earth electrodes	-	Ω

3.6.7.1 Decrement factor (D_f)

In designing the earth grid the asymmetrical fault current must be taken into consideration. In general, the asymmetrical fault current includes the sub-transient, transient, and steady-state AC components, as well as the DC offset current component. Both the sub-transient and transient AC components and the DC offset decay exponentially, each having a different attenuation rate. IEEE 80 applies the principle of the AC component not decaying with time, but remaining at its initial value. In adopting the IEEE 80 principles in this standard means that the same principle is applied here. Refer to Figure 5 for a comparison of the asymmetrical to the symmetrical fault currents over time.

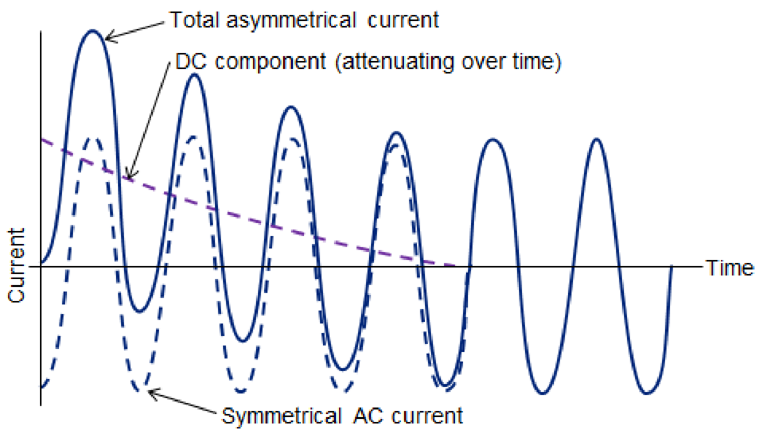


Figure 5: Asymmetrical versus symmetrical fault current

The network X and R components of the system sub-transient fault impedance should be used to determine the X/R ratio at the fault location which is further used to determine the decrement factor D_f which is used to calculate the asymmetrical fault current at a given time interval after inception of a fault.

Refer to Table 9 for the decrement factors for 50Hz derived by making use of equation (84) in IEEE 80-2013.

Table 9: Typical values for D_f applicable to 50Hz

Fault duration, t_f	**Decrement factor, D_f**							
(s)	**X/R = 5**	**X/R = 10**	**X/R = 15**	**X/R = 20**	**X/R = 25**	**X/R = 30**	**X/R = 35**	**X/R = 40**
0.04	1.181	1.316	1.404	1.462	1.504	1.534	1.558	1.576
0.05	1.148	1.269	1.355	1.417	1.462	1.497	1.523	1.544
0.10	1.077	1.148	1.213	1.269	1.316	1.355	1.389	1.417
0.20	1.039	1.077	1.113	1.148	1.181	1.213	1.242	1.269
0.30	1.026	1.052	1.077	1.101	1.125	1.148	1.170	1.192
0.40	1.020	1.039	1.058	1.077	1.095	1.113	1.131	1.148
0.50	1.016	1.031	1.047	1.062	1.077	1.091	1.106	1.120
0.60	1.013	1.026	1.039	1.052	1.064	1.077	1.089	1.101
0.70	1.011	1.023	1.033	1.044	1.055	1.066	1.077	1.0871
0.80	1.010	1.020	1.029	1.039	1.049	1.058	1.067	1.077
0.90	1.009	1.018	1.026	1.035	1.043	1.052	1.060	1.068
1.00	1.008	1.016	1.024	1.031	1.039	1.047	1.054	1.062

3.6.7.2 Current division factor

Where lines with overhead shield wires or power cables are bonded to the earth grid either overhead or underground, a portion of the earth fault current is diverted away from the earth grid through these connections. In such cases the impact of these alternative current paths should be taken into consideration when calculating the grid current.

Connecting the substation earth grid to overhead shield wires or neutral conductors, or both, and through them to line structures will usually have the overall effect of reducing the GPR at the substation while increasing it at the structure bases. This is because each the nearby towers will share in the voltage rise of the substation earth grid. Conversely, when a tower fault does occur, the effect of the connected substation earth system should decrease the magnitude of gradients near the tower bases.

The effect of connected overhead shield wires can be calculated by regarding them as parallel resistances to the grid resistance. To calculate the current division factor by hand can be very complex so as a first approximation the result presented in [7] shall be applied. Suggested values of these resistances are given in the Table 10.

Table 10: Approximated line resistances

	Line fitted with one shield wire	**Line fitted with two shield wires**
First line with shield wires connected	7.3Ω	3.5Ω
All subsequent lines with shield wires connected	10.6Ω	5.2Ω

If it is felt that the results yielded are not accurate enough it will be necessary to make use of finite element analysis software to simulate the actual connected network parameters.

3.6.8 Ground potential rise

Ground potential rise is the voltage rise of the substation earth grid relative to a remote earth point under fault conditions and is the product of the grid current (I_G) and the grid resistance (R_g).

3.6.9 Touch and mesh potentials (E_m)

The mesh potential is the highest touch potential in a mesh (or block) of the earth grid and is labelled the worst case touch potential. It is therefore important to note that if the calculated mesh potential is higher than the safe touch potential limit a possible unsafe condition exists and the grid design must be changed and all calculations repeated for the new layout.

Considering the complexity of these calculations the worst case mesh potential is the only calculation that is feasible to perform, and if all the other meshes forming part of the earth grid have similar dimensions all points on the grid should have similar mesh potentials.

The following equations from IEEE 80-2013 are applicable to the centre of the outermost mesh of the grid which is considered the worst case mesh potential.

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \qquad \text{Eq. (10)}$$

with E_m - mesh potential - V

ρ - soil resistivity in which the earth grid is buried - Ωm

K_m - geometric factor

K_i - correction factor for grid geometry, also referred to as the irregularity factor

I_G - grid current - A

L_M - effective grid conductor length - m

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot ln\left[\frac{8}{\pi \cdot (2 \cdot n - 1)}\right]\right] \qquad \text{Eq. (11)}$$

with D - spacing between parallel conductors - m

h - depth of the earth grid conductors - m

d - diameter of grid conductor - m

K_{ii} - corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh, simplified method

K_h - corrective weighting factor that emphasizes the effects of grid depth, simplified method

n - *geometric factor composed of factors* n_a, n_b, n_c, *and* n_d

For grids with no vertical earth-rods or grids with only a few vertical earth-rods, none located in the corners or on the perimeter:

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} \qquad \text{Eq. (12)}$$

For grids with vertical earth-rods along the perimeter, or for grids with vertical earth-rods in the grid corners, as well as both along the perimeter and throughout the grid area $K_{ii} = 1$.

$$K_h = \sqrt{1 + h} \qquad \text{Eq. (13)}$$

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \qquad \text{Eq. (14)}$$

$$n_a = 2 \cdot \frac{L_C}{L_p} \qquad \text{Eq. (15)}$$

$$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} \qquad \text{Eq. (16)}$$

$$n_c = \left[\frac{L_x \cdot L_y}{A}\right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} \qquad \text{Eq. (17)}$$

$$n_d = \frac{D_m}{\sqrt{L_x{}^2 + L_y{}^2}} \qquad \text{Eq. (18)}$$

$$K_i = 0.644 + 0.148 \cdot n \qquad \text{Eq. (19)}$$

with	L_c	-	total length of grid conductor	-	m
	L_p	-	peripheral length of the grid	-	m
	A	-	area of the grid	-	m^2
	L_x	-	maximum length of the grid in the x direction	-	m
	L_y	-	maximum length of the grid in the y direction	-	m
	D_m	-	maximum distance between any two points on the grid	-	m

For grids with no vertical earth-rods, or grids with only a few vertical earth-rods scattered throughout the grid, but none located in the corners or along the perimeter of the grid, the effective buried length, L_M, is:

$$L_M = L_C + L_R \qquad \text{Eq. (20)}$$

For grids with vertical earth-rods in the corners, as well as along the perimeter and throughout the grid, the effective buried length, L_M, is

$$L_M = L_C + L_R \cdot \left[1.55 + 1.22 \cdot \left(\frac{L_r}{\sqrt{L_x{}^2 + L_y{}^2}}\right)\right] \qquad \text{Eq. (21)}$$

with	L_C	-	total length of grid conductor	-	m
	L_R	-	total length of all vertical earth-rods	-	m
	L_r	-	length of each vertical earth-rod	-	m

3.6.10 Step potential (E_S)

The maximum step potential is assumed to occur over a distance of 1m, beginning at and extending outside of the perimeter conductor at the angle bisecting the most extreme corners of the grid.

$$E_S = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S} \qquad \text{Eq. (22)}$$

with	E_S	-	maximum step potential	-	V
	K_s	-	spacing factor for step voltage		
	L_S	-	effective buried conductor length of each vertical earth-rod	-	m
	K_i	-	correction factor for grid geometry, also referred to as the irregularity factor		
	I_G	-	grid current	-	A

$$K_S = \frac{1}{\pi} \cdot \left[\frac{1}{(2 \cdot h)} + \frac{1}{(D + h)} + \frac{(1 - 0.5^{n-2})}{D}\right] \quad \text{Eq. (23)}$$

$$L_S = (0.75 \cdot L_C) + (0.85 \cdot L_R) \quad \text{Eq. (24)}$$

with	L_C	-	Total length of grid conductor	-	m
	L_R	-	Total length of vertical earth-rods	-	m

3.6.11 Refine the design

The calculated mesh and step potentials shall be compared to the applicable allowable limits as described in section 3.6.4, and if required the grid design must be modified before recalculating all parameters. The most optimum solution shall be considered to ensure a safe substation at an optimal cost.

Should dangerous potentials exist the grid conductor spacings should be reduced (meshes in the grid made smaller).

To reduce an excessively high GPR it is necessary to consider the factors impacting GPR, i.e. reduce either the grid current (I_G), grid resistance (R_g) or both. To reduce the grid current the most effective way is to install current limiting reactors (typically a Tx application) or to reduce the resistance associated with overhead lines and other external earth electrodes. This can typically be achieved by installing an additional low impedance earth conductor to a remote located low impedance secondary earth grid. The most effective way to reduce the grid resistance is to increase the area covered by the grid or by reducing the soil resistivity. Reducing the soil resistivity is only an option if extensive platform excavation and backfill work during construction will be done when the backfill material properties can be specified and controlled during construction.

3.6.12 Remedial actions to obtain a safe earth grid design

The main factors affecting earth grid design are the fault current, expected fault duration, soil resistivity and grid shape and size and depending on the specific value combination it might make the control of the surface gradients problematic. Remedial actions to consider include:

- Connecting the substation's earthing system to a remote earth electrode. Of concern with this option is the transfer potential risk.
- Use of deep-driven vertical earth-rods for high-over-low soil models.
- Treating the soil to lower the resistivity as required.
- Making use of equipotential grids in areas of concerns.
- Satellite earth grids can be used if there are areas of low resistivity nearby the substation. The result should be an overall lower grid resistance when connected to the main earth grid, resulting in a lower GPR. Take note however of the transferred potential to this satellite earth grid under fault conditions.

When finite element analysis software is used to solve challenging designs the first pass is normally done without the equipment earth tails included. Should the solution prove challenging the earth tails should be added to account for its contribution in reducing surface potentials in the substation. The model under investigation can also be further optimised by including the line parameters and thereby achieving a more accurate model considering current sharing between the earth grid and other connected circuits.

Should it not be possible to achieve safe touch potentials on the fence from the outside remedial actions should be implemented. These might include:

- Extend the earth grid further outside the fenced area to force the areas of high surface potentials further away from the substation fence.
- Install counterpoises at the corners of the earth grid extending out and downwards to reduce the surface potential gradients close to the fence corners.

- Change the stoned area on the outside of the fence to reinforced concrete slabs with the reinforcing bonded to the earth grid to create equipotential zones. Take note that each reinforcing sheet should only be connected to the earth grid with one connection to create a voltage connection.
- Replace the normal crushed stone outside the substation fence with sharp edged solid stones of diameter between 70mm and 150mm to act as deterrent to prevent people and animals in close proximity of the fence.
- Change the fence from metal to a brick or concrete wall.

3.7 Process to be followed for work to be done at existing substations

Whenever work is required at an existing substation as a result of network reconfiguration, strengthening or refurbishment it will be necessary to confirm the adequacy of the existing earth grid based on the new parameters. The safety analysis of the existing earth grid with the required modifications incorporated must therefore be done based on the new requirements.

In many cases limited or no information is available for the existing substation earth grid. When this is the case it will be necessary to make a guess or perform a number of excavations to determine the basic grid layout. Once the grid layout is known the analysis can be conducted. The same basic inputs as for a new earth grid design is required, except that the soil model used for the simulations has to be “calibrated” before the safety analysis can be done. Refer to Figure 6 for the process to be followed.

First the soil model has to be determined. To do this, soil resistivity measurements for the existing substation has to be conducted as outlined in [25] (240-96393507), and the earth electrode resistance has to be measured in accordance with [26] (240-101940513). The obtained soil model and grid layout parameters are used to determine the grid resistance as outlined in section 3.6.6 above. The calculated grid resistance is then compared to the measured grid resistance and if different the soil model has to be adjusted until the measured and calculated grid resistance values are the same.

The adjusted soil model is then used for further calculations and the same basic process followed as outlined in sections 3.6.6 through 3.6.12 above.

3.8 Hand calculations versus the use of specialised software

The importance of being able to do the calculations by hand is that a better understanding for the underlying principles are obtained and how different parameters impacts the final solution. It is therefore important to understand the underlying theory to be able to solve problems experienced during the design.

Hand calculations should be adequate for the normal run-of-the-mill designs and should give acceptable results for most applications if applied properly. Of importance is to keep in mind that the hand calculations assume the mesh sides ratio to be 1:1 or very close to it.

It is advised that finite element analysis software be used to evaluate problematic designs, and that proper design layout optimisation can only truly be done with the use of finite element analysis software because of the limitations associated with hand calculations. It is advised that once the basic design has been completed by hand calculations design optimisation is done with finite element analysis software if required.

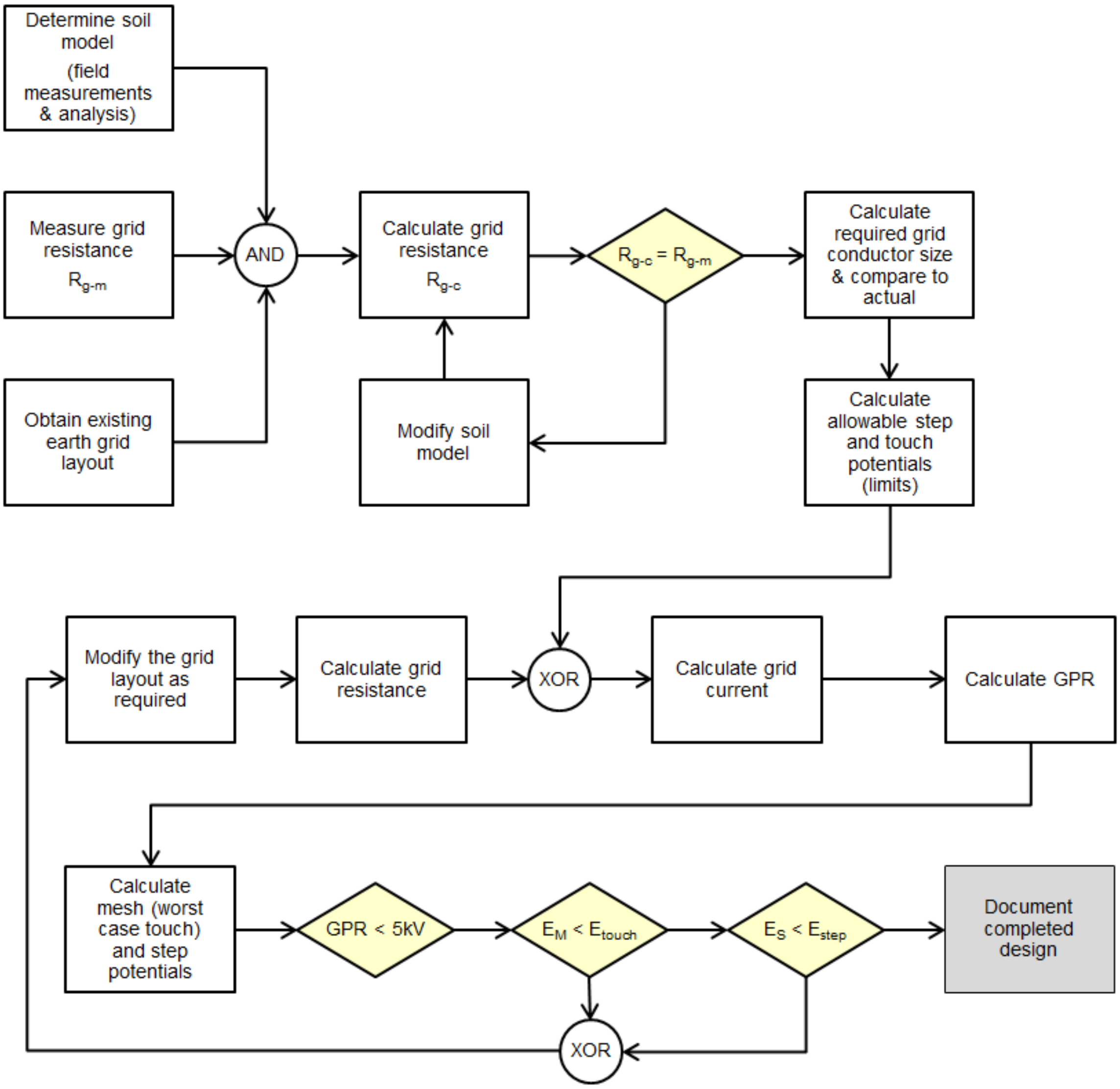


Figure 6: Earth electrode design process flow when existing grid design information is unavailable

3.9 Design report

Each substation earth grid design shall be documented in a design report containing all inputs, assumptions, design calculation results and decisions. The information captured should be adequate to redo all calculations and obtain the same results at any future time.

It is advisable that pertinent design inputs and results are also captured on the earth grid layout drawing for future reference.

3.9.1 Design inputs

The following minimum design inputs are required and should be stated:

- Substation layout on which the earth grid design is based.
- Fence type (metallic, non-metallic, wall, etc.).
- Earth grid boundaries in relation to outer fence, grid stops on the inside or outside of the fence.
- Earth grid and tail conductor material.

- Conductor jointing details.
- Surface layer material, aggregate size, electrical properties and layer thickness.
- Applicable network information, i.e. number of lines connected to the substation, number of shield wires per line, etc.
- Position of bonded line terminal towers in relation to the earth grid boundaries.
- Soil resistivity measurement results.
- Expected future earth fault current per voltage level as stipulated in the planning report or URS, including the time duration of applicability.
- Network X/R ratio per voltage level.
- Maximum fault clearing time.

3.9.2 Design assumptions

The following minimum design assumptions have to be captured:

- Chosen design earth fault current.
- Chosen soil model.
- Chosen decrement factor, D_f.
- Chosen conductor (material and dimensions).

3.9.3 Design outputs

The following minimum calculated results have to be captured:

- Number of earth tails per structure.
- Minimum required conductor dimensions as calculated.
- Dimensions of chosen conductor to be used.
- Safe step and touch potential design limits.
- Equivalent resistance associated with all connected external earth electrodes.
- Calculated grid resistance.
- Calculated grid current.
- Calculated GPR.
- Calculated worst-case step potential.
- Calculated worst-case touch potential.
- Earth grid layout drawing/s indicating all applicable dimensions and other required information to enable the contractor to correctly install the earth grid.

The applicable design document and drawings shall indicate all dimensions required to install the earth grid, including clearly specifying at what depth the earth grid must be installed and including the positions and dimensions of vertical earth-rods if required. Conductor material properties, joint types and any other details of the required installation shall be documented.

3.9.4 Design information to be added to substation earth grid layout drawings

It is advised that the information in Table 11 is added to the substation earth grid layout drawing for future reference. This table should be updated at any time that changes are made to the earth grid layout.

Table 11: Information to be added to the substation earth grid drawing

Parameter	***Values***	***Notes***
Soil model	ρ_1 = Ωm h_1 = m ρ_2 = Ωm h_2 = m ρ_3 = Ωm	*Initial values used for design, or as-build values based on soil measurements done on final terrace based on 240-96393507.*
Number of lines connected	*Lines with 1 shield wire:* *Lines with 2 shield wires:* *Calculated current division factor:*	*Actual network simulated or calculated based on 240-134369472.*
Fault clearing time	*seconds*	
Surface layer	*Material:* *Layer thickness: mm*	*Crashed stone as per standard 240-108982466, or industrial strength paving, etc.*
Current decrement factor	*Network X/R ratio:* *Decrement factor:*	
Single phase earth fault current	*Design current: kA* *Calculated grid current: kA*	*Future design current based on planning report, or table 1 in 240-134369472. (Specify which)*
Grid resistance	*Calculated/simulated: Ω* *Measured: Ω* *Date measured on:*	*Measure in accordance with 240-101940513.* *Indicate the date of the measurement as the time of year will impact on the value.*
GPR	*kV*	*Comment on value*
Step potential	*Calculated limit: kV* *Calculated maximum: kV*	
Touch potential	*Calculated limit: kV* *Calculated maximum: kV*	

3.10 Bonding of separate earth grids to each other

3.10.1 Terraced or multi yard substation with separate earth grids

All the individual earth grids in a single substation with multiple separate yards or separate terraces shall be interconnected as indicated in Figure 7. The number of connections shall depend on the size of the substation and design fault currents. Refer to 0.54/393 Sheet C32 for detail.

3.10.2 Bonding substation earth grids to power station earth electrodes

The HV yard earth grid shall be bonded to the Power Station earth grid as stipulated in [19] (240-56356396, Earthing and Lightning Protection Standard), with 2x10mm diameter copper rods at each unit.

3.10.3 Bonding third party earth electrodes to Eskom substation earth grids

Various practices are advocated in this regard, although the prevailing reasoning is that if two independent earth grids are installed in close proximity of each other they should be connected solidly. Should it be required by one of the parties that it be connected through “opening bonds” for testing purposes then this can be facilitated. It is however important that the number of connections and connection methods used are determined appropriately.

The advantage of interconnection separate earth girds is that the combined earth electrode resistance will be lowered which in turn will result in a reduced GPR.

It must be noted that this practice will introduce current flow between the interconnected grids under fault conditions resulting in possible transferred potentials.

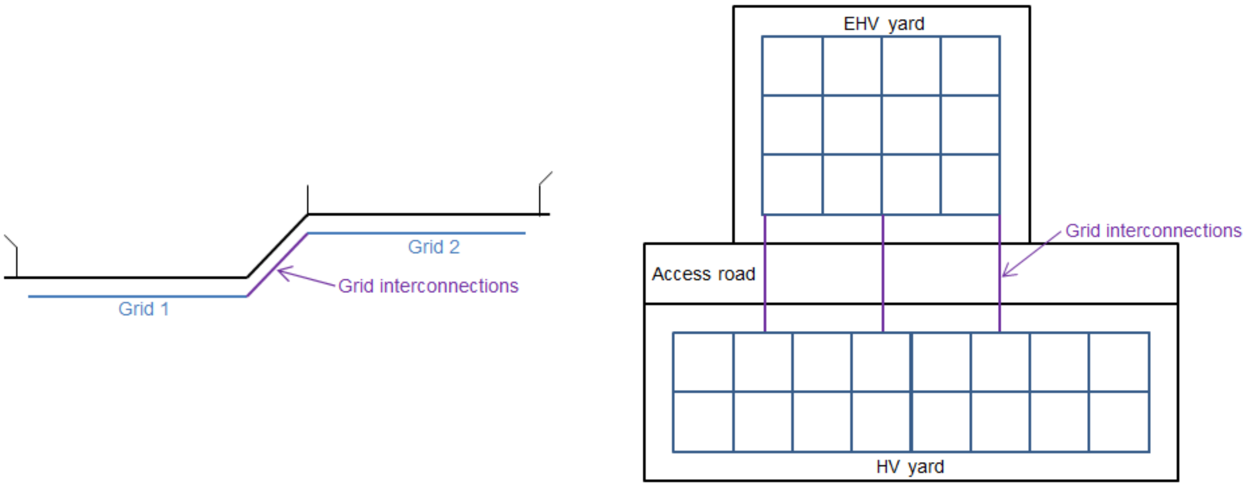


Figure 7: Examples of interconnected earth grids

3.11 Bonding of equipment

Different equipment earthing/bonding practices are applied in Dx substations compared to Tx substations as a result of the higher theft risk and generally lower earth fault levels in Dx substations.

Refer to section 3.6.1 above for the main earth grid conductor to conductor connections.

3.11.1 Dx substation structure earthing practice

For Dx applications all equipment shall be earthed in such a manner that no copper is visible to reduce the theft risk. All equipment shall be earthed according to the applicable Earthing Drawings given in D-DT-5240.

The number of earth tails per structure shall be based on the voltage specific earth fault design current and as per Table 2.

When copper is used for earth tails all connections shall be done through the foundations. Up to and including 25kA two earth tails per structure shall be applied through the foundation holding down bolts as indicated in D-DT-5240 Sheet 6. Above 25kA four earth tails shall be applied per structure with the additional two earth tails as indicated in D-DT-5240 Sheet 3.

When CCS is used as earth tails two earth tails shall be exothermically welded to the structure and main earth grid for fault currents up to and including 25kA, and three earth tails above 25kA as stipulated in Table 2.

3.11.2 Tx substation structure earthing practice

For Tx applications all equipment shall be earthed according to the applicable Earthing Drawings given in 0.54/393.

The number of earth tails per structure shall be based on the voltage specific design earth fault current and as per Table 2.

General structure earthing is indicated in 0.54/393 Sheets C7 and C31.

The bolted connection between 2x10mm diameter copper rods and 50x3 flat copper bar typically used for transformer/reactor/capacitor earthing purposes is indicated in 0.54/393 Sheet C26.

When CCS is used as earth tails two earth tails shall be exothermically welded to the structure and main earth grid for fault currents up to and including 25kA, and three earth tails between 25kA and 40kA and four earth tails above 40kA as stipulated in Table 2.

3.11.3 Isolator, pantograph and earth switch earthing

Dx applications:

- Isolators shall be earthed through the structure with the drive shaft earthed through a flexible copper strap as indicated in D-DT-5240 Sheet 8.
- Isolator/earth switch combinations and standalone earth switches in Dx substations shall be earthed as described in section 3.11.1 above.

Tx applications:

- Isolators, isolator/earth switch combinations, standalone earth switches and pantograph isolators shall be earthed in accordance to 0.54/393 Sheets T1, T2, T3, T4 and T17. All drive shafts shall be earthed through a flexible copper strap as stipulated.

3.11.4 CT, VT, CVT and surge arrestor earthing

Dx applications:

- CT's and VT's shall be earthed in accordance with D-DT-5240 Sheet 7 with a single bonding strap between the equipment earthing stud and the structure if the equipment base is painted. No bonding strap is required for equipment with galvanised bases.
- Surge arrestors shall be earthed in accordance with D-DT-5240 Sheet 8 through the structure.

Tx applications:

- CT's shall be earthed in accordance with 0.54/393 Sheet C17 with a single bonding strap between the equipment earthing stud and the structure if the equipment base is painted. No bonding strap is required for equipment with galvanised bases as per 0.54/393 Sheet C18.
- VT's shall be earthed in accordance with 0.54/393 Sheet T5 with an earth strap all the way to the equipment earthing stud.
- Surge arrestors without discharge counters shall be earthed in accordance with 0.54/393 Sheet T5 with an earth strap all the way to the equipment earthing stud. Surge arrestors with discharge counters shall be earthed in accordance with 0.54/393 Sheets T8 and T9. Surge arrestors mounted on insulated bases shall be earthed in accordance with 0.54/393 Sheets T14, T14A and T14B. Note that if the earth strap is insulated as indicated on 0.54/393 Sheets T9 but the counter not installed it is necessary to add the earth bridge to the cap as indicated.
- CVT's shall be earthed in accordance with 0.54/393 Sheet T6 if installed without carrier coupling equipment and according to Sheet T7 if installed with carrier coupling equipment.

3.11.5 Transformer and transformer surge arrestor earthing

All transformer neutrals shall be earthed in accordance with [22] (240-76624507, Standard for Neutral Earthing of Transmission and Distribution Networks).

Star connected transformer windings rated for voltages equal to and above 132kV use fully graded insulation with the result that the neutral points of such windings must be solidly earthed.

For Dx applications power transformers shall be earthed in accordance with D-DT-5240 Sheets 4 and 5, as well as the details given on the applicable transformer plinth drawings, refer to D-DT-5235. No earth strap shall be used for surge arresters fitted on brackets on the transformer tank, the transformer tank shall be used as the earth path.

For Tx applications power transformers shall be earthed in accordance with 0.54/393 Sheet C25, and auxiliary transformers in accordance with 0.54/393 Sheets T5 and T10. Surge arresters fitted on brackets on the transformer tank shall also be earthed through a 50x3.15mm earth strap to the earth grid.

3.11.6 Oil filled and air core reactor earthing

Reactors shall be earthed in accordance with the manufacturers' specification. The number of structure earth tails shall be in accordance with Table 2.

As a rule oil filled reactors have a single earth terminal for connection to the earth grid. The connection and conductors used shall be rated according to the expected earth fault current.

On air core reactors multi point ring earthing must be avoided as it will create the formation of flux linking loops in these conductors causing losses and the undue heating of these conductors. Special care should be taken in the design and installation of the earth grid in the vicinity of air core reactors and must be designed not to have closed loops. Current will be induced in such loops resulting in heating of the loop conductors with the possible degradation of the earthing system. It is also advisable that foundations without reinforcing are used

The manufacturer drawings shall indicate the magnetic clearance contour lines, what type of connections are allowed and where. As a rule all support legs shall be bonded together (not forming a loop) and then to the earth grid with a single bonding conductor.

3.11.7 Capacitor bank earthing

Capacitor banks shall be earthed in accordance with the manufacturers' specification. Also refer to 0.54/393 Sheets T13 and T13A.

3.11.8 Earthing of Ancillary Equipment

The following shall be applied for structures or supports that do not support system connected equipment:

- Lighting/lightning masts: minimum two connections to the earth grid.
- Metal fire walls: minimum one connection to the earth grid per support structure. In addition the metal sheets can be earthed as indicated in 0.54/393 Sheet C12.
- Free standing junction boxes and plug boxes: minimum one connection to the earth grid
  - Dx as indicated in D-DT-5240 Sheet 7
  - Tx as indicated in 0.54/393 Sheet C16.
- Label supports, hand rails and any other free standing objects: no connection to the earth grid required. These shall be left floating.
- Operating grids and equipment access pedestals/platforms: one connection to the earth grid only.

3.11.9 Line terminal structure earthing

Terminal structures of all overhead lines with shield wires shall be bonded to the substation earth mat in accordance with [21] (240-75880946, Earthing Standard (covering the earthing of sub-transmission line structures)) and [28] (240-130615862, Earthing of Transmission Line Towers).

This will result in a portion of the earth fault current being diverted out of the station earth grid through these connections. For this reason these connected lines with shield wires should be taken into consideration during the design process, and the connections verified through continuity tests as it forms an important integral part of the overall earth electrode.

3.11.10 Power cable earthing

All power cables shall be earthed as stipulated in [16] (240-56030640, General Information and Requirements for High Voltage Cable Systems Standard).

All MV power cables shall be earthed as stipulated in [17] (240-56063710, MV Cabling in Substations Standard).

Also refer to D-DT-5240 Sheets 19, 20 and 21, as well as 0.54/393 Sheets C19, C20 and C21 as applicable.

3.11.11 Fence, gate and perimeter security lighting earthing

Dx applications:

- Generally Dx substations have a single perimeter fence also doing duty as the safety fence around the HV/MV yard.
- The earthing of this fence is therefore of major importance because the fence is usually accessible to the general public. All corner and gate posts shall be earthed, and fence posts at intervals not exceeding 20 meters. The substation earthing design shall ensure that the touch voltage on the fence is within the calculated tolerable limit. Step voltage should also be checked in addition to touch voltages to verify compliance to the required design limits. Refer to D-DT-5240 Sheet 9 as well as the applicable fence detail drawings for details on the fence earthing.
- At all gates a concrete gate apron as indicated in D-DT-5240 Sheet 10 shall be provided to create an equipotential zone around the gate. The size of this apron shall depend on the type of gate, i.e. swing/leave or sliding gates. Anybody being able to touch the gate or any portion thereof shall be standing on this apron.

Tx applications:

- As a minimum Tx substations have three perimeter fences around the substation, namely the outer perimeter fence, non-lethal electric fence and the inner perimeter fence.
- In addition there are also individual safety fences around each of the HV yards and for some substations there might also be a property boundary fence some distance from the outer perimeter fence. Refer to 0.54/393 Sheet C3B, C13, C14, C15 for general fence earthing requirements.
- For on-terrace fences the following shall be applicable:
    - HV yard safety fences: All corner and gate posts shall be earthed to the earth grid, as well as fence posts at intervals not exceeding 20 meters. Gates shall be earthed as per 0.54/4963 Sheet 5.
    - Inner perimeter fence: If on terrace, all corner and gate posts shall be earthed to the main earth grid, including fence posts at intervals not exceeding 20 meters. Gates shall be earthed as per 0.54/4963 Sheet 5.
    - Perimeter security lighting: An earth electrode that is connected to the earth grid is normally installed as part of the supply to these lights. The substation design engineer must verify if this will be the case and apply it accordingly in the design safety analysis.
    - Non-lethal electric fence: An earth electrode that is connected to the earth grid is normally installed in close proximity to this fence. The substation design engineer must verify if this will be the case and apply it accordingly in the design safety analysis.
    - It is necessary for the design engineer to liaise with the non-lethal electric fence and perimeter security lighting designers to prevent duplication of earth electrodes.
    - Outer perimeter fence: All corner and gate posts shall be earthed to the non-lethal electric fence earth electrode, as well as fence posts at intervals not exceeding 20 meters. Gates shall be earthed as per 0.54/4963 Sheet 5.
- For existing off-terrace fences it will be necessary to determine if there are earth electrode connections from the earth grid to these fences, i.e. to a non-lethal electric fence or perimeter security lighting in the vicinity. In addition the possibility of a transfer potential risk shall be determined by making use of finite element analysis software and if present mitigating actions shall be taken. Refer to the section on remedial actions to obtain a safe earth grid design.
- For new substations with off-terrace fences a similar analysis must be done. The transfer risk will depend on the distance of these fences from the terrace and if earth electrodes that are bonded to the earth grid are present, typically in the case of non-lethal electric fences or perimeter security lighting, that can cause transfer potentials to these fences.

3.11.12 Control building, switch building and other building earthing

All wiring including the earthing inside buildings shall comply with [8] (SANS 10142-1, The wiring of premises part 1: low-voltage installations), and [9] (SANS 10142-2 Part 2: The wiring of premises Part 2: Medium-voltage installations above 1 kV AC not exceeding 22 kV AC and up to and including 3 MVA installed capacity).

An earth ring shall be installed around the building 1m deep and not more than 1m away from the building. This earth ring shall be integrated with the main earth grid at the same intervals as the main earth grid conductors.

All gutters and metal roof sheeting down wires shall be earthed to the building earth ring.

Metal roofs or steel trusses not in direct contact with earthed building steelwork shall be connected to the building earth ring at diagonally opposite points of the building.

In control buildings a 50x3.15mm copper earth bar shall be installed in the cable trench or on the cable tray all the way around the inside perimeter of the cable trench or on the cable tray. This earth bar shall be bonded to the substation earth main grid at each cable entrance into the building, with a minimum of at least two connections to the main earth grid.

The same is applicable to switch rooms/buildings with metal clad switchgear on the inside. A 50x3.15mm copper earth bar shall be installed in the cable trench all the way round the inside perimeter of trench and shall be bonded to the main substation earth grid at each cable entrance into the building, with a minimum of at least two connections to the main earth grid. All metal clad switchgear panels shall be bonded to this earth bar in accordance with D-DT-5240 Sheet 13, or o.54/393 Sheet C27.

Earth straps in buildings shall be fixed to cable racks, floors and walls in accordance to D-DT-5240 Sheet 12 or 0.54/393 Sheet C10.

3.11.13 Control plant panel and cable earthing

Control plant cabinets/panels/enclosures/cables shall be earthed in accordance with [18] (240-64100247, Standard for Earthing of Secondary Plant Equipment in Substations) to the earth bar provided.

Refer to D-DT-5240 Sheets 14 – 18 for typical Dx applications and 0.54/393 Sheets C22 – C24 and C28 – C30 for typical Tx application.

3.11.14 Earthing of equipment on building roofs

Equipment installed on top of (concrete) roofs is a non-standard application but are required from time to time. The installation requirements shall be application specific, but the following can be used as a guide:

- All equipment bases fitted directly to the slab, including surge arrester bases shall be bonded with at least one earth strap to ensure a single reference voltage is maintained.
- Structures if installed shall get the required number of earth tails as stipulated in Table 2 based on the design earth fault current.
- Lightning protection earthing and equipment earthing can be combined.
- The minimum number of conductors bonding the rooftop earthing to the earth grid shall be based on the design fault current and as stipulated in Table 2.

3.12 GIS substations, long bus ducts and gas insulated lines earthing

GIS substations can be subjected to the same magnitude of earth fault currents and require the same low-impedance earthing system similar to conventional substations. Typically, the GIS installation occupies a much smaller portion of land area compared to equivalent AIS substations. Because of this smaller area, it may be difficult to obtain adequate safety earthing solely by conventional methods. It is advisable that finite element analysis software is used to evaluate intended installations to ensure compliance to safety requirements.

GIS buildings shall be earthed in accordance to the GIS manufacturer's requirements. Particular attention should be given to the bonding of the metallic enclosures of the GIS assembly, as these enclosures might carry induced currents of significant magnitude, which must be confined to specific paths. In this respect, earthing recommendations by the manufacturer of a given GIS installation shall be strictly followed.

3.13 Corrosion mitigation of substation earth electrodes

Consideration shall be given to the effect of corrosion on the life expectancy of earthing connections and conductors. No material, including copper and stainless steel, is immune to corrosion when buried in soil. Appropriate checks of local soil conditions are necessary to determine the impacts thereof on the buried earthing materials used. This will include the interaction between different interconnected metals. No earthing compounds with added salts are permitted to be used as they can accelerate corrosion of electrodes.

Corrosion is mitigated through cathodic protection which is the process of turning the corroding metal from an anode to a cathode. This is achieved by either connecting the protected metal to a more anodic metal, known as a sacrificial anode, or by flowing a direct current between a protective metal and the metal to be protected, known as impressed current cathodic protection. This standard only covers the application of sacrificial anodes.

If required sacrificial earth anodes should be installed in accordance to D-DT-5240 Sheet 11 or 0.54/393 Sheet T12. These sacrificial anodes shall be installed:

- At a depth at least equal to the earth grid,
- On the outside of, and three to six meters away from the earth grid.

When brazing or exothermic welding is used as connection method it is advisable to specify that all joints be bitumen painted while still hot to prevent the onset of corrosion in and around the joints.

3.14 Earth grid installation

The applicable design document and drawings shall indicate all dimensions required to install the earth grid, including clearly specifying at what depth the earth grid must be installed and the positions and dimensions of vertical earth-rods if required. On the completed platform, before any trenching or foundation work is done soil resistivity measurements shall be done in accordance with the applicable sections in this document. These values shall be used to verify the applicability (correctness) of the design based on the actual as constructed terrace soil model. Should the design not comply with safety requirements it shall be modified to such an extent until all requirements are met before any installation work is started.

The only two acceptable earth grid installation methods are described below and illustrated in Figure 8.

a) Complete the platform to final specified level and then install the earth grid:

   1) Complete the platform to the final design level,
   2) Trench to the specified earth grid depth,
   3) Install the earth grid as specified,
   4) Backfill and compact the trenches at optimum moisture content with a mechanical plate compactor in maximum layers not exceeding 300mm to a density of 93% Mod AASHTO to the final platform level.

b) Install the earth grid before final platform level has been reached:

   1) Complete the platform only to 0.5m above earth grid level,
   2) Trench 0.5m deep,
   3) Install the earth grid as specified,
   4) Backfill and compact the trenches at optimum moisture content with a mechanical plate compactor (or similar hand compactor) in maximum layers not exceeding 300mm to a density of 93% Mod AASHTO to the existing platform level,

5) Backfill and compact the whole platform to final level as specified.

The main earth grid shall be buried at a depth stipulated in the design document and reflected on the earth grid layout drawing, typically 1000mm below the final platform level. If site conditions dictate a depth different than stipulated in the design it must be brought under the attention of the design engineer for approval as this might have a negative impact on the safe step and touch potentials. In this case the design engineer shall recalculate all parameters and modify the grid layout if required.

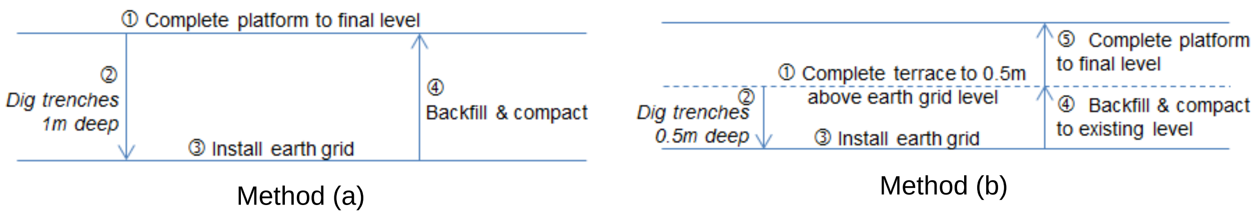


Figure 8: Acceptable earth grid installation methods

Where passing under deeper foundations and drains, the earth grid is to be at least 150mm below the concrete. Back-filling around such earth rods is to be well compacted.

Where a concrete blinding is cast under building foundations the earth grid meshes are to be installed on top of the blinding and under the concrete footing of columns etc.

Where passing over drains with less than 1000mm of cover, it is to be buried as deep as possible.

The outer grid is to be between 600mm and 1000mm outside the safety fence, as specified on the foundation or earth-grid layout drawing.

3.15 Testing of earth grids

After installation the following tests shall be performed on the earth grid to verify compliance with the design:

- Substation earth electrode resistance shall be measured in accordance with [26] (240-101940513) and compared with the design grid resistance.
- Earth continuity shall be measured as stipulated in [23] (240-84854974) to ensure all structures, fences, line terminal towers, etc. are connected to the earth grid as required.
- Safe conditions can also be confirmed by conducting step and touch potential surveys. These tests should be considered for new substation installations and work done as a result of network strengthening, especially when there are large discrepancies between calculated and measured grid resistances. It should also be considered especially when the computed values are close to tolerable limits and further improvement of the earth grid to provide a larger safety factor is difficult or costly.
- In severely corrosive environments it is advised that the earth grid conductors and connections be inspected visually from time to time. It is not practical to inspect the whole grid, so a number of test pits will have to be dug for this purpose. The quantity of test pits required will depend on the size of the substation. Depending on the condition of the earth conductors and connections remedial actions will have to be applied to the whole grid if required.
- In addition, for refurbishment projects the earth grid conductor and connection condition must be verified by a visual inspection. Similar to the point above a number of test pits will have to be dug for this purpose. The outcome of this inspection will inform the design requirements associated with the earth gird.

These tests shall be repeated periodically as stipulated in the applicable documents listed above and compared to the original values captured after first installation. Should there be sizable differences a more in-depth investigation to the reason for the differences shall be undertaken and remedial actions implemented.

3.16 Future developments

The following two areas will be developed further in the foreseeable future and the results used to update this standard:

- The use of alternative surface covering materials instead of crushed stone, i.e. heavy duty paving.
- National seasonal soil resistivity correction factors to be developed. It has been proven in [3] and [4] that these correction factors are required and a process will be derived to develop these for as many of the various geological areas nationally as is possible.

4. Authorization

This document has been seen and accepted by:

Name and surname	Designation
Alex Ndlela	Senior Manager – Distribution division, Engineering
Braam Groenewald	Corporate Consultant – Transmission Division, Substation Engineering
Andile Madikizela	Senior Technician – Distribution Division, Cape Coastal Cluster
Best Khoza	Senior Technologist – Distribution Division, Cape Coastal Cluster
Christy Thomas	Senior Engineer – Transmission Division, Substation Engineering
Derrick Delly	Chief Engineer – Transmission Division, Substation Engineering
Enderani Naicker	Chief Engineer – Transmission Division, Substation Engineering
Fannie Masango	Senior Advisor – Distribution Division, Gemma Cluster
Gavin Strelec	Chief Engineer, RT&D
Jayant Raghubir	Senior Engineer – Distribution Division, CentralEast Cluster
Kabelo Molapise	Engineer – Distribution Division, Limlanga Cluster
Mark Peffer	Chief Engineer – Transmission Division, Substation Engineering
Matthews Baloyi	Senior Engineer – Distribution Division, Limlanga Cluster
Modiri Seate	Senior Engineer – Distribution Division, CentralEast Cluster
Nkululeko Mazibuko	Engineer – Transmission Division, Substation Engineering
Percy Seboco	Chief Technologist – Transmission Division, Substation Engineering
Rukesh Ramnarain	Chief Engineer – Transmission Division, Substation Engineering
Sipho Zulu	Chief Engineer – Transmission Division, Substation Engineering
Sydney Mukhawane	Senior Technologist – Distribution Division, Gemma Cluster
Vusi Cele	Senior Technologist – Distribution Division, Gauteng Cluster

5. Revisions

Date	Rev	Compiler	Remarks
Sept 2021	2	TJ Marais	Sections added: 2.1.3; 3..6.4.3; 3.9.4 Annex C.6 Sections updated: 2.2; 2.3.1; 2.4; 2.6; 2.7 3.2; 3.3.2; 3.3.3; 3.5 3.6.1, 3.6.2.2, 3.6.3; 3.6.4.1 3.10.3; 3.11.1; 3.11.2; 3.11.4; 3.11.5; 3.11.12 3.13; 3.16; 4 Annex B Annex C Equation numbers corrected: 10 - 24 Tables updated: 1, 6, 8
March 2018	1	TJ Marais	First Issue

6. Development team

- TJ Marais

7. Acknowledgements

All employees that participated in doing the monthly soil resistivity measurements used to derive the seasonal correction factors.

Christy Thomas for the work done on the original seasonal correction factors.

Annex A – Determining the soil model manually (by hand)

The soil model is an important input to the earth grid design process.

A.1 Soil resistivity measurement:

The four-probe 'Wenner method' of soil resistivity measurement as outlined in [25] (240-96393507), shall be used.

The results of the measurements are to be tabulated in the appropriate table.

Emphasis should be placed on the value of meaningful and accurate on-site measurements, as the basis for important decisions regarding site suitability and earthing system design.

A.2 Measuring equipment requirements:

Details of the measuring equipment requirements are given in [25] (240-96393507).

In areas of high soil resistivity, and especially at wide probe spacings, the current injected by the test set may be extremely low. This introduces the potential for significant measurement errors due to the limitations of the equipment sensitivity. In such cases, the resistance of the current probes should be decreased by wetting the soil in contact with the probes, or by driving the probes deeper into the soil. Alternatively, a better current injection system should be used.

A.3 Analysis of measurements – soil models:

Finite element analysis software can generate elaborate soil models. However, for practical purposes, a horizontal two layer stratification model is generally sufficient for a substation electrode design. A two-layer model is often an adequate approximation of the in situ soil structure, even when measurements indicate a more complicated structure.

The soil model may be generated by simulation software if available, or developed from first principles as detailed in the following description below.

Figures A1 and A2 illustrate the two possible configurations for a horizontal two-layer soil model. In the high-over-low soil indicated in Figure A1 the top layer of soil has a higher resistivity than the bottom layer, i.e. $\rho 1 > \rho 2$.

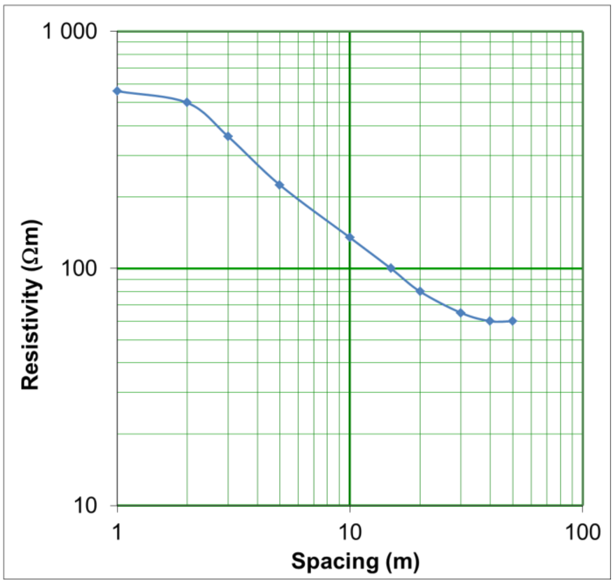


Figure A.1: High-over-low soil

In the low-over-high soil indicated in Figure A2 the top layer of soil has a lower resistivity than the bottom layer, i.e. $\rho 1 < \rho 2$.

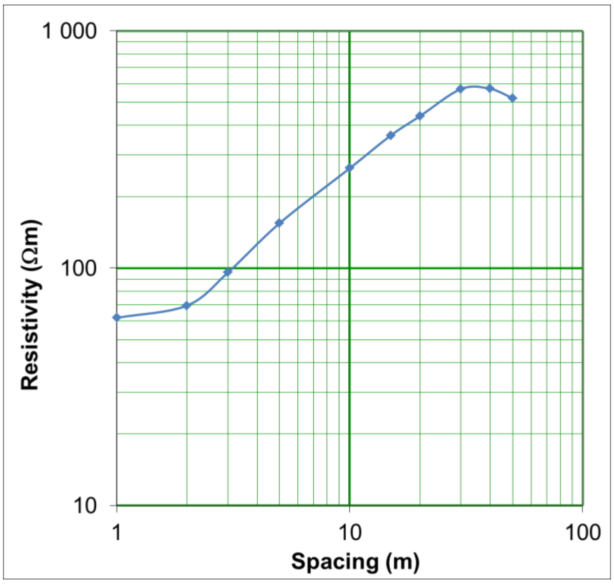


Figure A.2: Low-over-high soil

A.3 Curve matching techniques:

The analysis of the field-measured results in order to obtain the soil parameters is critical in determining the suitability of the in situ soil in relation to the earth grid design.

Although in most cases the apparent resistivity, plotted as a function of the electrode spacing, shows a large variation of resistivity, the field curve is approximated as a two-layer soil model. The logarithmic curve matching technique outlined in (e) is recommended to obtain h_1, ρ_1 and ρ_2 with h_1 indicating thickness of the top soil layer, ρ_1 the resistivity of the top soil layer and ρ_2 the resistivity of the lower soil layer.

This method uses the theoretical family of master curves in [10] (SANS 10199), which have been included as a transparency in Figure A.3. The best fitting theoretical curve is used as a reference to calculate the unknown soil parameters.

A.4 Curve fitting procedure:

1) Plot the averaged field measurement results on bi-logarithmic paper (use the graph paper in Figure A.4).

2) Lay the SANS 10199 master curves transparency (Figure A.3) on top of the field graph. Ensure that the master curve graph and the field measurement curve graph have the same vertical and horizontal scales, and that the horizontal and vertical axes are kept parallel to each other.

3) Move the plot of the field measurements, keeping the axes parallel to the theoretical master curve axes at all times, until the best fit between the field graph and one of the theoretical graphs is obtained.

4) Deduce the values for h1, ρ1 and ρ2 from this curve.

The intersection of the vertical axis of the SANS 10199 master curves and the horizontal axis of the field graph gives the thickness (h_1) of the top soil layer.

The intersection of the horizontal axis of the SANS 10199 master curves and the vertical axis of the field graph gives the resistivity of the top soil layer (ρ_1).

The fitted SANS 10199 curve gives the relationship between ρ_1 & ρ_2.

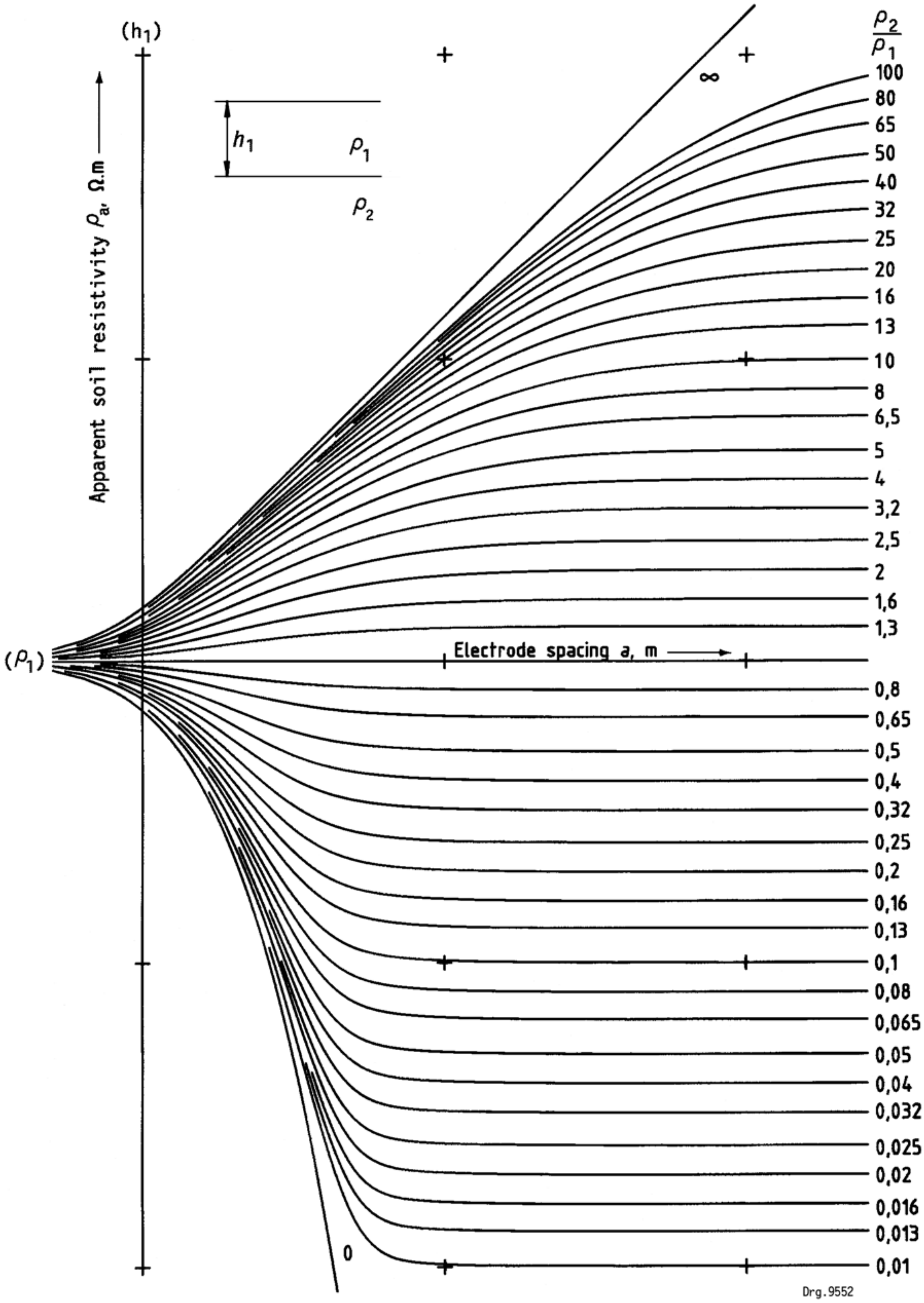


Figure A.3: SANS 10199 two-layer soil model master curves

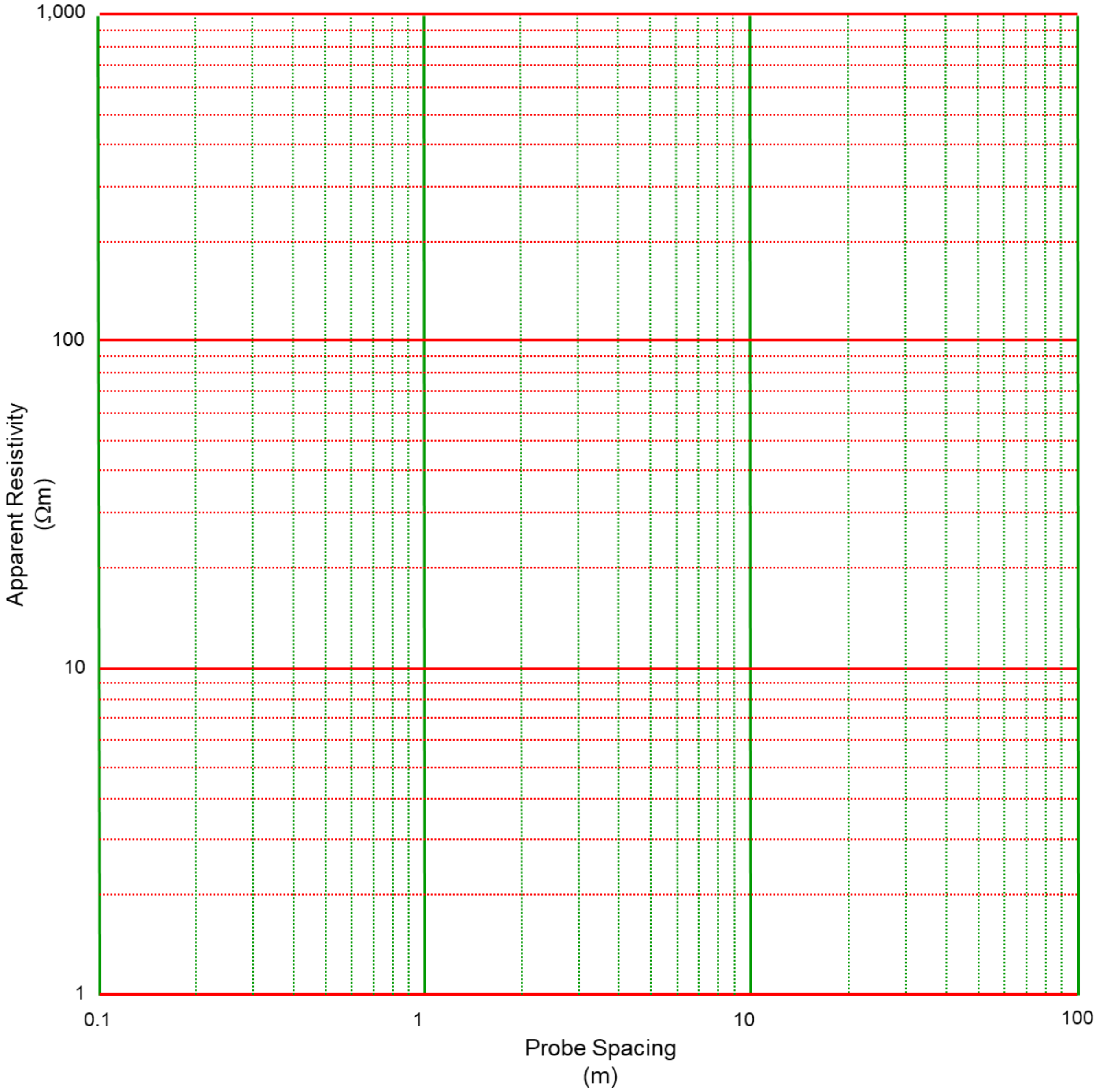


Figure A.4: Bi-logarithmic graph paper sample

Annex B – Seasonal correction factor

It is a known fact that the soil moisture content impacts the soil resistivity and that the soil moisture content varies with the seasons.

Soil resistivity is a measure of how much the soil resists the flow of electricity and varies not only with the type of soil but also with temperature, moisture, salt content and the level of compaction. Variations in soil resistivity have considerable influence on the performance of most earthing systems, affecting both the value of earth resistance and ground potential rise as well as the step and touch potentials.

References [3] and [4] document the work that has been done on the Eskom Megawatt Park property in central Gauteng. The correction factor derived from these measurements indicates that for the area under investigation the seasonal moisture variation has a big impact on the soil resistivity. Therefore depending on when the site soil resistivity measurements are done it can have a significantly negative impact on the design resulting in the design not complying with required safety limits for some of the seasons during the year.

At present measurement data from five sites spanning over a period of two years are available to use as local correction factors. Correction factors for the other geographical areas in South Africa will be developed over time and made available.

B.1 Correction factors

It is proposed that substation locations are compared to the measurement locations listed below to determine if the geology of the proposed new substation site is similar to the closest measurement site.

- Eastern Cape

  It is proposed that the correction factors given in Table B.1 are used for the greater East London area. These are based on measurements done for 24 months in the East London area starting in June 2018 and ending in May 2021 with measurement centre at latitude S32.951264° and longitude E27.934969°.

Table B.1: Monthly soil resistivity correction factors for the greater East London area

	Upper layer (≤ 2m)	Lower layer (> 2m)
January	1.24	1.06
February	1.30	1.11
March	1.92	1.13
April	1.05	1.10
May	1.03	1.09
June	1.00	1.03
July	1.20	1.00
August	1.06	1.00
September	1.08	1.01
October	1.22	1.01
November	1.19	1.02
December	1.33	1.06

- Gauteng

  It is proposed that the correction factors given in Table B.2 are used for the greater Gauteng area. These are based on measurements done for 24 months in the Sunninghill area starting in December 2015 and ending in November 2017 with measurement centre at latitude S26.035756° and longitude E28.081431°.

Table B.2: Monthly soil resistivity correction factors for the greater Gauteng area

	Upper layer (< 3m)	Lower layer (≥ 3m)
January	2.30	1.18
February	1.62	1.11
March	1.61	1.21
April	1.34	1.12
May	1.43	1.10
June	1.20	1.05
July	1.12	1.01
August	1.13	1.00
September	1.00	1.10
October	1.41	1.01
November	2.11	1.17
December	1.46	1.06

- Limpopo

It is proposed that the correction factors given in Table B.3 are used for the greater Polokwane area. These are based on measurements done for 24 months close to Polokwane starting in June 2018 and ending in August 2021 are with measurement centre at latitude S23.893700° and longitude E29.405300°.

Table B.3: Monthly soil resistivity correction factors for the greater Polokwane area

	Upper layer (< 3m)	Lower layer (≥ 3m)
January	1.54	1.29
February	2.06	1.35
March	1.31	1.15
April	1.49	1.22
May	1.50	1.09
June	1.00	1.03
July	1.15	1.05
August	1.23	1.00
September	1.07	1.04
October	1.53	1.12
November	1.88	1.22
December	1.56	1.21

- Northern Cape

It is proposed that the correction factors given in Table B.4 are used for the Northern part of the Northern Cape Province. These are based on measurements done for 25 months close to Kimberley starting in September 2018 and ending in August 2021 with measurement centre at latitude S28.806111° and longitude E24.785278°.

Table B.4: Monthly soil resistivity correction factors for the Northern part of the Northern Cape Province

	Upper layer (< 3m)	Centre layer (≥ 3m to < 10m)	Lower layer (≥ 10m)
January	2.28	1.98	1.17
February	3.12	1.92	1.17
March	2.38	1.53	1.08
April	2.37	1.78	1.17
May	3.58	2.24	1.19
June	1.45	1.31	1.09
July	1.29	1.23	1.05
August	2.10	1.53	1.08
September	1.01	1.03	1.01
October	1.00	1.12	1.00
November	1.04	1.00	1.00
December	1.88	1.52	1.07

- Western Cape

  It is proposed that the correction factors given in Table B.5 are used for the Western and Southern coastal areas of the Western Cape. These are based on measurements done for 24 months in the Kraaifontein area starting in August 2018 and ending in July 2021 with measurement centre at latitude S33.810197° and longitude E18.695400°.

Table B.5: Monthly soil resistivity correction factors for the Western and Southern coastal areas of the Western Cape

	Upper layer (≤ 2m)	Lower layer (> 2m)
January	1.49	1.03
February	1.32	1.02
March	1.00	1.02
April	1.11	1.03
May	1.11	1.00
June	1.09	1.03
July	1.44	1.09
August	1.11	1.01
September	1.02	1.01
October	1.27	1.03
November	1.32	1.04
December	1.19	1.05

B.2 Application of the correction factor:

Depending on the month during which the soil resistivity measurements are done, the measured values shall be multiplied with the values against that month for all measured values.

Refer to Table B.6 for an example of soil measurements taken in the month of May in the Gauteng area. From Table B.2 the values for probe separations 1m and 2m is multiplied by 1.43 and the values associated with probe separations 3m to 50m are multiplied with 1.10.

The corrected soil resistivity shall then be used as input to the design.

Table B.6: Soil resistivity correction factor application example

Probe separation (a)	**Tester reading** (R)	**Resistivity** (=2πaR)	**Correction factor for May**	**Corrected soil resistivity**
m	**Ω**	**Ωm**		**Ωm**
1	13.53	85	1.43	121.55
2	7.96	100	1.43	143.00
3	7.06	133	1.10	146.3
5	5.73	180	1.10	198.00
10	4.07	256	1.10	281.6
15	3.12	294.1	1.10	323.51
20	2.63	330	1.10	363.00
30	1.88	354	1.10	389.40
40	1.47	369	1.10	405.90
50	1.20	377	1.10	414.70

A continuation of the example is to derive the two-layer soil models from the above resistivities. The proposed soil models are given in Table B.7 to highlight the impact of "correcting" the measured soil resistivities.

Both SANS 10199 and RESAP (soil evaluation module from CDEGS) were used to derive the soil models. The reason for this is to compare the results of the two methods with each other. For the example used the results compare favourably with each other as indicated in Table B.7.

Table B.7: Two-layer soil model comparison between measured soil and corrected soil

	As measured soil model for May		**As corrected soil model for May**	
	SANS 10199	**RESAP (CDEGS)**	**SANS 10199**	**RESAP (CDEGS)**
Top soil layer thickness (h_1)	2.0 m	1.8 m	3.2 m	2.9 m
Top soil layer resistivity (ρ_1)	80.0 Ωm	77.5 Ωm	137.0 Ωm	121.5 Ωm
Bottom soil layer resistivity (ρ_2)	400.0 Ωm	387.0 Ωm	438.4 Ωm	441.0 Ωm

Annex C – Hand calculated example

C.1 Design inputs:

Design an earth grid for a 2x20 MVA 132/22 kV substation with the following as applicable:

- Substation layout on which the earth grid design is based:

  Refer to Figure C.1. Fence to fence dimension are 70.25 m by 68.30 m

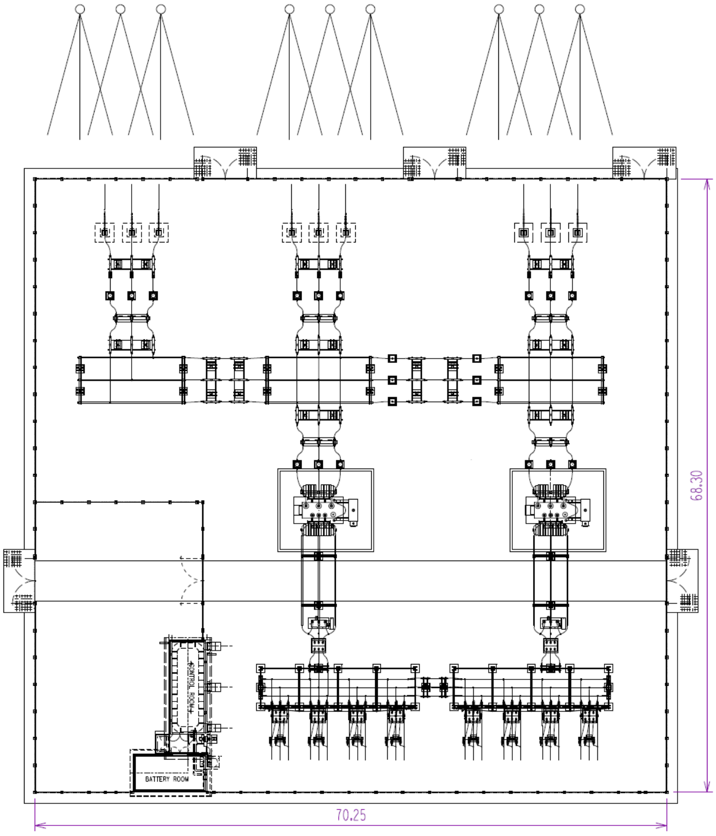


Figure C.1: Design example substation layout

- Fence type:

  Standard steel palisade

- Earth grid boundaries in relation to outer fence:

  The earth grid shall extend 1m to the outside of the perimeter fence in all directions

- Conductor jointing details.

  Earth grid connections: Silver Copper Phosphorus Brazing Filler Metal brazed, maximum temperature rise 650 ^{o}C from Table 5

  Earth tail connections: Bolted to holding down bolts in foundations, Silver Copper Phosphorus Brazing Filler Metal brazed to main earth grid, maximum temperature rise 250 ^{o}C from Table 5

- Surface layer material, aggregate size, electrical properties and layer thickness:

  Surface layer material: Crusher run granite

  Aggregate size: Between 26,5 mm and 37,5 mm nominal size

Electrical properties: 3000 Ωm

Layer thickness: 100 mm = 0.1 m

- Applicable network information, i.e. number of lines connected to the substation, number of shield wires per line, etc.:

  Three 132 kV lines with shield wires, terminal towers are bonded to the earth grid

  Two lines with one shield wire each

  One line with two shield wires

- Position of bonded line terminal towers in relation to the earth grid boundaries:

  All terminal towers are 16m outside the perimeter fence

- Soil resistivity measurement results:

  The following from site measurements:

Probe separation (a)	**Tester reading** (R)	**Resistivity** (=2πaR)
m	**Ω**	**Ωm**
1	7.96	50.0
2	4.11	51.70
3	2.88	54.20
5	1.97	62.00
10	1.31	82.00
15	0.99	92.90
20	0.80	100.00
30	0.60	114.00
40	0.47	118.60
50	0.38	120.90

- Expected future earth fault current per voltage level as stipulated in the planning report or URS, including the time duration of applicability.

  Expected future earth fault current: 132 kV: 7.8 kA Expected duration of applicability: 10 years

  22 kV: 720 A Expected duration of applicability: End of life

- Network X/R ratio per voltage level.

  132 kV network X/R ratio: 30.

  22 kV network X/R ratio: N/A

- Maximum fault clearing time.

  Standard main plus backup protection is applicable with a backup protection fault clearing time of 0.5 s.

C.2 Design assumptions:

- Chosen design earth fault current (I_F):

  15 kA will be used for the design based on the expected 10 year maximum value of 7.8 kA based on Table 1.

- Chosen soil model, in this case based on SANS 10199 (refer to Annex A):

  Two layer model with the following will be used:

Top soil layer thickness (h_1):	4 m
Top soil layer resistivity (ρ_1):	50 Ωm
Bottom/Top layer relationship (ρ_2/ρ_1):	2.5
Bottom soil layer resistivity (ρ_2):	125 Ωm

  The earth grid will be buried in the top soil layer so for design purposed ρ = 50 Ωm.

- Chosen decrement factor (D_f).

  D_f = 1.091 will be used as obtained from Table 9 and based on a fault clearing time of 0.5 s and network X/R ratio of 30.

- Chosen earth grid and earth tail conductor material:

  Earth grid material: Standard 10 mm diameter round annealed soft-drawn copper

  Earth tail material: Standard 50 mm x 3.15 mm flat copper bar

C.3 Design calculations:

- Number of earth tails per structure:

  Based on the chosen design current of 15kA and from Table 2 each structure shall have 2 earth tails connected to the main earth grid as indicated in Figures 1 (a) and (b).

- Minimum required conductor dimensions:

  The maximum expected current magnitude that will flow in the earth grid conductor is based on the number of earth tails and the current split factor per earth tail as indicated in Table 3. For two earth tails the current split is 80% : 20%, and the current in each earth tail will flow in two directions in the main earth grid conductor. Therefore the maximum expected current in the grid conductor for the chosen design earth fault current of 15 kA is:

$$I_c = 0.8 \cdot 0.5 \cdot I_F = 0.8 \cdot 0.5 \cdot 15 = 6\ kA \qquad \text{Calc. (C.1)}$$

  Equation 1 is used to calculate the minimum required conductor cross sectional area with the following as applicable, conductor properties are obtained from Table 4:

I_c	= 6 kA
TCAP	= 3.4 J/(cm3·°C)
t_f	= 0.5 s
α=	= 0.00393 1/°C
ρ_r	= 1.72 μΩ-cm
K_0	= 234 °C
T_m	= 650 °C

T_a = 20 °C

$$A_c = I_c \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_f \cdot \alpha_r \cdot \rho_r}\right) ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} = 6 \cdot \frac{1}{\sqrt{\left(\frac{3.4 \cdot 10^{-4}}{0.5 \cdot 0.00393 \cdot 1.72}\right) ln\left(\frac{234 + 650}{234 + 20}\right)}}$$ Calc. (C.2)

$$Ac = 16.899\ mm^2$$

From this Equation 2 is used to calculate the minimum required conductor diameter:

$$d_c = 2 \cdot \sqrt{\frac{A_c}{\pi}} = 2 \cdot \sqrt{\frac{16.899}{\pi}} = 4.64\ mm$$ Calc. (C.3)

The minimum required copper conductor diameter to be used is 4.64 mm.

- Dimensions of chosen conductor to be used:

The standard 10 mm diameter copper conductor will be used which provides more than 50% margin for corrosion mitigation.

- Safe step and touch potential design limits:

Equations (3), (4), (5) and (6) are used to calculate the allowable step and touch potential limits with the following as applicable:

R_b = 1000 Ω

ρ_s = 3000 Ωm

t_f = 0.5 s

ρ = 50 Ωm

h_s = 0.1 m

$$I_b = \frac{0.116}{\sqrt{t_f}} = \frac{0.116}{\sqrt{0.5}} = 0.164\ A$$ Calc. (C.4)

The maximum allowable current through the body for a duration up to 0.5 seconds is only 164 milli-ampere.

$$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho}{\rho_s}\right)}{2 \cdot h_s + 0.09} = 1 - \frac{0.09 \cdot \left(1 - \frac{50}{3000}\right)}{2 \cdot 0.1 + 0.09} = 0.695$$ Calc. (C.5)

$$E_{step} = I_b \cdot (R_b + 6 \cdot \rho_s \cdot C_s) = 0.164 \cdot (1000 + 6 \cdot 3000 \cdot 0.695) = 2216\ V$$ Calc. (C.6)

The maximum allowable step potential for a duration up to 0.5 seconds is only 2219 volt. The earth grid layout design must therefore ensure that the maximum expected step potential is limited to below this value.

$$E_{touch} = I_b \cdot (R_b + 1.5 \cdot \rho_s \cdot C_s) = 0.164 \cdot (1000 + 1.5 \cdot 3000 \cdot 0.694) = 677\ V$$ Calc. (C.7)

The maximum allowable touch potential for a fault up to 0.5 seconds is only 677 volt. The earth grid layout design must ensure that the maximum mesh potential is limited to below this value.

- Grid layout design:

Because of the grid extending beyond the fence boundary by 1 metre the grid length and width is more than the stated substation fence to fence dimensions. The grid outer dimensions are therefore:

Grid length: $L_x = 70.25 + (2 \cdot 1) = 72.25\ m$ Calc. (C.8)

Grid width: $L_y = 68.30 + (2 \cdot 1) = 70.30\ m$ Calc. (C.9)

Choose t number of conductors perpendicular to the length: Qty_y = 10 conductors

Calculate the distance between conductors perpendicular to the length:

$$D_x = \frac{L_x}{Qty_y - 1} = \frac{72.25}{10 - 1} = 8.028\ m$$ Calc. (C.10)

Calculate the number of conductors perpendicular to the width:

$$Qty_x = \frac{L_y}{D_x} + 1 = \frac{70.30}{8.028} + 1 = 9.7\ conductors\ rounded\ to\ 10\ conductors$$ Calc. (C.11)

Calculate the distance between conductors perpendicular to the width:

$$D_y = \frac{L_y}{Qty_x - 1} = \frac{70.30}{10 - 1} = 7.811\ m$$ Calc. (C.12)

Refer to Figure C.2 for an indication of the proposed earth grid layout including dimensions.

Although the values of D_x and D_y are used for the actual grid layout, only one conductor separation value can be used for calculation purposes, i.e. either D_x or D_y. To consider the worst case condition the maximum value of the two shall be used for calculation purposes:

$$D = Max(D_x; D_y) = Max(8.028; 7.811) = 8.028\ m$$ Calc. (C.13)

Total grid conductor length:

$$L_C = (L_x \cdot Qty_x) + (L_y \cdot Qty_y) = (72.25 \cdot 10) + (70.30 \cdot 10) = 1425.5\ m$$ Calc. (C.14)

Total length of all vertical earth-rods installed:

$L_R = 0\ m$ (no vertical earth-rods have been specified) Calc. (C.15)

Total buried length of conductors including vertical earth-rods:

$$L_T = L_C + L_R = 1425.5 + 0 = 1425.5\ m$$ Calc. (C.16)

Area occupied by the earth grid:

$$A = L_x \cdot L_y = 72.25 \cdot 70.30 = 5079.2\ m^2$$ Calc. (C.17)

Earth grid peripheral length:

$$L_p = 2 \cdot L_x + 2 \cdot L_y = 2 \cdot 72.25 + 2 \cdot 70.30 = 285.1\ m$$ Calc. (C.18)

Maximum distance between any two points on the grid:

$$D_m = \sqrt{L_x^2 + L_y^2} = \sqrt{72.25^2 + 70.30^2} = 100.8\ m$$ Calc. (C.19)

It must be noted that the equation for D_m above is only applicable to square or rectangular grids.

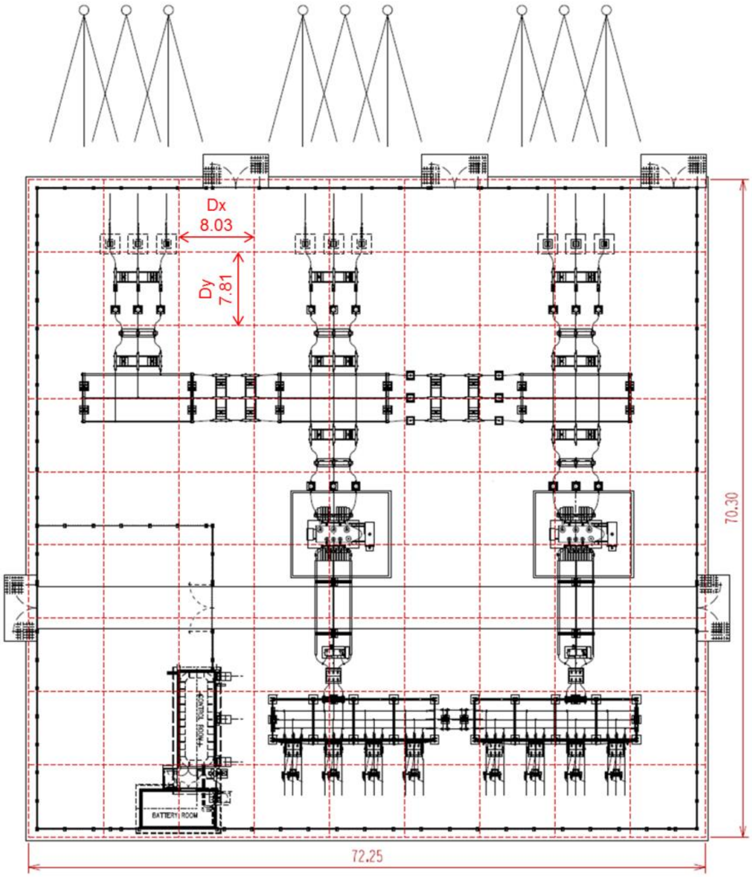


Figure C.2: Initial earth grid design

- Calculated the grid resistance:

Equation (7) is used to calculate the grid resistance with the following as applicable:

ρ	= 50 Ωm
L_T	= 1425.5 m
A	= 5079.2 m²
h	= 1 m

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20 \cdot A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right]$$ Calc. (C.20)

$$R_g = 50\left[\frac{1}{1425.5} + \frac{1}{\sqrt{20 \cdot 5079.2}}\left(1 + \frac{1}{1 + 1 \cdot \sqrt{\frac{20}{5079.2}}}\right)\right] = 0.340\ \Omega$$

- Equivalent resistance associated with all connected external earth electrodes:

  In this case it is the equivalent parallel earth resistance associated with the three 132 kV lines with shield wires bonded to the earth grid. It was stated that one line has two shield wires and the other two lines with have one shield wire each. From Table 10 and considering the worst case, i.e. highest parallel resistance, the following combination shall be used: 7.3 Ω // 10.6 Ω // 5.2 Ω.

$$R_{rest} = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}} = \frac{1}{\frac{1}{7.3}+\frac{1}{10.6}+\frac{1}{5.2}} = 2.361\,\Omega$$ Calc. (C.21)

- Calculate the grid current:

  Equation (9) is used to calculate the current division factor and Equation (8) to calculate the expected grid current. D_f = 1.091 as obtained from Table 9 and based on a fault clearing time of 0.5 s and network X/R ratio of 30. The following is applicable:

  R_{rest} = 2.361 Ω

  R_g = 0.340 Ω

  D_f = 1.091

  I_F = 15 kA

  The current division factor is:

$$S_f = \frac{R_{rest}}{R_{rest}+R_g} = \frac{2.361}{2.361+0.340} = 0.874$$ Calc. (C.22)

  The grid current is:

$$I_G = D_f \cdot S_f \cdot I_F = 1.091 \cdot 0.874 \cdot 15 = 14.307\ kA$$ Calc. (C.23)

- Calculate GPR:

$$GPR = I_G \cdot R_g = 14.307 \cdot 0.340 = 4.858\ kV$$ Calc. (C.24)

- Calculate the worst-case touch potential, which is the mesh potential:

  Equation (10) is used to calculate the mesh potential, and Equations (11) to (21) to calculate all the required parameters.

  First the geometric factor composed of factors n_a, n_b, n_c, and n_d is calculated with Equations (14) to (18), with the following as applicable:

  L_C = 1425.5 m

  L_p = 285.1 m

  A = 5079.2 m^2

  L_x = 72.25 m

  L_y = 70.30 m

  D_m = 100.8 m

$$n_a = 2 \cdot \frac{L_C}{L_p} = 2 \cdot \frac{1425.5}{285.1} = 10.000$$ Calc. (C.25)

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}} = \sqrt{\frac{285.1}{4 \cdot \sqrt{5079.2}}} = 1.000$$ Calc. (C.26)

$$n_c = \left[\frac{L_x \cdot L_y}{A}\right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} = \left[\frac{72.25 \cdot 70.30}{5079.2}\right]^{\frac{0.7 \cdot 5{,}079.2}{72.25 \cdot 70.30}} = 1.000$$ Calc. (C.27)

$$n_d = \frac{D_m}{\sqrt{{L_x}^2 + {L_y}^2}} = \frac{100.8}{\sqrt{72.25^2 + 70.30^2}} = 1.000$$ Calc. (C.28)

$$n = n_a n_b n_c n_d = 10.000 \cdot 1.000 \cdot 1.000 \cdot 1.000 = 10.000$$ Calc. (C.29)

For grids with vertical earth-rods along the perimeter, or for grids with vertical earth-rods in the grid corners, as well as both along the perimeter and throughout the grid area $K_{ii} = 1$, otherwise Equation (12) must be used. For the grid under investigation no vertical earth-rods are considered so the corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh is:

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} = \frac{1}{(2 \cdot 10.000)^{\frac{2}{10.000}}} = 0.549$$ Calc. (C.30)

From Equation (13) calculate the corrective weighting factor that emphasizes the effects of grid depth:

$$K_h = \sqrt{1 + h} = \sqrt{1 + 1} = 1.414$$ Calc. (C.31)

Calculate the geometric factor with Equation (11) with the following as applicable:

D = 8.028 m

h = 1 m

d = 0.010 m

K_{ii} = 0.549

K_h = 1.414

n = 10.000

$$K_m = \frac{1}{2\pi} \cdot \left[ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot ln\left[\frac{8}{\pi \cdot (2 \cdot n - 1)}\right]\right]$$ Calc. (C.32)

$$K_m = \frac{1}{2\pi}\left[ln\left[\frac{8.028^2}{16 \cdot 1 \cdot 0.010} + \frac{(8.028 + 2 \cdot 1)^2}{8 \cdot 8.028 \cdot 0.010} - \frac{1}{4 \cdot 0.010}\right] + \frac{0.549}{1.414} ln\left[\frac{8}{\pi(2 \cdot 10.00 - 1)}\right]\right]$$

$$K_m = \frac{1}{2\pi} \cdot [ln[534.358] + 0.388 \cdot ln[0.134]]$$

$$K_m = 0.875$$

Calculate the correction factor for grid geometry, also referred to as the irregularity factor with Equation (19):

$$K_i = 0.644 + 0.148 \cdot n = 0.644 + 0.148 \cdot 10.000 = 2.124$$ Calc. (C.33)

Because no vertical earth-rods are used on the grid the effective grid conductor length is calculated with Equation (20):

$$L_M = L_C + L_R = 1425.5 + 0 = 1425.5\ m$$ Calc. (C.34)

Now the mesh potential is calculated with Equation (10), with the following as applicable:

ρ = 50 Ωm

K_m = 0.875

K_i = 2.124

I_G = 14.307 kA

L_M = 1425.5 m

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} = \frac{50 \cdot 0.875 \cdot 2.124 \cdot 14.307}{1425.5} = 0.933\ kV$$ Calc. (C.35)

$$E_m = 0.933\ kV \cdot 1000 = 933\ V$$

- Calculate the worst-case step potential:

Equation (22) is used to calculate the step potential, and equations (23) and (24) to calculate the outstanding parameters with the following as applicable:

h = 1 m

D = 8.028 m

n = 10.000

L_C = 1425.5 m

L_R = 0 m

The step potential spacing factor is calculated with Equations (21):

$$K_S = \frac{1}{\pi} \cdot \left[\frac{1}{(2 \cdot h)} + \frac{1}{(D + h)} + \frac{(1 - 0.5^{n-2})}{D}\right]$$ Calc. (C.36)

$$K_S = \frac{1}{\pi} \cdot \left[\frac{1}{(2 \cdot 1)} + \frac{1}{(8.028 + 1)} + \frac{(1 - 0.5^{10.000-2})}{D8.028}\right]$$

$$K_S = 0.234$$

The effective buried conductor length is calculated with Equations (22):

$$L_S = (0.75 \cdot L_C) + (0.85 \cdot L_R) = (0.75 \cdot 1425.5) + (0.85 \cdot 0) = 1069.1\ m$$ Calc. (C.37)

Calculated the step potential with Equation (20), with the following as applicable:

ρ = 50 Ωm

K_s = 0.234

K_i = 2.124

I_G = 14.307 kA

L_S = 1069.1 m

$$E_S = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S} = \frac{50 \cdot 0.234 \cdot 2.124 \cdot 14.307}{1069.1} = 0.332\ kV$$ Calc. (C.38)

$$E_S = 0.332\ kV \cdot 1000 = 332\ V$$

- Verify that the solution comply with requirements:

The requirements that shall be complied with are:

Mesh potential shall be less than the maximum touch potential limit,

Step potential shall be less than the maximum step potential limit,

GPR shall be less than 5 kV.

The calculated results compares to the required limits as follows:

Mesh potential = 933 V	>	Maximum touch potential limit = 677 V
Step potential = 332 V	<	Maximum step potential limit = 2216 V
GPR = 4.858 kV	<	GPR should be less than 5 kV

From the above it is clear that the design must still be optimised because the mesh potential is higher than the maximum touch potential limit by reducing the grid sizes, i.e. increasing the number of parallel conductors.

The earth grid design is an iterative process to be continued until the most optimal financially cost effective safe layout is obtained.

C.4 Design optimisation:

- When optimising the design the following generally stays unchanged:
  - Substation layout
  - Fence type
  - Earth grid boundaries in relation to the outer fence
  - Conductor jointing details
  - Surface layer material and thickness
  - Number of lines with shield wires bonded to the substation earth grid
  - Future earth fault current per voltage level
  - Network X/R ratio
  - Fault clearing time
  - Soil model
  - Number of earth tails per structure
  - Minimum required conductor dimensions and dimensions of chosen conductor to be used
  - Safe step and touch potential design limits
- Depending on the magnitude of the design constraint the following might be considered for changing:
  - Fence type, if necessary it can be changed to a brick or concrete wall to reduce the touch risk.
  - If the fence type is changed earth grid boundaries in relation to the outer fence might also change, impacting the grid size.
  - If necessary the surface layer material or thickness might be changed.
  - If necessary reducing the fault clearing time can be considered. This shall only be done in agreement with the Protection Coordination and Configuration Engineer.
  - Safe step and touch potential design limits must be recalculated if the surface layer material or thickness is changed, or if the fault clearing time is changed
- The grid layout design has to be changed and all subsequent parameters recalculated. This is done by choosing a new number of conductors perpendicular to the length, Qty_y.

Qty_y =	20 conductors		
L_x =	72.25 m	(stay unchanged for this design)	Calc. (C.8)
L_y =	68.30 m	(stay unchanged for this design)	Calc. (C.9)
D_x =	3.803 m		Recalculate (C.10)
Qty_x =	19.4 rounded to 19 conductors		Recalculate (C.11)
D_y =	3.906 m		Recalculate (C.12)
D =	3.906 m		Recalculate (C.13)
L_C =	2778.8 m		Recalculate (C.14)
L_R =	0 m		Recalculate (C.15)

L_T =	2778.8 m		Recalculate (C.16)
A =	5079.2 m^2	(stay unchanged for this design)	Calc. (C.17)
L_p =	285.1 m	(stay unchanged for this design)	Calc. (C.18)
D_m =	100.8 m	(stay unchanged for this design)	Calc. (C.19)
R_g =	0.322 Ω		Recalculate (C.20)
R_{rest} =	2.361 Ω	(stay unchanged for this design)	Calc. (C.21)
S_f =	0.880		Recalculate (C.22)
I_G =	14.398 kA		Recalculate (C.23)
GPR =	4.643 kV		Recalculate (C.24)
n_a =	19.493		Recalculate (C.25)
n_b =	1.000	(stay unchanged for this design)	Calc. (C.26)
n_c =	1.000	(stay unchanged for this design)	Calc. (C.27)
n_d =	1.000	(stay unchanged for this design)	Calc. (C.28)
n =	19.493		Recalculate (C.29)
K_{ii} =	0.687		Recalculate (C.30)
K_h =	1.414	(stay unchanged for this design)	Calc. (C.31)
K_m =	0.619		Recalculate (C.32)
K_i =	3.529		Recalculate (C.33)
L_M =	2778.8 m		Recalculate (C.34)
E_m =	566 V		Recalculate (C.35)
K_S =	0.3060		Recalculate (C.36)
L_S =	2084.1 m		Recalculate (C.37)
E_S =	372 V		Recalculate (C.38)

- Verify that the modified solution comply with requirements:

The calculated results compares to the required limits as follows:

Mesh potential = 566 V	<	Maximum touch potential limit = 677 V
Step potential = 372 V	<	Maximum step potential limit = 2,216 V
GPR = 4.643 V	<	GPR should be less than 5 kV

From the above it is clear that the proposed layout renders a safe design because all safety limits are met.

It must however be noted that the safety margin between the mesh potential and the maximum touch potential limit is 19.6%, meaning that this proposal is overdesigned by nearly 20% and can be optimised for cost while still complying to safety requirements by reducing the number of conductors.

C.5 Final optimised design:

- The grid layout design has to be changed again and all subsequent parameters recalculated. This is done by choosing a new number of conductors perpendicular to the length, Qty_y.

Qty_y =	16 conductors		
L_x =	72.25 m	(stay unchanged for this design)	Calc. (C.8)
L_y =	68.30 m	(stay unchanged for this design)	Calc. (C.9)
D_x =	4.817 m		Recalculate (C.10)
Qty_x =	15.6 rounded to 16 conductors		Recalculate (C.11)
D_y =	4.687 m		Recalculate (C.12)
D =	4.817 m		Recalculate (C.13)
L_C =	2280.8 m		Recalculate (C.14)
L_R =	0 m		Recalculate (C.15)
L_T =	2280.8 m		Recalculate (C.16)
A =	5079.2 m^2	(stay unchanged for this design)	Calc. (C.17)
L_p =	285.1 m	(stay unchanged for this design)	Calc. (C.18)
D_m =	100.8 m	(stay unchanged for this design)	Calc. (C.19)
R_g =	0.326 Ω		Recalculate (C.20)
R_{rest} =	2.361 Ω	(stay unchanged for this design)	Calc. (C.21)
S_f =	0.879		Recalculate (C.22)
I_G =	14.377 kA		Recalculate (C.23)
GPR =	4.693 kV		Recalculate (C.24)
n_a =	16.000		Recalculate (C.25)
n_b =	1.000	(stay unchanged for this design)	Calc. (C.26)
n_c =	1.000	(stay unchanged for this design)	Calc. (C.27)
n_d =	1.000	(stay unchanged for this design)	Calc. (C.28)
n =	16.000		Recalculate (C.29)

K_{ii} =	0.648		Recalculate (C.30)
K_h =	1.414	(stay unchanged for this design)	Calc. (C.31)
K_m =	0.690		Recalculate (C.32)
K_i =	3.012		Recalculate (C.33)
L_M =	2280.8 m		Recalculate (C.34)
E_m =	655 V		Recalculate (C.35)
K_S =	0.280		Recalculate (C.36)
L_S =	1710.6 m		Recalculate (C.37)
E_S =	354 V		Recalculate (C.38)

- Verify that the modified solution comply with requirements:

  The calculated results compares to the required limits as follows:

Mesh potential = 655 V	<	Maximum touch potential limit = 677 V
Step potential = 354 V	<	Maximum step potential limit = 2,216 V
GPR = 4.693 V	<	GPR should be less than 5 kV

  This is the most cost effective design that also complies to the safety requirements. Reducing Qty_y to 15 conductors will result in the mesh potential increasing to above the maximum touch potential limit leaving the design unsafe.

- The final layout is given in Figure C.3. Take note of the following that must be added:
  - Additional conductors 0.6 m on the inside of the outer perimeter fence to ensure an equipotential zone around the fence is created,
  - Line terminal towers must be bonded to the main substation earth grid.

C.6 Hand calculated results compared to results from finite element analysis software

The grid layout as indicated in Figure C.3 and the parameters listed in sections C.1 and C2 were simulated with finite element analysis software, in this case with the CDEGS MALT module.

The CDEGS evaluation area was set to the edge of the curbed area which is 0.2m beyond the earth grid outer dimensions. The simulated results are shown in Figures C.4 and C.5.

The following is observed:

- The CDEGS calculated safe limits (minimum thresholds) are 6% lower compared to the values calculated with IEEE80, with safe touch limit at 636V and safe step limit 2093V.
- As expected, and as can be seen in Figure C.4, the highest touch voltages are on the outer edges of the earth grid with the maximum values at the four outermost corners.
- In Figure C.5 it can be seen that the touch voltage is higher than the safe limit right at the earth grid outer corners. This is however not a concern because in section C.3 it is stipulated that the earth grid extends 1m beyond the fence so this point is more than 1m from the closest point to the perimeter fence, and is therefore still safe from a touch perspective.

This supports the statements made in Section 3.8 that hand calculated results are adequate for run-of-the-mill designs with a mesh side ratio close to 1:1. The advantage of making use of finite element analysis software is that the grid layout can be optimised to reduce the amount of copper to be use while still ensure that it is safe.

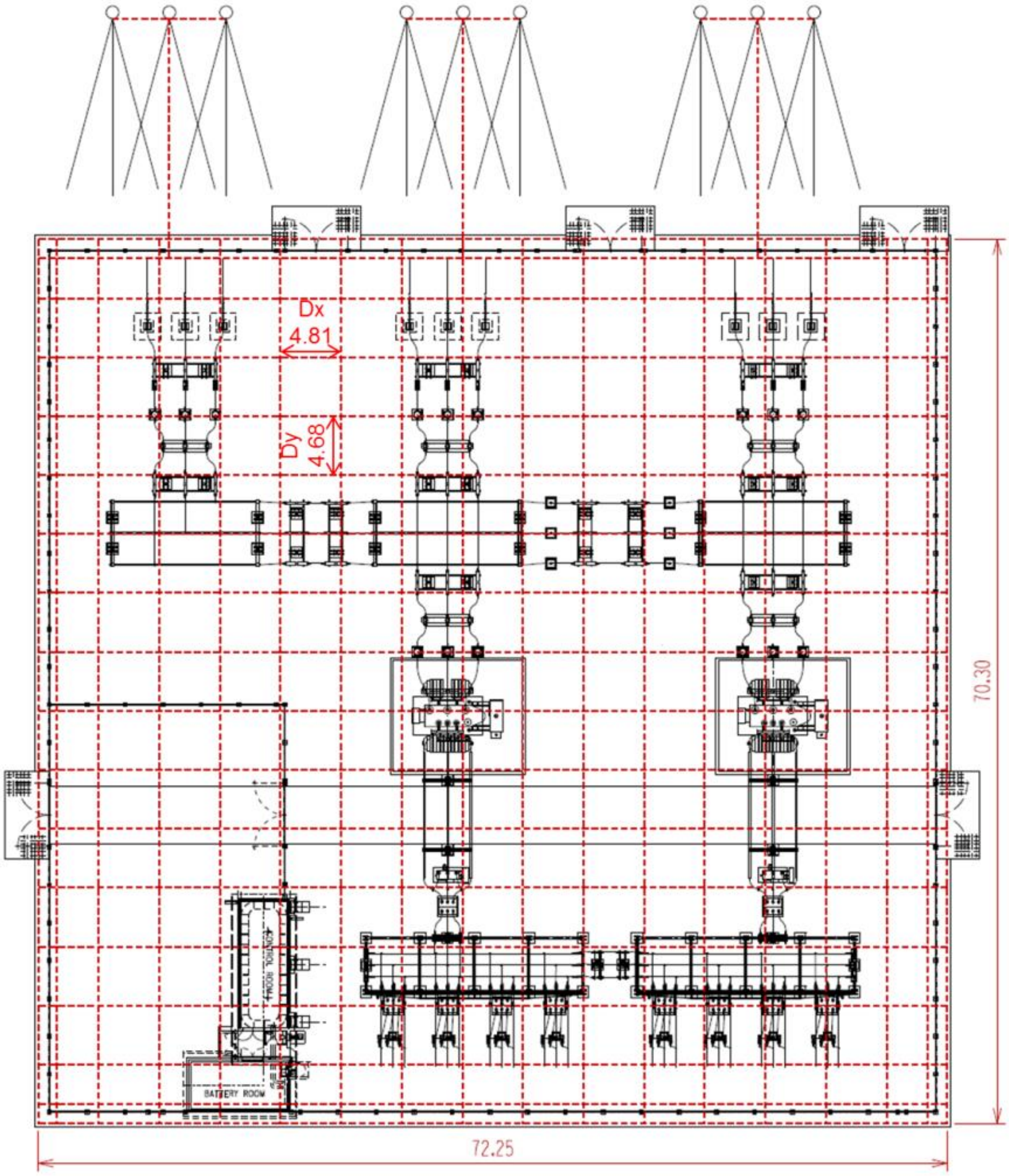


Figure C.3: Final earth grid layout excluding equipment earth tails

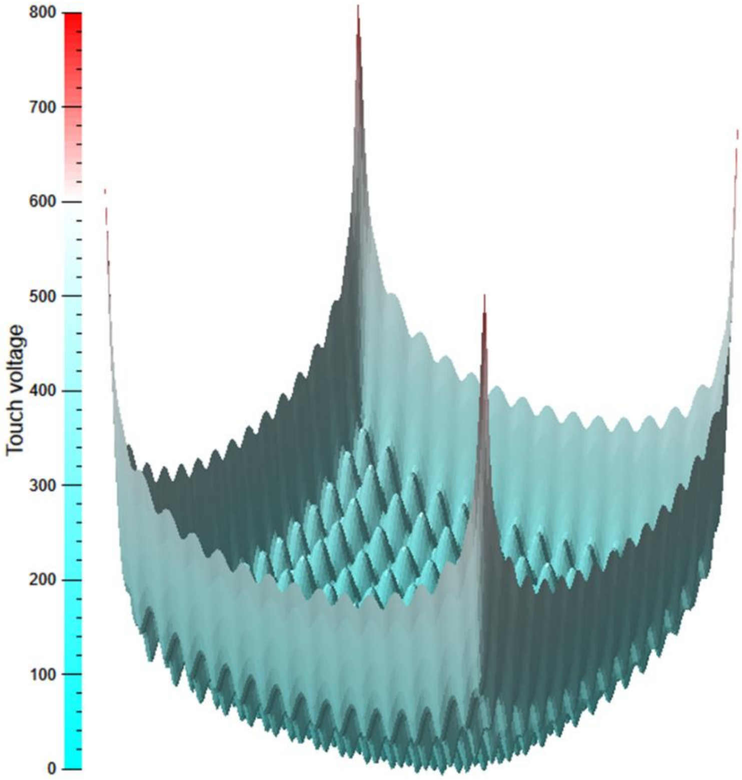


Figure C.4: CDEGS simulated touch potentials (touch limit 636V)

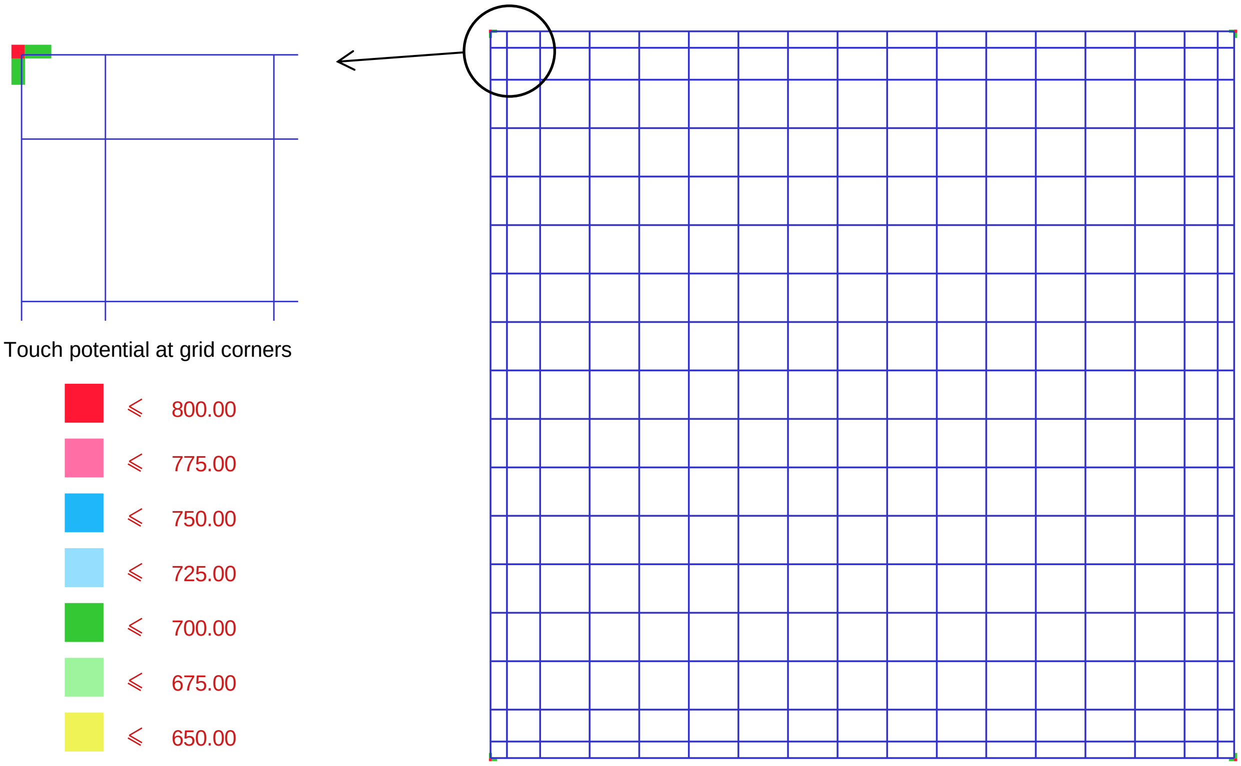


Figure C.5: CDEGS safe touch potential results (touch limit 636V)