LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Degree Programme in Electrical Engineering

Samuel Heino

SUBSTATION EARTHING AND HAZARDOUS VOLTAGES

Examiners: Professor Jarmo Partanen
D. Sc. Jukka Lassila

ABSTRACT

Lappeenranta-Lahti University of Technology
School of Energy Systems
Degree Programme in Electrical Engineering

Samuel Heino
Substation Earthing and Hazardous Voltages
Master’s Thesis
2021
82 pages, 37 figures, 7 tables

Examiners: Professor Jarmo Partanen
D. Sc. Jukka Lassila

Keywords: earthing, hazardous voltage, fault current distribution, transient overvoltage

The primary purpose of a substation earthing system is to ensure safety to personnel and to protect the equipment from damage and interference. Safety aspects are assessed by means of step and touch voltages presented in the standard SFS 6001, where the key influencing factors are e.g. earthing resistance, fault currents and their current paths.

The purpose of this thesis is to clarify the distribution of fault currents essential for the earth potential rise and the fault currents used in calculations. The work investigates the fault currents flowing through the station in different fault situations and which of these currents are relevant for the rise in earth potential. In addition, the use of reduction factors, additional resistances and calculational aspects based on the SFS 6001, EN 50522 and IEC -standards are presented. The work also examines the available, but less used, means of improving earthing resistance, such as the use of vertical earthing rods and electrodes drawn to conductive soil.

In addition to fault currents, the work also presents transferred voltages, examining the measures recommended by the standard to take these risks into account. The work also examines the transient overvoltages occurring in gas-insulated switchgear, presenting available methods for mitigating their effects.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
School of Energy Systems
Sähkötekniikan koulutusohjelma

Samuel Heino
Sähköaseman maadoitus ja vaarajännitteet
Diplomityö
2021
82 sivua, 37 kuvaa, 7 taulukkoa

Työn tarkastajat: Professori Jarmo Partanen
TkT Jukka Lassila

Hakusanat: maadoitus, vaarajännite, vikavirtojen jakautuminen, transienttiylijännite

Sähköaseman maadoituksien ensisijaisena tarkoituksena on taata henkilöturvallisuus ja suojata laitteita vaurioitumisilta ja häiriöiltä. Henkilöturvallisuuden toteutumista arvioidaan standardin SFS 6001 esittämien askel- ja kosketusjännitteiden avulla, joihin vaikuttavina keskeisiä tekijöitä ovat mm. maadoitusresistanssi, vikavirrat ja niiden virtatiet.

Tämän diplomityön tarkoituksena on selventää sähköaseman maadoituspotentiaalille olennaisten vikavirtojen jakautumista sekä laskennassa käytettäviä vikavirtoja. Työssä selvitetään asemalla kulkevia vikavirtoja eri tilanteissa esitellen aseman maadoituspotentiaalin nousun kannalta olennaisia virtoja. Lisäksi työssä esitellään reduktiokertoimien käyttöä, lisäresistansseja sekä laskentaan liittyviä tekijöitä SFS 6001, EN 50522 ja IEC -standardien pohjalta. Työssä perehdytään myös saatavilla oleviin, mutta vähemmän käytössä oleviin keinoihin maadoitusresistanssin parantamiseksi, kuten pystysuuntaisten elektrodien ja kosteikolle vedettävien maadoitusjohtimien käyttöön.

Työssä käsitellään vikavirtojen lisäksi myös aseman ulkopuolelle siirtyviä jännitteitä, tutkien standardin suosittelemia toimenpiteitä niiden aiheuttamien riskien huomioimiseksi. Työssä perehdytään myös kaasueristeisissä kojeistoissa esiintyviin transienttiylijännitteisiin esitellen menetelmiä niiden vaikutusten minimoimiseen.

ACKNOWLEDGEMENTS

This thesis was written for Hitachi ABB Power Grids, to whom I would like to express my gratitude for providing this subject. I would like to thank my instructor Juha-Matti Huhtanen for providing his support and knowledge during the process of writing this thesis, as well as all other personnel that expressed their interest in the topic. I would also like to thank the LUT University for the education I have gained during my studies, especially the electricity markets and power systems team.

Special thanks to my friends and family for all their support during my studies, this would not have been possible without you.

Samuel Heino
Vaasa 23.03.2021

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

A	cross section
BF	body factor
d	diameter of earthing electrode
d_{T}	distance between towers
D_{F}	far-from-station distance
G	earth fault current density
h	installation depth of earthing electrode
HF	heart current factor
I_0	zero-sequence current
$I_{(0)\mathrm{A}}$	partial zero-sequence current through station A
$I_{\mathrm{B}}(t_{\mathrm{f}})$	body current limit depending on the fault duration
I_{E}	earth current
I_{EF}	current to earth at the fault point
I_{EBn}	current to earth at station B, fault at tower n
$I_{E\delta A}$	earth current flowing through earth to station A
I_{k}	steady state short-circuit current
I'_{k}	transient short-circuit current
I''_{k}	initial (subtransient) short-circuit current
I''_{F}	fault current
I''_{k1}	initial earth fault current
I''_{k3}	initial three-phase short circuit current
K	constant depending on the material of the current-carrying component
L	(electrode) length
r	reduction factor
r_3	reduction factor for three single-core cables
r_{s}	medium radius of the sheath or shield
$\mathrm{Re}\{\sqrt{\underline{Z}_{\mathrm{Q}}}\}$	real part of the square root of the earth wire impedance $\underline{Z}_{\mathrm{Q}} = \underline{Z}'_{\mathrm{Q}}\ \mathrm{d}_{\mathrm{T}}$
R_{EF}	resistance at the fault point
R_{ES}	resistance to earth of the mesh electrode
R_{H}	additional hand resistance
R_{F}	additional foot resistance
R'_{s}	resistance per unit length of the sheath or shield
R_{T}	tower footing resistance
t_{f}	duration of the fault current in seconds

U_{TP}	touch voltage
U_{EBn}	earth potential for station B, fault at tower
U_{vTP}	prospective permissible touch voltage
$\underline{Z}_{EB}$	earth impedance for station B
$\underline{Z}_{ET}$	earthing impedance of the short-circuit tower
$\underline{Z}_{P}$	driving point impedance of an infinite chain
Z_{Pn}	driving point impedance of a finite chain
$\underline{Z}_{Q}$	earth wire impedance between two towers with earth return
$\underline{Z'}_{Q}$	earth wire impedance per unit length with earth return
Z_{∞}	chain impedance of the overhead line assumed to be infinite

Abbreviations

AIS	air insulated switchgear
ECC	earth continuity conductor
EPR	earth potential rise
GIS	gas insulated switchgear
TEV	transient enclosure voltage
VFTO	very-fast-front transient overvoltage

Greek letters

ρ	resistivity of the soil
δ	equivalent earth penetration depth
ℓ_{A}	cable length from fault point to station A
φ	earth surface potential
θ_{i}	initial temperature in degrees Celsius
θ_{f}	final temperature in degrees Celsius
ω	angular frequency
μ_{0}	magnetic constant, $\mu_0 = 4\pi*10^{-7}$
β	reciprocal of the temperature coefficient of resistance of the current-carrying component at 0 °C

1. INTRODUCTION

Hitachi ABB Power Grids in Finland manufactures, designs, supplies and maintains transformers and reactors, power grid management guidance, automation and control systems, as well as transmission and distribution network solutions, such as substations, for energy, industry, transport and other infrastructure sectors. This thesis was made for the Grid Integration unit in Vaasa, Finland, which delivers substation projects from design to commissioning both in Finland and abroad.

1.1 Background and objective

Earthing system is one of the most important parts of a functioning substation, as it ensures safety for personnel and eliminates interferences to equipment. This thesis focuses mainly on the safety aspects of grounding design.

Earthing system is an extensive subject where a lot of research has been done. Even though many substation projects have been successfully implemented, it has been noticed that some parts of the earthing design are not completely clear to designers. The basic calculation for earthing voltages is relatively well known for engineering design and are therefore excluded from this thesis. However, research was done regarding additional resistances, vertical earthing rods and additional straight earthing electrodes to remote conductive ground to include them in the design calculations.

The purpose of this master's thesis is to research substation earthing, especially the fault currents that affect the dimensioning of the earthing grid. Earthing is studied from the perspective of the standards SFS 6001 and EN 50522, as well as the relevant IEC-standards regarding fault current calculations and distributions.

The objective is to clarify the magnitude of fault currents in different parts of the system in different fault events, considering current distributions. The goal is to give earthing designers information on how fault currents behave in a fault event, and therefore to differentiate between currents contributing to earth potential rise, and those that do not affect earthing grid dimensioning. Additionally, the hazardous voltages and transferred potentials both within and outside of the substation area are examined, so that a more comprehensive report could be made in future projects. The earthing of a gas insulated switchgear substation is also examined especially regarding transient overvoltages to better understand the phenomenon and the mitigation methods available.

1.2 Research questions, structure and limitations

This thesis is conducted through methods of literature review, based on material from public sources as well as the company's internal databases. Internal company interviews on practical implementations are also used. The thesis can be divided to three subjects, all related to substation earthing. The research questions by subject are as follows:

Current distribution

- How do fault currents flow in the earthing system?
- In various fault scenarios, what fault currents are relevant?
- In what way can additional resistances be applied?
- Are there other earthing measures available for difficult earthing conditions?

Hazard voltages

- How can hazard voltages transfer outside the substation?
- How must hazard voltages be accounted for?

GIS earthing

- What are the special considerations for GIS earthing?
- How to account for transient overvoltages?

In addition to the research questions above, the existing earthing voltage calculation tool is reviewed as a part of this thesis.

Due to the vast amount of information available on earthing, and the fact that many subject areas are interdependent, many options for structuring the thesis exist. The structure of this thesis is presented in the figure 1.1.

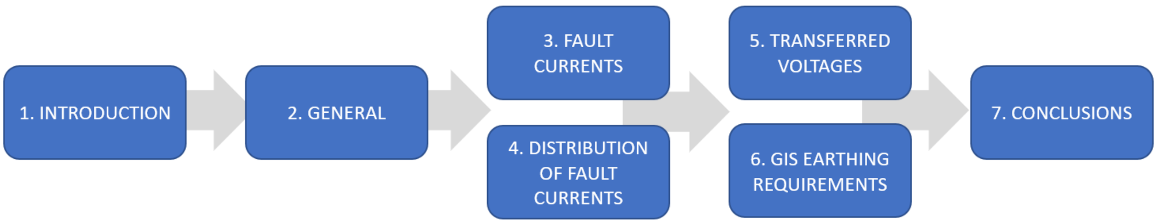


Figure 1.1 Structure of the thesis.

Theoretical background of substation earthing systems, and earthing systems in general, are presented in chapter 2, after which the different fault types and relevant fault currents for design are discussed in chapter 3. Chapter 4 presents the distribution of fault currents in various fault events, both for overhead lines and underground cable connections. Additional resistances, as well as other earthing measures for difficult earthing conditions are also presented in this chapter. A case analysis of a project with difficult earthing conditions was conducted, where the key findings of this thesis were applied in practice. Chapter 5 discusses the risks of transferred potentials and how they should be accounted in earthing design. Lastly, in chapter 6, gas insulated switchgear earthing is presented shortly, with special emphasis on transient overvoltages and the available mitigation effects for this phenomenon. Chapter 7 gives short summary of the results of this research, also considering possibilities for future research subjects.

All substation primary voltage levels of Finland, 400 kV, 220 kV and 110 kV, are included in this thesis. As earthing systems can vary, the technical solutions are approached from an earthing system standpoint, and not separately for each voltage level. The thesis follows the SFS 6001 standard applicable in Finland, which is based on the standard EN 50522 with some special national conditions given for Finnish conditions.

As it was not possible to research and examine the substation earthing design completely comprehensively, some contents such as earthing measurement techniques and practical earthing implementation methods had to be excluded from the study. These are areas that are well known and well described in other theses and were not considered necessary within the framework of this study. Also detailed calculations or formulas are not given as they are well presented in the relevant standards.

2. GENERAL

The earthing system in a substation consists of earth electrodes and earthing conductors, whereby definition, earth electrodes are embedded in the soil, and earthing conductors provide the path between a system, installation or equipment and the earth electrode (EN 50522 2010). However, as the use of these terms often vary in literature and standards, both are used similarly in this thesis, meaning a conductor buried in the soil. The in-air conductors from system, installation or equipment to earth electrode are not researched unless otherwise stated.

The purpose of the earthing system is to ensure proper safety to personnel and to eliminate interference or damages to operating equipment and property. In addition, the earthing grid must be corrosion resistant, have adequate mechanical strength and be able to withstand the high fault currents causing thermal stress to system components. (Elovaara & Haarla 2011, SFS 6001 2018)

The primary factors regarding safety are step and touch voltages, to which standards give limit voltages that must be met at every point at the substation. Fault duration also affects the tolerable touch voltages as determined in the standards. These voltage calculations are also often requested by the customer to prove that the substation design is safe. Normally these prerequisites are achieved by installing earthing electrodes underground in a grid form. This chapter presents the key basic factors that must be considered in earthing design.

2.1 Earthing system and conditions

Usually the location of the substation is predetermined on other factors than good earthing conditions. The other deciding factors are commonly existing power line structures, local zoning ordinances and other technical and financial aspects. Even if the conditions are good, the soil may need to be changed due to ground bearing capacity, often to a less conductive soil material. This leads to problems in efficient earthing, as current carrying capabilities in the soil are weakened as the resistance increases. The magnitude and duration of the current from the electrodes to the soil also cause drying, which further increases soil resistivity (IEEE Std 80-2013).

Earthing is usually divided into two terms, system earthing and protective earthing. Sometimes the term equipment earthing is also used instead of protective earthing. In system earthing the function is to keep the voltages of the current carrying conductors relative to earth in a way that the possibility for hazards or equipment failure are minimal. The second function is to minimize disturbances caused to low current circuits such as communication circuits. This is done by connecting a part of the circuit to the through a small impedance. Protective earthing is focused on connecting non-live parts to the earth, eliminating possible arising touch voltages during faults or other cases. (Elovaara & Haarla 2011)

2.1.1 Soil resistivity

Soil resistivity is dependent on several factors such as the type of soil, temperature, density and moisture. Fault currents in earthing conductors may cause significant drying which affects soil resistivity especially if the duration is long. Therefore, current density should conservatively not exceed 200 A/m^2 for 1 s. (IEEE Std 80-2013)

Gravel or other surface material is usually used to cover the top layer to prevent moisture from evaporating and to reduce shock currents due to high resistivity. Resistivity depends on stone type, size and depth. Usually about 0.08 m to 0.15 m depth of topsoil covering is used. (IEEE Std 80-2013)

The table 2.1 given below gives average resistivities for different types of soils. As seen in the table, soil resistivities can vary greatly based on soil type. The SFS 6001 standard also states soil resistivities for materials prevalent in Finland.

Table 2.1 Frequently measured values for soil material resistivities. (EN 50522 2010)

Type of soil	Soil resistivity ρ_E Ωm
Marshy soil	5 to 40
Loam, clay, humus	20 to 200
Sand	200 to 2 500
Gravel	2 000 to 3 000
Weathered rock	mostly below 1 000
Sandstone	2 000 to 3 000
Granite	up to 50 000
Moraine	up to 30 000

Substation site soils are rarely uniformly resistive from just a single type of soil. Therefore, measurements are essential to determine the actual resistivity on-site. Even measured resistances are subject to change due to temperature and moisture variations. The following figure 2.1 gives reference on how soil resistivity changes in relation to salt, moisture and temperature.

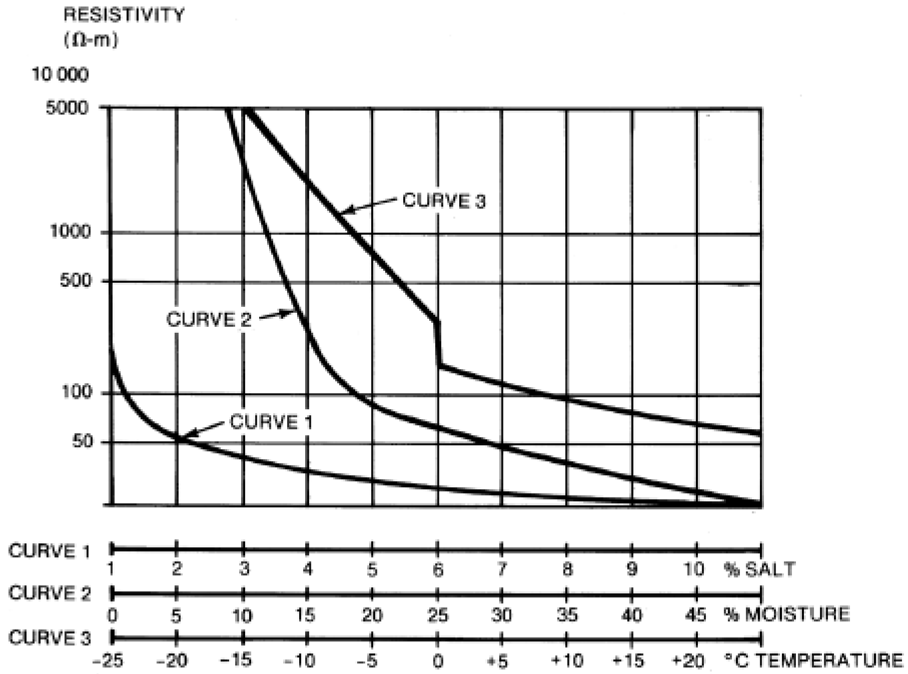


Figure 2.1 Effects of salt, moisture and temperature on soil resistivity. (IEEE Std 80-2013)

As seen from the figure, soil resistivity rises rapidly when temperature decreases below the freezing point of water. Above 0 °C, soil resistivity changes are nearly negligible. In cold environments, such as Finland, these major changes in resistivity below the freezing point must be considered in design.

There are several methods for measuring soil resistivity, based on voltage and current measurements between points. Important factor to consider is the availability of multi-layer models when choosing measurement techniques, as this provides good input for the earthing designer. Soil resistivity measurements provide a practical way to determine the soil resistivity more accurately, but the available methods are not researched further in this thesis.

2.1.2 Earthing grid and layout

The earthing grid for a substation is typically in a mesh form dimensioned around the substation equipment with the purpose of lowering earthing impedance to preserve safe function of the system. In difficult earthing conditions, vertical earth rods can be driven into the ground to further lower earthing voltages. The earthing grid distributes the fault current to a larger area lowering touch and step voltages that are hazardous to humans. Equipment malfunctions can also occur in case of induced interferences, which can be mitigated by earthing design.

There are different metals available for earthing electrodes such as copper, copper-clad steel, steel and aluminum. Copper is usually favored because it is corrosion resistant, highly conductive, durable and has good thermal capacities. Downside of pure copper is its high cost. One solution is a mixture of the properties steel and copper, which goes by the name of copper-clad, a steel core covered in copper. Steel gives the conductor more strength, but loses some conductivity compared to copper conductors. Thermal capacities are to be considered, as overcurrent can cause significant heating in the earthing conductor. Corrosion effects must also be paid attention to, as some materials are more prone to corrosion than others. Typically soils that are less corrosive are high in resistivity and vice versa. (Loo & Ukil 2017)

Sometimes vertical earthing rods driven into the earth are used to improve the resistance to earth, where adequate earthing grid resistance is difficult to achieve. For vertical earthing rods, corrosion-resistant or galvanised steel electrodes are usually used for a more cost-effective solution. (CIGRE 213 2002)

The following figure 2.2 illustrates how the resistance to earth of earth rods change in relation to their length in homogeneous soil.

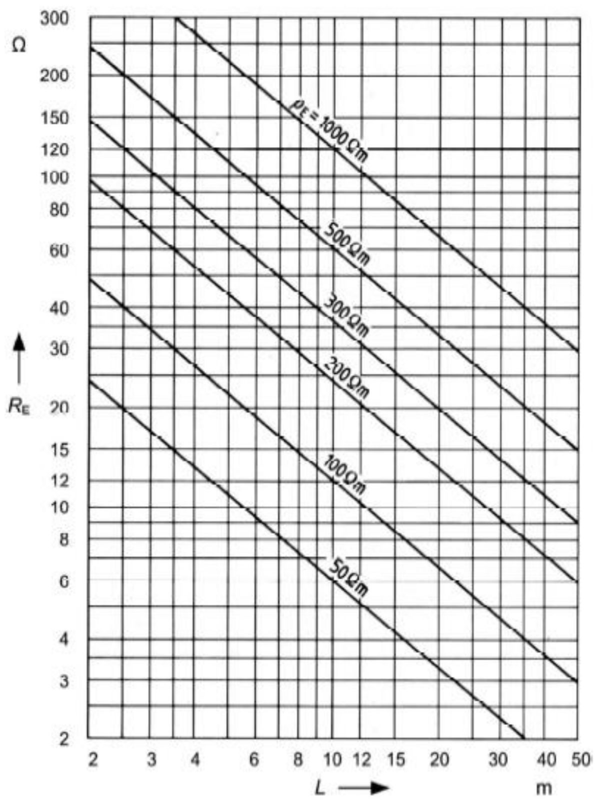


Figure 2.2 Resistance to earth of earth rods buried vertically in homogeneous soil. (EN 50522 2010)

As can be seen from the figure, doubling the earthing rod length typically lowers the resistance by about 40-50 %. Increasing the rod's diameter does not greatly affect the resistance in the same way. Vertical earthing rods should be separated by a distance greater than the immersed length of the rod (EN 50522 2010). Figure 2.3 illustrates how the spacing affects the resistance reduction percentages.

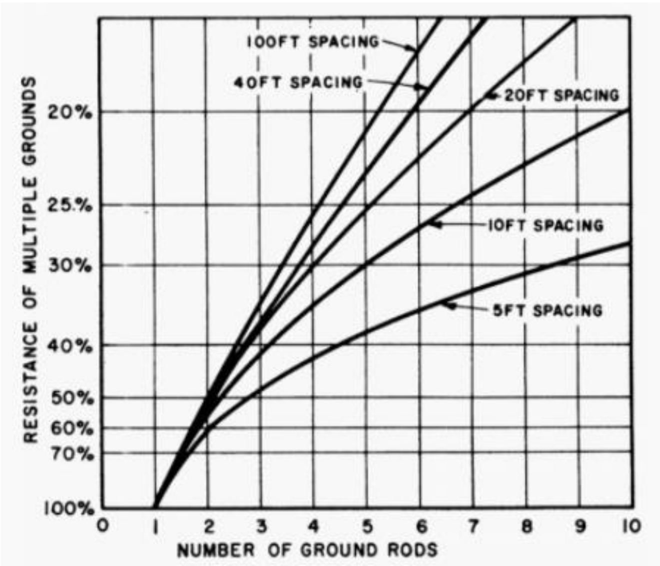


Figure 2.3 Effect of ground rod spacing on resistivity of the earthing. (Csanyi 2016)

As can be seen from the figure, special attention must be paid to spacing when the number of grounding rods increase. Therefore, it is not practical to cover the whole earthing grid area with vertical grounding rods, but to keep appropriate distances between them. (Csanyi 2016)

However, driving grounding rods to soil may prove difficult to do as soil materials vary. Also, the rod may vibrate or move during the driving, which may cause poor contact with the surrounding earth leading to higher resistivity than anticipated. Several other factors should also be considered that may affect the intended results for vertically driven electrodes (Lim et al. 2013):

- electrodes near larger vegetation such as trees may be subjected to fluctuations in grounding resistance over time
- electrodes near water masses may show large fluctuations in grounding resistance with time as well as unexpectedly higher resistances than thought
- electrodes near buildings have a similar effect as they have in open spaces

The earthing grid and mesh size are usually dimensioned around the equipment and equipment earthing, not regarding earthing voltages. It should however be noted that lower earth potential rise is achieved with smaller, denser mesh sizes. In homogeneous soil, the highest earth potential rises exist in the corners of the earthing grid, while the lowest potential rise is perceived in the middle of the grid if viewed from above. (Elovaara & Haarla 2011) Due to this effect, any vertical earthing electrodes should first be installed in the corners of the earthing grid.

Earth potential rise in substations can be lowered by improving earthing or by lowering the fault currents. Fault currents can be lowered by removing neutral groundings or by using earthing chokes at neutral points. These options are often however limited due to maintaining reliable relay protection as fault currents must be high enough for reliable detection. Earthing potential rise can also be reduced in 110 kV – 400 kV substations by reducing the reduction factors of the fault feeding lines. Steel aluminum ground wires should be used for this purpose, preferably always as changing shield wires afterwards is significantly more expensive. (Elovaara & Haarla 2011)

2.1.3 Earthing system

Earthing systems can be categorized into four systems; a system with isolated neutral, a system with resonant earthing, a directly earthed system and a system with low-impedance neutral earthing. The different earthing systems are briefly explained below.

In an isolated neutral system, the neutrals of the transformers and generators are not intentionally connected to the earth, except for high impedance connections for signaling, measuring or protection purposes. In Finland this is mainly used for lower voltage systems such as the 20 kV network. (EN 50522 2010)

In a system with resonant earthing, at least one neutral of a transformer or earthing transformer is earthed via an arc suppression coil and the combined inductance of all coils is essentially tuned to compensate the earth capacitance of the system at operating frequency. This is to make arc faults self-extinguish in the system. This system is used for some 20 kV lines in Finland and 110 kV lines in Lapland, northern Finland. (EN 50522 2010) (Elovaara & Haarla 2011)

In a directly earthed system, most of the generator and transformer neutrals are connected to the ground either straight or via a current limiting impedance. Directly earthed systems in Finland are mainly for small voltage systems (400/230 V) due to safety precautions. Earthing resistance and touch voltages are easy to keep low for safety, and protection measures are easy to implement as earth fault currents are close to the magnitude of short-circuit currents. (Elovaara & Haarla 2011)

In a system with a low-impedance neutral earthing, at least one neutral is earthed via a transformer, earthing transformer or a generator, either directly or via a choke. The impedance of the choke is designed to lead to a reliable automatic tripping to an earth fault at any location due to the magnitude of the fault current. If the voltages in healthy phases during earth fault is at most 1,4 times the phase voltage in normal operation, the system is referred to as an effectively grounded system. (EN 50522 2010)

It is important to consider the earthing system in use, as this varies by country, and in some cases, even by regional areas. The earthing system affects flow and magnitude of fault currents and it is therefore vital to understand different systems before design. The earthing system type is different at different voltage levels, as each voltage level equipment have their own factors affecting design and the risk of touch voltages. Earthing system type is chosen considering various factors such as typical soil resistivity, relay protection and the ability to keep tolerable earthing voltages.

In Finland, the 400 kV and 220 kV power lines are effectively grounded, either straight or through current limiting chokes. The chokes are dimensioned to reduce voltage rises in healthy phases as well as to keep high enough earth fault currents to preserve quick protection functions during fault events. 110 kV lines are partially grounded via chokes to keep large enough earth fault currents so that protection relays can work selectively. By earthing the neutrals of only some transformers, earth fault currents can be limited to keep a low grounding voltage to ensure a safer system by keeping touch voltages low. This is a cheaper alternative and easier to implement than reducing earthing resistance. This is also referred to as a system with low-impedance neutral earthing. (Elovaara & Haarla 2011)

2.2 Standards

Standards are developed to maintain a uniform approach to engineering. Standards ensure equipment and systems are compatible and operate in a safe manner the way they are intended. Countries have different standards according to their technical specification of choice, and the specific standard and its specific requirements must always be studied for design of installations in other countries.

This thesis is focused on the standard SFS 6001, which is used when designing substation in Finland. SFS 6001 is based on the EN standards EN 50522 and EN 61936-1, taking local Finnish requirements and factors into account. These standards give technical factors that must be considered during design, such as permissible voltage levels as well as thermal and mechanical stress. Most relevant design factors from SFS 6001 and EN 50522 are presented next.

2.2.1 Acceptable voltage levels

The SFS and EN standards give acceptable voltage levels for touch and step voltages. These voltages are based on how dangerous the current is for humans considering current routes through the body, fault duration, resistances and human body impedance. Generally, it can be said that if a system meets touch voltage requirements, it also meets step voltage requirements, as touch voltage limits are a lot more restricting due to the current having a more harmful route through the human body. (SFS 6001 2018)

Safety criteria are based on the dangers an electrical current can have in humans, such as the current flowing through the heart causing ventricular fibrillation and fault duration. Current flow paths through the body and the corresponding impedance of the human body are also considered in the limit values, as well as the resistances between points of contact such as hands and feet. The resistance of gloves, footwear and other resistance increasing factors such as insulating surface layers can be accounted as additional resistances, which are explained in more detail in chapter 4.7. Limit values for current passing through the body have been converted into voltage limit values to enable comparing to calculated and measured step and touch voltage values. Permissible touch voltages according to EN 50522 and SFS 6001 are presented in the figure 2.4. Permissible values depend on the fault duration, so that in longer fault durations, higher touch voltages are no longer allowed. (SFS 6001 2018)

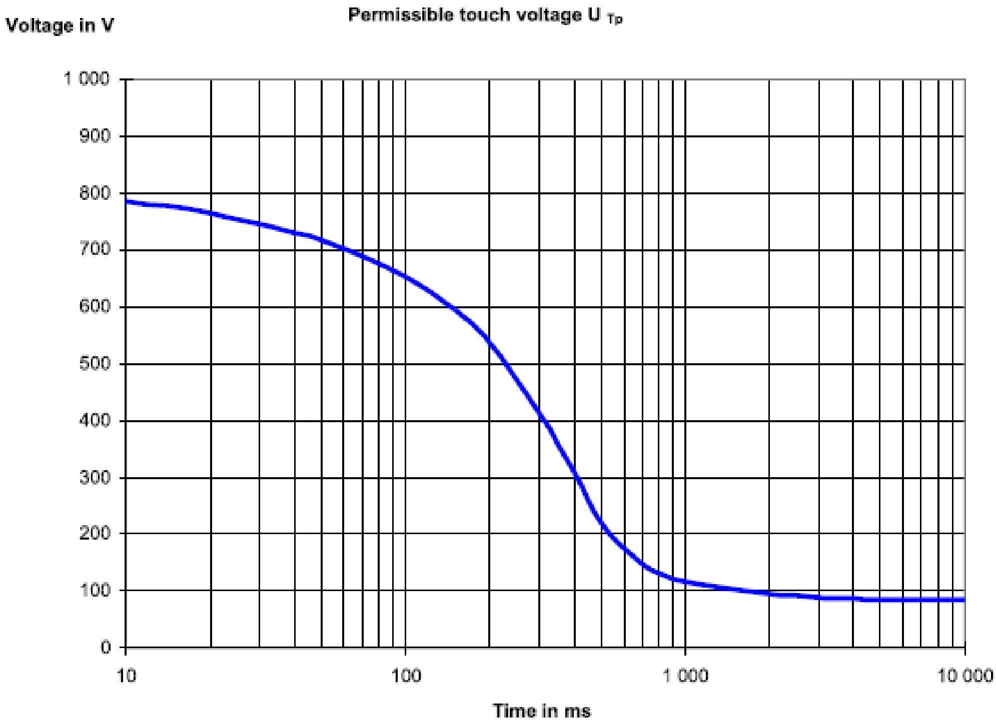
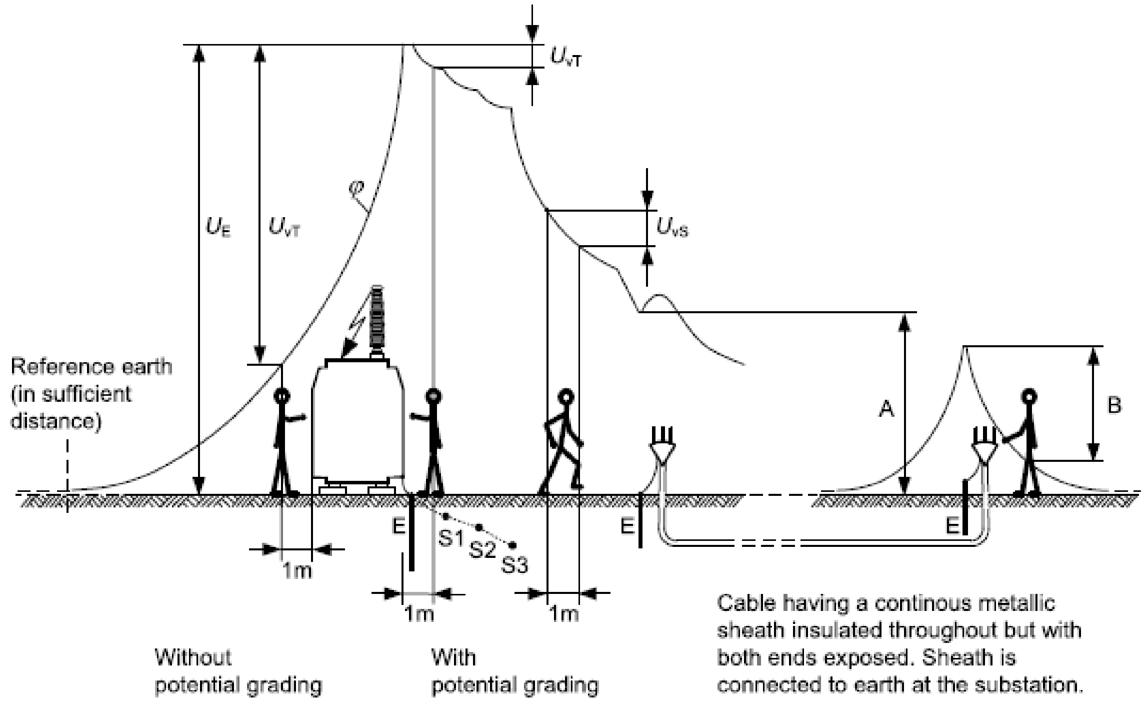


Figure 2.4 Permissible touch voltages in relation to fault duration. (EN 50522 2010)

If a fault duration is considerably longer than 10 s a value of 80 V may be used as permissible touch voltage (EN 50522 2010). For high voltage lines and substations, a fault duration of more than 10 s is however not expected as protection times are fast compared to lower voltage systems.

Optimally touch voltages could be limited to safe values by decreasing earthing resistance with the earthing conductors, but this is not always a cost-effective solution. Therefore, relay protection operation times may need to be adjusted to a shorter time duration to achieve both a cost-effective and safe solution. Another solution is to completely isolate the area where high earth potentials occur from vulnerable subjects, or to cover the area with poorly conductive materials such as asphalt and gravel. Touchable metal parts can also be covered with insulating layers to prevent touch voltages. (Elovaara & Haarla 2011) Isolating and other special measures are often easy to apply at a substation and many times already done even without the touch voltage limits demanding so. Even if the area is closed off, the possibility of hazardous transferred potential outside the isolated area must be assessed.

The following figure 2.5 visualizes how touch and step voltages are carried over from equipment and earth to humans. As seen in the figure, transfer voltages are also a risk that should be considered during design.



E	Earth electrode	U_E	Earth potential rise
S1, S2, S3	Potential grading earth electrodes (e.g. ring earth electrodes), connected to the earth electrode E	U_{vS}	Prospective step voltage
		U_{vT}	Prospective touch voltage
		A	Prospective touch voltage resulting from transferred potential in case of single side cable sheath earthing
		B	Prospective touch voltage resulting from transferred potential in case of cable sheath earthed on both sides
		φ	Earth surface potential

Figure 2.5 Touch and step voltages (EN 50522 2010)

As can be seen from the figure, the potential curve φ is the steepest at the fault point. Therefore, the highest earth potentials occur at the faulted structure that the current travels to earth via. Earthing can significantly reduce the effects of the hazardous potentials in this case as indicated.

Some form of risk analysis can be done, as to probabilities of vulnerable subjects being in the proximity of the possible earth potential rise area. Some substations may be located very far from any population with only occasional passing by traffic. On the other hand, some substations, especially GIS installations, can be in proximity or in the middle of highly populated areas. In this case special attention must be paid to transferred potentials and reliable isolation of the area.

2.2.2 Thermal and mechanical strength

Earthing electrodes must be dimensioned to withstand both thermal and mechanical loads in all events. Therefore, electrodes must be able to endure the highest possible fault currents as well as to withstand corrosion and any mechanical influences during installation and service of the asset. Standards give minimum cross-section dimensions for electrodes to meet these mechanical requirements, as well as acceptable load capacities for different conductors. (SFS 6001 2018)

Relevant currents differ depending on earthing system, but often ready-made tables of allowable electrode cross sections are available. The different currents as well as the relevant tables and formulas from the standard for thermal dimensioning are presented in chapter 3.2.2.

2.2.3 Design process

The designing process of a substation earthing grid is given in the form of a block diagram in standards. The block diagram is presented in figure 2.6. (EN 50522 2010)

As given in the standard, if the system is part of a global earthing system, or if the earthing voltage is less than 2 U_{TP}, the system is considered safe regarding touch voltages. A global earthing system is a system where no or only minor potential differences occur. There are no specific rules to define whether the system is part of a global system or not and must be evaluated on a case-by-case basis as given in the standard. Substations are rarely considered part of a global system and designed according to the block diagram below.

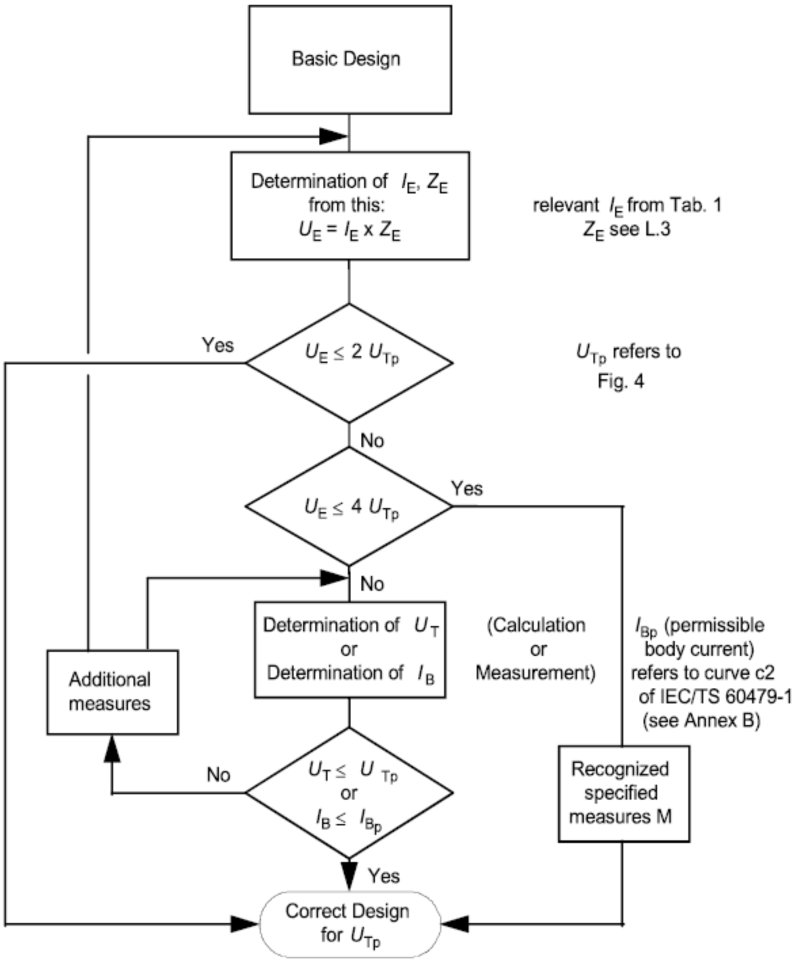


Figure 2.6 Block diagram for designing earthing systems not part of a global earthing system. (EN 50522 2010)

If 2 U_{TP} values are economically unreasonably hard to achieve, higher U_{TP} values may be applied in design if certain special conditions M presented in the SFS 6001-standard annex E are met. (SFS 6001 2018)

These special conditions are often met at a substation, which means that the 4 U_{TP} after applying measures can be considered safe. Touch potential level of 4 U_{TP} is usually reasonably achievable both technically and economically in most cases.

3. FAULT CURRENTS

It is important to consider the fault events causing earth potential rise (EPR) at the substation area. The substation must be considered safe under any fault event and all seasonal conditions, during the whole life cycle of the asset. The most essential factors for earthing system sizing are the magnitude of the earth fault current, fault duration and resistive properties of the soil. Different fault scenarios are shortly presented in this chapter to demonstrate how different faults occur and how relevant currents for design change between different applications.

3.1 Fault scenarios

Faults in the power system are relatively uncommon, as various measures are taken to reduce interruptions in supply which can cause wide blackouts in the electricity network. Different fault events must always still be considered in design to maintain safety and correct operation in the system.

Faults may occur both for the primary or secondary side and currents may travel even far between systems if there is a conductive travel path for the current. Figure 3.1 showcases these typical fault scenarios and how fault currents can travel between earthing systems.

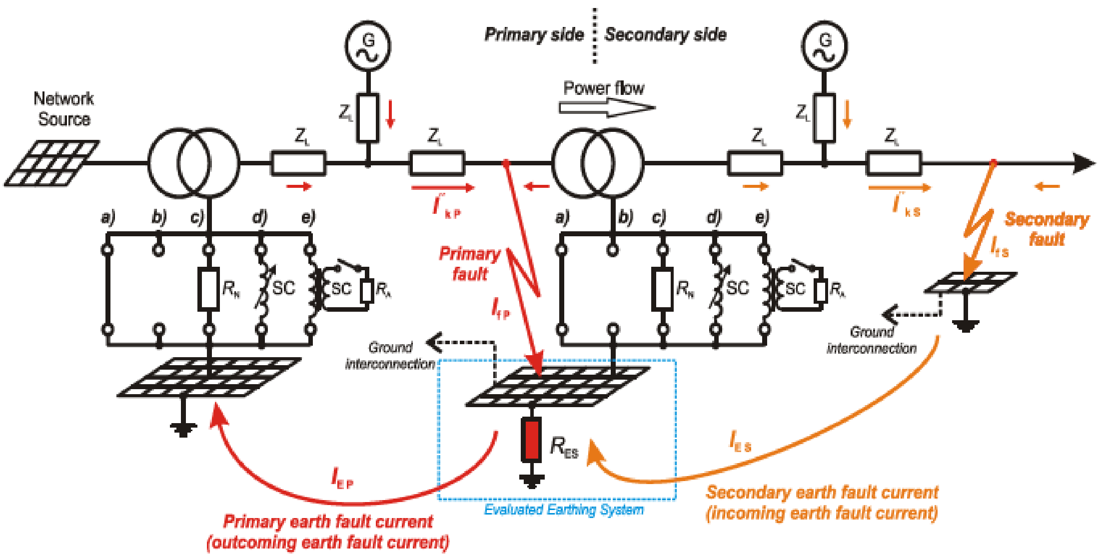


Figure 3.1 Typical fault scenarios both for primary and secondary side. (CIGRE 749 2018)

Fault are often categorized into short circuits and earth faults, and further categorized into single- and multi-phase fault cases. These are both briefly presented in the following chapters. Secondary earth faults are limited outside the scope of this thesis.

3.1.1 Short circuit

Short circuit occurs when live parts of the electrical system are connected through low resistance. Typical features for short circuits are high current and low voltage at fault, and they are often caused by environmental overvoltages such as lightnings, equipment malfunctions or human error. Short circuit currents do not flow through the earth, so they do not contribute to earth potential rise. Different occurrences of short circuits are presented below in figure 3.2.

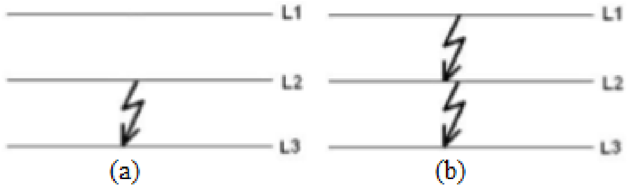


Figure 3.2 Short-circuit types. (a) 2-phase short circuit, (b) 3-phase short circuit. (Koivunen 2011)

A 2-phase short circuit is a relatively common occurrence in the distribution network in comparison to other short circuits. 2-phase short circuit occurs when two current carrying conductors are in contact with each other. A 2-phase short circuit is unsymmetrical fault, that can be caused for example by wind causing two phases to short circuit between each other (Elovaara & Haarla 2011).

A 3-phased short circuit is a symmetrical fault unlike a 2-phase short circuit, which means that voltages and currents are the same in all phases. A typical 3-phase short circuit is often a 3-phase short circuit through earth caused by lightning (Elovaara & Haarla 2011). A 3-phase short circuit can occur for example through earthing knives, which means that the earthing grid in the proximity of the earthing knives should be designed thermally resistant for the 3-phased short circuit current to prevent any damage to conductors. However, according to the standard this is not required, as illustrated in the table 3.1 presented later.

The following figure 3.3 illustrates the difference between a symmetrical and unsymmetrical fault event. Both 1-phase and 2-phase earth faults presented next are unsymmetrical events.

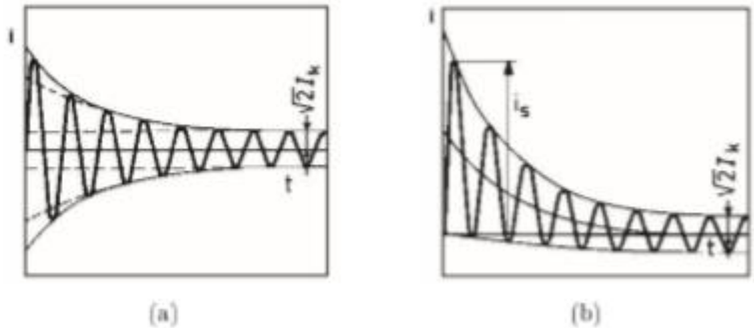


Figure 3.3 (a) Symmetrical short circuit current (b) unsymmetrical short circuit current. (Koivunen 2011)

Short circuits, even though having large fault currents, do not contribute to earth potential rises as the earth is not a part of the circuit. Short circuits can however escalate into earth faults if the rise of phase voltage causes insulation breakdown. Different types of earth faults are presented in the following chapter.

3.1.2 Earth fault

Earth fault, also referred to as ground fault, is an occurrence where the live conductor is accidentally conductive with the earth. This can happen through various events like through steel structures, failure of insulation or of the live overhead line dropping to the ground. A high current earth fault can be classified as a type of short circuit, where the fault current travels through the ground. Fault current magnitudes are typically lower during earth fault events than during short circuit events, but earth fault maximum currents affect the sizing of the earthing grid and are therefore important for ensuring safe operation of the substation. Different earth fault occurrences are presented below in figure 3.4.

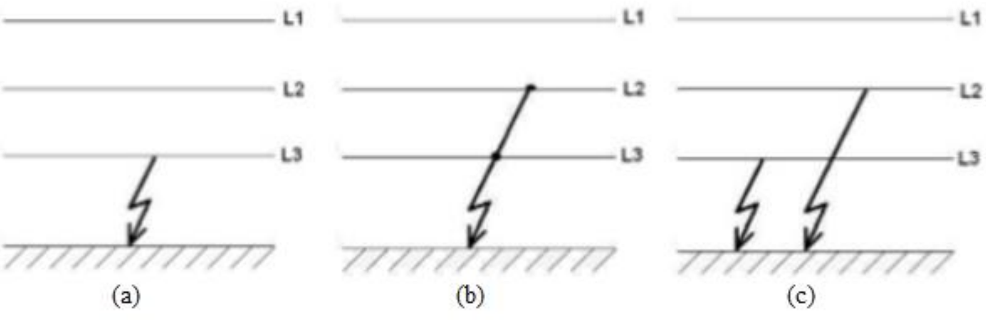


Figure 3.4 Earth fault types. (a) 1-phase earth fault, (b) 2-phase earth fault, (c) Double earth fault. (Koivunen 2011)

A 1-phase earth fault is the most common occurrence often caused by lightning. This fault can spread into a 2-phase earth fault as the insulation limits are exceeded by the rising voltage in the healthy phases (Elovaara & Haarla 2011). Earth faults in a system earthed straight or via a low impedance have considerably higher fault currents than in other systems. Usually the fault currents are of such magnitude, that the term 1-phase short circuit can be used. Under certain conditions, the fault current of a 1-phase short circuit can be even higher than in a 3-phase short circuit. This is specially the case in systems where the transformer connection is Yz, Dy or Dz and the fault occurs close to an earthed secondary winding (Salminen 2009). By earthing the neutral point, earth fault current magnitude current can be limited. In some lower voltage installations, the system can in some situations even stay fully operational during an earth fault as touch voltage limits are not exceeded. This is however not the case in transmission lines due to the earthing system and the magnitude of the transmitted power.

During an earth fault, voltages in healthy phases can rise higher than at normal operation. Therefore, a 1-phase earth fault can sometimes lead to a 2-phase earth fault. 2-phase earth faults can occur as two simultaneous earth faults at different locations (double earth fault), or at the same location. The latter is also referred to as a 2-phase short-circuit with an earth connection. In a straight or low impedance earthed system the voltage rise in the healthy phase is usually smaller due to a lower total fault impedance in the fault circuit. Effects from overvoltages are also shorter as due to the high fault current, short circuit protection often trips the feeding line faster than earth fault protection would. (Salminen 2008)

The magnitude of earth fault current and the effects of the fault depend both on the fault resistance and grounding system. Transmission lines and transformers increase the fault impedance and therefore limit the fault current. This means that the fault current decreases as the further the fault is from the feeding station.

It is important to know both maximum and minimum fault currents, as generally the maximum currents determine technical aspects and sizing of the components, and minimum currents must be known for designing protection systems. For earthing grid design, the current resulting in the highest earth potential rise is of most importance, as the earthing voltages must be kept under a certain limit to be considered safe.

3.2 Relevant currents according to SFS 6001 and EN 50522

It is important to know what the relevant current contributing to earth potential rise is as to not over- or undersize the system. Relevant currents are different for various earthing system types, as indicated in the table 3.1.

Table 3.1. Relevant currents for earthing design. References refer to the ones in the standard (EN 50522 2010)

Type of high voltage system	Relevant for thermal loading [a e]		Relevant for earth potential rise and touch voltages
	Earth electrode	Earthing conductor	
Systems with isolated neutral			
	I''_{kEE}	I''_{kEE}	$I_E = r \cdot I_C$ [b]
System with resonant earthing Includes short time earthing for detection			
Substations without arc-suppression coils [f]	I''_{kEE}	I''_{kEE}	$I_E = r \cdot I_{RES}$ [b]
Substations with arc-suppression coils	I''_{kEE}	I''_{kEE} [c]	$I_E = r \cdot \sqrt{I_L^2 + I_{RES}^2}$ [b h]
Systems with low-impedance neutral earthing Includes short time earthing for tripping [g]			
Substation without neutral earthing	I''_{k1}	I''_{k1}	$I_E = r \cdot I''_{k1}$
Substation with neutral earthing	I''_{k1}	I''_{k1}	$I_E = r \cdot (I''_{k1} - I_N)$ [d]

[a] If several current paths are possible a split up may be considered.

[b] If there is no automatic disconnection of earth faults, the need to consider double earth faults depends on operational experience.

[c] The earthing conductor of the Petersen coil has to be sized according to the maximum coil current.

[d] It has to be checked if external fault may be decisive.

[e] The minimum cross-sections of annex C are to be considered.

[f] In case of not well compensated system the general approach of 10% I_C can not be applied. The reactive/capacitive component of residual current has to be considered additionally.

[g] Short term earthing of system with resonant earthing starts automatically within 5 s after earth fault detection.

[h] In case of a fault in the substation the capacitive earth fault current I_C has to be considered. In case of further coils external to the substation they may be considered.

Legend:

I_C Calculated or measured capacitive earth fault current
I_{RES} Earth fault residual current (see Figure 3b)
If the exact value is not available, 10 % of I_C may be assumed.
I_L Sum of the rated currents of the parallel arc-suppression coils in the relevant substation
I''_{kEE} Double earth fault current calculated in accordance with IEC 60909.
For I''_{kEE} 85 % of the initial symmetrical short-circuit current may be used as a maximum value
I''_{k1} Initial symmetrical short-circuit current for a line-to-earth short-circuit, calculated in accordance with EN 60909
I_E Current to earth (see Figure 2)
I_N Current via neutral earthing of the transformer (see Figure 2)
r Reduction factor (see Annex I)

If the lines and cables leaving the substation have different reduction factors, the relevant current has to be determined (in accordance with Annex L).

For 110, 220 and 400 kV high voltage lines in Finland, the used systems are basically the systems with low-impedance neutral earthing. In northern Finland, some parts of the 110 kV network are earthed via with arc-suppression coils, where different parameters must be applied as shown in the table. Figures and annexes in table 3.1 refer to the ones in the standard EN 50522.

3.2.1 Current contributing to earth potential rise

For systems other than with isolated neutral, the earth fault current leading to earth potential rise can be calculated from the zero-sequence current. As given in the standard annex L

$$I_E = r\sum 3I_0 \tag{3.1}$$

where

r is the reduction factor

$\sum 3I_0$ is the vector-sum of the zero-sequence currents of all phases of all lines feeding the station

(SFS 6001 2018)

The initial symmetrical short-circuit current for a line-to-earth short-circuit shown in the table 3.1 is equal to three-times the zero-sequence current described above. The zero-sequence currents contributing to earth potential rise can vary by fault location according to IEC 60909-3, this is explained in more detail in chapter 4.

If the shield wire reduction factors are different to each other, the earth current can be derived from

$$I_E = r_A 3I_{0A} + r_B 3I_{0B} + r_C 3I_{0C} + \cdots \tag{3.2}$$

where

r_A is the reduction factor for the shield wire of line A, respectively r_B is the reduction factor for line B etc.

I_{0A} is the zero-sequence current for a phase (e.g L1) of line A, I_{0B} respectively for a phase of line B etc.

(SFS 6001 2018)

If the station has an outgoing cable instead of a HV overhead line, the reduction factor of the cables is to be used in place of the shield wire reduction factor. Reduction factors for cable sheaths are given in the standard or from the manufacturer and are much smaller than for overhead lines. (SFS 6001 2018)

In a fault occurring at the station, $\sum 3I_0$ is the earth fault current subtracted by the current through the transformer neutral, if the transformer neutral is earthed. In this case, a scenario of a fault event occurring outside the station and its effect on earth potential rise must be evaluated. These different fault scenarios for different fault locations are presented in chapter 4.

3.2.2 Current contributing to thermal stress

The current to be used for dimensioning for thermal capacities in transmission systems is typically I''_{k1} as given in the standard. This is for both earth electrodes and earthing conductors as illustrated in table 3.1. The table also gives relevant currents for other earthing systems, but the above applies for typical Finnish high voltage systems. In some cases, the 3-phased short-circuit may pass through the earth, and the earthing conductors must be dimensioned accordingly. The possibilities of higher fault current flowing through the earth must be evaluated separately for each case, for example in the case of earthing knives at the substation. It is important to note that the whole earthing system must not be dimensioned for the 3-phased fault current, but only the part between the faulted phases where the 3-phase short-circuit current I''_{k3} may flow.

The cross section of earthing conductors and earth electrodes is dependent on fault current magnitude and duration. In faults lasting under 5 s, the formula 3.3 is used. (SFS 6001 2018)

$$A = \frac{I}{\mathrm{K}} \sqrt{\frac{t_f}{\ln \frac{\theta_f - \beta}{\theta_i + \beta}}} \tag{3.3}$$

where

A	is the cross section in mm^2
I	is the conductor current in amperes (RMS value)
t_f	is the duration of the fault current in seconds
K	is a constant depending on the material of the current-carrying component: table 3.2 provides values for most common conductor materials in 20 °C
β	is the reciprocal of the temperature coefficient of resistance of the current-carrying component at 0 °C.
θ_i	is the initial temperature in degrees Celsius. Values may be taken from IEC 60287-3-1. If no value is laid down in the national tables, 20 °C as ambient ground temperature at a depth of 1 m should be adopted.
θ_f	is the final temperature in degrees Celsius

Table 3.2 Material constants for different type conductors. (EN 50522 2010)

Material	β in °C	K in $A \cdot \sqrt{s} / mm^2$
Copper	234,5	226
Aluminium	228	148
Steel	202	78

The figure 3.5 below gives short-circuit densities for different type earth electrodes and conductors in relation to the fault current.

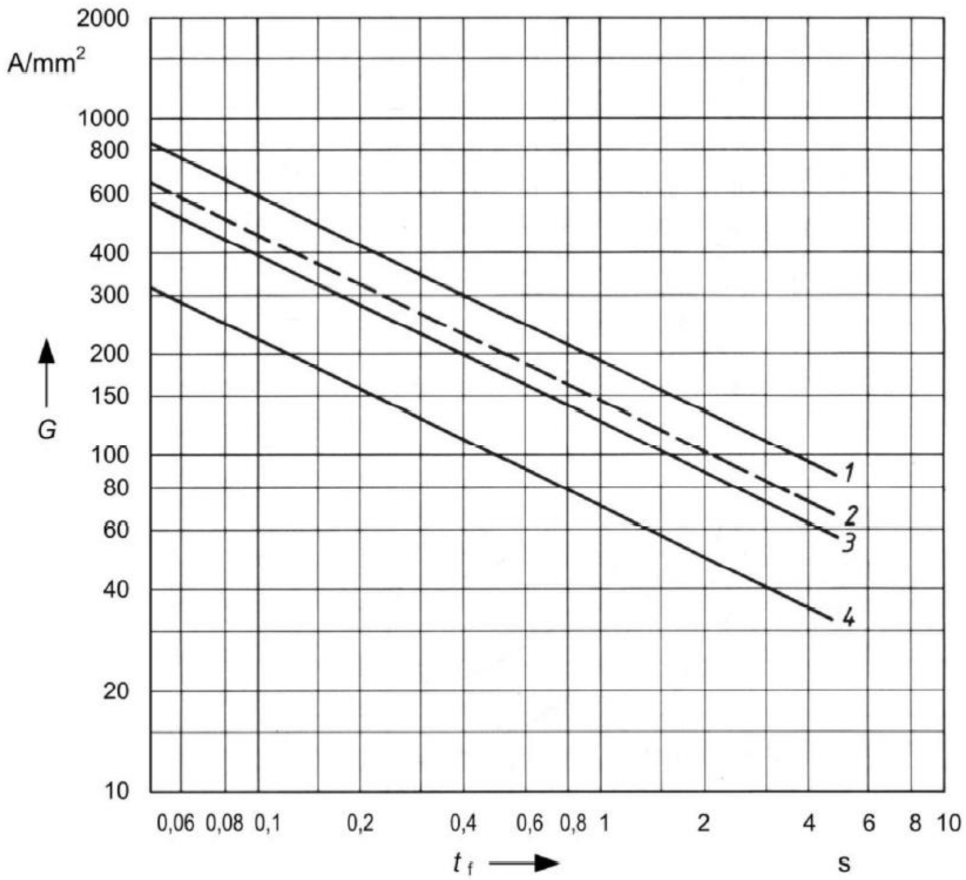


Figure 3.5 Short-circuit current density G for earth electrodes and earthing conductors relative to the duration of the earth fault current t_f. Line 1, 3 and 4 apply for a final temperature of 300 °C, whereas line 2 applies for 150 °C. Lines correspond to the following materials (EN 50522 2010):

1 Copper, bare or zinc-coated

2 Copper, tin-coated or with lead sheath

3 Aluminum, only earthing conductors

4 Galvanized steel

The minimum cross-section can be determined from the table and the fault current using the formula

$$A = \frac{I}{G} \tag{3.4}$$

where

I is the maximum earth-fault current in A

G is the earth-fault current density in A/mm^2 from the table

Standards give conversion factors if other than 300 °C (for bare or galvanized copper, aluminum or galvanized steel) or 150 °C (for tinned or lead coated copper) are used, however this is only allowed if specific conditions are met and not generally applicable. Due to challenging earthing conditions in Finland, bare copper is heavily favored. (EN 50522)

3.3 Fault time contributing to earth potential rise

Used fault time in earthing design calculations has a significant effect on dimensioning of the system. As the touch voltage limits decrease and the probability of the risk grows in relation to increasing fault time, fault duration is an important aspect to consider in design. For transmission lines, the times are typically in the range of 0.25 – 1.0 s (CIGRE 213 2002).

Available information on recorded fault clearance times in Finland was researched, but none were found publicly available. However, recorded data from UK transmission network from a 10-year period as well as Portuguese HV earth fault clearing time data were found and are presented in figures 3.6 and 3.7.

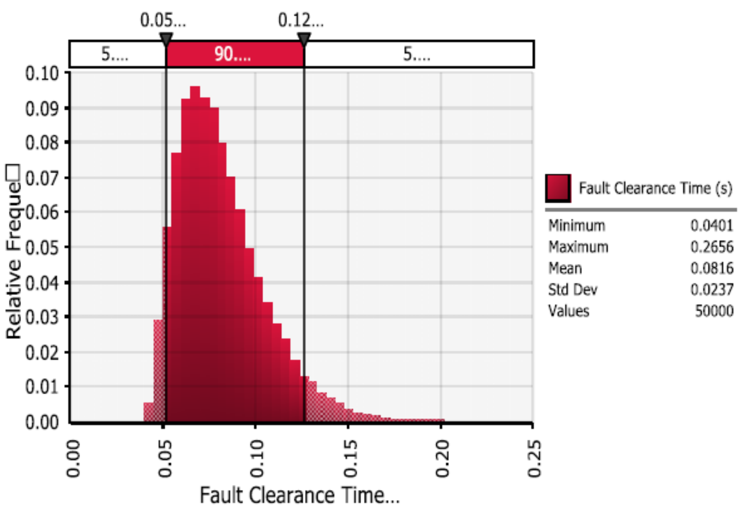


Figure 3.6 Fault clearance times in UK transmission network over a 10-year period. (CIGRE 749 2018)

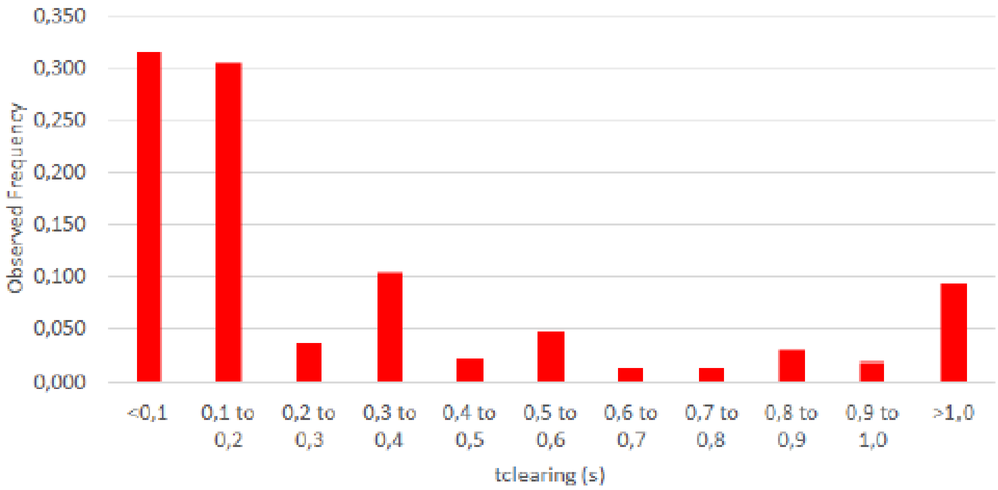


Figure 3.7 Recorded data from Portugal for HV earth fault clearing time. (CIGRE 749 2018)

As can be seen from the figures, the clearance times can vary greatly by country. The fault types for the UK clearing times have not been clarified and may include other fault types than earth faults. The applied earthing system also affects the currents and therefore the operation of relay protection, which is why fault clearance times are not directly comparable between different system configurations. However, most of the faults are cleared relatively fast according to the figures.

According to Fingrid, owner of transmission lines in Finland, the clearance times for 400 kV network short-circuits must be cleared within 0.1 s. For the 110 and 220 kV lines, clearance times for short-circuits and ordinary earth faults (with a fault resistance of < 20 Ω) are cleared latest at 0.5 s. The back-up protection mainly functions with a 0.1 s – 1.0 s delay depending on the substation fault current and fault location. High resistance earth faults (20…500 Ω) are cleared in the range of 1…3 s, latest at 5 s from fault event. (Fingrid 2017)

CIGRE recommends that earthing grid is designed with the back-up protection clearing time in mind (CIGRE 213 2002). However, in calculations it must be noted that while the duration increases, the applicable permissible touch voltage decreases. In practice, a 0,2 s fault duration is often used, but this must always be determined on a case-by-case basis.

Fault currents are divided into classes, the initial short-circuit current, transient short-circuit current and the steady-state current. The initial short-circuit, I''_k, is an important tool as a dimensioning current for the design. The transient short-circuit current, I'_k, follows the initial short-circuit current but is not used as dimensioning factor for earthing design. Both the initial short-circuit current and transient short-circuit current dampen by their time constants.

The steady-state current, I_k, is only reached in lower voltage distribution grids, and very rarely there as well, as the protection times for transmission grids is between 0,1 s and 0,5 s. (Elovaara & Haarla 2011)

The IEC 60909-0 standard gives detailed advice on how the steady-state currents should be calculated, where the methods are different for three-phase short circuits and for unbalanced short circuits. According to the standard, for unbalanced short circuits, such as a line-to-earth fault, the flux decay in the generator is not taken into account and the following formula (3.5) should be used. The same principle applies for other unbalanced fault events as indicated in the standard.

$$I_{k1} = I''_{k1} \tag{3.5}$$

For balanced three-phase short circuits it can generally be said that the further away the fault point is from the network feeding points, the less difference there is between the steady-state and initial short-circuit current. Various parameters regarding generator properties and system configurations must be considered for this case which are not further researched within this thesis. (IEC 60909-0 2016)

4. DISTRIBUTION OF FAULT CURRENTS

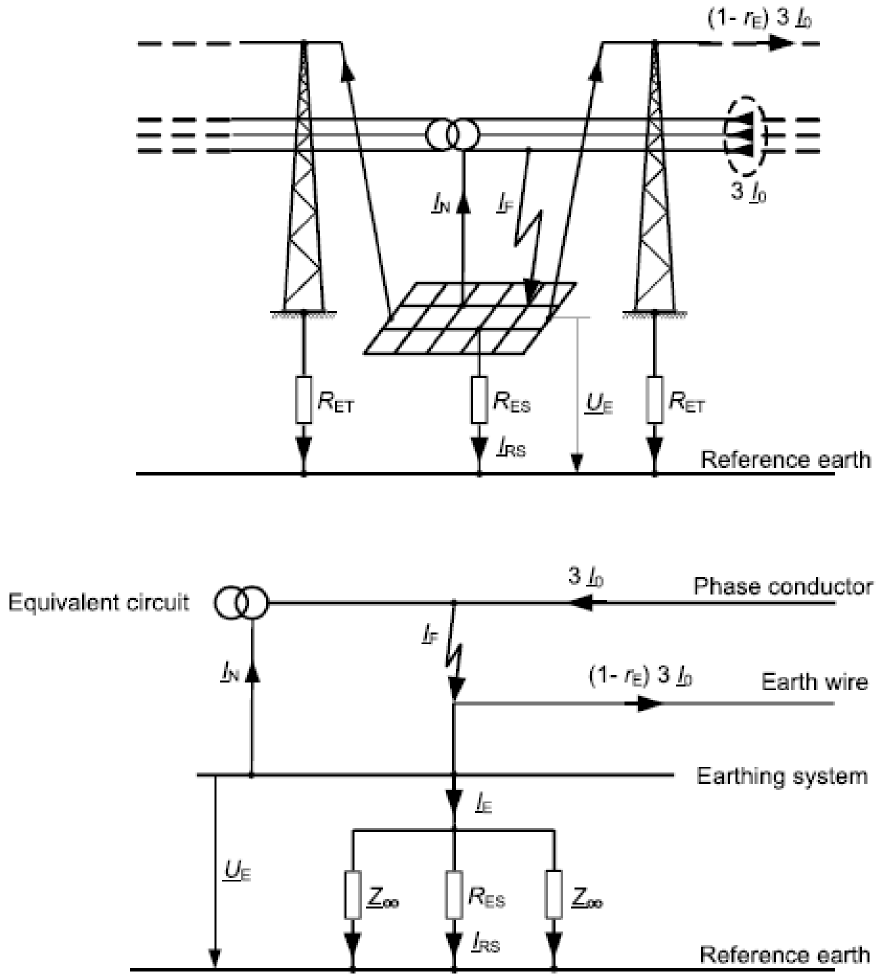
The relevant designing currents according to the SFS standard were researched in the previous chapter. In this chapter, the current distribution between different parts of the system is researched to form a better understanding of the partial currents that contribute to earth potential rise and those that do not.

Dimensioning the earthing grid according to the highest fault current may be causing unnecessary oversizing in the system. When designing earthing systems, only the portion of fault current returning through the earth and buried components causes earth potential rise. This current is often referred to as “current to earth”, “earth current” or earth return current” in different standards and labeled as I_E. (CIGRE 749 2018)

In an earth fault event, with a transformer earthed from its neutral point (star-point) and one high voltage line supplying the earth fault current, the current flows are divided into three parts. (Elovaara & Haarla 2011)

- The current flowing along the earthing grid to the transformer neutral
- The current returning along the overhead shield wires
- The current returning through the earth

Armoring and shields of cables can also be accounted for, with their respective reduction factors instead of shield wire reduction factors. Current distributions are visualized in the figure 4.1. Current distribution pathways and magnitudes vary with different earthing systems and fault situations, which must be considered in design. Differentiating the current contributing to earth potential rise and other fault currents that influence other design parameters is important as to not undersize or oversize the earthing system.



$$\underline{I}_F = 3\,\underline{I}_0 + \underline{I}_N$$
$$\underline{I}_E = \underline{r}_E \cdot (\underline{I}_F - \underline{I}_N)$$
$$\underline{U}_E = \underline{I}_E \cdot \underline{Z}_E$$

$$\underline{Z}_E = \frac{1}{\frac{1}{R_{ES}} + n\,\frac{1}{\underline{Z}_\infty}}$$

For equal earth wire tower footing impedances of the overhead lines

$3\,\underline{I}_0$	Three times zero sequence current of the line
$\underline{I}_N$	Current via neutral earthing of the transformer
$\underline{I}_F$	Earth fault current
$\underline{I}_E$	Current to earth (cannot be measured directly)
$\underline{I}_{RS}$	Current via the resistance to earth of the mesh earth electrode
$\underline{r}_E$	Reduction factor of the overhead line
R_{ES}	Resistance to earth of the mesh earth electrode
R_{ET}	Resistance to earth of the tower
$\underline{Z}_\infty$	Chain impedance (earth wire/tower footing) of the overhead line assumed to be infinite
$\underline{Z}_E$	Impedance to earth
$\underline{U}_E$	Earth potential rise
n	Number of overhead lines leaving the substation (here: n = 2)

Figure 4.1 Earth fault in a transformer substation with low impedance neutral (star-point) earthing. (EN 50522 2010)

The proportion of the fault current returning along the overhead shield wires, $(1-r)3I_0$, is determined by the reduction factor r. Some current is also distributed through the neutral earth and nearest tower footings, as illustrated in figure 4.1. The earthing grid and the effect of nearest tower footings are often in the same field potential, and therefore the accurate calculation of earthing impedance is often impossible. Earthing measurement is the only way to accurately determine the earthing impedance.

The main purposes of tower earthing are to:

- reduce lightning disturbances by reducing the tower earthing potential, so that the lightning strike does not cause an electric breakdown between the insulated part and the conductor
- enable the function and improve the sensitivity of earth-fault protection even on lines equipped with shield wires
- lower the tower earth potential rise

In Finland's challenging earthing conditions, it has been noticed that tower earthing is crucial to maintain the effect of shield wires. In extreme cases, designing earth-fault protection according to regulation may prove to be impossible without shield wires. (Elovaara & Haarla 2011)

Shield wires and tower footings are important regarding reducing earth potential rise, especially with steel aluminum shield wires, as the current flowing through the earth is reduced by a significant amount compared to a system without shield wires. Generally the reduction factors for steel shield wires are in the range of 0,9-0,95, and for steel aluminum shield wires in the range of 0,3-0,55. In Finland's high resistant soil, shield wires are often always required to maintain a tolerable earth potential rise. (Elovaara & Haarla 2011)

Often the hardest earthing problems are caused by earth-fault potentials transferring to low voltage systems (Elovaara & Haarla 2011). These can be hard to account for in the design phase and must often be assessed on a case-by-case basis. Further consideration on transferred voltages is done in chapter 5.

As the table 4.1 illustrates, short-circuit and earth fault currents vary significantly between different voltage levels. These values can be useful for reference when designing the earthing grid, as for example designing for a 110 kV system, the engineer can see that earth fault current magnitude should typically be between 0 kA and 5 kA. If higher fault current values for dimensioning are used, special considerations for the core reason of these higher values must take place to not unnecessarily oversize the earthing system.

Table 4.1 Short-circuit and earth fault current ranges in Finland in year 2008. (Elovaara & Haarla 2011)

U_R/kV	I''_k/kA		$3I_0$/kA	
	max	min	max	min
400	22	10	13	6
220	12	2	11,5	1,5
110	37	1	5	0

The next subchapters present how fault currents flow in the different fault events. For simplifying the procedure, the network is considered to consist of overhead lines with a single circuit and one earth wire, with three substations A, B and C separated by a distance more than twice the far-from-station distance D_F which is calculated with the following formula (IEC 60909-3 2009):

$$D_F = 3\sqrt{R_T}\frac{d_T}{Re\{\sqrt{Z_Q}\}} \tag{4.1}$$

where

R_T is the tower footing resistance

d_T is the distance between towers

$\mathrm{Re}\{\sqrt{\underline{Z}_Q}\}$ is the real part of the square root of the earth wire impedance $\underline{Z}_Q = \underline{Z}'_Q\, d_T$

The calculations of $\underline{Z}'_Q$ for $\mathrm{Re}\{\sqrt{\underline{Z}_Q}\}$ are presented more in more detail in standard IEC 60909-3 page 20 and are not further researched in this thesis. The standard also gives examples of calculations and derives many formulas that are presented next in this thesis. These are clearly presented in the standard and therefore excluded from this thesis. Only formulas considered relevant for understanding the current flows in different systems and situations are presented.

4.1 Line-to-earth single phase earth fault at a station

Figure 4.2 illustrates how fault currents are distributed at an earth fault event inside a substation.

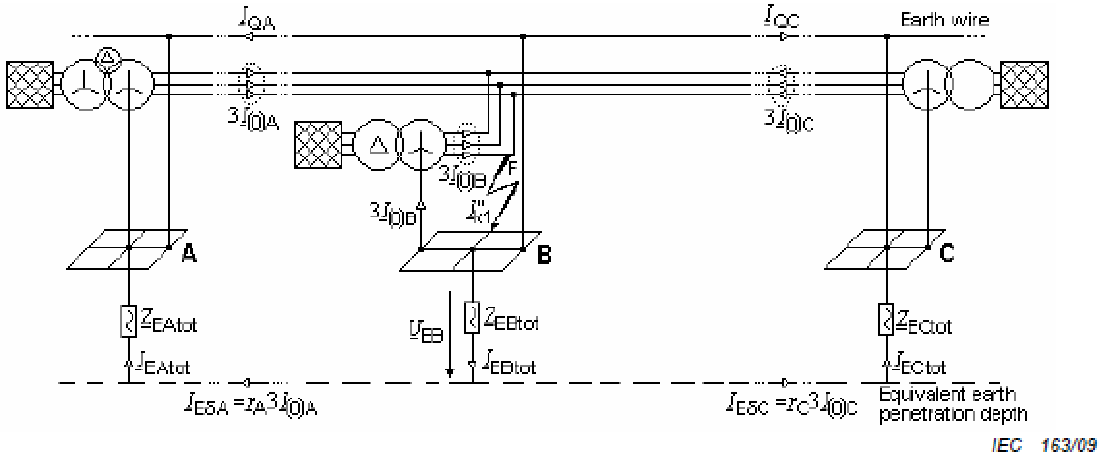


Figure 4.2 Partial short-circuit currents in a single-phase earth fault event inside substation B. (IEC 60909-3 2009)

As seen from the figure, the fault current is distributed through the shield wires, via the earthing grid to transformer neutral, and the earth. The fault current from line-to-earth is equal to three times the zero-sequence currents flowing to the fault location:

$$I"_{k1} = 3I_{(0)A} + 3I_{(0)B} + 3I_{(0)C} \tag{4.2}$$

The current $3I_{(0)B}$ does not contribute to earth potential rise as it flows back through the transformer neutral if the transformer is earthed. Currents $3I_{(0)A}$ and $3I_{(0)C}$ flow to substations A and C through the earth and shield wires and are distributed by respective reduction factors as seen in the figure. Therefore, the total current to earth contributing to earth potential rise at station B, when the station is earthed from transformer neutral point, can be calculated with the formula (4.3). (IEC 60909-3 2009)

$$I_{EBtot} = r_A 3I_{(0)A} + r_C 3I_{(0)C} \tag{4.3}$$

If the transformer is not earthed, the earth fault current can be calculated using formula (3.1), where the current through transformer neutral is not subtracted. Using I_{EBtot} and the total earthing impedance of the substation B, earth potential can be calculated using Ohm's law to verify safe design of the system.

Even if the stations A and C are nearer than D_F to station B in an earth fault inside the station, the total current I_{EB} is reduced by an additional part of the zero-sequence currents $r_A 3I_{(0)A}$ or $r_C 3I_{(0)C}$, therefore requiring no further actions. However, special considerations may be needed in the case of double-circuit lines or parallel lines with coupled zero-sequence systems as the induced currents can cause need for further examination especially regarding protection systems. (IEC 60909-3 2009)

The current to earth at substation B can be even higher if the earth fault occurs at a close distance (distance smaller than D_F) to the station, than the current calculated for a fault occurring inside the station with an earthed neutral. This scenario is presented in chapter 4.3.

4.2 Line-to-earth single phase earth fault outside a station

The figure 4.3 visualizes how fault currents flow during an earth fault event occurring outside of the station.

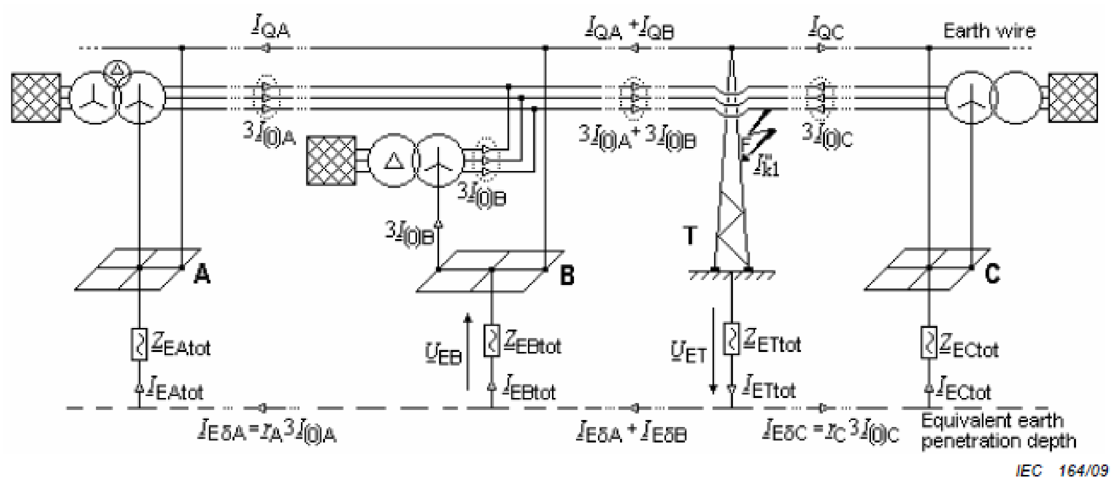


Figure 4.3 Partial short-circuit currents in a single-phase earth fault event at a tower outside substation B. (IEC60909-3 2009)

As seen in the figure, partial fault currents are flowing back to the stations A, B and C through the shield wires and the earth. The earth fault current is three times the zero-sequence current flowing to the fault point, similarly as in a fault happening inside the station.

The total current to earth at the faulted tower T far from the substation B and C (further than distance D_F) can be calculated with the following formula

$$I_{ETtot} = r_C\left(3I_{(0)A} + 3I_{(0)B} + 3I_{(0)C}\right) = r_C I''_{k1} \tag{4.4}$$

This current contributes to the earth potential rise at the faulted tower through the total tower earthing impedance, including footing resistance and driving point impedance. Tower potential risks are usually considered when designing the transmission lines by the network operator and are to be reassessed if changes to the system occur.

The current to earth at substation B can be calculated using the formula:

$$I_{EBtot} = r_c\left(3I_{(0)A} + 3I_{(0)B}\right) - r_A 3I_{(0)A} \tag{4.5}$$

Earth potential of station B can then be determined when earthing impedance of the station is known

$$U_{EB} = Z_{EBtot} I_{EBtot} \tag{4.6}$$

As can be seen from formula (4.5), the earth potential rise at the substation in this fault case is typically lower than other scenarios and is therefore not considered when designing substation earthing grids.

4.3 Line-to-earth single phase earth fault near the substation

An earth fault occurring a few kilometers from the station may cause a larger earth potential rise at the substation than a fault inside the station, therefore this case must be considered. This is the case especially if the shield wires are different and the substation transformer is earthed from the neutral point (Elovaara & Haarla 2011). The figure 4.4 illustrates how fault currents flow in a fault occurring in the vicinity of the substation.

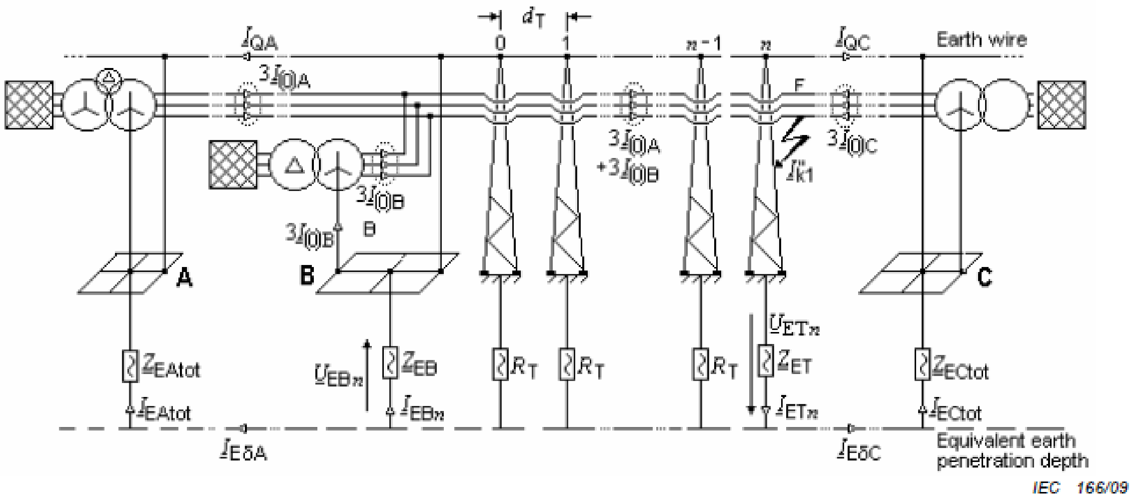


Figure 4.4 Partial short-circuit currents in a single-phase earth fault event in the vicinity of the substation B at tower *n*. (IEC60909-3 2009)

The current to earth contributing to earth potential rise at the station can be given as

$$I_{EBn} = r_C I"_{k1} \frac{Z_{ET}}{Z_{ET} + Z_{Pn}} \cdot \frac{2Z_P - Z_Q}{(Z_{EB} + Z_P)k^n - \left(Z_{EB} - Z_P + Z_Q\right)k^{-n}} - r_C 3I_{(0)B} \frac{Z_P}{Z_{EB} + Z_P} \quad (4.7)$$

where

$\underline{Z}_{ET}$	is the earthing impedance of the short-circuited tower
$\underline{Z}_P$	is the driving point impedance of an infinite chain
$\underline{Z}_{Pn}$	is the driving point impedance of a finite chain
$\underline{Z}_Q$	is the earth wire impedance, Z'_Q*d_T
$\underline{k}^n$	is calculated as 1+(Z_P/ R_T)

The earthing impedance of the short-circuited tower can be calculated with the following formula (IEC 60909-2 3009)

$$Z_{ET} = \frac{1}{\frac{1}{R_T} + \frac{1}{Z_P}} \quad (4.8)$$

where the driving point impedance of an infinite chain is

$$Z_P = 0{,}5Z_Q + \sqrt{\left(0{,}5Z_Q\right)^2 + R_T Z_Q} \quad (4.9)$$

Basically, a big part of the current can travel through the neutral point of the transformer if the fault occurs in the vicinity of the station. In this case, the current through the transformer neutral point also contributes to the earthing potential rise as it flows through the station B earthing impedance. The reduction factors also influence the current distribution in this scenario, as a significant part of the fault current can flow through the closest station earth if the reduction factors are significantly different. After knowing the earthing impedance Z_{EB}, the earth potential for station B during a fault at the tower *n* can be calculated with the following formula

$$U_{EBn} = Z_{EB} I_{EBn} \quad (4.10)$$

As for the different fault situations for overhead lines presented above, different fault situations for underground cables also affect the dimensioning and must be accounted for as explained in the next chapter.

4.4 Current distribution and reduction factor for underground cables

Similarly, as fault currents are distributed through shield wires, underground cables with metallic sheath or shield earthed at both ends can also act as current carrying conductors. The reduction factor depends on the type of cable and is given by the cable manufacturer (IEC 60909-3 2009). According to the standard SFS 6001, the chain impedance of the cable sheath and neighboring earthing grids can be considered in addition to the reduction factor, but only if the cable is significantly longer than the sections forming the chain impedance.

If the substation has an outgoing cable, according to SFS 6001 the reduction factor of the cables is to be used in place of the shield wire reduction factor. IEC 60909-3 goes deeper into how reduction factors are calculated but as they are given in the standard or from the manufacturer, this calculation is not included in this thesis. For three single-core cables, the reduction factor can even be much lower than indicated, as all 3 sheaths can contribute to distribution of fault currents (Popovic 2003). The calculation of reduction factor r_3 for three single-core cables is given in the formula (4.12). However, the reduction factor for one cable sheath is often enough, as the reduction factors for cables is even smaller than for overhead line shield wires.

In calculations, a distinction between a system with three single-core cables and a three-core cable connection must be made. As the outgoing cables from a substation are typically very large in diameter, the three single-core cable situation is the usual case and is considered below. The case of three-core cables is thoroughly presented in IEC 60909-3, but not presented here due to relevancy and limitations. A distinction must also be made between two fault events, a line-to-earth short-circuit in station B with the short-circuit current fed from the station A, or a short-circuit between the stations A and B. These fault events with their respective fault current distributions are explained in the next subchapters.

4.4.1 Line-to-earth short circuit in station B

Figure 4.5 illustrates how the fault currents flow in the system in a case where the fault at station B is fed from station A.

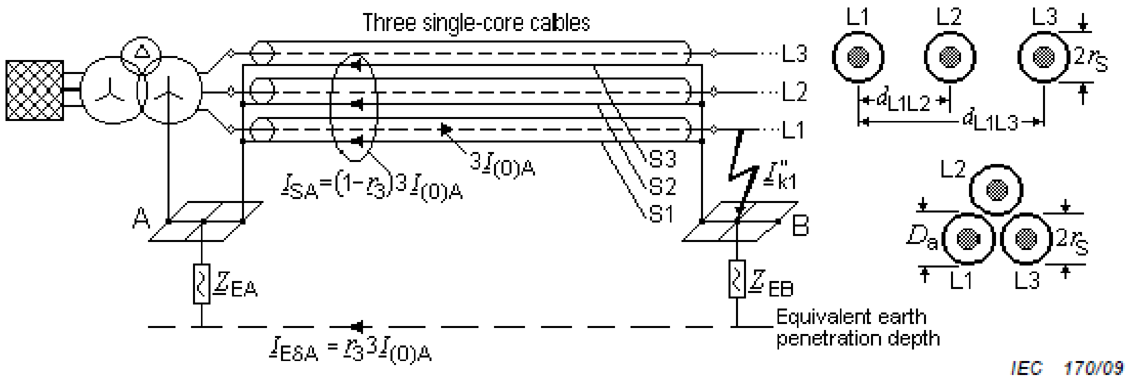


Figure 4.5 Line-to-earth short circuit in station B with fault current fed from station A only. (IEC 60909-3 2009)

In this fault case, the current through earth that flows back to station A can be calculated with the formula as also indicated in the figure

$$I_{E\delta A} = r_3 3I_{(0)A} \tag{4.11}$$

where $\underline{r}_3$ is the reduction factor for the three cables, that can be calculated by the formula (4.12) given in standard IEC 60909-3, where the layout and distances between cable phases are considered, or by using the reduction factors given in the standard SFS 6001. $3I_{(0)A}$ can be assumed to be equal to I''_{k1} in this case.

$$r_3 = \frac{R'_S}{R'_S + 3 \cdot \omega \frac{\mu_0}{8} + j3 \cdot \omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{\sqrt[3]{r_S d_{L1L2} d_{L1L3}}}} \tag{4.12}$$

The IEC 60909-3 standard gives detailed examples for calculating the reduction factors among other things. Therefore, the exact calculations and all formulas for variables are not presented.

4.4.2 Line-to-earth short circuit between stations A and B

Figure 4.6 illustrates how the fault currents flow in the system in a case where the fault occurs between two stations and is fed from both directions.

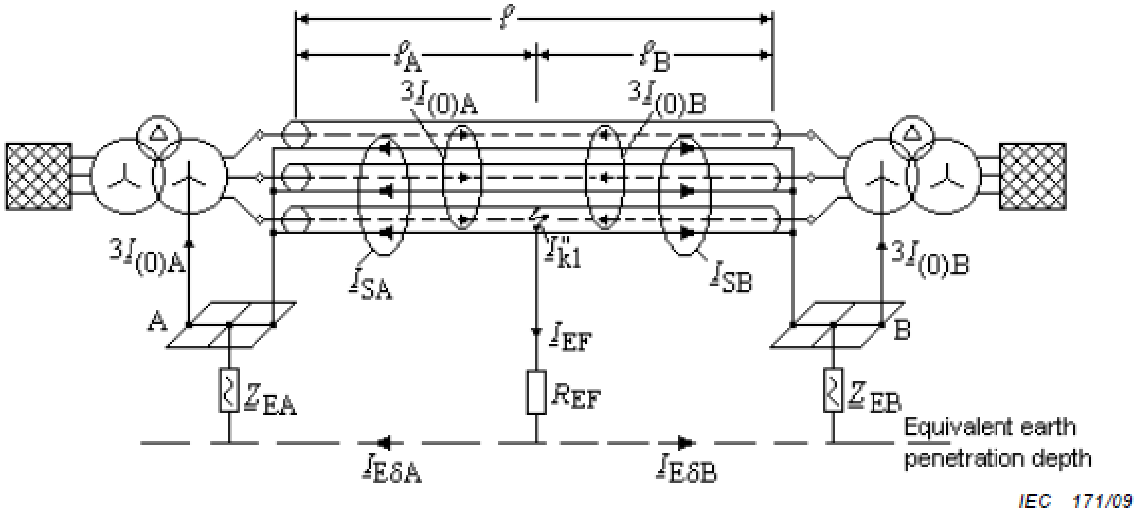


Figure 4.6 Line-to-earth short-circuit between stations with fault current fed from stations A and B, where

$I''_{k1} = 3\underline{I}_{(0)A} + 3\underline{I}_{(0)B}$

$3\underline{I}_{(0)A} = \underline{I}_{SA} + 3\underline{I}_{E\delta A}$

$3\underline{I}_{(0)B} = \underline{I}_{SB} + 3\underline{I}_{E\delta B}$

(IEC 60909-3 2009)

Calculations of the current flowing through earth are considerably more complicated than in the simpler fault case presented in chapter 4.4.1. Two cases must be considered regarding earth potential rise, the current to earth at the short circuit location, and the currents through earth that flow to stations A and B.

The current to earth at the short circuit location is calculated as follows

$$I_{EF} = r_3 3I_{(0)A} \frac{Z_{EStot}}{R_{EF}} + r_3 3I_{(0)B} \frac{Z_{EStot}}{R_{EF}} \tag{4.13}$$

where R_{EF} is the resistance at the fault point against reference earth as shown in figure 4.6 and Z_{EStot} is calculated as follows

$$Z_{EStot} = \frac{1}{\frac{1}{Z'_S\ell_A} + \frac{1}{Z'_S\ell_B} + \frac{1}{R_{EF}}} = \frac{Z'_S\ell_A\ell_B}{\ell + \frac{Z'_S\ell_A\ell_B}{R_{EF}}} \tag{4.14}$$

Equation is valid for cable lengths of at least $\ell = \delta/2$, where δ is the equivalent earth penetration depth calculated with the following formula

$$\delta = \frac{1{,}851}{\sqrt{\omega \frac{\mu_0}{\rho}}} \tag{4.15}$$

where

ω is the angular frequency, $\omega = 2\pi f$

μ_0 is the magnetic constant $\mu_0 = 4\pi * 10^{-7}$

ρ is the resistivity of the soil

Equivalent earth penetration depths for different soil types are also given in the standard 60909-3, which are presented in table 4.2. (IEC 60909-3 2009)

Table 4.2 Equivalent earth penetration depths for different soil types. (IEC 60909-3 2009)

Soil types	Soil resistivity ρ Ωm	Equivalent earth penetration depth δ m	
		for 50 Hz	for 60 Hz
Granite	>10 000	>9 300	>8 500
Rocks	3 000 ... 10 000	5 100 ... 9 330	4 670 ... 8520
Stony soil	1 000 ... 3 000	2 950 ... 5110	2 690 ... 4 670
Pebbles, dry sand	200 ... 1 200	1 320 ... 3 230	1 200 ... 2 950
Calcareous soil, wet sand	70 ... 200	780 ... 1 320	710 ... 1 200
Farmland	50 ... 100	660 ... 931	600 ... 850
Clay, loam	10 ... 50	295 ... 660	270 ... 600
Marshy soil	<20	<420	<380

The currents flowing to the stations A and B are calculated as follows

$$I_{E\delta A} = r_3 3I_{(0)A} \frac{Z_{EStot}}{Z'_S \ell_B} + r_3 3I_{(0)A} \frac{Z_{EStot}}{R_{EF}} - r_3 3I_{(0)B} \frac{Z_{EStot}}{Z'_S \ell_A} \tag{4.16a}$$

$$I_{E\delta B} = r_3 3I_{(0)B} \frac{Z_{EStot}}{Z'_S \ell_A} + r_3 3I_{(0)B} \frac{Z_{EStot}}{R_{EF}} - r_3 3I_{(0)A} \frac{Z_{EStot}}{Z'_S \ell_B} \tag{4.16b}$$

Z'_S is the self-impedance per unit length of one of the three sheaths or shields, which can be given as

$$Z'_S = R'_S + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S} \tag{4.17}$$

where

R'_S resistance per unit length of the sheath or shield (copper, aluminum, lead)

$R'_S = 1/(\kappa \cdot q_s)$ with $q_s \approx 2\pi r_s d_s$ where d_s is the thickness of the sheath or shield

r_s is the medium radius of the sheath or shield δ is the equivalent earth penetration depth presented above

Two further cases must then be considered regarding the fault point resistance as it is typically unknown:

$R_{EF} \rightarrow \infty$ no connection at the short-circuit location between sheath/shield and the soil

$R_{EF} \rightarrow$ min. connection between the cable sheath/shield and the soil

(IEC 60909-3 2009)

4.4.2.1 $R_{EF} \rightarrow \infty$

In this case the resistance between the cable sheath or shield and the soil is infinite. It is assumed that the thermoplastic sheath is not destroyed by the fault current or by the arc at the fault location. In this case the equations for earth current are as follows

$$I_{E\delta A} = r_3 3I_{(0)A}\frac{\ell_A}{\ell} - r_3 3I_{(0)B}\frac{\ell_B}{\ell} \tag{4.18a}$$

$$I_{E\delta B} = r_3 3I_{(0)B}\frac{\ell_B}{\ell} - r_3 3I_{(0)A}\frac{\ell_A}{\ell} \tag{4.18b}$$

Highest currents through the sheath or shield will occur if the fault location is close to station A or station B, and the short-circuit current is fed from both directions. Similarly, the highest currents through earth are found if the fault occurs near either station. (IEC 60909-3 2009) This can also be seen from the earth current formulas (4.18) above, which are as follows when the distance ℓ_A or ℓ_B is 0

$$I_{E\delta Amax} = -r_3 3I_{(0)B} \quad ,(\ell_A = 0) \tag{4.19a}$$

$$I_{E\delta Bmax} = -r_3 3I_{(0)A} \quad ,(\ell_B = 0) \tag{4.19b}$$

where

r_3 is the reduction factor for three single-core cables

$3I_{(0)A}$ ($\ell_A = 0$) is the short-circuit current fed from the station A only

4.4.2.2 $R_{EF} \rightarrow$ min.

According to IEC 60909-3, a value of 5 Ω can be used as a conservative estimate for the minimum resistance, as the connection to the surrounding earth is small. For determining the currents through the earth, the formulas given above can be applied. As the determining current for earthing grid dimensioning is the highest current through the earth at the station, the prementioned formulas lead to

$$I_{E\delta Amax} = r_3 3I_{(0)A} \quad , (\ell_A = \ell) \tag{4.20a}$$

$$I_{E\delta Bmax} = r_3 3I_{(0)B} \quad , (\ell_A = 0) \tag{4.20b}$$

If the current is fed from the station A only and the current fed from the other side is neglected for the worst-case scenario, the current $3I_{(0)A}$ ($\ell_A = 0$) is equal to I''_{k1}. The above design practices are valid for three single core cables regarding station earthing potential, and other practices must be followed when designing other systems with three-core cables. More detailed formulas are available in the IEC 60909-3 standard, and only the most important formulas considering this thesis's subject area were presented.

4.5 Earthing of HV cables between substations

Earthing of HV cable sheath, also referred to as bonding, affects the current distribution of earth fault currents. The earthing method must be considered to know if the reduction factors of the sheaths can be used in calculations. Cable bonding type also influences the maximum load capacity of the cable in addition to the current distribution, which is often the determining factor in choosing the bonding type. In some bonding methods, such as earthing from both ends, the phase current induces a current to the cable sheath which causes extra load and heat to the cable. Therefore, the load capacity of cables with an earthed sheath is smaller than for cables with non-earthed sheaths or shields. (Elovaara & Haarla 2011)

CIGRE 797 gives detailed analysis on different bonding methods, which are presented below. (CIGRE 797 2020)

- Solid or multi-point bonding (both ends)
- Single point bonding
- Mid-point bonding
- Cross-bonding
- Cross-bonding in tunnel installation
- Impedance bonding
- Siphon lines (circuits connecting to overhead lines and underground cables)
- Bonding for special cable systems

These are not detailly introduced in this thesis due to limitations, but for earthing design, the most important factor to consider is if the fault current has a path back to the fault current feeding point. If the cable is bonded from only one end, the fault current does not distribute to the cable sheath and the cable reduction factor cannot be applied in earthing grid design calculations. In this case, an earth continuity conductor (ECC) must be installed parallel to the cable and earthed from both ends to maintain tolerable earth potential rise. (CIGRE 797 2020)

The earth continuity conductor earthed form both ends functions similarly as solid bonded cable sheaths regarding fault current distribution, providing an earth return path. The reduction factor depends on various properties of the earth conductors as well as single-core cables, in addition to the soil parameters. The reduction factor is smaller if the distance to phase conductors or the earth conductivity is smaller but is not dependent on length of the conductor. Calculation and examples are given in (Sarajcev et. al. 2003), where the calculated reduction factors for single point bonded 110 kV AXLJ 3x1000/95mm^2 cables with 50 mm^2 copper ECC were approximately between 0,25-0,55 for soil resistivities between 100 - 2000 Ωm. (Sarajcev et. al. 2003)

4.6 Summary regarding current distribution for both overhead lines and cables

As various factors regarding currents distribution in the HV system were reviewed, it was considered necessary to summarize the results shortly. To account for the highest possible earth current at the substation for overhead lines or underground cable systems, the following fault situations must be considered in earthing design:

Overhead lines
- Fault at the station
- Fault near station (if the main transformer neutral is earthed)

Underground cables
- Fault at the station B with the fault current fed from station A (or opposite)

The scenario of a fault between station A and B must be considered when determining touch voltages at the cable route, outside the station. This fault can happen anywhere, and the highest substation earthing potential results from a fault at the either station. This leads to the same equation of $\underline{r}*3I_{(0)A}$ where $3I_{(0)A}$ is equal to I''_{k1} as the fault current is completely fed from one station. Therefore, the evaluation of station earth potential rise stays the same. For keeping calculations as simple as possible, the case of a fault at the station with the transformer neutral isolated may be considered as a worst-case scenario. With this assumption, the earthing grid will fill the requirements and save design hours by not overcomplicating the calculation. Reduction factors can be applied for the fault feeding line, either for cable sheath or shield wire reduction factors. Cable sheath reduction factor cannot however be used if the sheath is single point bonded, as the fault current has no pathway. In this case, an earth continuity conductor must be installed in parallel with the cables to ensure safe earth potential during a fault.

The mentioned are applicable for designing substation earthing grid, and different fault scenarios may have to be considered when designing other earthing systems, such as tower earthing for high voltage lines. Design characteristics also change when the earthing system changes, and the above mentioned are valid for earthing systems with low-impedance neutral earthing. Fault duration must also be considered, as when the fault duration increases, the permissible touch voltages are lower. This means that fault events that are not defining for earthing grid design by earth current magnitude, may be defining if the protection tripping times for such faults are longer. Reduction factors of overhead lines and cable sheaths, as well as the current through the transformer neutral point, can be considered when determining the earthing voltage at the station. Further considerations must take place if designing more complex systems due to the simplifications given earlier.

4.7 Additional resistances

Additional resistances such as shoe resistance or surface soil resistance can be accounted for in permissible touch voltages as illustrated in the standard. These resistances are referred to as R_{F1} for footwear and R_{F2} for resistance to earth of the standing point in the standards EN 50522 and SFS 6001. The permissible touch voltages can be calculated with

$$U_{vTp} = I_B(t_f) \cdot \frac{1}{HF} \cdot (Z_T(U_T) \cdot BF + R_H + R_F) \tag{4.21}$$

where

U_{vTp} is the prospective permissible touch voltage

$I_B(t_f)$ is the body current limit given in standards, where probability of ventricular fibrillation is less than 5%, value depends on fault duration t_f

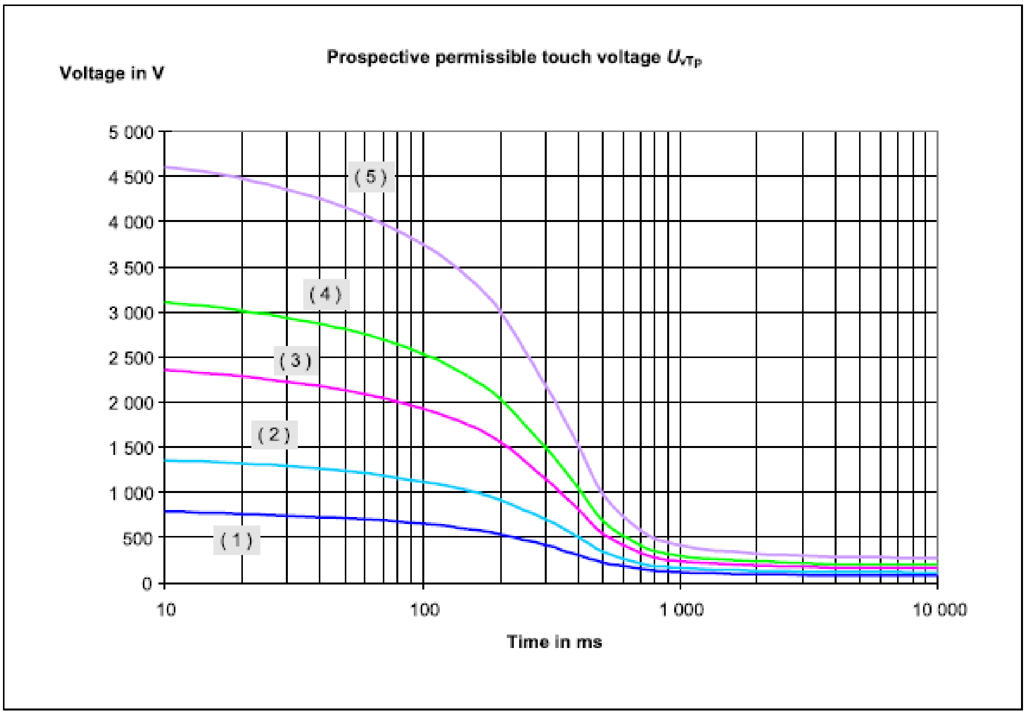
HF is the heart current factor given in standards IEC/TS 60479-1, i.e.
1,0 for left had to feet,
0,8 for right hand to feet,
0,4 for hand to hand

$Z_T(U_T)$	is the body impedance given in IEC/TS 60479-1, Z_T not exceeded by 50 % of the population, dependent on touch voltage. First calculation done with assumed level
BF	is the body factor given in IEC/TS 60479-1, i.e. 0,75 for hand to both feet, 0,50 for both hand to feet
R_H	is the additional hand resistance
R_F	is the additional foot resistance

Tolerable touch voltages can differ with different touch voltage conditions as indicated by the body factor, *BF*. Therefore, weighted averages are used in figures given in standards, which can be different for other countries. Standard EN 50522 as well as SFS 6001 give the following example curves for different additional resistances shown in figure 4.7. Standards give a more accurate representation on how the prospective permissible touch voltages are calculated for this figure. Calculation of used impedances is shown in the table 4.3 as presented in EN 50522 annex B.

Table 4.3 Assumptions for calculations of additional resistances. (EN 50522 2010)

Type of contact	Different touch voltage conditions weighted
Probability factor for the value of Z_T	50 %
Curve $I_B = f(t_f)$	c_2 in Figure 20 of IEC/TS 60479-1
Circuit impedance	Z_T (50 %) + R_F
Additional resistance	$R_F = R_{F1} + R_{F2} = R_{F1} + 1{,}5\ m^{-1} \cdot \rho_S$



(1): Permissible touch voltage according Figure 4
(2): R_F = 750 Ω (R_{F1} = 0 Ω, ρ_s = 500 Ωm)
(3): R_F = 1 750 Ω (R_{F1} = 1 000 Ω, ρ_s = 500 Ωm)
(4): R_F = 2 500 Ω (R_{F1} = 1 000 Ω, ρ_s = 1 000 Ωm)
(5): R_F = 4 000 Ω (R_{F1} = 1 000 Ω, ρ_s = 2 000 Ωm)

NOTE R_{F1} = 1 000 Ω represents an average value for old and wet shoes. Higher values of footwear resistance may be used where appropriate.

Figure 4.7 Prospective permissible touch voltages by different additional resistances from footwear and soil resistivity near the surface. (EN 50522 2010)

As can be seen from the figure, the touch voltages are vastly different if additional resistances are applied. The used 1000 **Ω** value is for old and wet shoes, and higher values can be used where appropriate. In an IEEE study, a value of 2000 **Ω** was considered as a conservative value for work shoe resistance. This is limited to shoe voltages of 1200 V, after which it must be assumed that shoe insulation will fail resulting in a resistance of 0 **Ω**. (Godlewski 1999)

However, even if work shoes are used inside the substation, civilians may not be using high resistance shoes outside the fenced area which must accounted for in design. This risk assessment must be done for each conductive path and area separately. It is essential to consider the areas on a case-by-case basis to consider the risks for passing public traffic, and if they are expected to walk barefoot or wearing shoes. It is also important to assess the risks further from the stations as well, as currents can travel far from the fault point. Risk assessments of this kind are especially important in residential areas where conductive paths such as water pipes may even be connected to residential systems.

In Finland, the surface layer soil is often exchanged to gravel with the properties 2000 – 3000 Ωm. With a shoe resistance value of 2000 Ω and a surface soil resistivity value of 2500 Ω, the R_F value would be 5750 Ω according to the formula given in table 4.3.

As standard SFS 6001 allows to use the 4 U_{TP} value when recognized specified measures from the annex E in the standard are applied, consideration of additional resistances can give advantages, but not likely as a part of normal design. However, this can be considered in special cases where higher additional resistances for shoes and/or surface soil can be applied and the 4 U_{TP} level may be hard to achieve without unreasonable measures. Shoe resistances must be carefully evaluated to make sure the insulation does not fail with higher voltages.

4.8 Parallel earthing grid

If the earthing voltage is still too high after prementioned measures on the substation earthing grid, and lowering the earthing voltage would require expensive measures, one possibility is to connect the earthing grid to other earthing systems. This helps to distribute the fault currents to a larger area lowering the hazardous voltages. The substation earthing system is connected to the tower earthing systems, but a connection to other earthing systems can also be applied if necessary. The other network earthing resistance can be applied to calculations similarly as tower footing impedances, as are shown in figure 4.1 with the following formula

$$Z_E = \frac{1}{\frac{1}{R_{ES}} + n\frac{1}{Z_\infty}} \tag{4.22}$$

where

R_{ES} is the resistance to earth of the mesh electrode

n is the number of overhead lines leaving the substation

Z_∞ is the chain impedance (earth wire/tower footing) of the overhead line assumed to be infinite (SFS 6001, 2018)

Therefore, connecting to a parallel earthing grid improves the earthing voltages at the applied substation by lowering the earthing impedance. Transferred voltages must still be carefully evaluated to confirm that they do not dangerously conduct to other earthing systems. If other earthing systems are close and easily connectable, connection should be established as a normal practice.

Two situations are considered helpful for lowering the earthing voltages at the station in addition to connecting to already existing earthing systems. One of these is connecting a horizontal earthing electrode to the earthing grid and installing the other end to better conductive soil. The latter is installing vertical earthing electrodes to the soil to make use of better conductive soil properties of the deeper soil layers.

The standard SFS 6001 gives the following formulas for calculating the earthing resistances for the mentioned method. For a horizontal electrode under the surface the earthing resistance can be calculated as follows

$$R_E = \frac{\rho_E}{2\pi L} \ln \frac{L^2}{1{,}85 \cdot h \cdot d} \tag{4.23}$$

where $d << 4h$.

And for a vertical rod or pipe under the surface, the earthing resistances are calculated by

$$R_E = \frac{\rho_E}{2\pi L} \ln \frac{4L}{1{,}36 \cdot d} \cdot \frac{2h + L}{4h + L} \tag{4.24}$$

where $d << L$.

L is the electrode length (m)
ρ_E is the earth resistance (Ωm)
d is the diameter of the electrode (m)
h is the installation depth of the electrode (m)
(SFS 6001 2018)

The formulas (4.23) and (4.24) differ from the standard EN 50522 given formulas, due to special national conditions given in Finnish standard SFS 6001. The Finnish formulas give slightly lower resistance values than their counterparts in EN 50522.

These are calculated similarly as parallel grids as given earlier in formula (4.22). It is essential to know the resistivities of different soil layers to determine the usefulness and practicality of the vertical earthing rods. If the resistivity of the deeper soil layers are high in comparison to the surface soil layer, the use of earthing rods may prove to be of no effect. Furthermore, the driving of rods to hard soil can be very difficult to implement in practice.

The SFS 6001 standard does not directly require earthing calculations beforehand, but the safety of the station should be proven safe by measurements. These measurements are required at regular intervals during the installation's lifetime. Design calculations are in practice required for earthing design to dimension everything correctly for construction.

4.9 Case Analysis

The researched topics were taken into practice in a project where the earthing conditions were more demanding than normal. Fault currents were higher than usual, with undesirable soil resistance values. Current distributions and the connection of parallel earthing grids had to be considered for earthing grid dimensioning, as the configuration of the network was different than in typical situations. Some of the HV connections between substations were implemented as underground cables, where the current distributions and therefore application of reduction factors were considered as researched in this thesis.

The consideration of reduction factors and the connection of parallel grids as discussed in this thesis gives a reasonably economical solution that meets the requirements of the standard and customer. This thesis also provides the tools of additional measures should an even lower earthing grid resistance be pursued, by the application of additional resistances, vertical earthing rods and earthing conductor drawn to better conductive soil as described above. These methods are to be added to the company calculational tool in the near future, so that they are practical to implement in other projects as well.

5. TRANSFERRED VOLTAGES

The effects of hazard voltages have been researched in the previous chapters. The substation earthing is often seen as an independent isolated installation that is connected to other earthing systems such as tower earthing. These voltages can however transfer outside the considered substation earthing system and cause harm to property or humans if not considered appropriately. Voltages can transfer through various structures and possible danger voltages may occur even a long distance from the fault point. These potentials outside the considered earthing system are referred to as transferred voltages and are researched in this chapter.

5.1 Voltage travel paths

Voltages can flow between different earthing systems, such as between connected substations or from a HV system to a MV system or vice versa. Hazard voltages can even transfer far from the fault point via metal structures in the earth such as cable sheaths, fences, pipes and low-voltage neutral wires. Potential rises via conductive structures can be especially dangerous as they may cause hazardous voltages to common areas where civilians are at risk. The knowledge of structures in the soil is of most importance to consider the routes the fault current may take in design. No general rule for assessment of danger elements can be given and must be evaluated on a case-by-case basis (SFS 6001 2018).

Buried metallic structures are often not a problem in substations built for distribution solutions at sparsely populated areas. However, in industrial applications these can be dangerous as there may be buildings or other structures with conductive paths nearby. Often dangerous potential differences form in a case where high voltage fault currents flow into the earthing of a low voltage system. This event is illustrated in the figure 5.1 below. Further review of potentials close to the station is often necessary, as the substation potential can often be 4 U_{TP}, which is not applicable outside the installation unless special measures are taken. It may be necessary to calculate the earthing voltages outside the station at a distance where humans may be present, to see how the earthing potential curve lowers.

If the system is complex, evaluation of the risks may prove to be very hard to impossible using traditional manual calculation. Sometimes the help of software analysis tools may prove to be necessary. Differences between software are present, as some are limited and only capable of analyzing simple scenarios with single surface treatment.

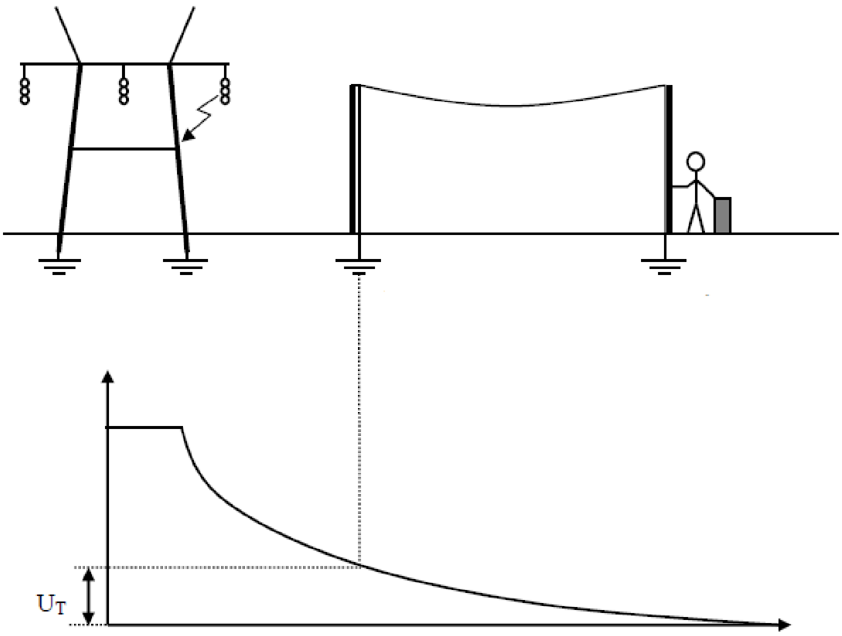


Figure 5.1 Transferred potential from high voltage system to a low system. (Lapinkorpi 2011)

Hazardous voltages may also travel similarly, but in the opposite direction, if the other end of an earthing installation is in a different potential. This effect referred to as backwards potential is illustrated in the figure 5.2 below.

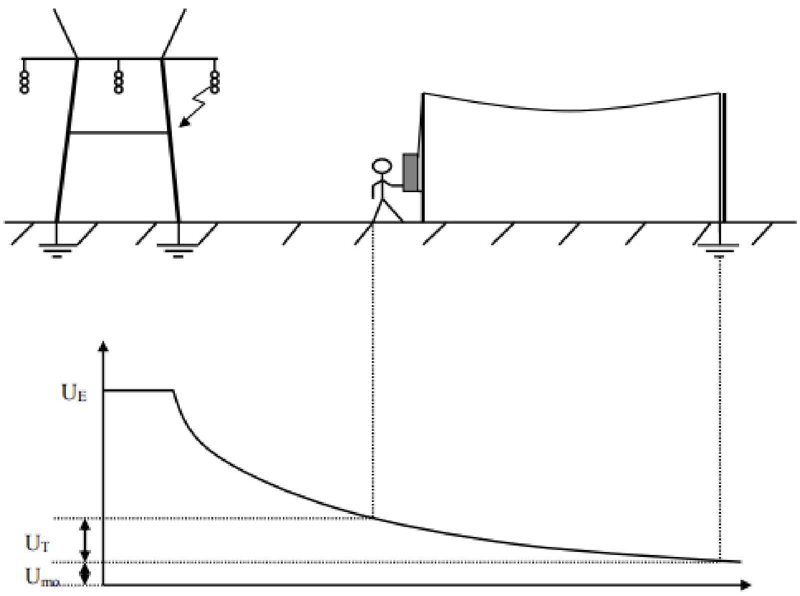


Figure 5.2 Backwards potential between systems. (Lapinkorpi 2011)

There are two practices to account for transferred potentials to low voltage systems, interconnecting all high and low voltage earthing systems, or to separate the high voltage earthing system from low voltage systems. Standard SFS 6001 recommends connecting the earthing systems if possible. If the low voltage system is completely limited inside the high voltage earthing system area, the systems must be connected, even if it is not part of a global earthing system. (SFS 6001 2018)

If the high voltage earthing system is part of a global earthing system, or it is connected to a multi-earthed HV neutral conductor in a balanced system, full compliance is ensured. If there is no global earthing system, table 5.1 shall be used to identify situations where interconnecting earthing systems with low voltage supply outside the high voltage installation is applicable.

Table 5.1 EPR based minimum requirements for interconnection of high voltage and low voltage earthing systems. (EN 50522 2010)

Type of LV system [a, b]		***EPR Requirements***		
		Touch Voltage	***Stress Voltage*** [c]	
			Fault duration $t_f \le 5$ *s*	*Fault duration* $t_f > 5$ *s*
TT		*Not applicable*	*EPR ≤ 1 200 V*	*EPR ≤ 250 V*
TN		$EPR \le F \cdot U_{Tp}$ [d, e]	*EPR ≤ 1 200 V*	*EPR ≤ 250 V*
IT	*Distributed protective earth conductor*	*As per TN system*	*EPR ≤ 1 200 V*	*EPR ≤ 250 V*
	Protective earth conductor not distributed	*Not applicable*	*EPR ≤ 1 200 V*	*EPR ≤ 250 V*

[a] *For definitions of the type of LV systems, see HD 60364-1.*

[b] *For telecommunication equipment, the ITU recommendations should be used.*

[c] *Limit may be increased if appropriate LV equipment is installed or EPR may be replaced by local potential differences based on measurements or calculations*

[d] *If the PEN or neutral conductor of the low voltage system is connected to earth only at the HV earthing system, the value of F shall be 1.*

[e] U_{Tp} *is derived from Figure 4.*

NOTE The typical value for F is 2. Higher values of F may be applied where there are additional connections of the PEN conductor to earth. For certain soil structures, the value of F may be up to 5. Caution is necessary when this rule is applied in soils with high resistivity contrast where the top layer has a higher resistivity. The touch voltage in this case can exceed 50 % of the EPR.

If high voltage and low voltage earthing systems are kept separate, earth electrodes must be separated in a way that no danger to persons or equipment can occur in the low voltage installation. Step, touch and transfer potentials must be within the safe limits in the low voltage system as well in the case of a high voltage fault. Systems below 50 kV are in many cases considered to be separated if the distance between the systems is more than 20 m. For higher voltage substations, the distance between the installations must be over 100 m to be considered separate.

If the installation is part of a global earthing system where typically no hazardous potential differences exist, issues may arise via conductive equipment such as cables, pipes etc. to an area in different earth potential. However, a general safe distance between the earthing conductors and conductive equipment cannot be specified and design must be done on a case-by-case basis. (EN 50522 2010)

Significant currents and voltages may occur in the cable screen and/or armoring, depending on the way the cable screen and/or armoring are earthed, as well as in metallic pipes. Possible touch voltages in the other end must be considered in design, and the insulation of cables and pipes be dimensioned accordingly. The following precautions may be taken if necessary:

- interruption of the continuity of metallic parts where they leave the area of the earthing system
- insulation of conductive parts or areas
- installation of suitable barriers around conductive parts or areas to prevent touching
- installation of an insulated barrier between parts connected to different earthing systems
- suitable potential grading
- limiting overvoltages by using suitable devices

Potentials from high voltage systems can also transfer to telecommunication systems and cause interference to equipment. EMC issues of this type are excluded from this thesis. (EN 50522 2010)

As dangerous potentials can occur via cables, special attention is to be paid to any work equipment having their power supply from the station, especially if the supply is from the station and the equipment used outside the substation earthing grid. Special attention must also be paid to transferred potentials when working close to a live station and necessary measures such as additional earthing must be applied to preserve safety for personnel.

5.2 Permissible voltages outside the station

Voltage limits outside the facility are the same as close to the electrical installations. However other factors must be considered differently, as for example additional resistances from shoes may not always be applicable.

Transferred voltages can be especially dangerous in highly populated areas, due to the probability of a human being affected by the fault current. Special care in design must be taken when designing stations close to parks or residential areas. This can be a more common case for GIS installations that are often built in areas where the available space is limited. GIS earthing systems are explained in more detail in the next chapter.

Earth faults can also cause harm to communication networks, which must be considered as a part of earthing design according to FICORA regulation 43 F/2015 M. Permissible voltage limit values differ during time and are presented in the International Telecommunication Union publication ITU-T K.68, chapter 6.2.2, table 18, as pointed by the FICORA regulation 43 F/2015 M. Regarding communication network transferred potentials, further considerations can take place on earthing methods, network structure and variables that affect the transferred potential magnitude. These are presented in the above-mentioned regulations and not further researched within this thesis.

5.2.1 Special considerations for GIS stations in residential areas

GIS substations are often at densely populated areas due to the space limitations the areas have. This can cause problems regarding transferred voltages that are typically of no concern to AIS installations. As the GIS installation can often be close to residential grounding systems, the hazards of potential differences must be evaluated on a case-by-case basis. The following figure 5.3 gives indication on how the different systems can overlap.

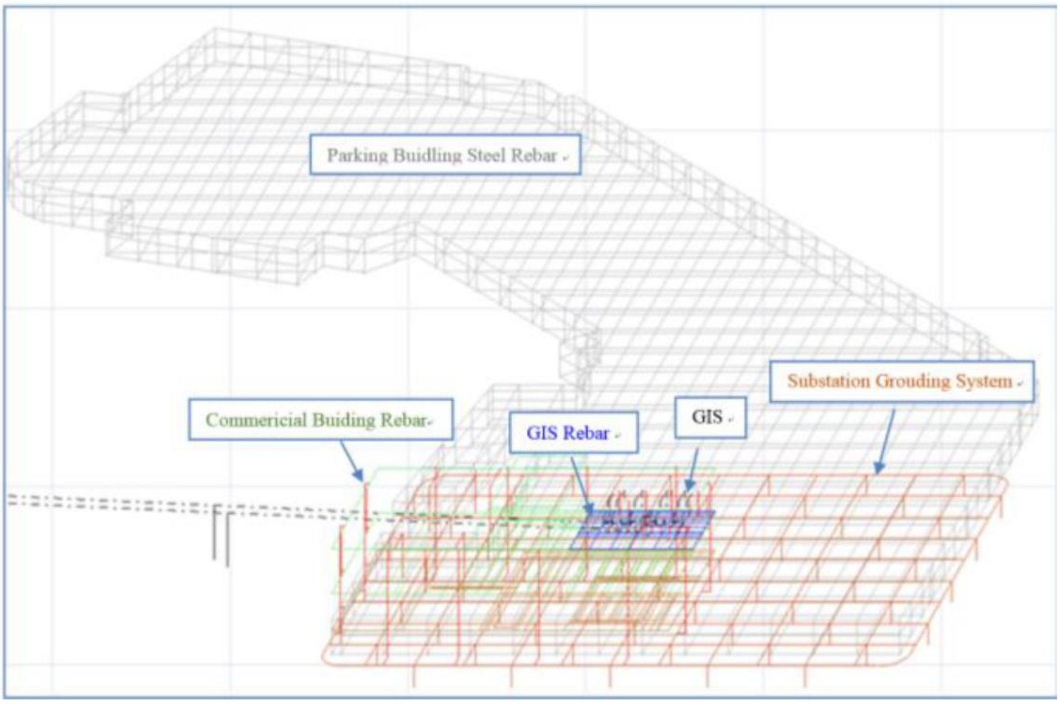


Figure 5.3 Example of city structures and substation earthing system overlapping. (Jinsong et al. 2015)

GIS and residential system earthing systems can in theory be separated to eliminate the possibility of transferred potentials. However, in practice separating the low voltage distribution neutrals and city metallic structures are often inevitably directly or indirectly connected to the GIS earthing grid. In a certain way, connecting residential and substation systems is good regarding EPR as it improves the safety inside the substation. On the other hand, the transferred voltages to other metallic city and residential structures must be checked to not cause hazards to people outside the substation area. To ensure the safety of transferred potentials, an accurate knowledge of conductive structures underground is essential. As structures in highly populated areas can be very complex, computer modeling of the system can sometimes be the only way to reliably model transferred potential risks. (Jinsong et al. 2015)

5.3 Hazard voltage analysis

Hazard voltage report may sometimes be necessary for the substation. This includes the assessment of any dangers and how they are considered in construction, as well as short reporting on earthing voltages and how they compare to permissible touch voltages. Any specific measures taken to reduce the risk of hazardous voltages to persons can be presented. A general hazard voltage analysis cannot be made to cover all substation project types, as every element posing a risk regarding transferred voltages must be reviewed individually.

Simulation tools for hazard voltage analysis both inside and outside the station exist. These are great tools for drafting earthing potentials in different parts of the station, with the advantage to avoid possibly complicated and burdensome calculations and present the potential with help of graphical tools. It must however be considered that the system is using the correct standard and technical limitations, and that the input parameters are correct.

6. GAS INSULATED SWITCHGEAR EARTHING REQUIREMENTS

Gas insulated switchgear (GIS) provides a more compact solution compared to an AIS solution. GIS is metal encapsulated and safely operable in confined spaces by using gas insulation that has better insulation properties than air. Many advantages to a traditional AIS installation are present, such as the obvious space saving, but also more reliable operation and being less maintenance intensive due to being protected from different contaminants in the air. The switchgear unit can also be assembled at a factory, which can be of benefit in the construction and installation phase of the project. Applications of the GIS can range from power transmission solutions to railways, and are available for various voltages, ratings and applications. An added benefit of GIS is the cleaner outward appearance compared to an AIS installation due to the switchgear being inside a building. This can be of great value in historical areas or in other ways scenically valuable locations.

The basic requirements of GIS earthing are not any different from the aspects of a traditional AIS substation. Requirements are based on maintaining personnel safety at the station and protecting equipment from interferences and damage. The typical area of a GIS installation typically is 10-25 % of an equivalent AIS installation, which makes designing a safe earthing voltage with allowable voltage limits more difficult.

GIS installations have a variety of possible physical arrangements, which makes general evaluation of fault current paths more difficult. GIS manufacturers often give their own calculations for basic design parameters due to this. Location of the faults influence the flow of current similarly as in AIS installations. The following figure 6.1 gives indication on the different typical fault situations in GIS. (IEEE Std80 2013)

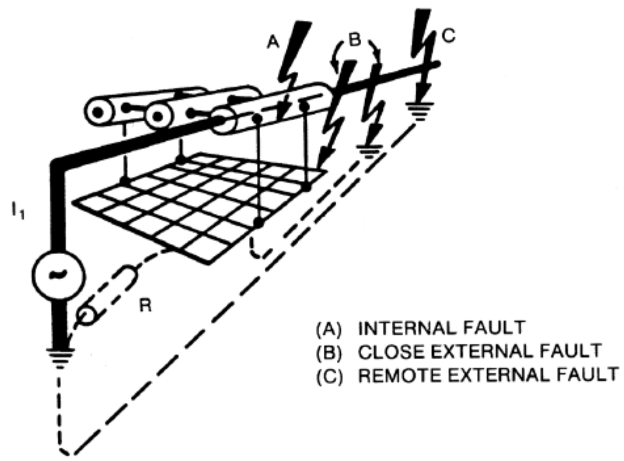


Figure 6.1 Different typical fault situations in GIS. (IEEE Std80 2013)

In GIS solutions the conductive paths for fault currents are somewhat different compared to AIS substations. The earthing structure of a GIS is presented in the next chapter to further clarify the analysis of GIS earthing.

6.1 Fault currents in different situations

Similarly, as in traditional AIS substations, the different fault situations lead to varying fault currents in GIS stations as well. However, due to the configuration of GIS, the principles are a bit different. The current flow in different parts is explained in some detail in this chapter. The basic configuration of the GIS is presented in the figure 6.2.

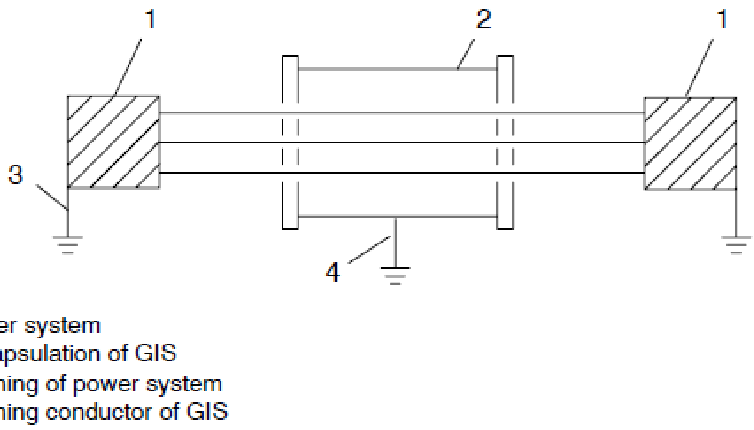


Figure 6.2 Basic configuration of the GIS. (ABB 2009)

In practice, the configuration and the different compartments in the switchgear are considerably more complex, but for explaining different fault situations within this thesis, this model is sufficient.

6.1.1 Three-phase short circuit within encapsulation

A three-phased short circuit, causing a fault current of I''_{k3}, is a symmetrical fault event. This fault is presented in the figure 6.3.

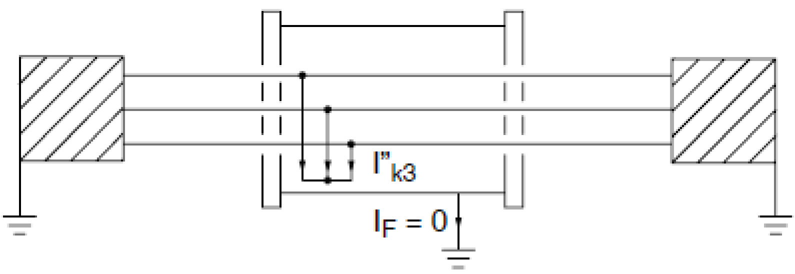


Figure 6.3 Three-phase short circuit within encapsulation of GIS. (ABB 2009)

No current flow within the encapsulation is present, meaning the fault current in the GIS earthing conductor is $I_F = 0$. (ABB 2009)

6.1.2 Line-to-earth short circuit within encapsulation

A line-to-earth short circuit, also referred to as single phase earth fault, results in a fault current of I''_{k1} in the GIS earthing conductor. The earth in this case is the encapsulation of the GIS, meaning that the fault in the earthing conductor is $I_F = I''_{k1}$. This current occurs in solidly earthed systems. If the single-phase earth current magnitude is unknown, the assumption of $I_F = I''_{k1} < 0.85 * I''_{k3}$ can be used. This is also appliable to line-to-line short circuit with earth connection and for earth faults in resonant earthed systems. (ABB 2009)

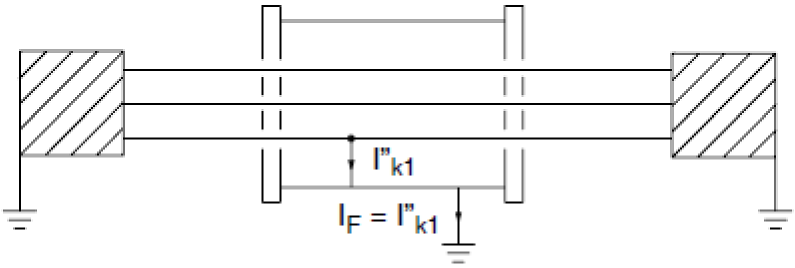


Figure 6.4 Line-to-earth short circuit within encapsulation of the GIS. (ABB 2009)

Three-phase encapsulated GIS also have a behavior, where a line-to-earth short circuit develops into a short circuit between all three phases within less than 50 ms. Therefore, the effects of a single-phase earth fault are relatively short. (ABB 2009)

6.1.3 Three-phase short circuit outside of GIS

As a pure three-phase short circuit does not have a connection with earth, the fault current in the GIS earthing conductor can be assumed to be $I_F = 0$. (ABB 2009)

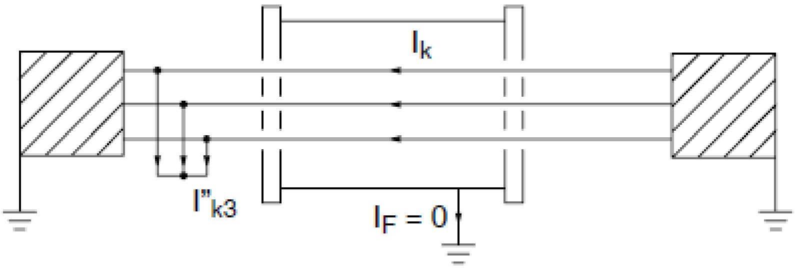


Figure 6.5 Three-phase short circuit outside of GIS. (ABB 2009)

Also, as HV cables are often used in GIS solutions, a three-phased short-circuit is not a likely event to happen outside the station.

6.1.4 Line-to-earth short circuit outside of GIS

The line-to-earth short circuit current outside of the GIS does not flow in the enclosure of the GIS. (ABB 2009)

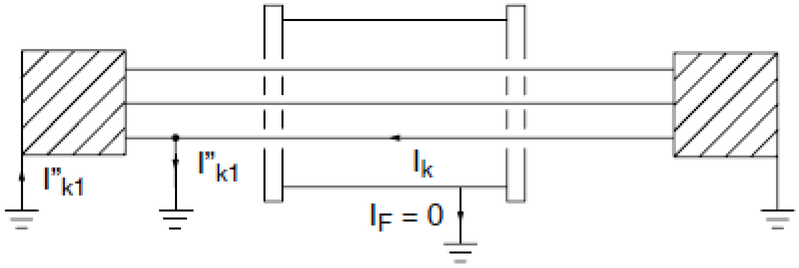


Figure 6.6 Line-to-earth short circuit outside of GIS. (ABB 2009)

However, the earth fault current I''_{k1} can flow through earth similarly as in AIS systems, for example through an earthed transformer neutral contributing to earth potential rise, which must be considered in design. Fault current can also flow through other connected earthing systems which is dependent on location of the fault and impedances in the system.

6.1.5 Summary of different faults in GIS systems

From situations presented above, the highest current through the encapsulation earthing is in the case of a line-to-earth short circuit within the encapsulation of GIS. This therefore determines the cross-section of the earthing conductors for the earthing system. This line-to-earth short circuit develops to a three-phased short circuit within 50 ms, but for safety margin a fault duration of 1 s is recommended. From this, the total cross section per installation for earthing conductors can be calculated. The manufacturer of the GIS may also provide this information in the product manual. Since the fault current divides to the different conductors unevenly, cross section at a size of 60% of the total cross section must be used for each earthing conductor. (ABB 2009)

6.2 GIS earthing structure

Earthing principle of GIS can be comparable to AIS solutions. However, as the switchgear is enclosed inside in a metallic enclosure, the earthing methods in practice are somewhat different. An even potential field is acquired by reinforced concrete floors and earthing conductors in the ground. The following figure 6.7 illustrates a general earthing system of a GIS substation.

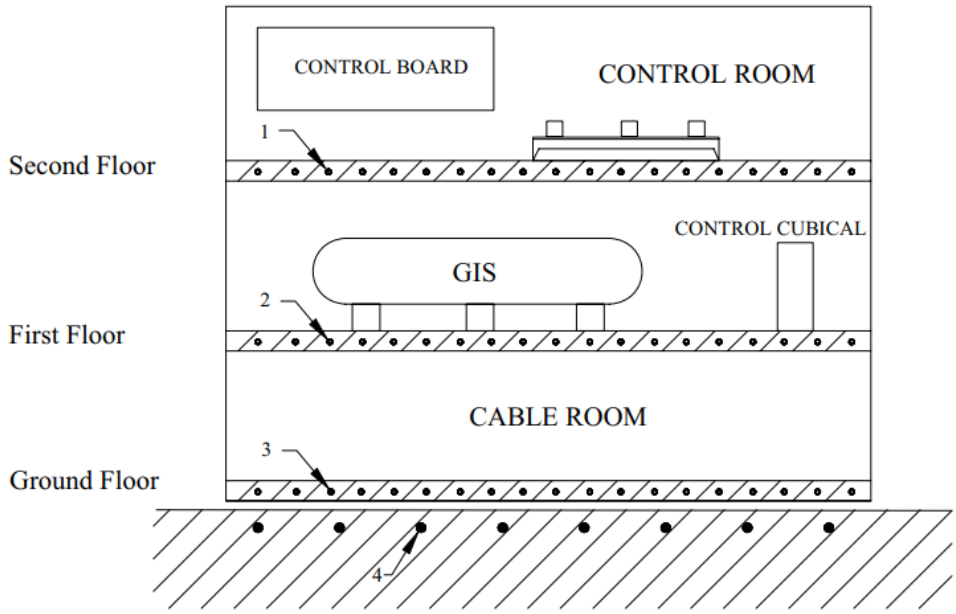


Figure 6.7 General earthing layout of GIS installation. 1) control room earthing grid, 2) GIS earthing grid, 3) cable room earthing grid, 4) main earthing grid. (Thasananutariya et al. 2004)

The layout in the figure 6.7 is a three-story building but building layouts may vary. Possible layouts may for example include only two floors, or a cable cellar where the bottom floor is built underground. The principle remains the same. There must also be a ring earth electrode around the building to limit step and touch voltages. This ring is then connected to earthing of adjacent substation or neighboring buildings. (ABB XTC1-398 1993)

The reinforcement steels in the concrete floors can be considered a part of the earthing system, but galvanized flat steel 30 mm x 3.5 mm should be installed and bonded with the structural steels to form a mesh system. This is to assure the electrical conductivity of the reinforcement. They should be bound together with 3 m distances maximum. Also, anti-corrosion measures are to be taken at concrete to air exit points if necessary. (ABB XTC1-398 1993)

The purpose of the main earthing grid is to provide a low impedance path for the earth fault current. It is typically buried in the soil, and the design is very much the same compared to AIS earthing grid design. The reduced area available for the earthing grid may however sometimes cause problems in reaching tolerable EPR values. (Thasananutariya et al. 2004)

The metallic enclosures of the GIS play an important part in carrying the induced currents, which can be of significant magnitudes. Therefore, the grounding recommendations of the GIS manufacturer must be strictly followed. The enclosure types can be divided to two different designs, continuous and non-continuous enclosure design. In a continuous enclosure design, a longitudinal flow in the enclosure is caused by the current in the conductor, inducing a voltage in the enclosure. Short connections at both ends exist to maintain continuity of all phase enclosures, resulting in enclosure current being only slightly less than the one flowing in the inner bus in the opposite direction. Enclosure current then returns through enclosures of adjacent phases when the load equalizes between phases. Enclosure current cancels much of the magnetic field outside the enclosure, with most of the magnetic field being contained within the enclosure. Non-continuous enclosure design in turn does not have external paths for enclosure currents such as in continuous enclosure design. Therefore, no longitudinal current flow is caused, voltages can be induced other than currents in the conductors enclosed by it, resulting in non-uniform voltages and currents. As a result, non-continuous design is not actively in use in the industry. (IEEE Std 80 2013)

The earthing grids in the floors are referred to as equipotential earthing grid, which function is to protect personnel that have access inside the building by establishing an even potential surface, to prevent touch or step voltages from occurring. The main ground grid should be connected to the different GIS enclosures to minimize potential differences between parts. The connections should be made as short and straight as possible to reduce impedance at higher frequencies, as high frequency voltages, also referred to as transient voltages, may cause local transient potential rise due to high reactance of the earthing conductors at high frequency. To eliminate high reactance through long earthing conductors as well as possible, this earthing principle should ideally already be thought of during the design of the building. GIS enclosures should be installed close to ground level and avoiding any unnecessary bends in the earthing conductor is preferable. It is also recommended that the size of the earthing conductor down from the enclosure is the same size that the main grid conductor. Transient overvoltages are further researched next. (Thasananutariya et al. 2004)

6.3 Transient overvoltages

Voltages are usually divided into two groups: constant operating voltage and short-term overvoltages. The latter is used for voltages that exceed the largest permissible operation voltage peak value for the insulation gap. Short term overvoltages can further be divided into transient overvoltages and low frequency overvoltages. Low frequency overvoltages are typically in cycles and long in duration, while transient overvoltages are short-term high frequency events. Transient voltages can further be divided to slow-front, fast-front and very-fast-front overvoltages, where the most essential difference is the voltage stress duration, which determines the insulation dimensioning. (Elovaara & Haarla 2011)

Slow-front overvoltages reach their peak in within hundreds of microseconds with a duration of a few milliseconds. Slow-front overvoltages are often caused by faults in the network as well as switching operations i.e. circuit breaker and disconnector operations conducted for example due to faults in the network. Fast-front overvoltages reach their peak in a few microseconds and fade away within tens of microseconds. Fast-front overvoltages are often caused by lightning. (Elovaara & Haarla 2011)

Very-fast-front transient overvoltages (VFTO) are extremely fast and reach their peak somewhere in the nanosecond range. VFTO are characteristically very short and of very high frequency and arise when there is an instantaneous change in voltage, such as in switching operations. VFTO pose a problem specifically for gas-insulated substations, especially problematic at higher voltage substations. Very-fast-front overvoltages are often caused by SF6-insulated disconnector switching operations. VFTO can sometimes also be generated by earthing switch closing operation, circuit breaker operation or a line-to-earth fault. Due to the slow operating speed of the disconnector, a higher number of re-strikes and pre-strikes occur compared to a circuit breaker, which is why disconnector switching operations are the main cause of VFTO problems. (CIGRE 519 2012)

Classification on transient voltage terms is not completely uniform in literature. Sometimes the term transient voltage is used when referred to VFTO, and vice versa. It can also sometimes be practical to refer to transient overvoltages by their origin, such as lighting or switching operations. In this thesis, the effects of very-fast-front transient voltages are examined. Due to the high frequency, some typical problems may arise especially in GIS installations. These typical features are examined, and some solutions presented in the next chapters.

6.3.1 Very-fast-front overvoltages

Transient overvoltage is a phenomenon already known from conventional AIS substations, but it can be of more concern in GIS stations due to visible sparking between enclosures and other grounded components. Due to the high frequency and restricted power of the phenomenon, any injuries from VFTO is considered unlikely. However, the sight of a possible spark can possibly cause harm indirectly, for example by causing the person to fall from a ladder or working platform. The transient overvoltages are more significant regarding interference to secondary equipment such as control, protection and measurement functions. Generally, the higher the substation voltage, the more VFTO related problems arise. (Boersma 1987)

Generation of VFTO can cause internal or external transient overvoltages, where the main concerns are of internal VFTO between the conductor and the enclosure that can cause high stress to the insulation system. Disruptive discharges to earth have been found when switching small capacitive currents with gas-insulated disconnector, especially at ultra-high voltages. Different parameters such as voltage, gap distance, electrode geometry, contact speed, gas pressure and magnitude and frequency of VFTO affect the development of an earth fault. Earth faults can be eliminated by considering these factors in disconnector design, by designing the contact gap properly and screening the strike area with special shielding electrodes and initiating the strike near the axis of the gap. External VFTO can in turn cause harm to secondary and adjacent equipment. External transient voltages occur between the enclosure and ground at GIS-air interfaces, across insulating spacers in the vicinity of GIS current transformers in the case they do not have metallic screen on the outside surface, instrument transformer secondary terminals and in radiated electromagnetic fields that can cause interference or damage to adjacent control or relay equipment. Of these enclosure discontinuities, air terminations are the most significant and the largest potential source of high frequency effects (Lewis 1993). The following figure 6.8 illustrates the division of VFTO to internal and external transient voltages. (CIGRE 519 2012)

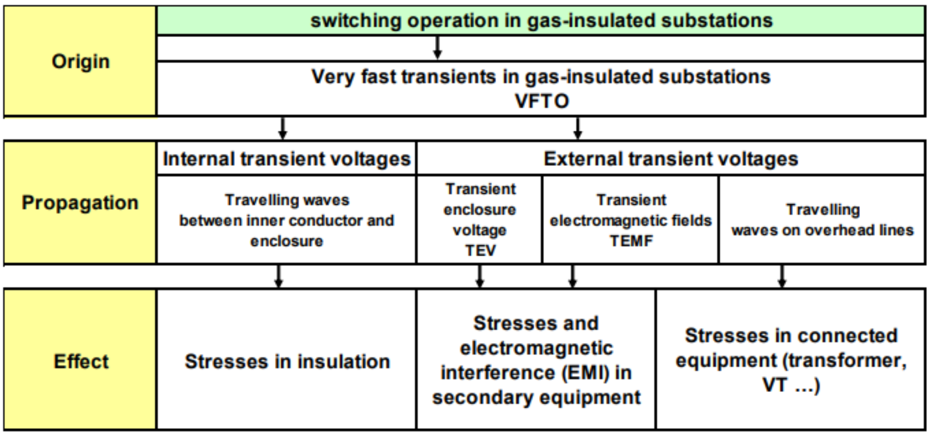


Figure 6.8 VFTO type classification in GIS installations. (CIGRE 519 2012)

6.4 VFTO mitigation

VFTO mitigation can take place at different parts of the system and the manufacturing process. One significant opportunity for reducing the effects of VFTO is at the GIS manufacturing stage, and the other is during GIS earthing and building design. These areas are presented separately to simplify the subject.

6.4.1 VFTO mitigation – switchgear

There are three main methods for VFTO damping, which are the high frequency resonator method, ferrite magnetic ring method and the inductive arrangement of surge arrestors (Li et al. 2019). All methods are relatively new and limited test data is publicly available. There is also an additional method under recent research, called the spiral tube damping busbar. However, some discrepancies between different sources exist on how good or applicable the methods are for different solutions are.

6.4.1.1 High frequency resonator

A slightly older concept is the application of specially formed shielding parts inside the GIS to serve as a high frequency, also referred to as radio-frequency (RF), resonator. Reduction effect is only achieved if the resonance frequency and the value of the resistor across the gap fit the VFTO parameters very well. (Burow et al. 2014) The figure 6.9 illustrates the effects of this mitigation method.

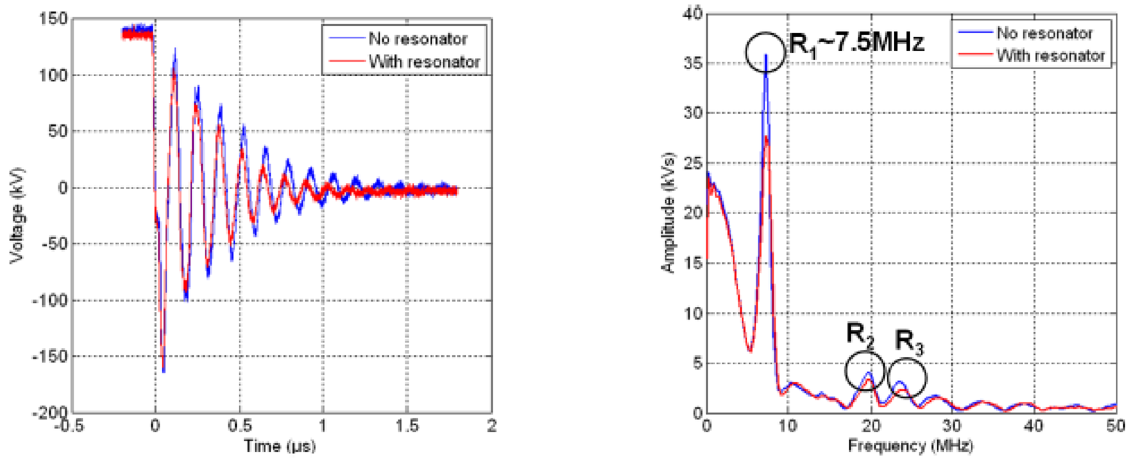


Figure 6.9 Measured VFTOs with or without high frequency resonator. (Riechert et al. 2012)

As can be seen from the figure, some frequencies were dampened to a significant degree. This can especially be seen with the dominant 7.5 MHz harmonic component marked as R1 in the figure. The parameters of the resonator could also be changed to increase its damping efficiency. An important aspect is also that the damping effect of the high frequency resonator is not only limited to disconnector switching operation generated VFTOs, but also other switching or fault events that are not as common as causes of VFTO. (Riechert et al. 2012)

6.4.1.2 Ferrite rings

Implementation of ferrite rings is a relatively easy to realize mitigation measure, where rings of ferrite material are arranged on the GIS inner conductor. Simulations and some small-scale measurements have been conducted, with promising results for VFTO mitigation potential. However, in HV solutions where the VFTO travelling waves reach larger values, the high magnetic field saturates the ferrite material completely, leading to considerably worse dampening effect. Measurement results for a 550 kV GIS are shown in the figure 6.10.

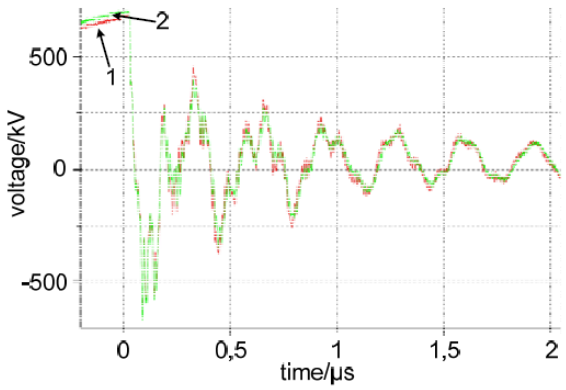


Figure 6.10 Comparison VFTOs without ferrite rings (1) and with 6 ferrite rings (2). (Riechert et al. 2012)

As can be seen from the figure 6.10, the potential of ferrite ring applications for VFTO mitigation for HV GIS applications is limited. For lower voltage applications where the ferrite rings do not saturate, ferrite rings can have good damping qualities. (Riechert et al. 2012)

New method, a material referred to as nanocrystalline alloy rings, has been researched to provide better magnetic qualities than ferrite rings, especially for HV applications. Rings are similarly arranged on the inner conductor of the GIS where good damping qualities have been found. It has also been found that damping qualities can be increased with adding more rings around the GIS conductor. (Burow et al. 2014)

6.4.1.3 Inductive arrangement of surge arrestors

This damping method is based on the helical slotted part of a GIS conductor that serves a small inductance. Surge arresters are installed inside the conductor parallel to the helical slotted part. This arrangement is illustrated in figure 6.11.

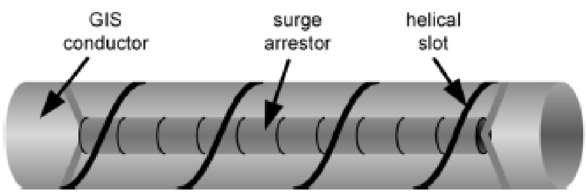


Figure 6.11 Inductive arrangement, where the surge arrestors are installed parallel inside the helical slotted conductor. (Burow et al. 2014)

The VFTOs are damped due to the surge arresters absorbing energy if the voltage drop across the arrangement exceeds the residual voltage. The arrangement must be designed considering the optimum number of arrester discs and the parameters of the slotted conductor. (Burow et al. 2014)

6.4.1.4 Spiral tube damping busbar

This new application of spiral tube damping busbar has showed promising results in recent studies. The method is based on hollowing the conventional busbar to a spiral tube, and then the busbar conductor is turned into a series circuit with multi-turn hollow inductance coil and multiturn gap. This parallels the damping resistance with the spiral tube inductance circuit, absorbing the transient energy. Main structure of the busbar consists of three parts, the spiral tube damping busbar, non-inductive damping resistors and an epoxy glass support to ensure the mechanical strength of the busbar. These parts are presented in the figure 6.12.

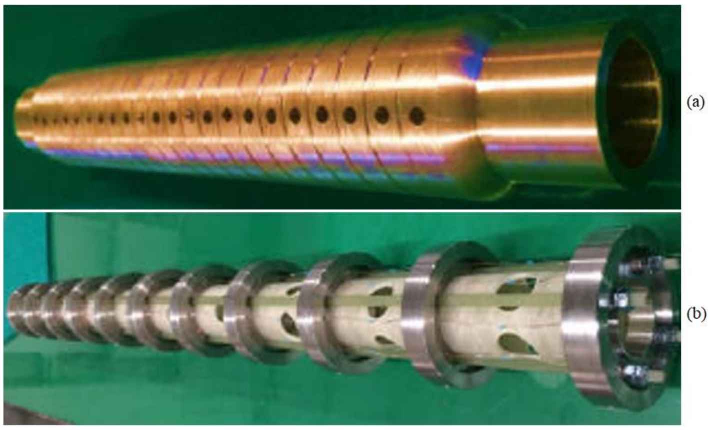


Figure 6.12 Spiral tube damping busbar (a) and an epoxy support with damping resistor (b). (Li et al. 2019)

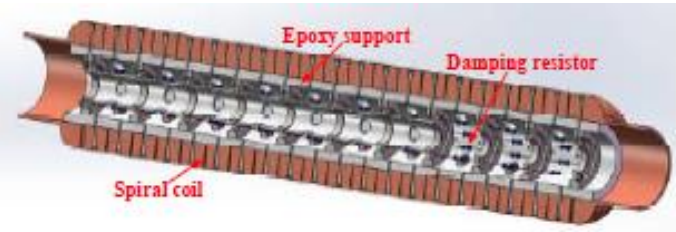


Figure 6.13 The different parts of a spiral tube damping busbar assembled. (Li et al. 2019)

The damping busbar, structure illustrated in figure 6.13, does not affect current or voltage at rated operational frequency and will operate only at higher frequencies. Advantages of the damping busbar are that it is a relatively easy installation as it is formed based on the conventional busbar, and that it has no magnetic saturation problems. In tests, the suppressing effects of VFTO have been significant and the peak magnitude as well as the high frequency components are reduced remarkably. Therefore, the results are very promising for the implementation of this novel method. (Li et al. 2019)

Transient enclosure voltages (TEV) effect can be minimized by keeping short and straight ground leads to minimize inductance, by increasing the number of connections to the ground, by installing voltage limiting arrestors with spacers or by applicating shielding to prevent internally generated transient voltages to reach the outside of the enclosure. Cable sheath earthing should be kept as short and as straight as possible to minimize the interference to control cables. (CIGRE 519 2012)

6.4.2 VFTO mitigation - earthing

In this chapter, alleviating VFTO's is considered from an earthing and building design standpoint. These include both hazardous step and touch voltages as well as electromagnetic interference issues. Following measures are given in IEEE Std80:

- Frequent bonding and grounding of the system
- Special attention to bonding of the metallic enclosures
- conductive platforms (ground mats)
- operating metallic enclosures at ground voltage level
- separating power cable sheath grounds from the enclosures
- Enclosure return currents must not flow through any mounted CT's

It is important to note, that even after applying measures, the circulating currents can still cause slight potential differences between GIS housings. These do not normally cause any kind of health hazards to humans but can possibly cause sparking between parts. This sparking can lead to secondary incidents, such as falling from a ladder, tripping or any of such sorts. (IEEE Std80 2013)

Even though health hazards for humans are not realistically likely, transient overvoltages can often cause interference to control circuits. These interferences can be alleviated by careful choosing of routes and screening of control cables. Control cables should be placed as far away from the enclosure as possible to eliminate any induced currents from TEV. As interferences may still happen, screening measures should carefully be investigated. Effective screening can be produced by enclosing individual cables in their own screens, or by grouping several cables together in metallic conduits or totally enclosed cable trays. This screen should be bonded to the equipment cabinet or housing, which are in turn connected to the main earth. Continuous screens are recommended instead of braided screens as the latter has high impedance at high frequencies. The high-frequency currents can cause local transient potential rise due to the relatively high reactance of traditional earth connections. For this reason, connections must be made as short as possible as bends in copper conductors can also cause high reactance at high frequencies. (Lewis 1993)

For ultra-sensitive control equipment, even complete shielding by Faraday cage may prove to be necessary. This can especially be the case if the sensitive equipment is in the GIS building. Control cabinet cables should still be completely screened and their screens bonded to the shield of the Faraday cage as directly as possible. Isolation transformers or interposing relays may prove to be necessary for cable runs over 60 m. (Lewis 1993)

Circulating currents are an important factor to be considered during earthing design, as the size of the earthing grid is not the only factor contributing to good earthing. Important questions are:

- what ratio of the circulating currents is expected between the ones in the GIS assembly and those circulating via a ground connection, if the currents divide and flow via all possible metallic paths?
- What circulating current value via a ground connection is considered too much?
- Is the GIS being designed to be safe if no circulating current would via ground connection? (At least for an external fault)
- How much earthing is needed for the best balance between operational and safety-related requirements?

These are to be discussed between the designer and the GIS manufacturer, however unfortunately no clear answers exist. Even manufacturer earthing configurations can vary greatly. Special attention should be paid on discontinuities of the GIS earthing system. As areas of the earthing grid require changes in the pattern of the electrodes due to concrete foundations, significant irregularities in earth current flow paths can occur. For this reason, reinforcing bars and other metals in the concrete should be applied and connected to the main ground bus to achieve an even potential field. (IEEE Std80 2013)

Problems in isolation are often found when equipment branches out and the same level of insulation is required in every interface point. All isolating elements should be able to stand the full potential difference to protect against transient voltages. Even other precautions may be necessary to protect against transient voltages. (IEEE Std80 2013)

7. CONCLUSIONS

In this thesis, the main objectives were to research the distribution of fault currents, transferred voltages and GIS VFTO mitigation in HV substations. The objective was to clarify the relevant fault currents and their distribution to improve the knowledge and understanding of earthing design. Other calculational factors from the relevant standards were considered as well, such as additional resistances, vertical earthing rods and earthing conductor to better conductive soil. These had not yet been considered in the company earthing design tool and were needed for special situations, where the normally used horizontal electrode earthing design practices may not provide sufficient results. In addition to these, the effects and mitigation of transferred voltages and VFTO were discussed from a grounding perspective. The key results and findings are given below.

7.1 Current distribution and relevant fault currents

Current distribution between the earth, shield wires, tower earthing, cable sheaths and the transformer neutral point were examined in different fault situations. In substation earthing design, the faults leading to the worst earth potential rise are of most concern. Therefore, the fault at the station must be considered for overhead lines during substation earthing design. If the substation main transformer is earthed from the neutral point, the fault case in the vicinity of the station must also be considered for worst-case scenario. In the case of an earthed transformer neutral, the current through the star-point can be subtracted when considering the event of a fault inside the station, as presented in chapter 4. However, for the purpose of simplifying calculations, the case of a fault inside the station with an isolated transformer neutral can be considered as a worst-case fault scenario. This gives the highest earth potential rise while keeping design input simple, saving engineering hours.

For underground cable systems, the earthed cable sheath provides a current path instead of the shield wires for overhead lines. When determining the current causing the highest earth potential rise inside the substation, the situation of a fault at the station when the current is fed only from the other station must be considered. If the underground HV cable is earthed only from one side, the reduction factor for the cable cannot be used. For these single-point bonded systems, a parallel earth continuity conductor must be installed to provide a path for the fault current.

This thesis serves as a general guide to designers, so that they can better understand the relevant currents as well as the distribution of currents, especially regarding current flow to different structures and the use of reduction factors. Other fault scenarios can be relevant for other earthing system design, such as when considering potential rises between substations.

In the worst case that should be applied in calculations, the fault current contributing to earth potential rise is the single-phase earth fault current, where the effect of shield wires or cable sheaths can be accounted for. This current is different for various earthing systems, but for the common low-impedance earthing system in Finland the above $r*I''_{k1}$ applies. Substation main transformer is also rarely earthed from neutral point and can therefore the current through the neutral point can usually not be reduced from the fault current contributing to the earth potential rise of the station. In the rare case where the neutral point is earthed, the case of an earth fault in the vicinity of the station must be considered, as it may lead to higher earth potential rise than a fault inside the station. This is specially the case if the shield wires and their reduction factors are significantly different. However, for keeping calculations as simple as possible, the case of a fault at the station with the transformer neutral isolated, $r*I''_{k1}$, may be considered as a worst-case scenario. With this assumption, the earthing grid will fill the requirements of SFS 6001 and save design hours by not overcomplicating the calculation.

7.2 Additional measures

Some additional tools for difficult earthing conditions were researched to be implemented in the company earthing design tool. Additional resistances can be applicable in difficult earthing conditions, especially if higher additional resistances can be applied for shoes or surface soil. Surface soil resistances can even be increased for this purpose by using highly resistive materials. The application of vertical earthing rods is also a relevant method, even though the results can vary depending on the soil parameters as the soil is usually layered with large variances in resistivity. Therefore, the knowledge of the soil structure is mandatory to determine if application of vertical earthing rods is of benefit. At least a two-layer model is preferred to determine that the resistivity of the deeper soil is conductive enough to justify driving vertical earthing rods to the ground. In addition to these methods, horizontal earthing electrodes to more conductive soil were researched. This can be a helpful method if there are variations in the area earth structure. An area with good conductive properties close to the substation provides a great earthing point for further lowering the resistance at the station.

7.3 Transferred potentials

Transferred potentials were studied and considered a risk for all substations, but especially ones close to residential areas. The SFS standard recommends separating the different earthing systems to make sure that no hazardous voltages are transferred outside the substation earthing grid area. For >50 kV systems, the separation must be +100 m according to the standard, and this can prove to be impossible to implement in areas that have many structures in the vicinity of the installation. Transferred potential magnitudes can be calculated, but it may be hard to achieve reliable results, as the impedances of underground structures or the structure or location of them overall are often unknown. If residential metallic or other conductive structures are very extensive, a computer modeling solution should be considered. Structures can also be earthed to eliminate potential differences. As evaluating the hazards of transferred potentials can be difficult, any possible structures that may directly or indirectly be connected to the substation earthing grid should be evaluated in the early stages. An analysis using the average soil resistivity can be used to determine earthing potential outside the station, as the potential inside the station with special measures is often not permissible outside the fenced area, where special measures are not applicable. This can give good indication of a safe perimeter, outside which transferred potentials are not considered to be of issue. It is important to note that not only are earthing potentials harmful to humans, but also to equipment, especially communication networks. This means that limit values for communication equipment must also be considered in earthing design.

7.4 GIS VFTO

GIS VFTO mitigation was researched, as it may cause sparking that can raise questions of the safety of the system. As a key outcome, it was found that due to the characteristics of VFTO, the possible sparks do not cause direct harm to personnel. However, secondary incidents can occur if personnel are surprised by the spark event, such as falling or tripping. Therefore, during commissioning or other site functions where the possibility of sparking due to switching actions is present, the personnel should be instructed to act safely and be prepared for the possible event. The mitigation of the phenomenon itself is still relatively new as a research subject, but multiple mitigation methods have been presented. These methods relate mostly to GIS manufacturing design, and the earthing design has only limited options for mitigation of high frequency events. During earthing design, the most important factors to consider for VFTO effect mitigation are frequent bonding and grounding of the system while keeping the earthing connections as short as possible, paying special attention to bonding of the metallic enclosures, conductive platforms, operating metallic enclosures at ground voltage level, separating power cable sheath grounds from the enclosures and ensuring that enclosure return current do not flow through any mounted CT's.

7.5 Results

The purpose was to improve the knowledge and understanding of designers regarding fault currents, reduction factors and current distribution to take the correct parameters into account. As a result, these factors were considered in a case analysis as presented in chapter 4.9, and this thesis serves as a good guide for further project designs.

As presented in this thesis, the calculation tool for earthing voltages can be developed further to include additional measures in addition to the normally designed horizontal mesh earthing grid. The calculation tool fundamentals were well defined and sufficient for basic installations in normal soil conditions, but in the case of exceptionally high fault current magnitudes or soil resistivity values, additional measures such as vertical earthing rods, electrode drawn to conductive soil or additional resistances can be considered as presented in this thesis. In addition to this, this thesis serves as a good guide for earthing designers regarding characteristics and mitigation of transferred voltages and transient overvoltages.

7.6 Future research options

The scope of this thesis was limited due to the extensive subject area of earthing systems. This thesis raised further questions that provide good options for future research. As the fault events in HV systems are rare events, and the substations are often located in remote areas, the analysis of risks and probabilities for different applications could provide an interesting research subject. This could be combined with information about earth fault time duration to form an understanding of how high or low the risk factors are for different installations.

One interesting aspect would also be to compare the earthing voltage results between calculation programs, manually calculated values and measured results. A comparison such as this would give good indication on how the results compare to each other and if the parameters in the programs match the ones given in the standard.

REFERENCES

(ABB 2009)	ABB, Necessary cross section of earthing conductors for three-phase encapsulated gas-insulated switchgear ELK-04. Product manual GIS, Technical Information. 2009. 1HDG 519 008 A en.
(ABB XTC1-398 1993)	ABB, Design Guideline for Earthing Systems in Substation Buildings, especially for GIS. XTC1-398, Dr. Remde. Mannheim, 31th August 1993.
(Boersma 1987)	Boersma, R., Transient Ground Potential Rises in Gas Insulated Substations with Respect to Earthing Systems. Reference ELT_110_2, ELECTRA 1987.
(Burow et al. 2014)	Burow, S., Straumann, U., Köhler, W., Tenbohlen, S., New Methods of Damping Very Fast Transient Overvoltages in Gas-Insulated Switchgear. IEEE Transactions on Power Delivery, VOL. 29, NO. 5, October 2014. ISSN 0885-8977.
(CIGRE 213 2002)	CIGRE. Metz, W., Working Group 23.04. Engineering Guide on Earthing Systems in Power Stations. Reference 213. Germany, 2002.
(CIGRE 519 2012)	CIGRE. Very Fast Transient Overvoltages (VFTO) in Gas-Insulated UHV Substations. Reference 519. WG D1.03. December 2012. ISBN: 978-2-85873-212-8.
(CIGRE 749 2018)	CIGRE. Substation earthing system design optimisation through the application of quantified risk analysis. Reference 749. B3/CIRED Technical Brochure. December 2018. ISBN : 978-2-85873-451-1.
(CIGRE 797 2020)	CIGRE. Sheath bonding systems of ac transmission cables – design, testing and maintenance. Reference 797. B1/WG B1.50. March 2020. ISBN: 978-2-85873-502-0.

(Csanyi 2016)	Csanyi, E., 3 good ways to improve earth electrode resistance. Electrical Engineering Portal, 2016. Available online at: https://electrical-engineering-portal.com/improve-earth-electrode-resistance
(Elovaara & Haarla 2011)	Elovaara, J., Haarla, L., Sähköverkot I, Järjestelmätekniikka ja sähköverkon laskenta. Helsinki, 2011, Otatieto. ISBN 978-951-672-360-3.
(Elovaara & Haarla 2011)	Elovaara, J., Haarla, L., Sähköverkot II, Verkon suunnittelu, järjestelmät ja laitteet. Helsinki, 2011, Otatieto. ISBN 978-951-672-363-4.
(EN 50522 2010)	Earthing of Power Installations Exceeding 1 kV A.C. European standard, Technical Committee Cenelec TC 99X, 2010.
(Fingrid 2017)	Fingrid, Kantaverkon ja asiakasliityntöjen relesuojaus. Sovellusohje, 2017.
(Godlewski 1999)	Godlewski, J. R.; Purdy, G. T.; Blattner, C. J., “Electrical resistance of work shoes,” Transmission and Distribution Conference, 1999 IEEE , vol.2, no., pp.523,525 vol.2, 11-16 Apr 1999.
(IEC 60909-0 2016)	IEC 60909-0 International Standard. Short-circuit Currents in three-phase a.c. Systems – Part 0: Calculation of Currents. IEC, Geneva, Switzerland, Edition 2.0, 2016-01. ISBN 978-2-8322-3158-6.
(IEC 60909-3 2009)	IEC 60909-3 International Standard. Short-circuit current in three-phase a.c. Systems – Part 3: Currents during two separate simultaneous line-to-earth short-circuits and partial currents flowing through earth. IEC, Geneva, Switzerland. Edition 3.0, 2009-03. ISBN 978-2-88910-328-7.
(IEEE Std 80-2013)	IEEE Standard 80. IEEE Guide for Safety in AC Substation Grounding. IEEE Power and Energy Society, 2013.

(Jinsong et al. 2015) Jinsong, Z., Feng, Q., Bing, G., Li, Y., Dawalibi, F., Grounding of urban GIS Substation Connected to Commercial Buildings and Metallic Infrastructures. International Journal of Materials, Mechanics and Manufacturing, Vol. 3, No. 3, August 2015.

(Koivunen 2011) Koivunen, T., Tuulipuiston sähköverkon suojaus. Master of Science Thesis, Tampere University of Technology, 2011.

(Lapinkorpi 2011) Lapinkorpi, A., 110 kV:n suurjännitelinjan pylväs-maadoitukset ja vaarajännitteet. Tampere University of Applied Sciences, 2011.

(Lewis 1993) Lewis, J., Earthing of GIS – an application guide. Working group 23.10, CIGRE, 1993.

(Li et al. 2019) Li, C., Wu, X., Yang, X., Feng, Y., Wang, H., Hou, H., A Novel method of Suppressing VFTO in GIS – Spiral Tube Damping Busbar. 5th International Conference on Electric Power Equipment – Switching Technology, 2019.

(Lim et al. 2013) Lim, S. C., Choun, L. W., Gomes, C., Kadir, M., Environmental Effects on the Performance of Electrical Grounding Systems. IEEE Conference, PEOCO 2013.

(Loo & Ukil 2017) Loo, K. H., Ukil, A., Design of Safety Critical Substation Earthing System Based on Soil Characteristics. IEEE Publication 201-PSEC-0814, 2017. ISBN 978-1-5090-4894-6.

(Popovic 2003) Popovic, L. M., Determination of the reduction factor for feeding cable lines consisting of three single-core cables. Article published in IEEE Transactions on Power Delivery, August 2003.

(Riechert et al. 2012) Riechert, U., Bösch, M., Smajic, J., Shoory, A., Szewczyk, M., Piasecki, W., Burow, S., Tenbohlen, S., Mitigation of Very Fast Transient Overvoltages in Gas Insulated UHV Substations. CIGRE 2012.

(SFS 6001 2018)	SFS 6001:2018, Suurjännitesähköasennukset. High-voltage electrical installations. SESKO Standardization in Finland, 2018.
(Salminen 2008)	Salminen, P., Teollisuussähköverkon mallintaminen ja vikavirtatarkastelut. Master of Science thesis. Tampere University of Technology, 2008.
(Sarajcev et.al 2003)	Sarajcev, I., Majstrovic, M., Medic, I., Current Reduction Factor of Compensation Conductors Laid Alongside Three Single-Core Cables in Flat Formation. IEEE International Symposium on Electromagnetic Compability, 2003. ISBN 0-7803-7779-6.
(Thasananutariya et al. 2004)	Thasananutariya, T., Spuntupong, K., Chatratana, S., Design of Grounding System for GIS Indoor Substation. IEEE Region 10 Conference TENCON 2004, Vol.C, p.413-416 Vol.3, 2004