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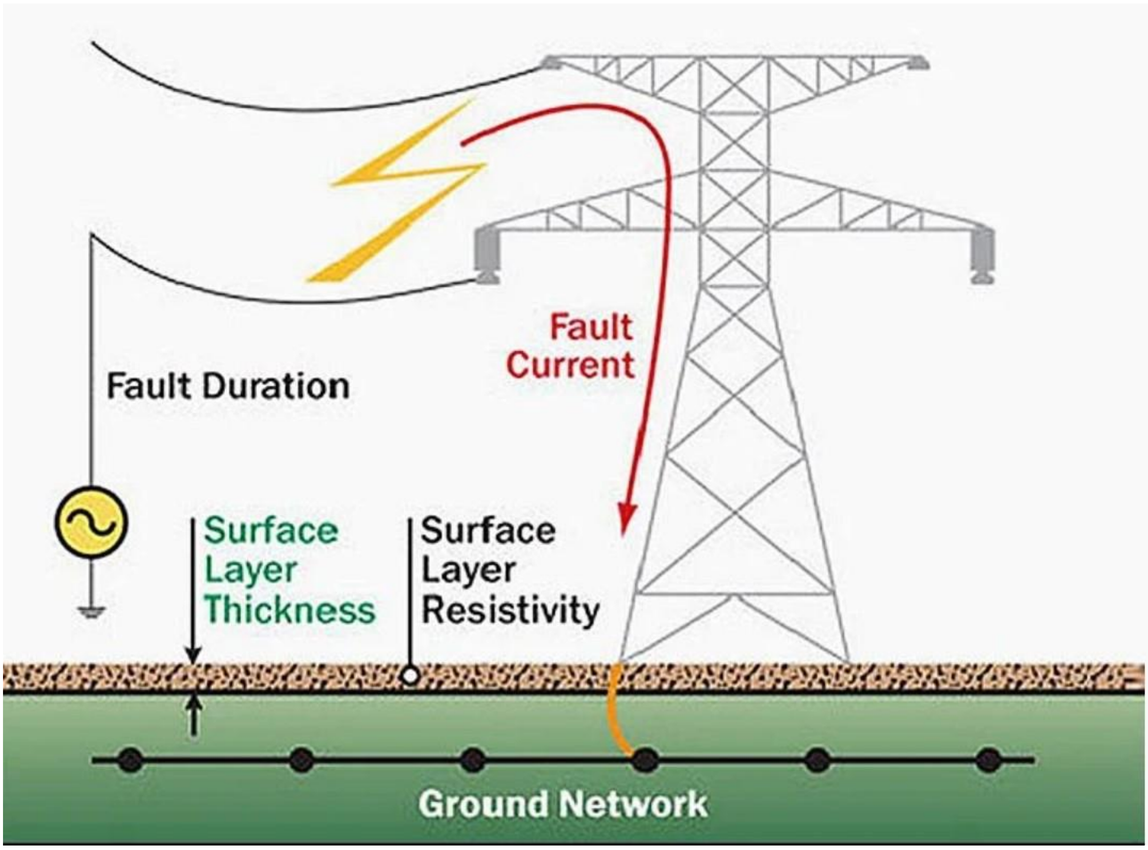
FMH606 Master's Thesis 2022

Electrical Power Engineering

System Grounding of 132 kV Networks



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Summary:

As the use of other renewable energy sources such as wind increases to reduce the carbon dioxide emission into the environment, the transmission and distribution network increase, and the Local Vestfold and telemark region is not an exception. However, this challenges system operations, planning, and protection to ensure that system reliability is sustained, especially during short circuit faults due to increased load on the transmission lines. Quick circuit analysis of a power system is of paramount importance as this provides the voltage and current needed in the design and rating of electrical equipment.

The project topic (System grounding of 132Kv network) focuses on the overvoltage impact of this development on the two primary grounding methods Compensated and direct (centralized and distributed)during single-phase to ground fault of a network in a radial system for both symmetrical and unsymmetrical transmission lines and how a single-phase fault voltage and current impact on one side of a transformer station is dependent on the type of grounding method, no of winding in the transformer unit and the winding connections.

This was validated using the powerfactory to design a typical Vestfold and telemark 132kv network with an external infeed. The simulation was carried out with both compensated and direct grounding methods for transposed and un-transposed transmission lines.

The research result proves that compensated grounding shows a higher overvoltage of 1.760pu with a reduced fault current of 0.003kA for transposed transmission lines, while the fault current was doubled to 0.006kA when the transmission line is un-transposed. Overvoltage at the end of a radial transmission line was lower (1.712p.u) compared to 1.760p.u at the middle of the radial line. Direct grounding overvoltage of 1.30p.u was recorded with a high fault current value of 1.129kA. Similarly, distribution of the compensated Peterson coil and direct grounding to several stations on the network reduces this overvoltage in both grounding methods. Still, it contributes significantly to the double fault current recorded for the directly grounded system.

Preface

This research aims to complete the FMH606 Master's Thesis requirement as part of the Electrical Power Engineering course program at the University of South-Eastern Norway.

This has deepened my understanding of what system grounding is all about, its importance, the ways of achieving them using Peterson coil and direct methods, and the implications of a single-line to ground fault on the different grounding systems in terms of overvoltage and earth fault currents thus giving me a broader range of options to choose from among a variety of research topics.

I highly appreciate my supervisor, Prof Gunne John Hegglid, for his time, understanding, and patience with me during this project and the University of Southeast Norway for the privilege and support with all the necessary materials and tools needed toward making sure that the project was a success.

Porsgrunn Norway

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Oluchi Mercy Okwo

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Nomenclature

HV	High voltage
PSI	Positive sequence impedance
NSI	Negative sequence impedance
ZSI	Zero sequence impedance
FeAl	Iron aluminides
IEC	International Electrotechnical Commission.
WTG	Wind turbine generators
St	Steel conductor
GMR	Geometric mean radius
IEEE	Institute of Electrical and Electronics Engineers
GRP	Ground potential rise
PPGB	Personal protective grounding/bonding
OCPDs	Overcurrent protection devices
RMS	Root means square

1 Introduction

With the quest to reduce carbon dioxide emission, several other sources of energy production have evolved. Compared to just 48 countries in 2005, 128 countries had enacted renewable energy assistance programs by 2017 [1], of which Norway is not an exception. These policies were critical in assisting countries in moving from conventional to renewable energy by removing impediments to renewable energy production [1]. Wind energy has continued to increase gradually in many parts of the world, fueled by favorable legislation and environmental concerns. Compared to 2017, the total global installed capacity of wind power increased by 9% in 2018[2]. Wind power generation is expected to grow by 6% in 2019 and 14% in 2020, according to the US Energy Information Administration, and wind power has been the fastest-growing source of electricity in the Electric Reliability Council of Texas in recent years [3].

This has led to the electrification of so many industries, such as transport industries, towards manufacturing electric cars to reduce Co2 emissions, increasing power consumption, and expanding the already existing transmission and distribution lines. Similarly, local Grenland and most regions of Vestfold and the telemark region may experience more than double increase in its load capacity as the majority of load growth will have to be 'imported' through the national transmission grid, which will need to very certainly be reinforced. Moreover, Significant wind power penetration poses significant issues for system protection, planning, and operations [4]. The power system community has put a lot of effort into developing and validating WTG models to investigate the impact of increased wind integration on system protection, and it's evident that this sort of generator behaves differently during short circuits than traditional generators [5].

Before now, research has been done to ascertain the temporary overvoltage due to ground faults in a medium voltage network for ungrounded and compensated Neutral [6], without considering a Grid expansion. It was proposed from [6] that a single phase to ground fault at the receiving end of a long overhead line for an ungrounded neutral can cause an overvoltage of 2.5-3p. u at the busbar and the healthy lines and 1.8p.u for a fully compensated neutral at worst-case scenarios [6]. Only in scarce circumstances of a total breakdown of the neutral grounding system can the identical phenomena indicated for ungrounded neutral. In contrast, partial failure of the HV neutral grounding gives a higher value of overvoltage but within the limit of 1.8-2.2p. u [6].

Resonant and isolated grounding is the most used grounding method in Norway. Only a few 132 kV networks are directly grounded. Skageraks' two 132 kV networks are all resonant– each of them with 3 – 5 Peterson coils, but all are in the central part of the networks. The compensated network is achieved using an arc suppression coil known as the Peterson coil, which could be centralized or distributed [7]. This compensates for the capacitive earth fault currents supplied by a substation's outbound feeders [7]. Because most of the overhead lines on towers inside transmission systems acquire earth wires, earth wires play a significant role in safety operations during faulty conditions in direct grounded systems [8].

Asides from the transmission lines, the transformer station may also be grounded either directly, by impedances, or isolated. Depending on the grounding method, the transformer tends to behave differently during single-phase fault in terms of the voltage/current impact transfer from one side of the transformer to another.

However, the existing high Voltage networks' non-transposed architecture, on the other hand, makes fault detection and location more difficult.

In this thesis, the overvoltage analysis is restricted to single-phase to ground fault, and as a result, it is essential to have sound knowledge of symmetrical components before analyzing the overvoltage impact on the transmission line and transformers during single-phase fault for both compensated and direct grounding methods.

1.1 Project description

The project aims at analyzing the impact of expanding an existing transmission and distribution 132kV local Vestfold and telemark network on its grounding systems, considering a change of grounding system from resonant to direct. The project objectives are divided into three folds:

1. Describe the formulae which give the capacitive and inductive parameters for a typical 132 kV overhead line and show why the impedances can be considered symmetrical. Further, describe how voltages in a three-phase system will develop if not symmetrical.
2. The difference in overvoltage due to single-phase ground faults in a compensated 132 kV grid system with compensation (Peterson) coils distributed in a radial system versus located only central in main transformer stations onto the transmission system. Compared with a system that is directly grounded only in the central transformer station or distributed.
3. For different transformer types grounding, show how single-phase faults on one side of a transformer will impact voltages/currents on the other side of the transformer, dependent on the number of windings in the transformer unit and winding connections.

To achieve the objectives mentioned above, some assumptions were made.

1.1.1 Assumptions

1. The grid resistance (R_G) is assumed to be 12ohm.
2. The temperature changes do not affect the resistance of the transmission line.
3. The sag of the transmission lines is neglected.
4. The soil is a homogenous mixture.
5. Skin and proximity effect likewise permeability of FeAl is neglected.
6. St. 50 conductor resistance was assumed to be 8-times FeAl 50 due to the skin effect.

1.2 Overview and scope of the thesis.

The approach implemented toward achieving the set objectives is divided into chapters as follows:

Chapter 2: To have a good literature study on what system grounding is all about, the types of faults on a three-phase system and, the single-phase to ground fault, symmetrical component, and how an unbalanced three-phase system can be resolved into positive, negative and zero sequences, transmission line parameters, unsymmetrical analysis of single-phase to ground fault, line transposition, and touch/step voltages.

Chapter 3: Show for different transformer types how single-phase faults on one side of a transformer can / will impact voltages/currents on the other side of the transformer, dependent on the number of windings in the transformer unit and winding connections.
Chapter 4: Design of 132kV model network of Grenland region in PowerFactory with the data provided by Prof. Gunne as in Appendix A.1.
Chapter 5: Simulation and results of transposed 132kV network designed for overvoltage analysis in a compensated Peterson coil and direct grounded located in a central station or distributed.
Chapter 6: Simulation and results of 132kV designed network for overvoltage analysis in a compensated Peterson coil and direct grounded located in a central station or distributed if symmetry is taken care of.
Chapter 7: Discussions on the result simulations of chapters 5 and 6.
Chapter 8: conclusion/further work

2 Literature Review

This chapter presents the literature review used as the basis for this research study. The study of fault in a three-phase system, symmetrical component for analyzing unsymmetrical fault conditions, Sequence impedance calculations of transmission lines, grounding, and its methods (Resonant and direct), transposition, transmission line parameter, and touch/step voltage are discussed in this chapter.

2.1 Faults in a Power System

A fault is an abnormal situation low-impedance connection (including an arc) between two sites of different potential, whether made accidentally or on purpose, in an electrical system that can lead to overvoltage causing damage to electrical equipment and disrupting the regular flow of current [9]. When power system equipment, such as circuit breakers, busbars, transformers, and cables, are put to fault tasks that exceed their rating, it might fail catastrophically If the fault currents exceed ratings [10]. Faults are classified as shown in figure 1[11].

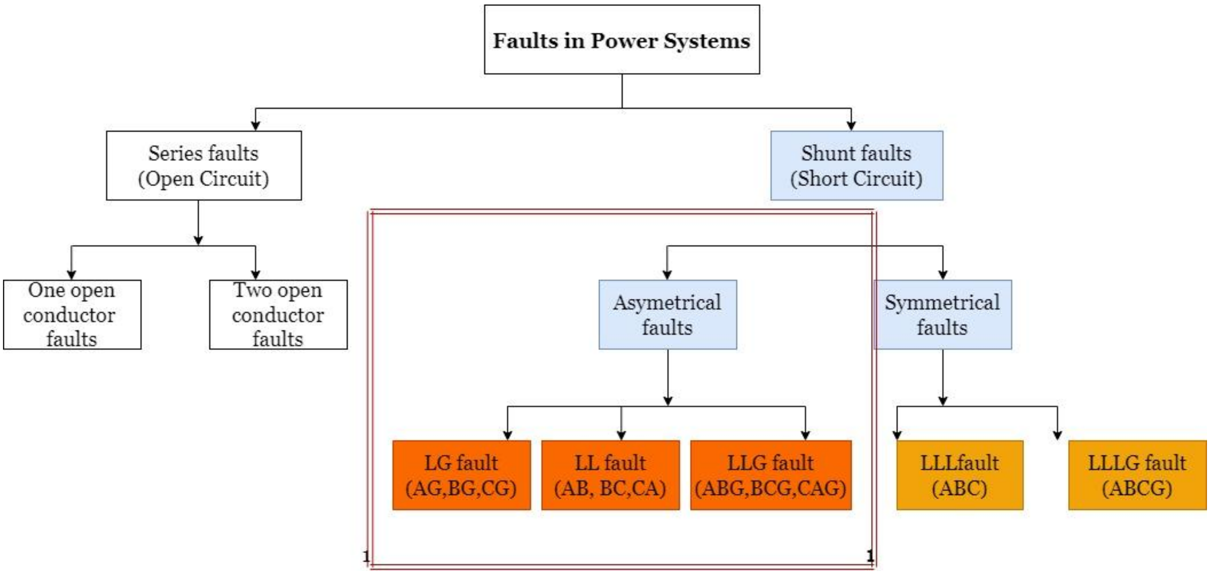
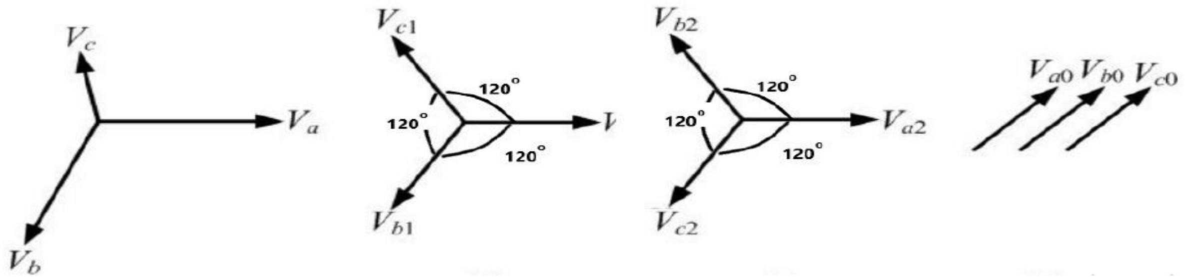


Figure 1: Classification of Fault

Short circuit faults have their source from phenomena like lightning, switching overvoltage, Insulation contamination, and conductor breakage. For asymmetrical or unbalanced faults, the earth wire serves as a return path for the overvoltage caused by these short circuits' faults [12]. Single-phase to ground fault (LG fault) is the most common type of fault in a three-phase power system, and to analyze an unbalanced fault such as that, we need to know how to apply the symmetrical components in other to calculate variables and parameters such as voltage, current and impedance respectively in short circuit analysis [12].

2.2 Symmetrical component

Unbalanced power networks, such as single-line to ground faults, unbalanced impedance, open phases, and so on, can be analyzed and understood using symmetrical components [13]. A ground fault is indicated by a zero-sequence component, whereas unbalanced loading causes negative components; as a result, having a thorough understanding of this method is a critical component of security [14]. An unbalanced phasor can be resolved into three balanced, symmetrical Positive, Negative, and Zero sequence components, shown in figure 2.



(a) (b) (c) (d)

Figure 2:Representation of (a)an unbalanced network (b) positive sequence (c) negative sequence (d) zero sequence [15].

2.2.1 Positive Sequence

A positive sequence is balanced of three phasors of identical amplitude that are separated by 120 degrees and have the same sequence as the original phasors [13]. At the system frequency, they also revolve in a counterclockwise manner and are represented as Va1, Vb1, Vc1.

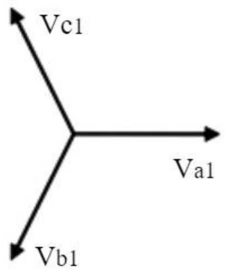


Figure 3: Positive sequence component, Positive sequence: abc.

2.2.2 Negative Sequence

Negative sequences are balanced three-phase systems separated by 120 degrees and with phasor sequences that are the opposites of the original phasors. Their phasor rotation is in the reverse direction.

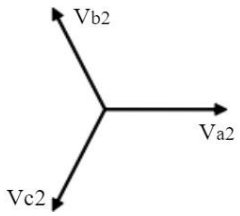


Figure 4: Negative sequence component, Negative sequence: acb.

2.2.3 Zero sequence

They are three phasors of equal magnitude but zero-degree phase angle where $I_{ao} = I_{bo} = I_{co} = I_o$ and $V_{ao} = V_{bo} = V_{co}$

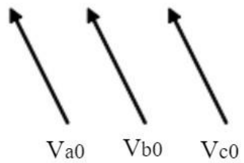


Figure 5: Zero sequence components.

2.3 Symmetrical components of three unbalanced phasors of a three-phase system.

Fortescue shows how to break down an unbalanced system of n-related vectors into n balanced vector systems called symmetric components of the original vectors[13].

According to the Fortescue method:

$V_a = V_{ao} + V_{a1} + V_{a2}$ (2.1)

$V_b = V_{bo} + V_{b1} + V_{b2}$ (2.2)

$V_c = V_{co} + V_{c1} + V_{c2}$ (2.3)

Using the operator, a = $1 < 120° = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$

$$a^2 = 1 < 240° = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

$$a^3 = 1 < 360° = 1$$

The symmetrical component transformation matrix (H) is :

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$V_{a012} = \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}, V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

And also inverse give original phasor components.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$ [15]

Thus, the sequence element of an unbalanced system is given as:

$$V_{a1} = \frac{1}{3}[V_a + aV_b + a^2V_c] \qquad (2.4)$$

$$V_{a2} = \frac{1}{3}[V_a + a^2V_b + aV_c] \qquad (2.5)$$

$$V_{a0} = \frac{1}{3}[V_a + V_b + V_c] \qquad (2.6)$$

It is importantant to know that there is no zero sequence in a balanced three phase system since : $V_a + V_b + V_c = 0$, Same sequence elements are applied for current.

2.4 Unsymmetrical fault analysis of single-line to ground fault.

A single line to ground fault is a shunt type of unbalanced fault between phases or between a phase and ground[16]. The following procedures are used to analyze a single-line to ground fault.

1. Draw a circuit diagram of the fault spot on phase if the fault occurs at line a, labeling the currents, voltages, and impedance, and include all phase connections to the fault.

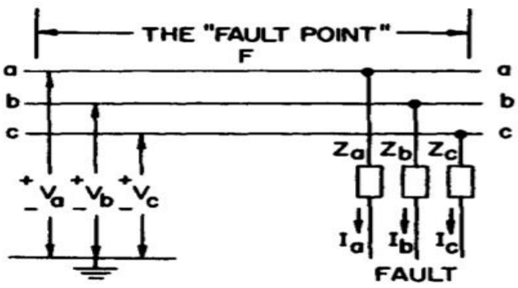


Figure 6: Circuit diagram of a fault point [16]

2. The second step is to write down the boundary conditions with respect to current and voltages for the single-line to ground fault.

$$I_b = I_c = 0 \text{ and } V_a = Z_f I_a$$

3. Using the transformation matrix $A^{-1}$to change current and voltage from step 2 from a-b-c to 0-1-2.

$$\mathbf{I_{sym} = A^{-1}I_{asym}}$$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b = 0 \\ I_c = 0 \end{bmatrix}$$

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3}I_a$$

What this means is that all the sequence currents are equal, as in equation 2.7

$$I_{ao} = I_{a1} = I_{a2} = \frac{1}{3}I_a \qquad (2.7)$$

Then, $I_a = I_f = 3I_{a1}$ where I_f = fault current.

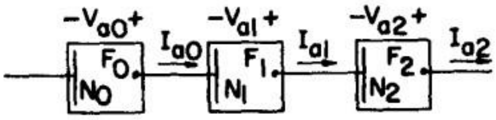
And the voltage at phase a:

$V_a = Z_f I_a = 3Z_f I_{a1}$. (2.8)

Using the symmetrical component properties:

$$V_a = V_{a0} + V_{a1} + V_{a2} = 3Z_f I_{a1} \quad (2.9)$$

4. Since the sequence currents are the same, so the network must be connected in series.



5. Because the sequence voltage adds up to give $Z_f I_{a1}$, an external impedance that represents the fault impedance must be added.

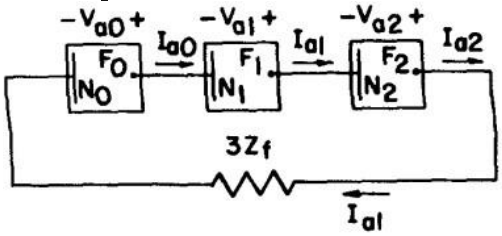


Figure 7: Sequence network connection for single-line to ground fault [16].

With the network in step 5, one can compute the positive, negative, and zero sequence current.

$$\mathrm{I}_{ao} = \mathrm{I}_{a1} = \mathrm{I}_{a2} = \mathrm{I}_f = \frac{V_f}{Z_{ao} + Z_{a1} + Z_{a2} + 3Z_f} \quad (2.10)$$

Knowing the sequence current, we can calculate the sequence voltages:

$$\mathrm{V}_{ao} = -\mathrm{Z}_{ao}\mathrm{I}_{ao} \quad (2.11)$$

$$\mathrm{V}_{a1} = \mathrm{V}_{an} - \mathrm{Z}_{a1}\mathrm{I}_{a1} \quad (2.12)$$

$$\mathrm{V}_{a2} = -\mathrm{Z}_{a2}\mathrm{I}_{a2} \quad (2.13)$$

The healthy phase voltages are calculated using the formular below:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

Where $\mathrm{V}_a = 3\,\mathrm{Z}_f \mathrm{I}_{a1}$ (2.14)

2.5 Transmission Line Parameters.

A transmission line is a long conductor with a particular design (bundled) for transporting large amounts of generated electricity at very high voltage from one station to another as voltage levels vary [17] and have its parameters: resistance, inductance, capacitance, and conductance distributed along the length of the line. The resistance is dependent on the conductor composition at a given temperature. Inductance and capacitance are a result of magnetic and electrical fields around the conductor, whereas the conductance is a result of leakage current, which is negligible compared to the rated current and can be neglected [18]. The transmission lines are not actually symmetrical. This results in an unbalance voltage on the lines due to the difference in the inductance and capacitance on each line.

2.5.1 Inductance of a three-phase transmission line.

For a three-phase conductor wire of radius r_A, $r_{B,} and\ \ r_C$ with horizontal distance of $D_{AB,}D_{BC,}D_{CA,}$ as shown in figure 8.

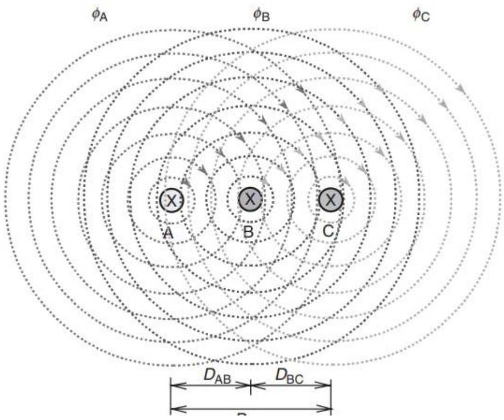


Figure 8: Magnetic flux produced by each conductor [18].

Where D>r and $I_{A,}I_{B,}I_C$ are the current flowing in each of the conductors, thus the sum of the magnetic flux of conductor A at a point P as in figure 9 is stated in equation 2.15.

$$\emptyset_{AP} = \emptyset_{AAP} + \emptyset_{ABP} + \emptyset_{ACP} \tag{2.15}$$

Where:

$\emptyset_{AAP}$ = flux produced by current $I_{A,}$ on conductor A at point P

$\emptyset_{ABP}$ = flux produced by current $I_{B,}$ on conductor A at point P

$\emptyset_{ACP}$ = flux produced by current $I_{C,}$ on conductor A at point P

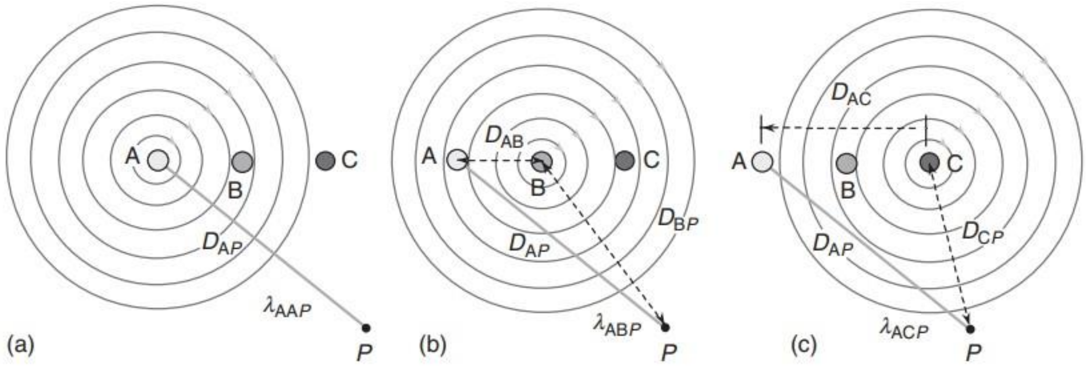


Figure 9: Flux linkage of (a)conductor A at point P, (b) conductor B on conductor A at point P and (c) conductor C on conductor A at point P[18].

For a 1m length conductor, the flux produced are represented in the equations below.

$$\emptyset_{AAP} = \frac{\mu_0}{2\pi} I_A \ln\left(\frac{D_{AP}}{GMR_A}\right) \quad [Wb/m] \tag{2.16}$$

$$\emptyset_{ABP} = \frac{\mu_0}{2\pi} I_B \ln\left(\frac{D_{BP}}{D_{AB}}\right) \quad [Wb/m] \tag{2.17}$$

$$\emptyset_{ACP} = \frac{\mu_0}{2\pi} I_C \ln\left(\frac{D_{CP}}{D_{AC}}\right) \quad [\,Wb/m] \tag{2.18}$$

The corresponding flux linkages of conductor A at the point P is stated as:

$$\lambda_{AP} = \lambda_{AAP} + \lambda_{ABP} + \lambda_{ACP} \tag{2.19}$$

$$\lambda_{AAP} = \frac{\mu_0}{2\pi} I_A \ln\left(\frac{D_{AP}}{GMR_A}\right) \quad [Wb/m] \tag{2.20}$$

$$\lambda_{ABP} = \int_{D_{AB}}^{D_{BP}} B_{BP} dP = \frac{\mu_0}{2\pi} I_B \ln\left(\frac{D_{BP}}{D_{AB}}\right) \quad [Wb/m] \tag{2.21}$$

$$\lambda_{ACP} = \int_{D_{AC}}^{D_{CP}} B_{CP} dP = \frac{\mu_0}{2\pi} I_C \ln\left(\frac{D_{CP}}{D_{AC}}\right) \quad [Wb/m] \tag{2.22}$$

λ_{AP} = total flux linkage of conductor A at point P

λ_{AAP} = flux linkage from magnetic field of conductor A on conductor A at point P

λ_{ABP} = flux linkage from magnetic field of conductor B on conductor A at point P

λ_{ACP} = flux linkage from magnetic field of conductor C on conductor A at point P

Substituting equation 2.20 through 2.22 into equation 2.19, then

$$\lambda_{AP} = \frac{\mu_0}{2\pi} \left[I_A \ln\left(\frac{1}{GMR_A}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] + \frac{\mu_0}{2\pi}\left[I_A \ln(D_{AP}) + I_B \ln(D_{BP}) + I_C \ln(D_{CP})\right] \tag{2.23}$$

According to natural logarithm law and the shifting of point P to infinity such that $D_{AP} = D_{BP} = D_{CP}$, Thus the flux linkage of A conductor becomes:

$$\lambda_A = \frac{\mu_0}{2\pi} \left[I_A \ln\left(\frac{1}{GMR_A}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] [\mathrm{Wb/m}] \tag{2.24}$$

Similarly flux linkage on conductor B and C will be:

$$\lambda_B = \frac{\mu_0}{2\pi} \left[I_B \ln\left(\frac{1}{D_{BA}}\right) + I_B \ln\left(\frac{1}{GMR_B}\right) + I_C \ln\left(\frac{1}{D_{BC}}\right)\right] [\mathrm{Wb/m}] \tag{2.25}$$

$$\lambda_C = \frac{\mu_0}{2\pi} \left[I_C \ln\left(\frac{1}{D_{CA}}\right) + I_B \ln\left(\frac{1}{D_{CB}}\right) + I_C \ln\left(\frac{1}{GMR_C}\right)\right] [\mathrm{Wb/m}] \tag{2.26}$$

Placing equation 2.24 to 2.26 in matrix form,

$$\begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

where λ_A, λ_B, λ_C = total flux linkages of conductors A, B, and C

L_{AA}, L_{BB}, L_{CC} = self-inductances of conductors A, B, and C field of conductor A at point *P*

L_{AB}, L_{BC}, L_{CA}, L_{BA}, L_{CB}, L_{AC} = mutual inductances among conductors

A single inductance can then be achieved if the distance of separation between the conductors is the same and the system is balanced. That is: D= $D_{AB} = D_{BC}$=D_{CA} $and\ \ I_A +\ I_B$+ $I_C = 0$.

$$L_{phase} = \frac{\mu_0}{2\pi}\ln\left(\frac{D}{GMR_{phase}}\right)\ [H/m] \qquad (2.27)$$

2.5.2 Capacitance in a three-phase line.

A balanced three phase line of conductor radii $r_{A,}r_B and\ r_c$, distance between the conductors as D_{AB}, D_{BC} and D_{AC}. Using the mirror charge method, the capacitance from phase to ground and phase to phase are given in the formulars stated in equation 2.28 and 2.29.

$$c_g = \frac{2\pi\varepsilon}{ln\left[\frac{4h}{d}\left(\frac{D`_{mean}}{D_{mean}}\right)^2\right]} \quad \left[\frac{nF}{km}\right] \qquad (2.28)$$

$$c_{ab} = \frac{2\pi\varepsilon ln\left[\frac{4h}{d}\right]}{ln\left[\frac{4h}{d}\left(\frac{D`_{mean}}{D_{mean}}\right)^2\right]\cdot ln\left[\frac{4hD_{mean}}{dD`_{mean}}\right]} \quad \left[\frac{nF}{km}\right] \qquad (2.29)$$

Where:

$\varepsilon =$ permittivity = $\varepsilon_0\varepsilon_r$

ε_0= permittivity of free space.

d= phase conductor diameter (m)

h = geometric mean conductor height above the ground = $\sqrt[3]{h_a h_b h_c}\ \ (m)$

D_{mean} = geometric mean distance between the phases = $\sqrt[3]{D_{AB}D_{BC}D_{AC}}$ (m)

D'_{mean}= geometric mean distance between mirror charge and phase= $\sqrt[3]{D'_{AB}D'_{BC}D'_{AC}}$ (m)

D_{AB}, D_{BC} and D_{AC} = distance between the phases (m)

2.6 The General method of Impedance Calculation

Each conductor has self-impedance, and any two conductors have mutual impedance. They are affected by the conductor material, construction, physical dimensions or geometry of the tower or line, as well as the earth's resistance [19]. An overhead line with physical dimensions and conductor spacing is depicted in figure 10. The currents are carried by tower conductors in a parallel path with clearance distance X and mutual distance dij [19]. The IEC 60909 report 2 provided an equation-based formula of the modified Carson method to calculate the Positive (PSI) and zero sequence impedance (ZSI), where the negative sequence impedance is the same as the positive sequence impedance.

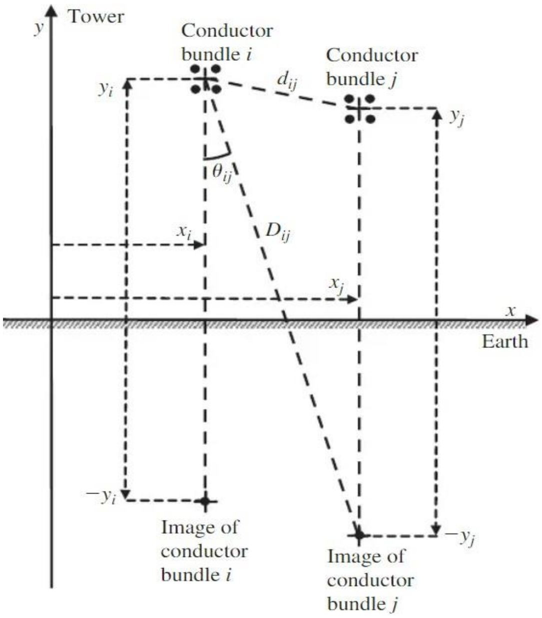


Figure 10: A general illustration of an overhead line physical dimensions and conductors spacings relative to tower center and earth [18].

The dimensions, spacings, and the mirror image to the ground in figure 10 above are used in the calculation of the line parameters. Every conductor has both self and mutual impedances between two conductors.

2.6.1 Self-Impedance

Using basic electromagnetic flux linkage formulae, the following equation defines the self-impedances for various distances.

$$Z_{ii} = R_i + \pi^2 10^{-4} f + j4\pi 10^{-4} f \left[\left(\frac{\mu}{4}\right) + log\frac{D_{erc}}{r} \right] \quad [\Omega/km] \tag{2.30}$$

Where:
*R*i is resistance of conductor in ohms
μ is relative permeability
f is line frequency in hertz
Derc is earth return path i.e., Derc=1.309125. Δ; Δ is skin depth
r is GMR of conductor, r=r0.0.7788; r0 is radius of conductor

2.6.2 Mutual Impedance

The formula used for calculating mutual impedance between two conductors i and j of figure 10 is written in the equation below.

$$Z_{ij} = \pi^2 10^{-4} f + j4\pi 10^{-4} f \left[log\frac{D_{erc}}{d_{ij}} \right] [\Omega/km] \tag{2.31}$$

Where:

d_{ij} is the distance between the two conductors in km

Derc is earth return path i.e., Derc=1.309125. Δ; Δ is skin depth
f is the line frequency in Hertz

2.7 IEC Method of Impedance Calculation

In general, the cable impedance can be determined using the IEC 60909-2 'Short-circuit currents in three-phase A.C. systems - Part 2: electrical equipment data for short-circuit current calculations' standard [20]. It is an equation based on the modified Carson's method.

2.7.1 Positive sequence Impedance

Positive sequence impedance is a characteristic that is used to calculate voltage and current relationships in alternating current (AC) circuits under typical operating conditions. It can be represented in either rectangular as seen below:

$$Z_1 = R_1 + jX_1 \tag{2.32}$$

where:
X_1 - positive sequence reactance

R_1 - positive sequence resistance

The effects of single and bundled conductors running in series or parallel are included in the inductance relationship, which is used to determine the performance of overhead transmission lines, as can be seen in the equation below for positive sequence inductance reactance [20].

$$X_1 = \omega L_1 = \left(\frac{\omega \mu_0 a}{2\pi}\right)\left(ln\frac{D_M}{r_B} + \frac{1}{4n_2}\right) [\Omega/km] \tag{2.33}$$

Where:

ω - angular frequency = 2 p f [Hz]
L_1 - positive sequence inductance [H/km] $=\left(\frac{\mu_0 a}{2\pi}\right)\left(ln\frac{D_M}{r_B} + \frac{1}{4n_2}\right)$
a - conductor length [km]
D_M - geometric mean distance
μo - constant of magnetic field = $4\pi \times 10^{-7}$[H/km]
r_B − bundle conductor equivalent radius

and

$$D_M = \sqrt[3]{(D_{BC}.D_{CA}.D_{AB})}$$

2.7.2 Zero Sequence Impedance

Impedance as a result of zero-sequence current is known as zero sequence impedance. For zero-sequence current to flow, there must be a current return path and is used in single-phase to ground short circuit calculations.

A. Single circuit without earth wire

The given formular below is used to calculate the zero sequence impedance:

$$Z'_{OS} = R_0 + jX'_0 = \frac{R'_1}{n_2} + \frac{3}{4} f \mu_0 \pi + jf\mu_0 \left(3ln.\frac{\delta}{\sqrt[3]{r_B.D_M^2}} + \frac{\mu_T}{4n_2}\right) \; [\Omega/km] \qquad (2.34)$$

Where:

R'_1 - conductor resistance per unit length
n_2 - number of sub conductors
f- frequency of the system [Hz]
DM - geometric mean distance
μ_T - permeability of conductor (aluminium μ_T =1)
δ- return depth of earth current [km] = $\frac{1.85}{\sqrt[2]{2f\mu_o\pi/\rho}}$

B. Single circuit with one earth wire

The zero-sequence self and mutual impedance, since there is a return circuit to the ground, are given as follows:

$$Z'_{OS1E} = Z'_{0S} - \frac{3(Z'_{CE})2}{Z'_{EE}} \; [\Omega/km] \qquad (2.35)$$

While the mutual impedance is as shown below:

$$Z'_{CE} = f\mu\frac{\mu_0}{4} + jf\mu_0 ln\frac{\delta}{D_{ME}} \; [\Omega/km] \qquad (2.36)$$

Where:

$$D_{ME} = \sqrt[3]{(D_{BC}.D_{CA}.D_{AB})}$$

D_{ME} is the mean distance between the conductor and the earth wire.

C. Single circuit with two earth wire

Self and mutual zero-sequence impedances are calculated using the formulas below:

$$Z'_{OS2E} = Z'_{0S} - \frac{3Z'_{CE}2}{Z'_{E1E2}} \; [\Omega/km] \qquad (2.37)$$

Mutual Impedance equation is as shown below:

$$Z'_{E1E2} = \frac{R'_E}{2} + f\mu\frac{\mu_0}{4} + jf\mu_0\left(ln.\frac{\delta}{\sqrt{r_E D_{E1E2}}} + \frac{\mu_E}{8}\right) \; [\Omega/km] \qquad (2.38)$$

D. Double Line with two earth wire

$$Z'_{OD2E} = Z'_{0D} - \frac{6(Z'_{CE1E2})2}{Z'_{EE}} \; [\Omega/km] \qquad (2.39)$$

And,

$$Z'_{CE1E2} = f.\mu.\frac{\mu_0}{4} + jf.\mu_0.ln\left(\frac{\delta}{D_{M2E}}\right) \; [\Omega/km] \qquad (2.40)$$

2.8 Earth Return Current.

During a ground fault in an HV network, the ground-fault current leaves the phase line conductor and travels over all available pathways to the feeding sources, where some flows into the surrounding earth and others flow back to the source through the neutral conductor as the earth return current [22]. Zero sequence impedance is seen in a direct grounded system due to the presence of the earth return path. Likewise, important behavior of the power system, such as Overvoltage, are defined based on this earth's return path as seen in single-line to ground fault. Figure 11 below shows the two-ground fault currents initiated during a fault in a substation.

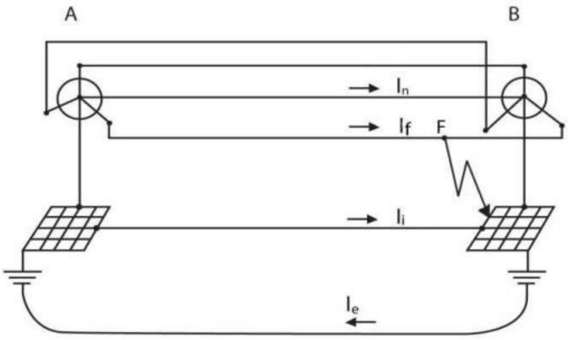


Figure 11: Main part of a ground fault current [22].

The amount of these earth return currents depends on the transmission line impedance, soil resistivity, and height of the line above the earth's surface.

2.8.1 Soil Resistivity

This is the ability of the soil to resist the flow of current through it; thus, the amount of current that returns to the source as the earth returns current depends on the soil's resistivity. The Wenner four-pin method is the most common method used in measuring soil resistivity [21]. The formula for the calculation of soil resistivity is given in equation 2.41 [22].

$$\rho = \frac{2\pi L R_E}{ln\frac{(4L)}{d}} \tag{2.41}$$

Where:

ρ = soil resistivity

R_E= earthing resistance

L = length of rod

d= diameter of the rod

Soil resistivity varies with the amount of mineral content of the soil, soil type, moisture content, and Ph values of the soil. The soil resistivity and its equivalent earth penetration depth (δ) depending on the soil type is given in table 1.

Table 1: soil resistivity and its equivalent earth penetration depth [24].

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 ... 8 520
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

Earth penetration depth decreases as the soil resistivity increases; this can be represented mathematically in the equation 2.42.

$$\delta = \frac{1.851}{\sqrt{\frac{\mu \cdot w}{\rho}}} \qquad (2.42)$$

where:
δ - equivalent earth penetration depth, m
μ - permeability of free space (= 4π × 10−7), H.m^{-1}
ρ - soil resistivity, Ωm
but earth return Path $D_{erc} = \delta . 1.309125$

$$D_{erc} = \frac{1.851}{\sqrt{\frac{\mu.\omega}{\rho}}} . 1.309125$$

Zero sequence impedance depends on the soil resistivity according to [23] using figure 12 below for analysis,

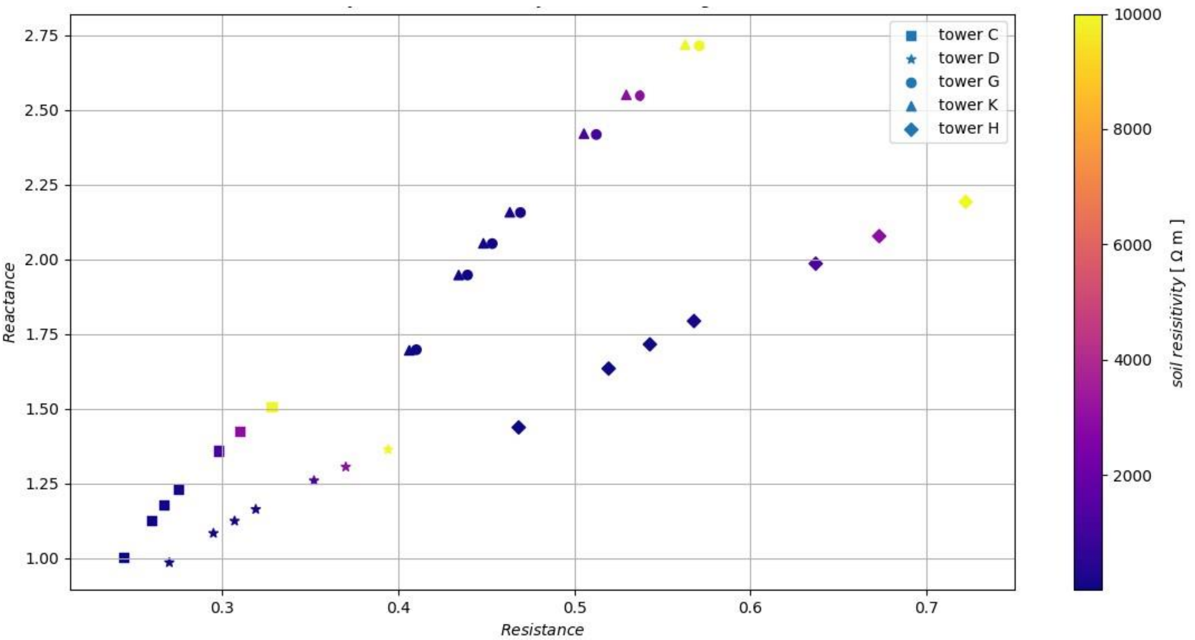


Figure 12: soil resistivity analysis based on tower configuration [23]

Tower H, K, and G, which are double circuits with one earth conductor, have more impact on the soil resistivity compared to towers C and D of a single circuit with one earth conductor. Likewise, tower D, a single-phase circuit with double earth wire, will have more impact on soil resistivity compared to tower C, a single circuit with one earth wire.

2.9 Reduction Factor.

This is part of the fault current that returns through the earth's return path as others flow through the earth wire. The formula for calculating the reduction factor is given below, as stated by IEC 60909-report 3[24].

$$r = 1 - \frac{Z_{QL}}{Z_{QQ}} \tag{2.43}$$

Where:

Z_{QL} = the mutual impedance between earth wires.

Z_{QQ}= self-impedance between earth wires.
It is of important to know that reduction factor depends on the soil penetration depth.

2.10 Touch voltage, Step voltage, and Ground Potential Rise (GPR)

According to IEEE std 80, the ground potential rise is the highest electrical potential that a substation grounding grid can achieve in relation to a distant grounding point, which is believed to be at the remote earth's potential [25]. GPR voltage is a product of grid current and grid resistance measured in volts. At normal conditions, the earth's potential zero is the same as the potential of a grounded station. However, when a fault occurs, the fault current moves to the ground and back to the source through the earth's return path. This increases the earth's potential due to the ground resistance.

The difference in potential between potential ground rise (GPR) and surface potential at the location where a person is standing with a hand in touch with a grounded structure is known as touch voltage, while step voltage is the variation in surface potential felt by a person crossing a 1m distance with their feet without touching any grounded item [25]. According to the Norwegian regulation, the touch voltage should be less than 75V, and the step voltage of about 1meters apart should be relatively small [26]. For a human body of resistance 1000Ω, the touch voltage of 100volts is not to be exceeded for a time duration of 1seconds, according to figure 14. These steps and touch voltage depend on the GPR and the earth's conductivity.

Mathematically,

$$\text{GPR} = I_{Gmax} \times R_G \tag{2.44}$$

Where:
I_G= maximum grid current(A)
R_G= grid resistance (ohms)
The grid resistance is determined by the impedance of the tower or that of the ground wire. This will give rise to a reduced total equivalent ground resistance when ground wires

resistance is interconnected in parallel [27]. This thereby creates the parallel path for earth fault current flow, thus reducing the GPR at the faulted point and consequently reducing touch and step voltage [27]. Some of the hazardous voltages caused by the earth fault current are represented in figure 13.

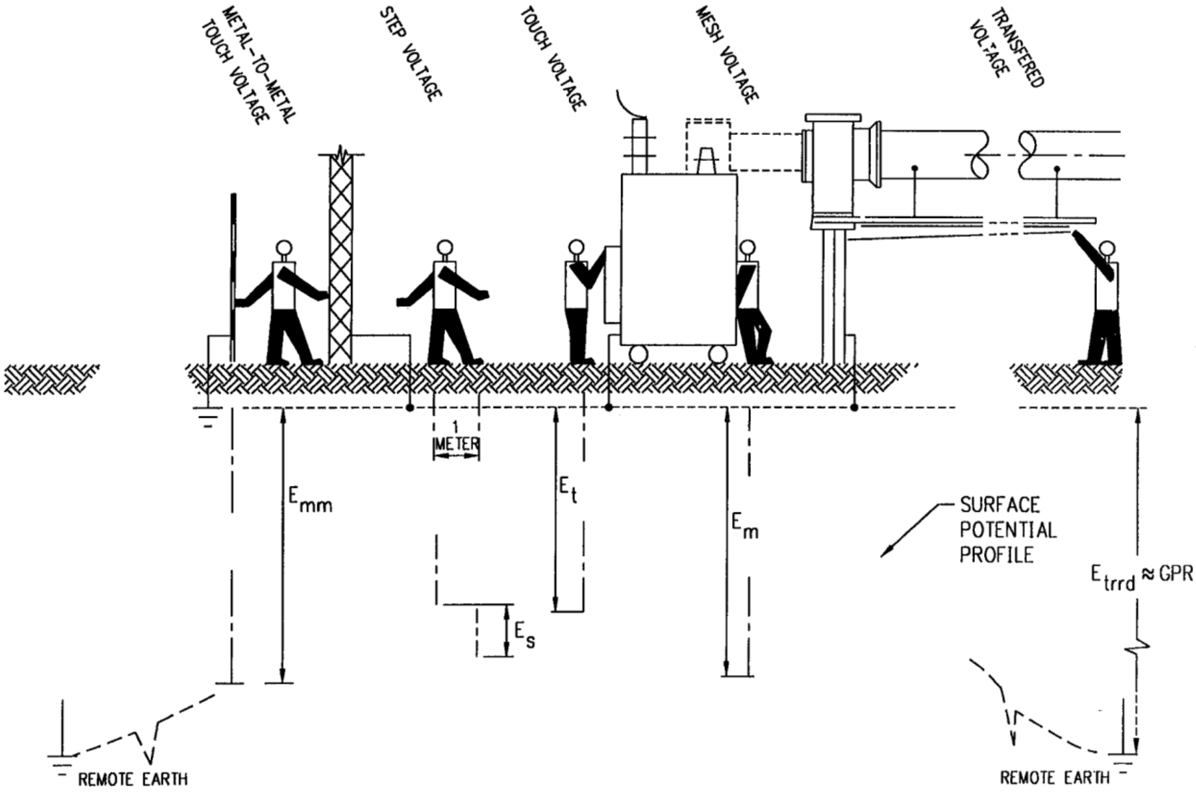


Figure 13: Hazardous voltage caused by earth fault current [25]

The effect these dangerous voltages have on an individual depends on the duration the earth fault current is allowed to pass through. This is represented in the graph plot of figure13.

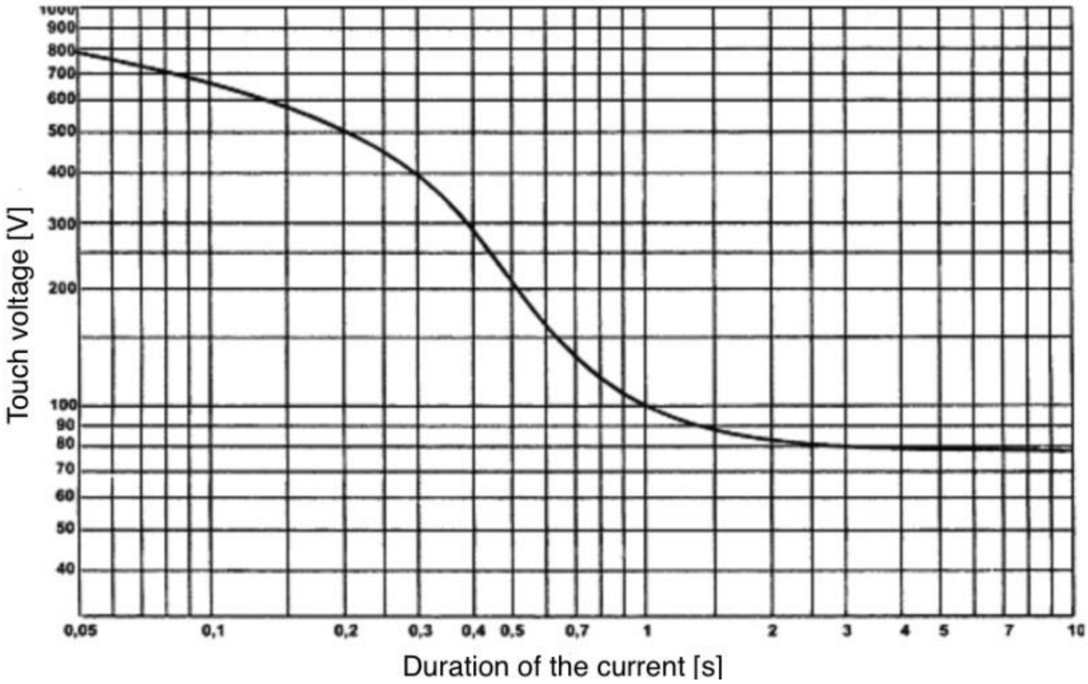


Figure 14: touch voltage as a function of the current duration [25].

The permissible touch and step voltage required before human heart fibrillate depends on the duration of fault, reduction factor, and the resistivity of the material surface. They are given by the equation 2.45 to 2.48 for a 50kg and 70kg of human weight [28].

$$V_{permissible\_touch50} = (1000 + 1.5\rho_s c_s).\,0.116/\sqrt{t} \tag{2.45}$$

$$V_{permissible\_touch70} = (1000 + 1.5\rho_s c_s).\,0.157/\sqrt{t} \tag{2.46}$$

$$V_{permissible\_step50} = (1000 + 6\rho_s c_s).\,0.116/\sqrt{t} \tag{2.47}$$

$$V_{permissible\_step70} = (1000 + 6\rho_s c_s).\,0.157/\sqrt{t} \tag{2.48}$$

Where:

ρ_s= resistivity of material surface $[\Omega m]$

c_s= Reduction factor

t= duration of fault 0.03s$\leq t \leq 3.0s$

From the equation 2.45 and 2.46 above, a reduced reduction factor will result in a reduced permissible touch voltage as well.

2.11 Transposition of single circuit three-phase line.

A complex alignment of conductors that are mutually linked with each other and with the ground wire makes up an overhead transmission line where electromagnetic and electrostatic mutual coupling are both present [19]. The asymmetrical relationship between the phase conductors, the earth wire, or the ground surface results in some phase impedance imbalance, which is undesirable. As a result of that, it is possible to switch the conductor phase at regular intervals throughout the line path to reduce the influence of line unbalances. This process is known as the transposition" technique [19]. The essence of transposition is to have an equal series of self-impedance and a series of mutual impedance in the phase frame of reference. The figure15 below shows a forward transposed conductor of a circuit.

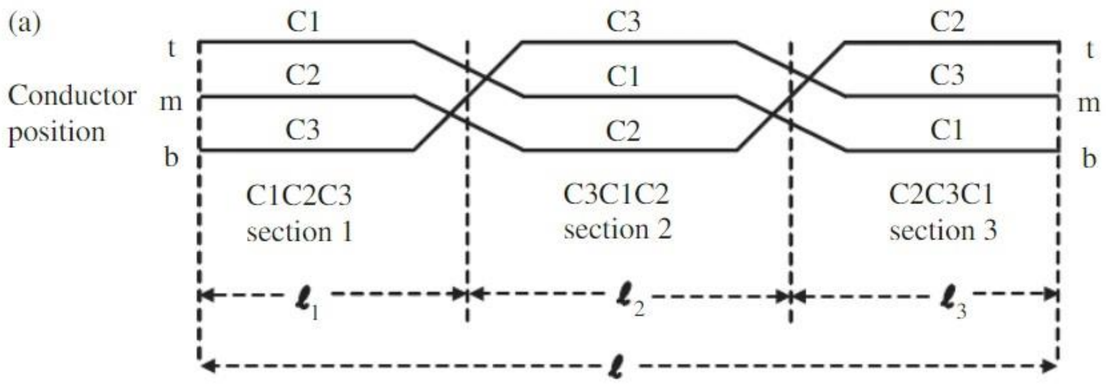


Figure 15: Forward successive phase transposition of a single circuit three phase line [18].

Voltage drop for each section of the line is given as:

$$\begin{bmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{bmatrix}_{\text{Section-1}} = \frac{1}{3} \begin{array}{c} C1 \\ C2 \\ C3 \end{array} \begin{bmatrix} Z_{tt} & Z_{tm} & Z_{tb} \\ Z_{mt} & Z_{mm} & Z_{mb} \\ Z_{bt} & Z_{bm} & Z_{bb} \end{bmatrix} \begin{bmatrix} I_{C1} \\ I_{C2} \\ I_{C3} \end{bmatrix} \quad \text{or} \quad \mathbf{V}_{C_{\text{Section-1}}} = \frac{1}{3} \mathbf{Z}_{\text{Section-1}} \mathbf{I}_{C}$$

$$\begin{bmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{bmatrix}_{\text{Section-2}} = \frac{1}{3} \begin{array}{c} C1 \\ C2 \\ C3 \end{array} \begin{bmatrix} Z_{mm} & Z_{mb} & Z_{mt} \\ Z_{bm} & Z_{bb} & Z_{bt} \\ Z_{tm} & Z_{tb} & Z_{tt} \end{bmatrix} \begin{bmatrix} I_{C1} \\ I_{C2} \\ I_{C3} \end{bmatrix} \quad \text{or} \quad \mathbf{V}_{C_{\text{Section-2}}} = \frac{1}{3} \mathbf{Z}_{\text{Section-2}} \mathbf{I}_{C}$$

$$\begin{bmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{bmatrix}_{\text{Section-3}} = \frac{1}{3} \begin{array}{c} C1 \\ C2 \\ C3 \end{array} \begin{bmatrix} Z_{bb} & Z_{bt} & Z_{bm} \\ Z_{tb} & Z_{tt} & Z_{tm} \\ Z_{mb} & Z_{mt} & Z_{mm} \end{bmatrix} \begin{bmatrix} I_{C1} \\ I_{C2} \\ I_{C3} \end{bmatrix} \quad \text{or} \quad \mathbf{V}_{C_{\text{Section-3}}} = \frac{1}{3} \mathbf{Z}_{\text{Section-3}} \mathbf{I}_{C}$$

Thus, total voltage drops across the three-line are given as shown below: E

$$\mathbf{V}_{\text{Total}} = \sum_{i=1}^{3} \mathbf{V}_{\text{Section-}i} = \frac{1}{3}(\mathbf{Z}_{\text{Section-1}} + \mathbf{Z}_{\text{Section-2}} + \mathbf{Z}_{\text{Section-3}})\mathbf{I}_{C} = \mathbf{Z}_{\text{Phase}}\mathbf{I}_{C} \tag{2.49}$$

Where $Z_{Phase} = \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix}$

And

$$Z_S = \frac{1}{3}(Z_{tt} + Z_{mm} + Z_{bb}) \quad Z_M = \frac{1}{3}(Z_{tm} + Z_{mb} + Z_{bt}) \tag{2.50}$$

Introducing an identity matrix for computer analysis,

$$T = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad T^{-1} = T^{t} = T^{2} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

Then the impedance transposition matrix of the three sections will be given as stated below:

$$\mathbf{Z}_{\text{Section-}i} = \begin{cases} \mathbf{Z}_{\text{Section-1}} & \text{for } i = 1 \\ \mathbf{T}^{t}\,\mathbf{Z}_{\text{Section-1}}\mathbf{T} & \text{for } i = 2 \\ \mathbf{T}\,\mathbf{Z}_{\text{Section-1}}\mathbf{T}^{t} & \text{for } i = 3 \end{cases}$$

By multiplying $Z_{section-1}$ by T matrix, row 2 elements are shifted up to row 1, row 3 elements up to row 2 and row 1 up to row 3 while multiplication of T^{t} with $Z_{section-1}$ shifts the impedance section 3 column 2 element to column 1, column 3 to column 2 and column 1 element to column 3. Representing the Positive, Negative, and zero phase sequences (PPS, NPS, and ZPS) into their corresponding phase quantities using the transformation matrix H.

$$Z^{PNZ} = H^{-1} Z_{phase} H$$

$$\mathbf{Z}^{\text{PNZ}} = \begin{bmatrix} Z^{\text{P}} & 0 & 0 \\ 0 & Z^{\text{N}} & 0 \\ 0 & 0 & Z^{\text{Z}} \end{bmatrix}$$

Where:

$$Z^{\text{P}} = Z^{\text{N}} = Z_{\text{S}} - Z_{\text{M}} = \frac{1}{3}[(Z_{\text{tt}} + Z_{\text{mm}} + Z_{\text{bb}}) - (Z_{\text{tm}} + Z_{\text{mb}} + Z_{\text{bt}})] \tag{2.51}$$

$$Z^{\text{Z}} = Z_{\text{S}} + 2Z_{\text{M}} = \frac{1}{3}[(Z_{\text{tt}} + Z_{\text{mm}} + Z_{\text{bb}}) + 2(Z_{\text{tm}} + Z_{\text{mb}} + Z_{\text{bt}})] \tag{2.52}$$

And the sequence voltage drop will be given with the equations below.

$$\Delta V^{\text{P}} = Z^{\text{P}} I^{\text{P}} \quad \Delta V^{\text{N}} = Z^{\text{N}} I^{\text{N}} \quad \Delta V^{\text{Z}} = Z^{\text{Z}} I^{\text{Z}}$$

2.12 Transposition of double circuit three-phase line

Three-phase overhead transmission lines with two circuits and earth wires are commonly used to transfer very high power [29]. Figure 16 below demonstrates distinct circuit transpositions for each circuit of a double-circuit line with either triangular or near-vertical phase conductor layouts[19].

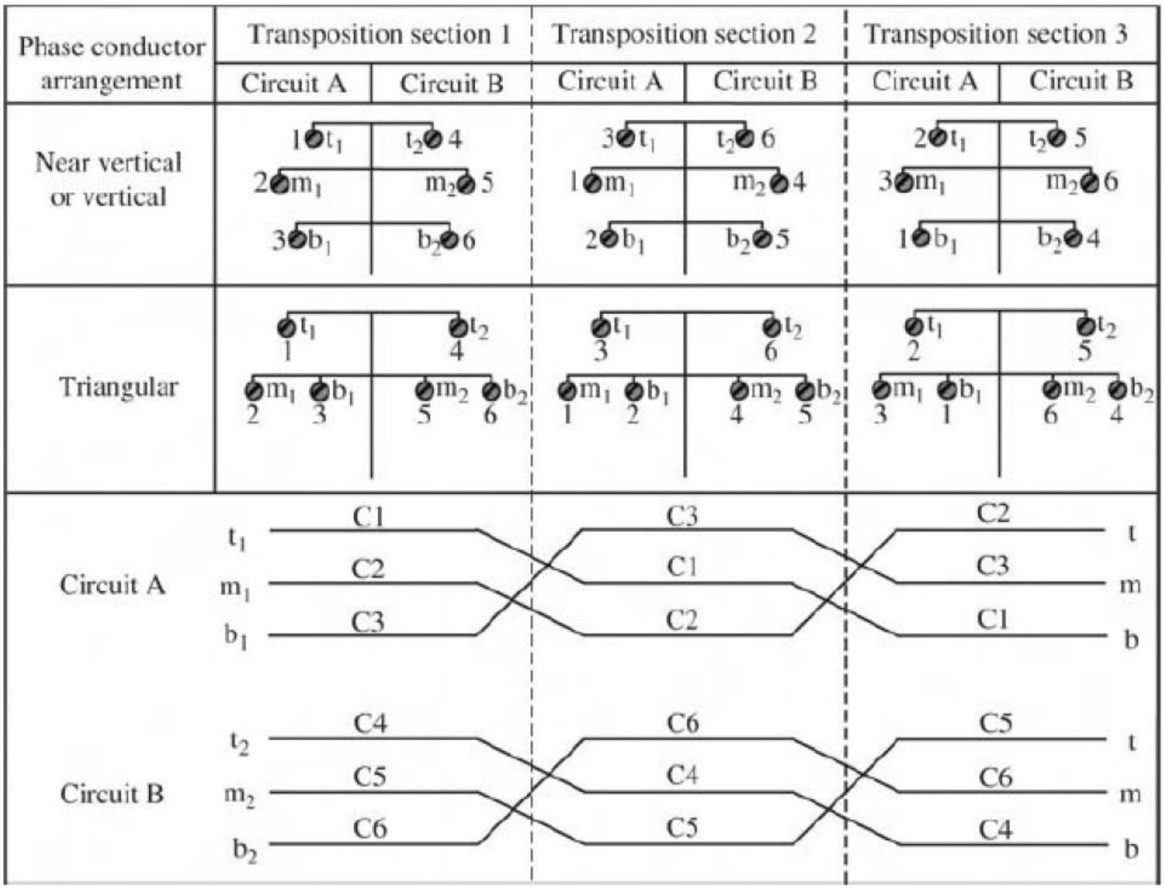


Figure 16: Typical double-circuit lines with perfect within circuit transposition [18].

Forward rotation of the circuit A per unit length is given as:

$$\mathbf{Z}_{\mathrm{AA}} = \begin{bmatrix} Z_{\mathrm{S(A)}} & Z_{\mathrm{M(A)}} & Z_{\mathrm{M(A)}} \\ Z_{\mathrm{M(A)}} & Z_{\mathrm{S(A)}} & Z_{\mathrm{M(A)}} \\ Z_{\mathrm{M(A)}} & Z_{\mathrm{M(A)}} & Z_{\mathrm{S(A)}} \end{bmatrix}$$

Where:

$$Z_{\mathrm{S(A)}} = \frac{1}{3}\left(Z_{\mathrm{t1t1}} + Z_{\mathrm{m1m1}} + Z_{\mathrm{b1b1}}\right) \quad \text{and} \quad Z_{\mathrm{M(A)}} = \frac{1}{3}\left(Z_{\mathrm{t1m1}} + Z_{\mathrm{m1b1}} + Z_{\mathrm{b1t1}}\right)$$

The series mutual impedance between the two circuits of the three sections of the line is stated below.

$$\mathbf{Z}_{\mathrm{AB}-1} = \begin{array}{c} \\ \mathrm{C1} \\ \mathrm{C2} \\ \mathrm{C3} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{C4} & \mathrm{C5} & \mathrm{C6} \end{array} \\ \begin{bmatrix} Z_{\mathrm{t1t2}} & Z_{\mathrm{t1m2}} & Z_{\mathrm{t1b2}} \\ Z_{\mathrm{m1t2}} & Z_{\mathrm{m1m2}} & Z_{\mathrm{m1b2}} \\ Z_{\mathrm{b1t2}} & Z_{\mathrm{b1m2}} & Z_{\mathrm{b1b2}} \end{bmatrix} \end{array}$$

$$\mathbf{Z}_{\mathrm{AB}-2} = \begin{array}{c} \\ \mathrm{C1} \\ \mathrm{C2} \\ \mathrm{C3} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{C4} & \mathrm{C5} & \mathrm{C6} \end{array} \\ \begin{bmatrix} Z_{\mathrm{m1m2}} & Z_{\mathrm{m1b2}} & Z_{\mathrm{m1t2}} \\ Z_{\mathrm{b1m2}} & Z_{\mathrm{b1b2}} & Z_{\mathrm{b1t2}} \\ Z_{\mathrm{t1m2}} & Z_{\mathrm{t1b2}} & Z_{\mathrm{t1t2}} \end{bmatrix} \end{array}$$

$$\mathbf{Z}_{\mathrm{AB}-3} = \begin{array}{c} \\ \mathrm{C1} \\ \mathrm{C2} \\ \mathrm{C3} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{C4} & \mathrm{C5} & \mathrm{C6} \end{array} \\ \begin{bmatrix} Z_{\mathrm{b1b2}} & Z_{\mathrm{b1t2}} & Z_{\mathrm{b1m2}} \\ Z_{\mathrm{t1b2}} & Z_{\mathrm{t1t2}} & Z_{\mathrm{t1m2}} \\ Z_{\mathrm{m1b2}} & Z_{\mathrm{m1t2}} & Z_{\mathrm{m1m2}} \end{bmatrix} \end{array}$$

The average of the three sections of the line series mutual impedance is:

$$\mathbf{Z}_{\mathrm{AB}} = \frac{1}{3}\sum_{i=1}^{3} \mathbf{Z}_{\mathrm{AB}-i}$$

Where:

$$\mathbf{Z}_{\mathrm{AB}} = \begin{array}{c} \\ \mathrm{C1} \\ \mathrm{C2} \\ \mathrm{C3} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{C4} & \mathrm{C5} & \mathrm{C6} \end{array} \\ \begin{bmatrix} Z_{\mathrm{S(AB)}} & Z_{\mathrm{M(AB)}} & Z_{\mathrm{N(AB)}} \\ Z_{\mathrm{N(AB)}} & Z_{\mathrm{S(AB)}} & Z_{\mathrm{M(AB)}} \\ Z_{\mathrm{M(AB)}} & Z_{\mathrm{N(AB)}} & Z_{\mathrm{S(AB)}} \end{bmatrix} \end{array} \quad \text{and} \quad \mathbf{Z}_{\mathrm{BA}} = \mathbf{Z}_{\mathrm{AB}}^{\mathrm{t}}$$

Thus, combining matrix ZAA and ZAB to get the series phase impedance of the double circuit line of the three phases (Z_{phase}) is given below as a 6× 6 matrix.

$$
\mathbf{Z}_{\text{Phase}} = \begin{array}{c} \\ \text{Circuit A} \\ \\ \\ \text{Circuit B} \\ \\ \end{array}
\begin{array}{c} \begin{array}{cc} \text{Circuit A} & \text{Circuit B} \end{array} \\
\left[\begin{array}{ccc|ccc}
Z_{S(A)} & Z_{M(A)} & Z_{M(A)} & Z_{S(AB)} & Z_{M(AB)} & Z_{N(AB)} \\
Z_{M(A)} & Z_{S(A)} & Z_{M(A)} & Z_{N(AB)} & Z_{S(AB)} & Z_{M(AB)} \\
Z_{M(A)} & Z_{M(A)} & Z_{S(A)} & Z_{M(AB)} & Z_{N(AB)} & Z_{S(AB)} \\ \hline
Z_{S(AB)} & Z_{N(AB)} & Z_{M(AB)} & Z_{S(B)} & Z_{M(B)} & Z_{M(B)} \\
Z_{M(AB)} & Z_{S(AB)} & Z_{N(AB)} & Z_{M(B)} & Z_{S(B)} & Z_{M(B)} \\
Z_{N(AB)} & Z_{M(AB)} & Z_{S(AB)} & Z_{M(B)} & Z_{M(B)} & Z_{S(B)}
\end{array}\right] \end{array}
$$

Looking at the Z_{phase} matrix, the self-diagonal sides are equal while the off diagonals can only be equal in a situation where the two circuits are symmetrical with a vertical or near vertical-conductor configuration [19].

Introducing the transformation matrix,

$$
H = \begin{bmatrix} 1 & 1 & 1 \\ h^2 & h & 1 \\ h & h^2 & 1 \end{bmatrix} \quad H_1 = \begin{bmatrix} h & h^2 & 1 \\ h^2 & h & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad H_{dc} = \begin{bmatrix} H & 0 \\ 0 & H_1 \end{bmatrix}
$$

$$
Z_{PNZ} = H_{dc}^{-1} . Z_{phase} . H_{dc}
$$

$$
Z_{PNZ} = \begin{bmatrix}
Z_{PA} & 0 & 0 & 0 & 0 & 0 \\
0 & Z_{NA} & 0 & 0 & 0 & 0 \\
0 & 0 & Z_{ZA} & 0 & 0 & Z_{ZAB} \\
0 & 0 & 0 & Z_{PB} & 0 & 0 \\
0 & 0 & 0 & 0 & Z_{NB} & 0 \\
0 & 0 & Z_{ZAB} & 0 & 0 & Z_{AB}
\end{bmatrix}
$$

2.13 Grounding and Over-Voltage Due to Single Phase Ground Fault.

The type of grounding and its relationship with over-voltages due to single-phase to ground fault will be discussed in this section. Substations are subject to electric shocks due to the way they are closely packed, and load consumption increases; as a result, there is a need for grounding to obtain low impedance values and allow fault currents to flow freely to the ground, limiting possible surges to substation equipment and clearing all sorts of transient surges quickly [30].

The two major types of grounding are shown in figure 17.

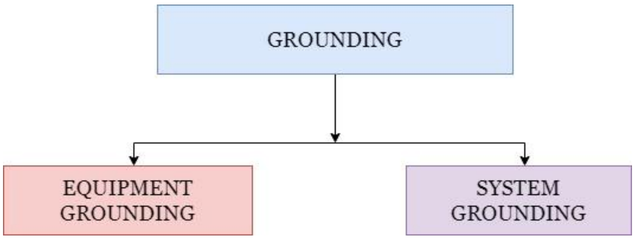


Figure 17: The two types of grounding.

When all metal coverings of equipment and enclosures housing electrical equipment or conductors are grounded by a permanent and continuous connection or bond, equipment grounding is established. While System grounding is carried out when the neutral point of a star transformer is connected to the ground to protect the system circuit from being damaged because of lightning or overvoltage from short circuit faults [31]. Both are represented in the diagram in figure18.

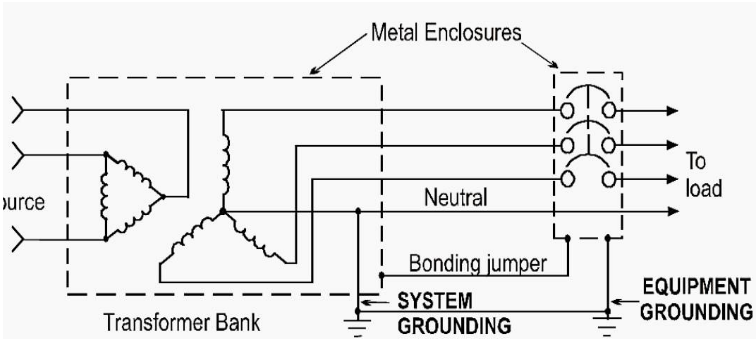


Figure 18: Grounding system [27].

The major aim of grounding is to provide safety for the personnel in the vicinity of the power system against touch and step voltages and ensure that adverse effects of fault conditions do not damage the power system.

2.13.1 System Grounding

This is the connection between the transformer neutral points and the ground. In other words, it is critical to a power system's behavior during an unsymmetrical fault for the purpose of earth fault detection and fault analysis in an electrical power system [32]. There are many ways in which the system neutral can be connected, such as solid or direct grounding, isolated and resonant grounding. However, in the subsequent section, we are only going to discuss resonant and direct grounding.

A. **Direct or Solid Grounding**

The system is said to be directly grounded when the transformer neutral is connected directly to the ground. The diagrammatical representation of it is shown below in figure 19.

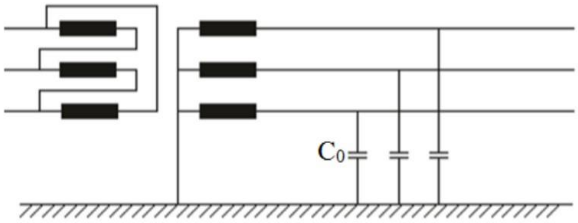


Figure 19: Solidly earthed system [29].

Although it creates very high fault currents and tripping as soon as the first fault occurs to minimize the likelihood of equipment damage, a directly earthed neutral or low impedance earthed neutral effectively limit overvoltage at the healthy phases [33]. This is normally used in high voltage transmission network systems.

B. Resonant/Compensated grounding

If the transformer neutral is connected to the ground via a reactance known as a Peterson coil invented by Waldemar Petersen, whose impedance is near to that of the total zero-sequence capacitance, such Network is known as compensated Network. The Peterson coil compensates for the zero-sequence capacitive current generated in case of a single-phase to ground fault and creates an infinite zero sequence impedance when connected in parallel with the capacitance, thereby reducing the fault current to a minimum value as well as extinguishing the fault arc [34]. Because the remaining earth fault current after compensation could be too small for the relay to monitor, it is usual practice to combine the neutral point inductor with a parallel resistance [27].

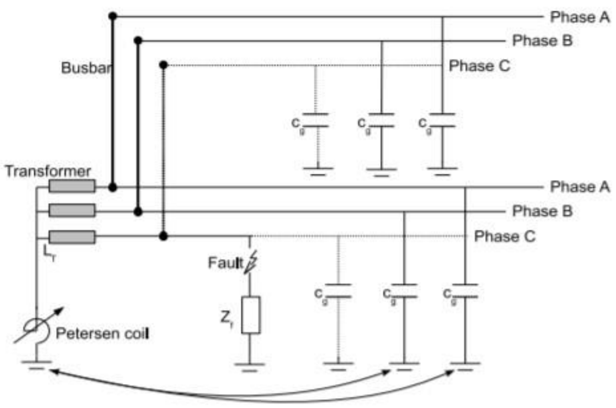


Figure 20: Compensated network in single phase to earth fault condition [33].

Asides from the above-mentioned advantages of using Peterson coil, their disadvantages are as follows [35]:

1. The network's capacitance changes over time due to changing operational conditions. As a result, the inductance L of the Peterson coil must be readjusted from time to time.
2. The transmission lines must be transposed.

To avoid resonance from occurring, the inductance of the Peterson coil should be higher than the capacitance line to the ground by 5%. This is commonly known as over-compensation. The compensation can either be centralized or distributed.

2.13.2 Equipment Grounding

Due to switching faults or induction, equipment might become energized far away from the work location; as a result, there is a need for personal protective grounding/bonding (PPGB) [36]. This quickly activates overcurrent protection devices (OCPDs) while also limiting the voltage that employees are exposed to safe levels; when a circuit has been appropriately grounded for worker safety but is mistakenly energized, the voltage on the system drops to near zero, thereby protecting the person from possible electric shock [36].

3 Sequence of Networks

Since zero sequence impedance cannot flow in a three-wire transformer, therefore the zero-sequence impedance depends on the type of grounding of the transformer station and its connections. This chapter explains how single-phase failures on one side of a transformer can affect voltages and currents on the other side, depending on the number of transformer windings and winding connections.

3.1 Formation of Zero sequence networks of transformers.

For a general circuit diagram of a transformer shown below, there are two series switches and two shunt switches. The principle of determining the zero sequence components depends on the opening and closing of these switches. Switches 1 and 2 are series switches, while 3 and 4 are shunt switches. If the side of the transformer is star connected and the neutral point is grounded, then switches 1 and 2 will close; otherwise, they will be open. Whereas Switches 3 and 4 will be closed if either side (primary or secondary) of the transformer is delta connected.

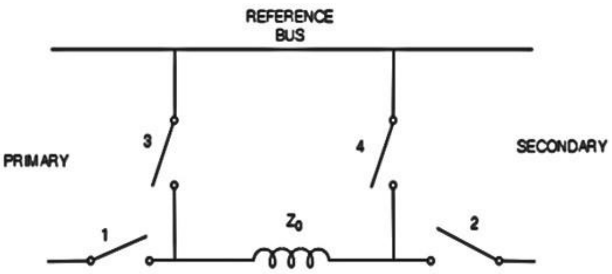


Figure 21: General circuit for determining transformer zero sequence networks

Applying the principle above, the following zero sequence network of some transformer configurations are as shown with examples below.

3.1.1 Zero sequence network for two winding transformers.

A. Star-Star connected transformer with isolated Neutral.

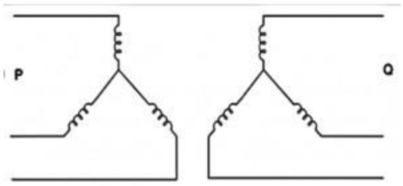


Figure 22: Star-star connected transformer with isolated neutral.

Switches 1 and 2 will remain open on both sides since both sides are star-connected and isolated, while switches 3 and 4 will remain open because either side is not delta connected. This will give the zero sequence equivalent circuit of figure 23.

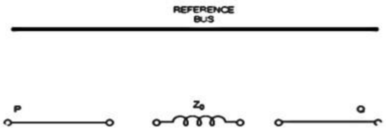


Figure 23: Zero sequences equivalent circuit for star-star transformer.

In this type of transformer configuration, there will be no transfer of zero sequence impedance since both windings are isolated.

B. Star-Star transformer with one Neutral Grounding.

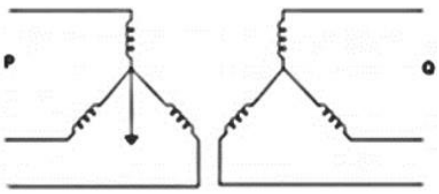


Figure 24: Star-star transformer with primary neutral grounding

Since the primary side of the transformer is star connected with neutral grounding and not delta connected, switch 1 will be closed while switch 3 will be open. On the secondary side, both sitch 2 and 4 will be open since the side is star connected without neutral grounding and no delta winding present. The equivalent circuit is shown below.

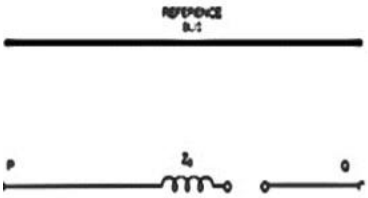


Figure 25: Zero sequences equivalent circuit for star-star transformer with primary neutral grounding.

There will be no transfer of zero sequence component to the secondary side in this type of transformer configuration.

C. Star-Star Transformer with both Neutral Grounded.

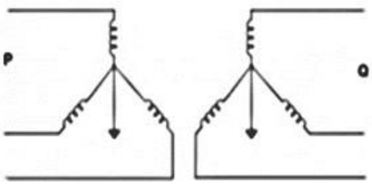


Figure 26: Star-star transformer with both neutral grounded.

With both sides star-connected with the neutrals grounded, the two series switches will both the closed as both shunt switches are open.

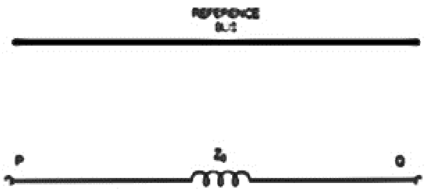


Figure 27: Zero sequences equivalent circuit for a star-star transformer with both neutral grounded.

Thus, zero impedance will flow through the primary and secondary winding.

D. Star-Delta Transformer with Isolated Star.

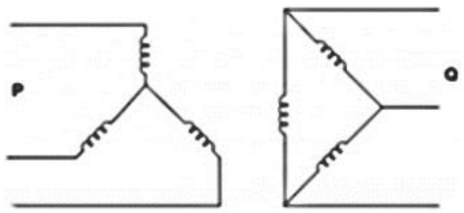


Figure 28: Star-delta connection with isolated star.

In this configuration, both the series switches will be open while switch 3 will be open as switch 4 is closed.

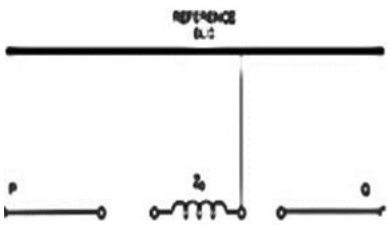


Figure 29: Zero sequences equivalent circuit for star-delta connection with isolated star.

With both 1 and 2 switches open, there will be no transfer of zero sequence components in this type of transformer configuration

E. Star-Delta Transformer with Grounded Neutral.

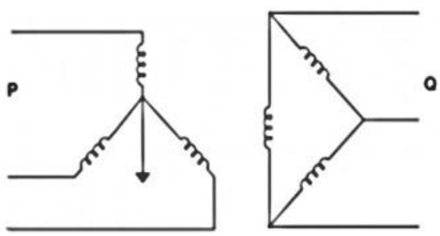


Figure 30: Star-delta transformer with grounded Y neutral.

In this type of transformer configuration, switches 1 and 4 will be closed while 2 and 3 switches will be open to give an equivalent circuit diagram below. No zero sequence impedance will flow from the primary to the secondary since switch 2 is open.

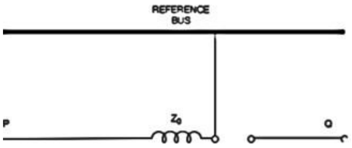


Figure 31: Zero sequences equivalent circuit (star-delta with grounded Y neutral).

F. Star-Delta Transformer with grounded Y-Neutral through reactor impedance Z_n

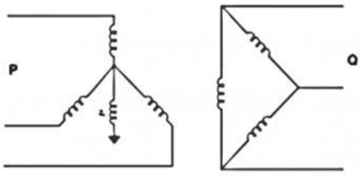


Figure 32: Star-delta transformer with grounded Y neutral impedance Zn.

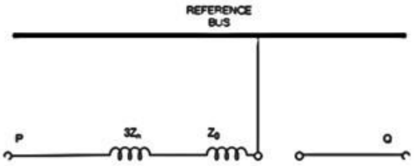


Figure 33: circuit equivalent of zero sequence impedance of a star-delta transformer with Zn.

At the star side with grounded neutral, the series switch will be closed while the shunt switch will be left open. However, the star neutral is grounded through the reactor of impedance Zn, and an impedance of 3Zn appears in series along with Zo (zero sequence impedance) in the sequence network, as shown below. No zero sequence impedance will be transferes in this type of transformer arrangement.

G. Delta-Delta Transformer.

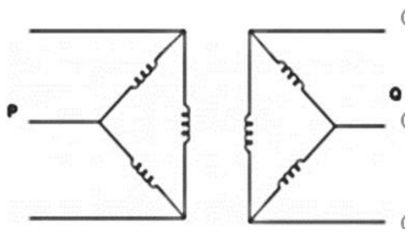


Figure 34: Delta-delta transformer.

There will be no zero-sequence impedance seen at both windings since both series switches are open.

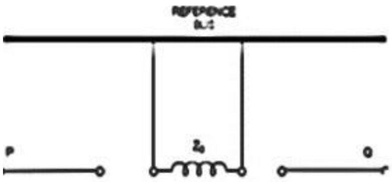


Figure 35: Zero sequences equivalent circuit for delta-delta transformer.

3.1.2 Zero sequence network for three winding transformers.

A. Star–Delta-Star connection without Neutral grounding

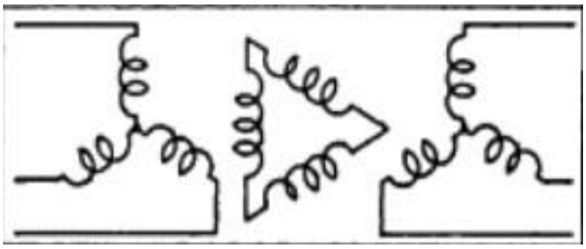


Figure 36: Star-delta-star transformer without neutral grounding.

There is no transfer of zero sequence impedances in this transformer arrangement since the primary and secondary series switches are in an open condition.

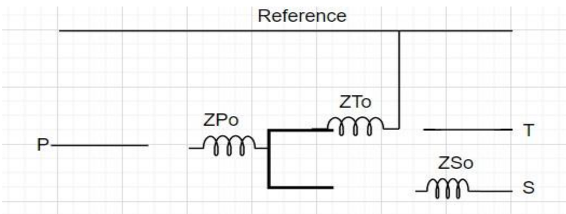


Figure 37: Zero sequences equivalent of a star-delta-star transformer.

B. Star-Delta-Star with neutral grounding at the secondary.

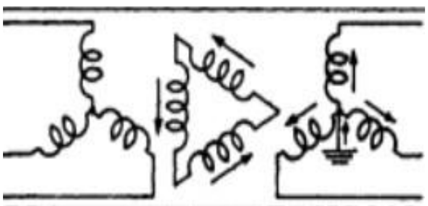


Figure 38: Star-delta-star transformer with secondary neutral grounding.

The transfer of zero sequence impedance will not occur since the primary series and shunt switches are open, as shown in figure 39 below.

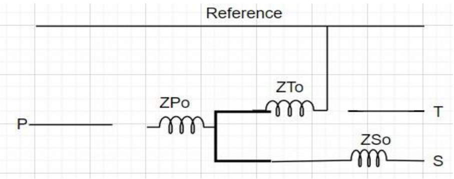


Figure 39: Zero sequences equivalent circuit of a star-delta-star transformer with secondary neutral grounding.

C. Star-Delta-Star connection with both Primary and Secondary winding grounded.

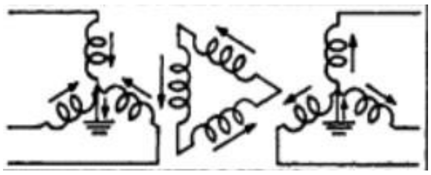


Figure 40: Star-delta-star transformer with both primary and secondary grounding.

In the transformer configuration, there will be a transfer of zero sequence components from the primary side to the secondary because the series switches on both winding sides are closed, as in figure 41.

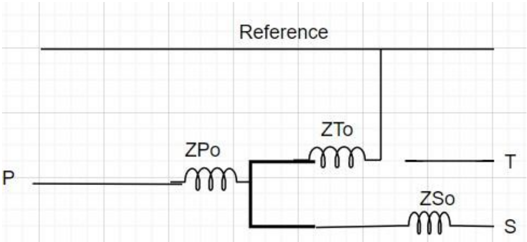


Figure 41: Zero sequences equivalent circuit (star-delta-star connection with both windings).

D. Star-Delta-Delta connection with no neutral grounding.

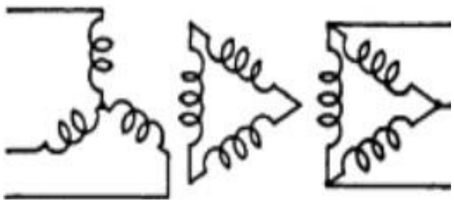


Figure 42: Star-delta-star transformer winding.

The zero equivalent circuits are shown below with open series switches with no transfer of zero sequence components.

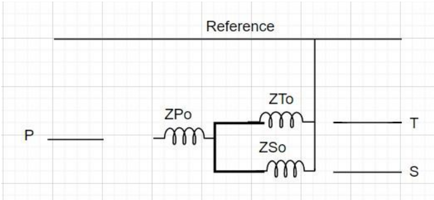


Figure 43: Star-delta transformer with no grounding zero sequences equivalent circuit.

The Star-Delta-Star connection with both Primary and Secondary winding grounded are the most used three winding transformers. The delta winding in-between is known as a stabilizing winding that is buried. It is usually used for harmonic suppression and does not feed a load as the bushings of the windings are not out.

4 132kV Network Design in PowerFactory.

Powerfactory is leading power system analyzing software with a wide range of capabilities to form basic functions to highly complex applications for system testing and supervision, such as wind power, distributed generation, real-time simulation, and performance monitoring.

The 132 kV network system in Vestfold and Telemark is simplified from a system containing about 100 busbars onto 20 busbars. The simplified network system contains two separate networks, each powered from the overlaying 300 – 420 kV transmission system described with two centrally located points. This together with several distributed stations which also may be equivalents of local hydropower units within vicinity of each other.

The network is divided into two study networks: Study network 1 and 2 for analyzing the differences in over-voltages that occurs during a single phase to ground fault in a compensated (centralized or distributed) and direct grounding because of grid expansion within the network. The two study networks are represented geographically in figure 44, where the red-colored buses are the radial study network 1, and the yellow-colored ones are the mesh study network 2.

To do so, the different components of the network are modeled using the given parameters as provided by the supervisor: Prof. Gunne Hegglid, in Appendix A.

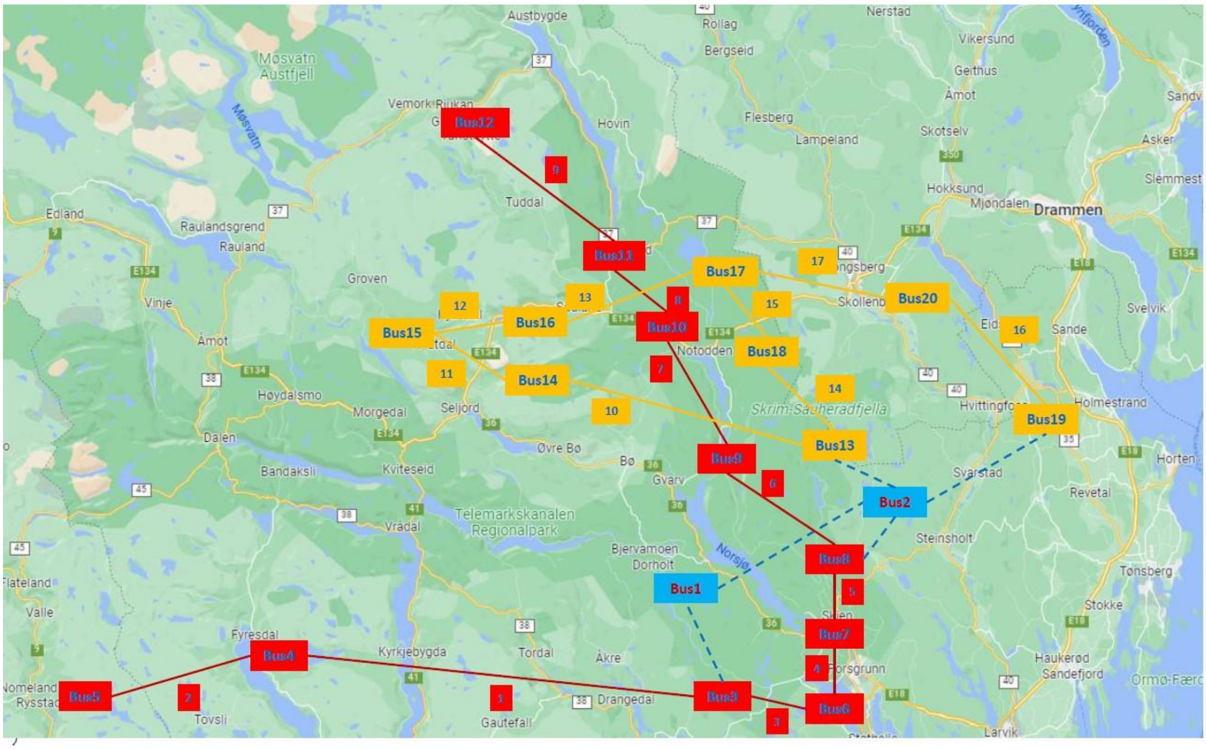


Figure 44: Geographical representation of 132kV Network Model.

The buses and their names as represented in PowerFactory is in table 2.

Table 2: Buses and their names as represented in PowerFactory.

Buses	Names
1	MG420
2	MG300
3	SD1-132
4	FI
5	BD
6	KS
7	Mn
8	SD2-132
9	Ng
10	GfA
11	Åf
12	Sh
13	SD3-132
14	ÅmA
15	Ha
16	ÅmB
17	GfB
18	Nd
19	SD4-132
20	Kb

4.1 Network Designs Components.

The below figure 45 PowerFactory network design is made up of the following components stated below with their corresponding parameter inputs in Appendix A.

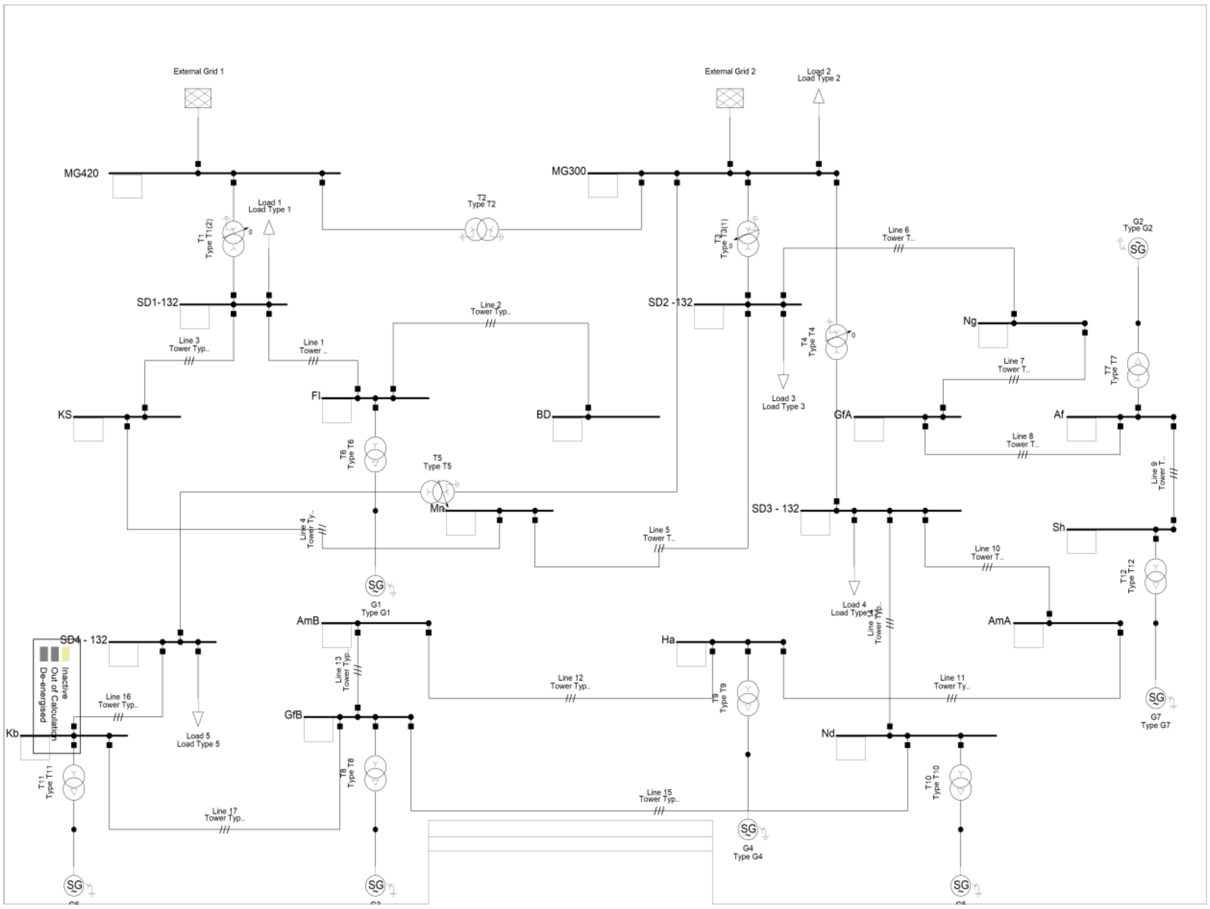


Figure 45: 132kV Network Model

4.1.1 External Grids

The system is made up of two external grids (external grid 1 and 2), with external grid one modeled as a slack bus and external grid two as a load bus (PQ) with a short circuit infeed capacity of 268.30MW. Transformer T2 in-between the network design of figure 45 serves as a stepdown backup transformer.

4.1.2 Transformers

There are 12 transformers in the network with Y-Y and Y-Δ winding connections with buried delta connections. Transformers located in the center of the main transformer stations onto the transmission system are Y-Y connections directly grounded on both sides YN-YN (T1, T2, T3, T4, and T5), while the distribution transformers are Y-Δ windings directly grounded on the star side Ynd (T6, T7, T8, T9, T10, T11, and T12). This implies that there will be no zero-sequence current at the loads in the network because of the absence of zero sequence current in the Y-Δ winding connections, as explained in chapter 3. Transformers T1, T3, T4, and T5 are with tap changers on the high voltage side to modify the transformer ratio of the power transformer and increase the voltage at the distribution busbars. In addition to the model, parameters are the zero-sequence impedance and positive sequence impedance of the transformers, which are set to be the same, assuming a buried delta stabilizing winding is present.

4.1.3 Generators.

The Network consists of 7 generators at the distribution network attached to the 11kV nodes. They contribute toward voltage control of the Network, and parameters are shown in Appendix A.

4.1.4 Transmission Lines.

They serve as a medium through which electrical energy is transmitted. In the designed 132kV Network, there are 17 transmission lines connected to 20 buses with cables and towers. The choices of cable conductors contribute to the cost and effective transmission of energy while the tower provides support to the conductor cables. In a direct grounded system, earth wires play a crucial role in ensuring that the system operates safely in the event of a malfunction. Furthermore, earth wires are attached to most of the overhead cables on transmission towers. Earth wires are primarily used to shield phase conductors from direct lightning strikes.

4.1.5 Conductor Data Type

Conductor choice depends on the cost, weight, and electrical and mechanical strength. Likewise, factors such as magnetic field, voltage, audible noise, and electrical field also affect the choice of the conductor. Over the years, copper has been used for transmission line cable conductors due to its high conductivity. However, due to its high cost and weight, Aluminum has become the most used cable conductor in transmission lines. As a result, Iron aluminides (FeAl) conductors are employed. When combined with iron, FeAl offers good electrical characteristics and provides the strength needed for extended spans. The cable data used in the network design is shown in table 3.1 from Amokabel [37]. The data were further used in the computation of the positive and zero sequence impedance (PSI and ZSI) of the transmission line in PowerFactory.

Table 3: FeAl cable data sheet

ID	FeAl	FeAlNavn	D	Bruddlast	Resistans	Ith
1	10	FeAl 10 6/1	5.52	625	1.791	118
2	16	FeAl 16 6/1	6.96	970	1.126	171
3	25	FeAl 25 6/1	8.7	1475	0.721	233
4	35	FeAl 35 6/1	10.32	2015	0.512	287
5	70	FeAl 70 26/7	14.82	4285	0.257	454
6	95	FeAl 95 26/7	17.24	5730	0.191	544
7	120	FeAl 120 26/7	19.38	7035	0.151	624
8	150	FeAl 150 26/7	21.66	8665	0.121	727
9	185	FeAl 185 26/7	24.01	10500	0.098	832
10	240	FeAl 240 26/7	27.36	13300	0.076	992
11	253	FeAl 253 Condor	27.72	13060	0.072	1020
12	300	FeAl 300 26/7	30.6	16560	0.061	1140
13	329	FeAl 329 Curlew	31.68	16790	0.055	1211
14	354	FeAl 354 Finch	32.85	18380	0.051	1299
15	380	FeAl 380 Grackle	34.03	19430	0.048	1360
16	405	FeAl 405 Pheasant	35.1	20380	0.045	1399
17	430	FeAl 430 Martin	36.17	21640	0.042	1459
18	456	FeAl 456 Plover	37.24	22930	0.04	1496
19	481	FeAl 481 Parrot	38.25	23700	0.036	1544
20	506	FeAl 506 Falcon	39.26	25100	0.036	1597
21	50	FeAl 50 6/1	12.33	2835	0.359	362

4.1.6 Tower Dimensions.

The typical Norwegian tower type used in the configuration of the 132kV transmission lines is shown in figure 46 as specified by IEC technical publication 60909 - Technical report 2. During the geometry design, the following dimensions were used as provided by the supervisor.

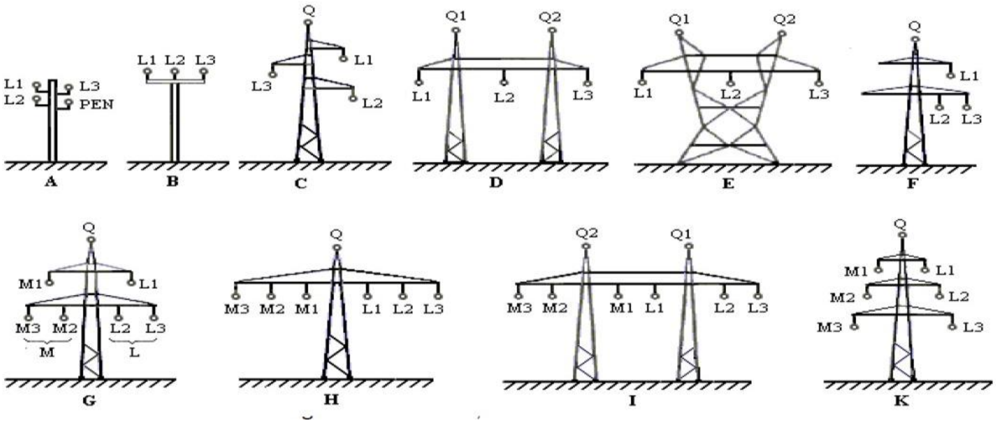


Figure 46: Typical Norwegian tower geometries in transmission and substation network [IEC 60909 report2]

In this thesis, the Tower types that were used are: C, D, G, H, and K. Their dimensions are stated below.
Dimensions

- The height of the 132kv tower is 14m.
- The phase distance is 4.5m.
- The average sag is 4.3m.
- The average height of the lowest conductor over the ground is 11.75m.
- Rated isolation distance for 132 kV equipment; lowest distance allowed from phase conduction to grounded item part of the tower: 1,2 m.
- The minimum horizontal distance (normal) from phase conductor to grounded item part of the tower: 2 m (Reason – phase conductor may from wind be swung out some 45 degrees.
- Minimum vertical distance when phase conductor has not swung out: 1,5 m = length of insulator chain.
- Width of a tower at lowest phase conductor – 1,5 m.
- Min horizontal distance between phase conductors from the two circuits in a double circuit tower is 10m.

A. Tower C

Tower C from figure 46 above is a single circuit of equal side triangular arrangement with one side vertical and one earth wire. The green circle is the earth wire, while the red color is the phase conductors. Diagram and dimensions for the sequence impedance calculations in PowerFactory are represented below.

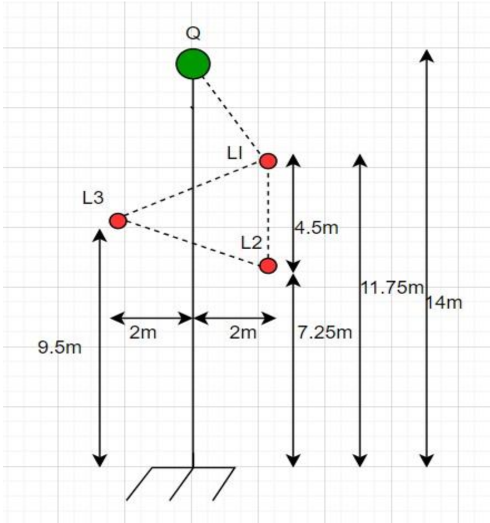


Figure 47: Single circuit tower type C.

The conductor and earth wire distance from the X and Y-axis plane as modelled in PowerFactory is seen in table 3.2 and table 3.3, respectively.

Table 4: Conductor coordinates of tower C.

	X1	X2	X3	Y1	Y2	Y3
Circuit 1	2	2	-2	11.75	9.5	7.25

Table 5: Earth wire coordinates of tower C.

	X	Y
Earth conductor 1	0	14

B. Tower D

Tower D from figure 46 above is a single circuit horizontal arrangement with two symmetrical earth wires over the phase's conductors. The phase conductors are L1-L3, while the ground wires are labeled as Q1 and Q2. Their coordinates in PowerFactory are represented below.

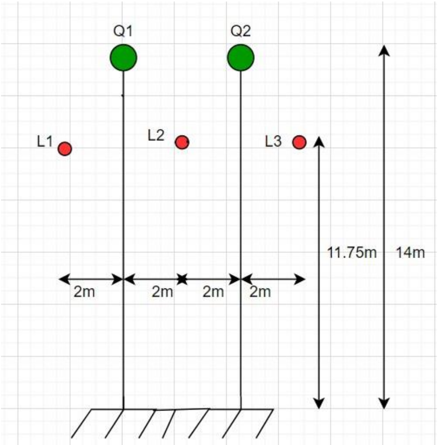


Figure 48: Single circuit tower type D.

Table 6: Conductor coordinates of tower D.

	X1	X2	X3	Y1	Y2	Y3
Circuit 1	-2	2	6	11.75	11.75	11.75

Table 7: Earth wire coordinates of tower D.

	X	Y
Earth conductor 1	0	14
Earth conductor 2	4	14

C. Tower G

It is a double circuit tower of equal triangle spacing conductors with one earth wire arrangement, as shown in figure 49 below. One phase circuit is marked as L1-L3 while the second circuit phases are represented as M1-M3 and one earth wire as Q1.

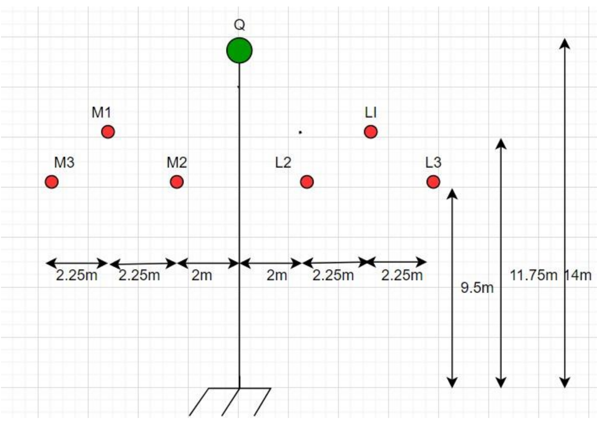


Figure 49: Double circuit tower type G.

Table 8: Conductor coordinates of tower G.

	X1	X2	X3	Y1	Y2	Y3
Circuit 1	4.25	2	6.5	11.75	9.5	9.5
Circuit 2	-4.25	-2	-6.5	11.75	9.5	9.5

Table 9:Earth wire coordinates of tower G.

	X	Y
Earth conductor 1	0	14

D. Tower H

It is a double circuit with horizontal conductors' arrangement and one earth wire. The conductors on one circuit are represented with LI-L3 and the second circuit with M1-M3.

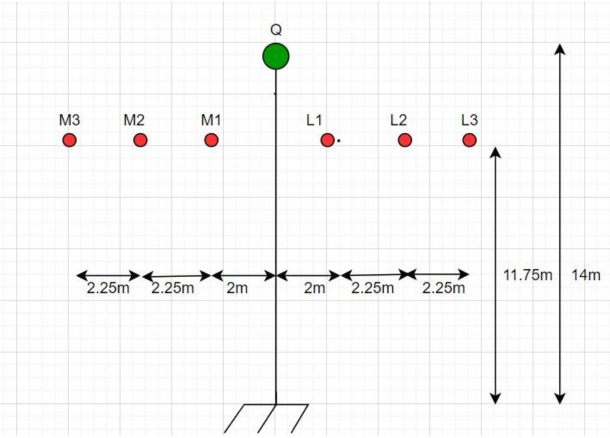


Figure 50: Double circuit tower type H.

Table 10: Conductor coordinates of tower H.

	X1	X2	X3	Y1	Y2	Y3
Circuit 1	2	4.25	6.5	11.75	11.75	11.75
Circuit 2	-2	-4.25	-6.5	11.75	11.75	11.75

Table 11: Earth wire coordinates of tower H.

	X	Y
Earth conductor 1	0	14

E. Tower K

On either side of the pole, three phase-conductors are mounted vertically. One earth wire, labeled Q, runs from the top of the tower to the grounds seen in figure 51.

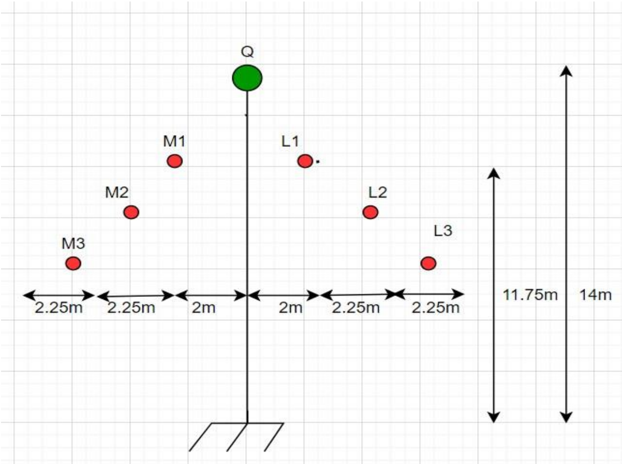


Figure 51: Double circuit tower type K.

Table 12: Conductor coordinates of tower K.

	X1	X2	X3	Y1	Y2	Y3
Circuit 1	2	4.25	6.5	11.75	9.5	7.25
Circuit 2	-2	-4.25	-6.5	11.75	9.5	7.25

Table 13: Earth wire coordinates of tower K.

	X	Y
Earth conductor 1	0	14

In summary, the Network physical topology is made up of 20 buses of nominal voltage 132kV, nominal frequency of 50Hz, seventeen transmission lines of tower types C, D, G, H, and K, twelve transformers, seven generators, seven nodes, and five loads.

5 Simulations and Results (Transposed Network)

In this chapter, all the simulations on the 132kv study networks 1 and 2 with more emphasis on the radial network (study network 1) in symmetrical mode to ascertain the overvoltage on the healthy phases for Peterson coil compensated and direct grounded systems during a single-phase to ground fault. The simulation is of four stages which include:

1. Compensated Peterson coil located centrally in the main transformer station.
2. Compensated Peterson coil distributed in a radial system.
3. Directly grounded located at the central transformer station.
4. Direct grounding distributed in a radial system.

However, before carrying out the above simulations, load flow calculation and short circuit calculation of the network are done to deduce the total fault current of the system needed to be compensated. The Peterson coil's inductive reactance is mathematically calculated afterward while neglecting the resistance since fault detection is not part of our objectives.

5.1 Load flow calculation.

The load flow calculations were carried out as shown in figure 52.

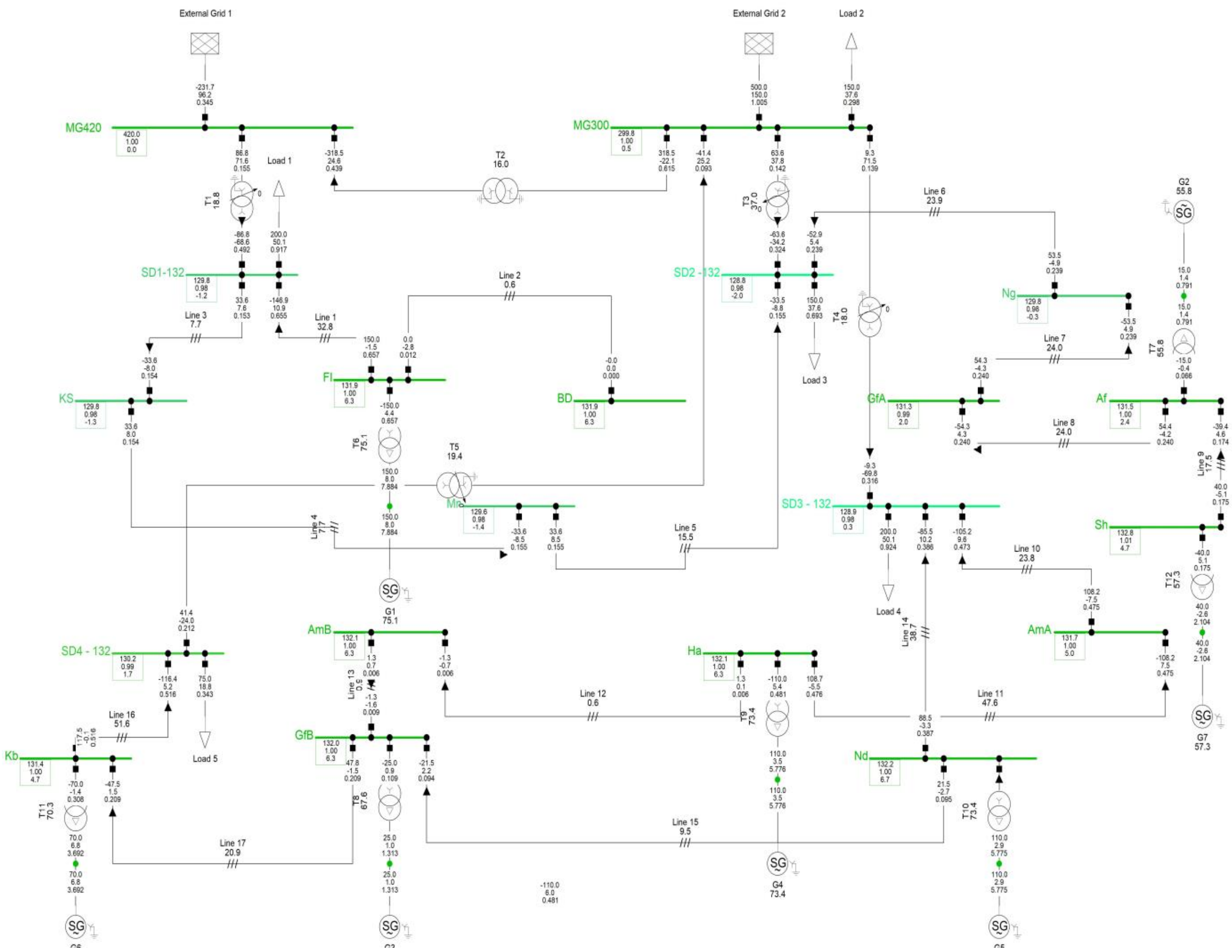


Figure 52: Load flow calculation

Expanding Bus Sh, and SD4-132 as in figure 27and 28,

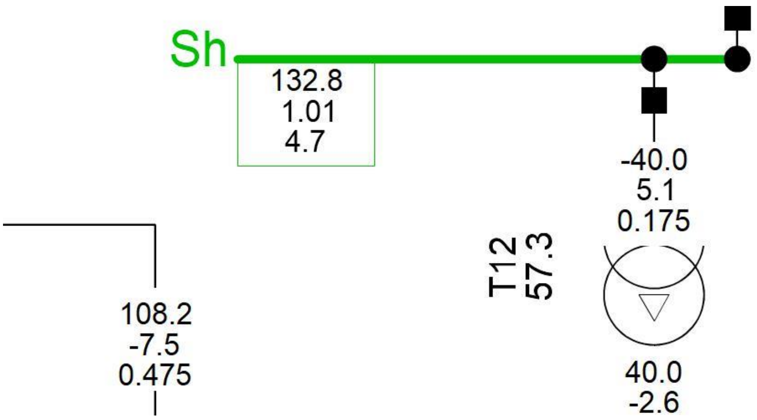


Figure 53: Bus Sh Load flow diagram before fault.

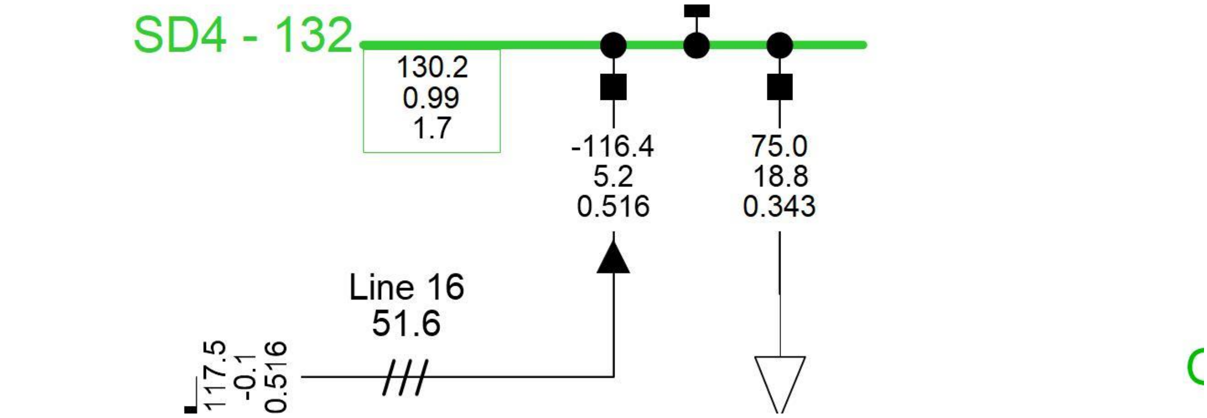


Figure 54: Bus SD4-132 Load flow diagram before fault.

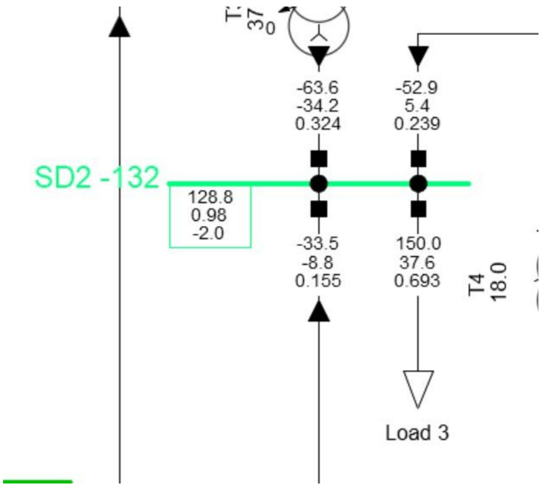


Figure 55: Bus SD2-132 load flow diagram before fault.

The flow diagram indicates bus voltages of Sh, SD4-132, and SD2-132 before fault as 1.01p.u, 0.99p.u and 0.98p.u respectively. The grid has a total generation of 520MW with the external infeed of 268MW to give a total generation of 788MW, a total load of 775.0MW, and an imbalance of 13.30MW because of Losses. See Appendix figure B1 for details.

Condition for deciding Overvoltage.

Voltages greater than 1.01p.u at bus Sh after a single-line ground fault is regarded as an Overvoltage.

Voltages greater than 0.99p.u at bus SD4-132 after a single-line to ground fault are considered an overvoltage.

Voltages above 0.98p.u at bus SD2-132 after a single-line to ground fault is taken to be an overvoltage.

These boundary conditions are important in determining the overvoltage in the subsequent sections.

5.2 Maximum single phase fault currents calculation.

This is done using the command prompt known as ComShc. Complete method for a single line to ground fault on phase A on all the buses at break time of 0.1second, fault clearing time of 1second, resistance and reactance of fault as 0 ohms respectively. Short circuit calculation of Appendix figure B2 shows the maximum fault current of radial study networks 1 and mesh study network 2 of an isolated network model of figure 45 are 129A and 109A respectively as shown in Appendix table B1. This is further used in calculating for the inductive reactance of the Peterson coil.

Table 14: Maximum fault current of study network 1 and 2.

Study Networks	Maximum fault current(A)
1(Radial Network)	129
2 (Mesh Network)	109

5.3 Peterson Coil Inductive Reactance Calculation.

For the Peterson coil to be able to compensate for the zero-sequence capacitance (C_{0N}), the neutral grounding inductive reactance (X_n) of the coil needs to be known, assuming the parallel resistance (R_n) is equal to zero since we are not interested in fault detection. It is advised to overcompensate the network at 5% to avoid the network going into resonance when one line/cable is disconnected during maintenance.

The formula for the calculation of the inductive reactance is given below in the equation---

$$X_n = \frac{1}{3\omega C_{0N}} \tag{5.1}$$

Where:

X_n = Peterson coil inductive reactance (ohms)

C_{0N}= zero sequence capacitance (farad)

ω= angular frequency = $2\pi f$ and f= $50Hz$

But,

$$C_{0N}= \frac{I_{cF}}{3\omega\frac{V}{\sqrt{3}}} \tag{5.2}$$

Where:

I_{cF}= capacitive fault current(kA)

V= line-line voltage (kV)

ω= angular frequency = $2\pi f$ (rad s^{-1})

5.3.1 For the 129A capacitive fault current (I_{cF}) of the radial study network1

$I_{cF} = 3\omega C_{0N}\frac{V}{\sqrt{3}}$

$C_{0N} = \frac{I_{cF}}{3\omega\frac{V}{\sqrt{3}}} = \frac{129}{3\times(2\pi f)\times\frac{V}{\sqrt{3}}} = \frac{129}{3\times(2\times\pi\times50)\times\frac{132kV}{\sqrt{3}}}$

C_{0N} = $1.80\times 10^{-6} Farad$

But,

$X_n = \frac{1}{3\omega C_{0N}} = \frac{1}{3\times(2\times\pi\times50)\times1.80\times10^{-6}}$, $\mathbf{X_n = 591ohm}$

5% overcompensation of X_n will be equal to **620ohm**

5.3.2 For the 109A capacitive fault current (I_{cF}) of the mesh study network2

$I_{cF} = 3\omega C_{0N}\frac{V}{\sqrt{3}}$

$C_{0N} = \frac{I_{cF}}{3\omega\frac{V}{\sqrt{3}}} = \frac{109}{3\times(2\pi f)\times\frac{V}{\sqrt{3}}} = \frac{109}{3\times(2\times\frac{22}{7}\times50)\times\frac{132kV}{\sqrt{3}}}$

C_{0N} = $1.50\times 10^{-6} Farad$

But,

$X_n = \frac{1}{3\omega C_{0N}} = \frac{1}{3\times(2\times\frac{22}{7}\times50)\times1.50\times10^{-6}}$, $\mathbf{X_n = 707ohm}$

5% overcompensation of X_n value will be equal to **742ohm.**

5.4 Overvoltage in a compensated centralized Peterson coil.

The essence of this simulation in Powerfactory is to ascertain the effect of overvoltage in a centralized compensated network of an extended 132kV network designed in figure 45.

The network has a total transmission line length of 450km with fault currents of 129A and 109A on both study networks, see table 14.

A bolted single-line to ground fault was initiated at the middle and end of the radial line of study network 1 as well as the end of the mesh study network 2. The Simulation results of chapters 5 and 6 are made up of two parts: transient and steady part. The transient part is because of the initiation caused by the simulation and that the compensation is near to the resonance point, while the RMS overvoltage value measured over ground potential is taken from the steady part of the simulation results.

5.4.1 Bolted single-line to ground fault at the middle of the radial study network 1.

Single-phase to ground fault was initiated at 80% length distance of line 6 feeder (Phase A) with centralized overcompensated Peterson coil of 620 ohms at transformer T3 as in figure 56. The measured three-phase line to neutral voltages at the bus Sh is shown in figure 57.

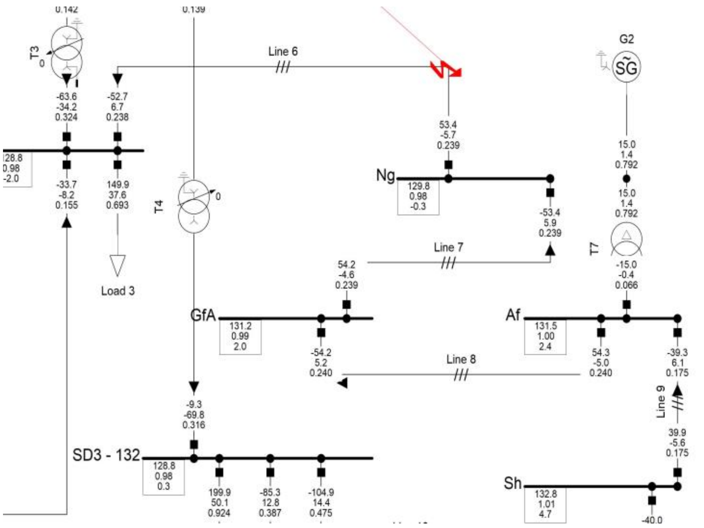


Figure 56: Single-line to ground fault at line 6 feeder with centralized Peterson coil at T3.

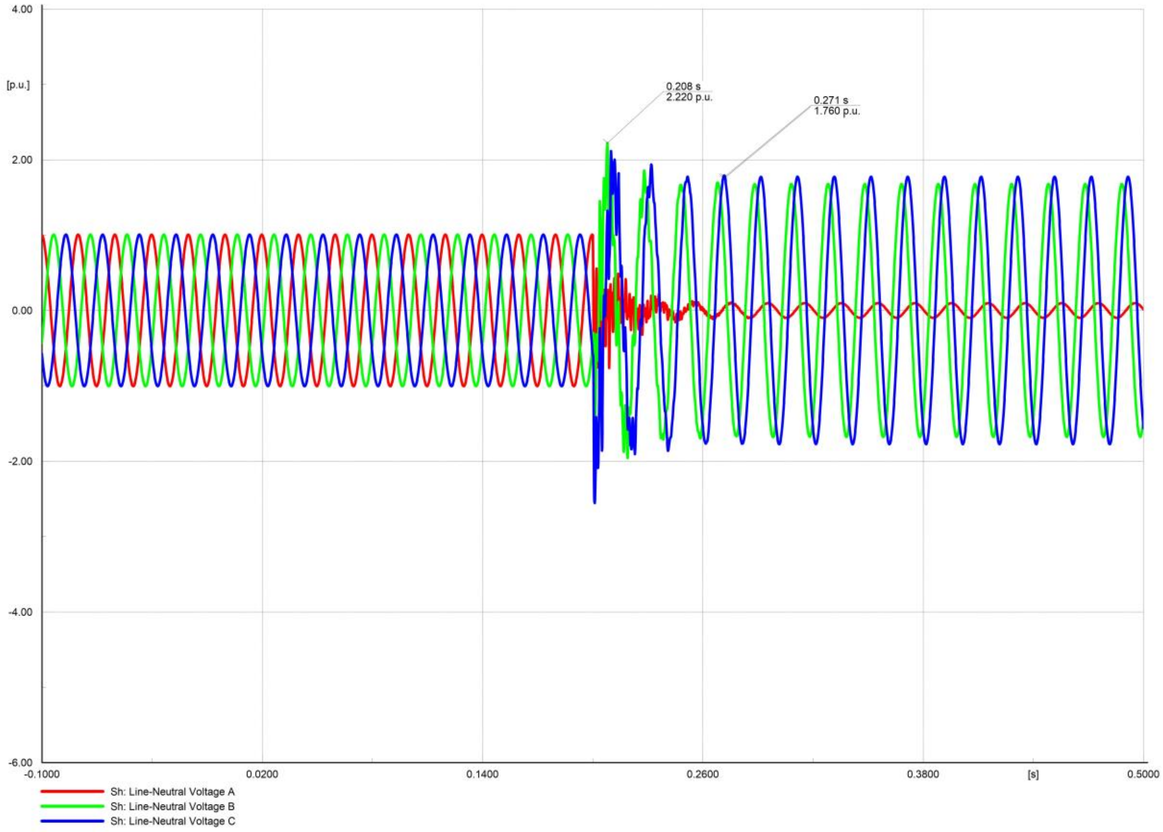


Figure 57: Bus Sh Line-Neutral voltages for Centralized Peterson grounding (fault at middle radial line).

Table 15: Overvoltage and fault current of centralized Peterson grounding (fault at middle radial line).

Overvoltage (p.u)	Fault current (kA)	Short circuit power (MVA)
1.76p.u	0.003	0.244

The fault current values are shown in Appendix table B2.

5.4.2 Bolted single-line to ground fault at the ends of a radial study network 1.

Single-line to ground fault was initiated at the end of the radial line bus BD, and its overvoltage impact at bus Sh was measured as in figure 58.

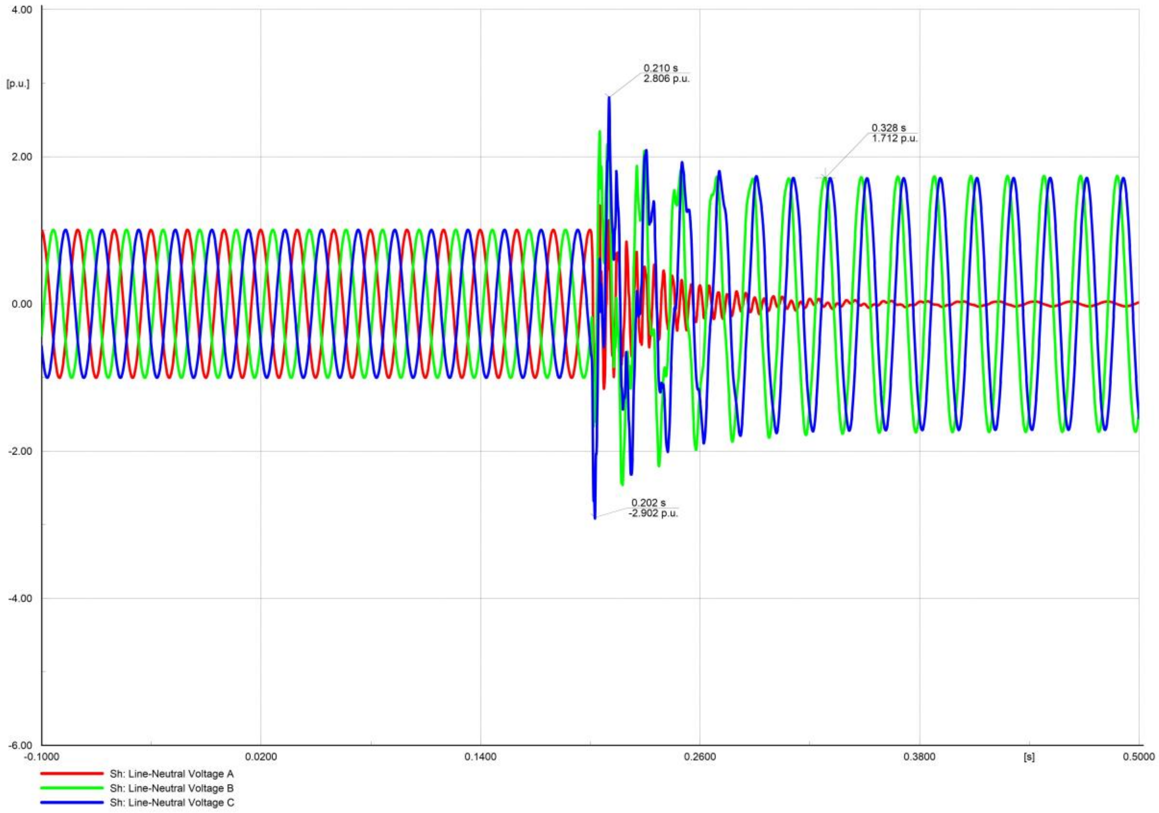


Figure 58: Bus Sh Line-Neutral voltages for Centralized Peterson grounding (fault at end of radial line).

Table 16: Overvoltage and fault current of centralized Peterson grounding (fault at end of radial line).

Overvoltage (p.u)	Fault current (kA)
1.712	0.003

5.4.3 Overvoltage measured at the receiving end of the radial line.

The overvoltage value at the receiving end busbar SD2-132 overvoltage is shown in figure 59. The reduction in overvoltage compared to 1.76pu measured at the sending end of bus Sh might be because of the Ferranti effect.

Table 17: Overvoltage and fault current of centralize Peterson grounding (measured at the receiving end SD2-132)

Overvoltage (p.u)	Fault current (kA)
1.692	0.003

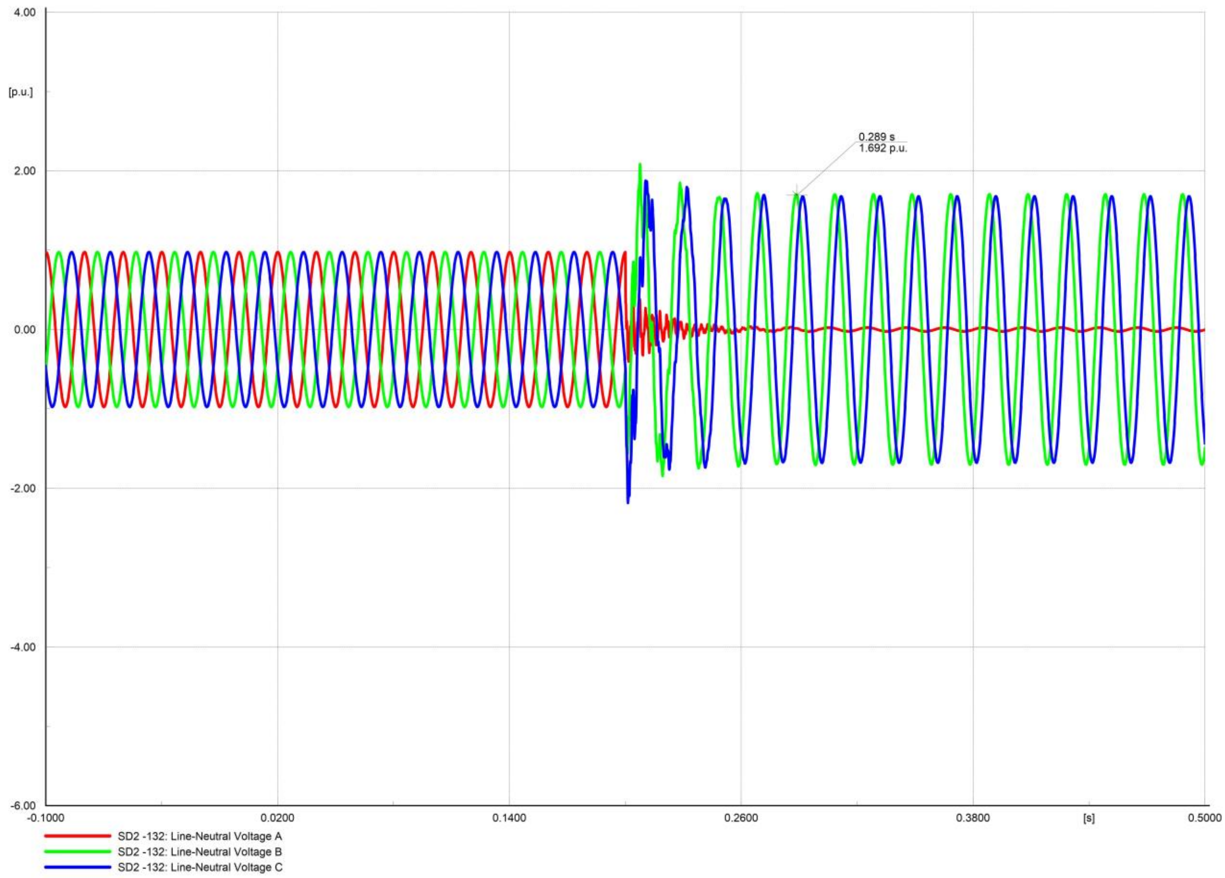


Figure 59: Bus SD2-132 Line-Neutral voltages of centralized compensation at the receiving end.

5.4.4 Bolted single-line to ground fault at the end of the mesh study network 2.

A single line to ground fault was introduced at the bus Ha with Peterson coil overcompensation of 742ohm at the central transformer station T5 of the mesh network of figure 60.

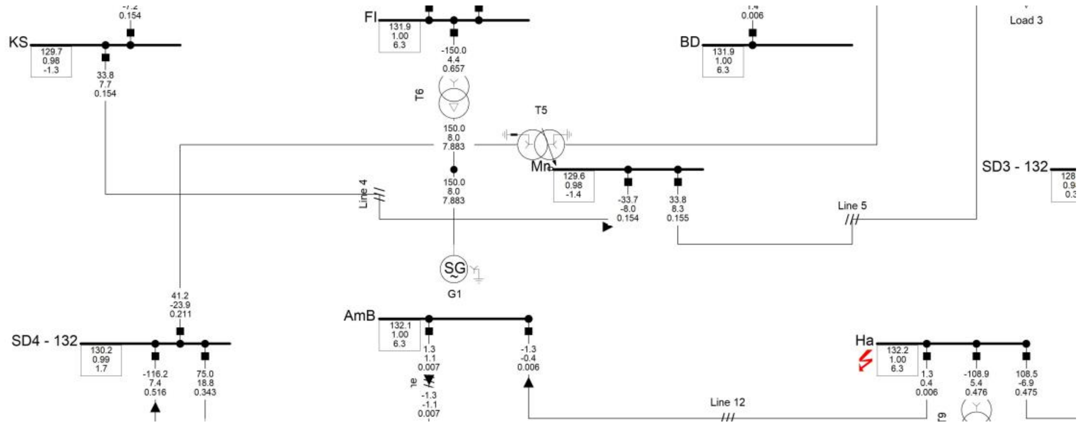


Figure 60: single-phase to ground fault at bus Ha with a Peterson coil inductive reactance at T5.

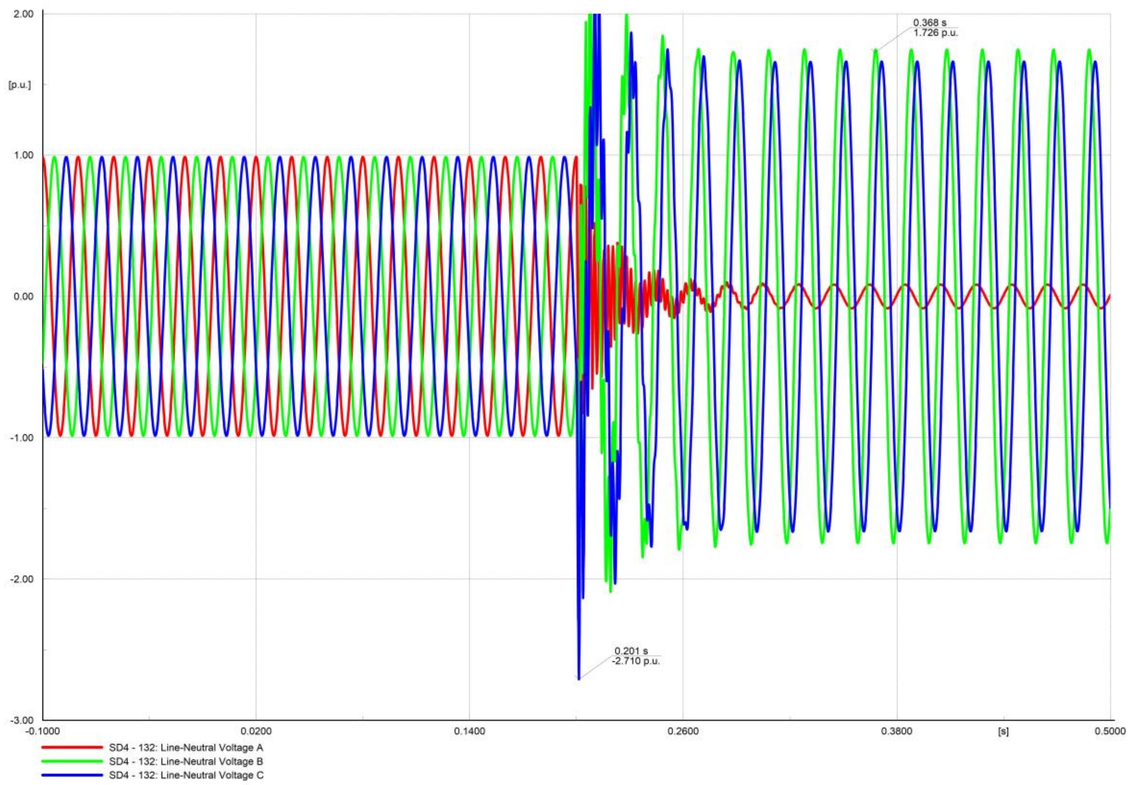


Figure 61: Bus SD4-132 Line-Neutral voltage (fault at end of mesh study network 2, bus Ha)

Table 18: Overvoltage and fault current of centralized Peterson grounding (fault at end of mesh line).

Overvoltage (p.u)	Fault current (kA)
1.726	0.007

See Appendix table B3 for the fault current detail.

5.5 Overvoltage in a compensated distributed Peterson coil.

Distributed compensation in a radial system is achieved with Peterson coil inductive reactance value being distributed into several distribution transformers in the radial network. Practically, for an equivalent 620 ohms Peterson inductive coil, two parallel neutral grounding inductive reactance of equal values of 1240 ohms are set in parallel with the line earth capacitance. The result of the simulation for 0.5seconds is shown below in figure 62.

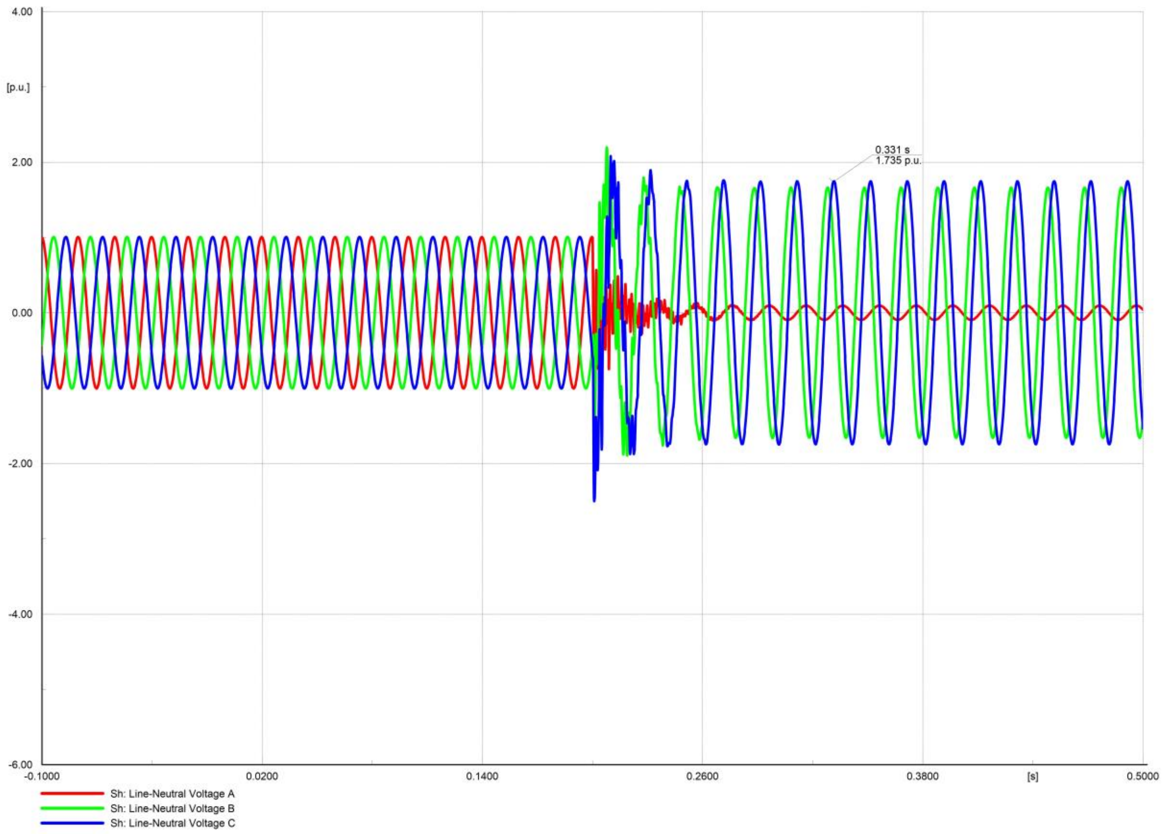


Figure 62: Bus Sh Line-Neutral voltage of distributed Peterson coil compensation.

Table 19:Overvoltage and fault current of distributed Peterson coil grounding.

Overvoltage (p.u)	Fault current (kA)	Short circuit power (MVA)
1.735	0.003	0.234

See Appendix table B4 for details.

5.6 Overvoltage in Directly grounded at the central transformer station.

This is carried out for faults in the middle of the transmission line. Transformer T3 is directly grounded at the low voltage side during a single phase to ground fault at line 6 feeder. The simulation result is as shown below:

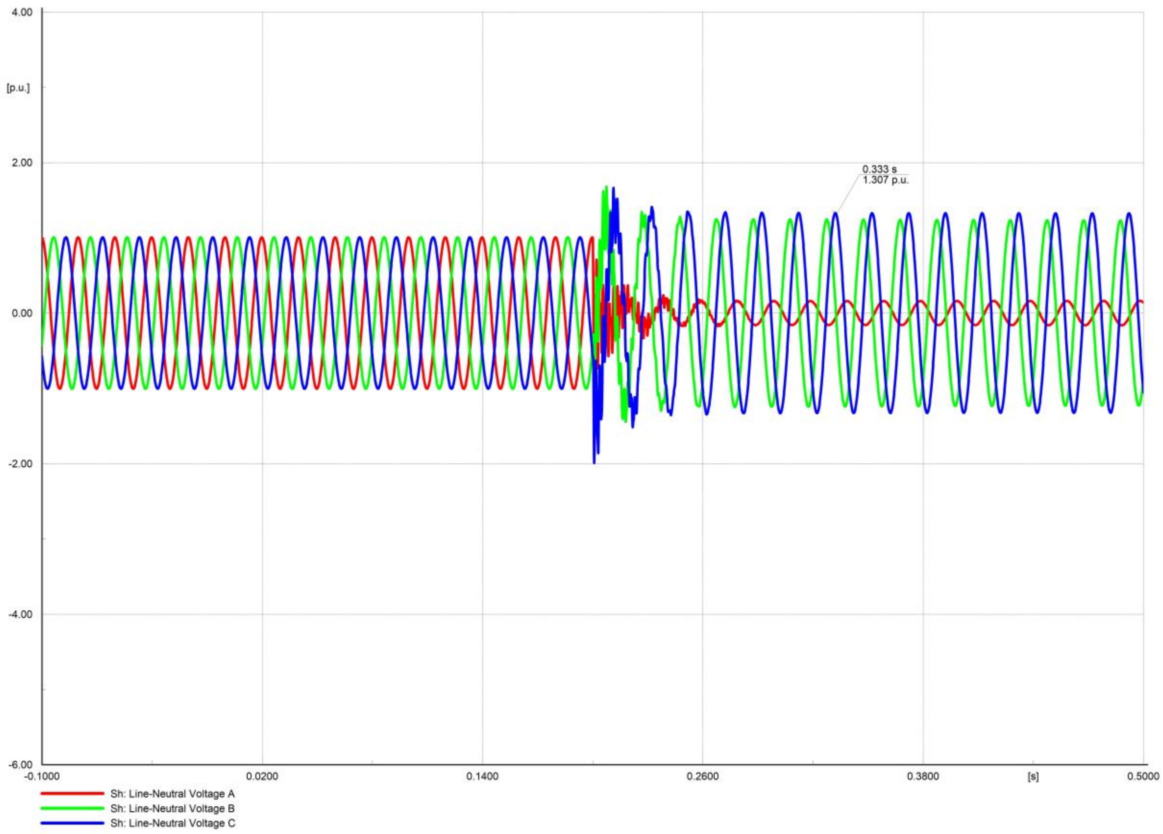


Figure 63: Bus Sh Line-Neutral voltage for centralized direct grounding (fault at middle radial line)

Table 20: Overvoltage and fault current for centralized direct grounding.

Overvoltage (p.u)	Fault current (kA)
1.307	1.126

The result shows a reduced overvoltage of 1.307p.u on the healthy phases of B and C, and a drastic increase in the earth fault current of 1126A. Appendix table B5 shows the detailed fault current.

5.7 Overvoltage in Directly grounded distributed in a radial system.

For a directly grounded network distributed in a radial transformer, the simulation result shown in figure 64 is for two transformer stations directly grounded as a single line to ground fault was carried out.

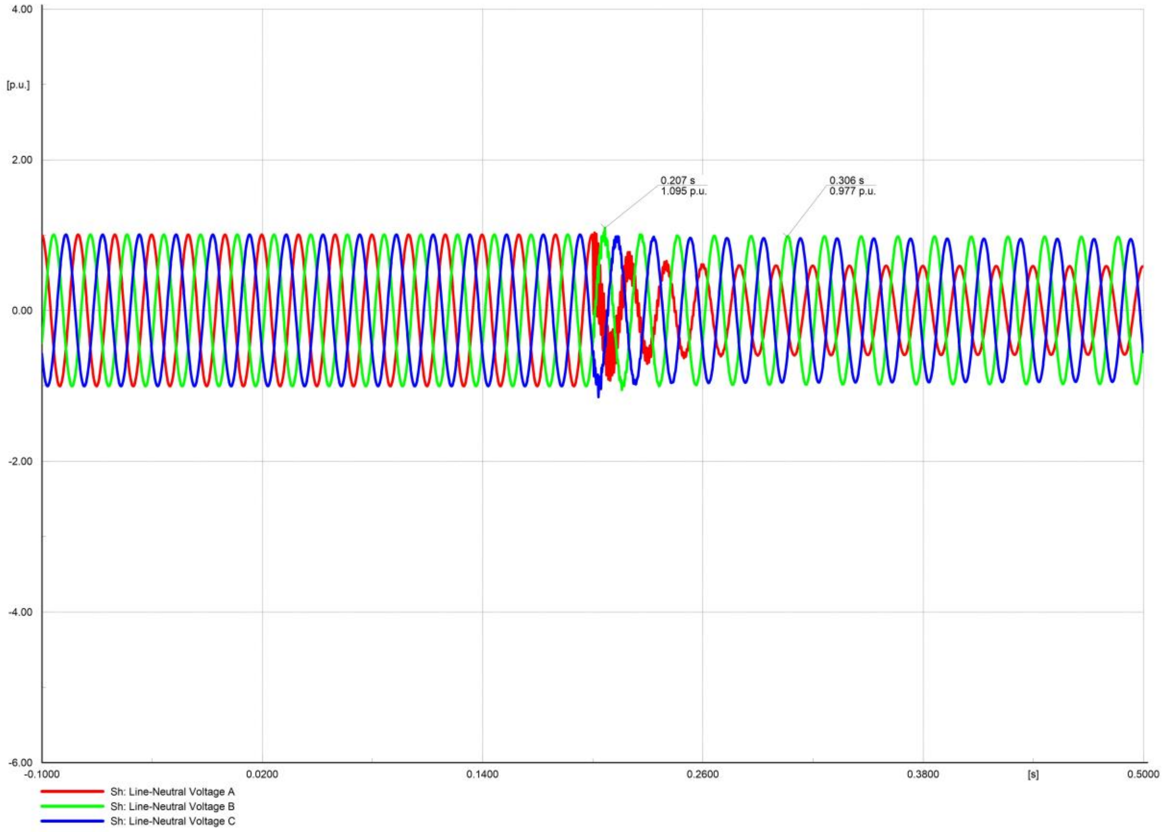


Figure 64: Bus Sh Line -Neutral voltages of a direct distributed grounding in a radial network.

There is no overvoltage in this case scenario because the voltage value 0.977<1.01 p.u.

6 Simulations and Results (Un-transposed Network)

The un-transposed network creates an unbalanced voltage and current in the steady-state operation of the system[38]. The following simulation was carried out on the 132kV network to ascertain the effect of an un-transposed line on the overvoltage due to events of single-phase to ground faults for a compensated and direct grounding centralized and distributed as follows.

1. Compensated Peterson coil located centrally in the main transformer station.
2. Compensated Peterson coil distributed in a radial system.
3. Directly grounded located at the central transformer station.
4. Direct grounding distributed in a radial system.

6.1 Overvoltage in a centralized compensated Peterson coil grounding.

The simulations were carried out for a single-line ground fault at the middle and end of a radial line of study network 1. Study network 2(mesh) was also studied for overvoltage that occurs at its end.

6.1.1 Single-line to ground fault at the middle of the radial study network 1.

Compensating an un-symmetrical system of 129A earth fault current with a neutral inductive reactive Peterson coil of 620 ohms on Powerfactory gave the simulation result below during a single-phase to ground fault at 80% length distance of line 6 feeder.

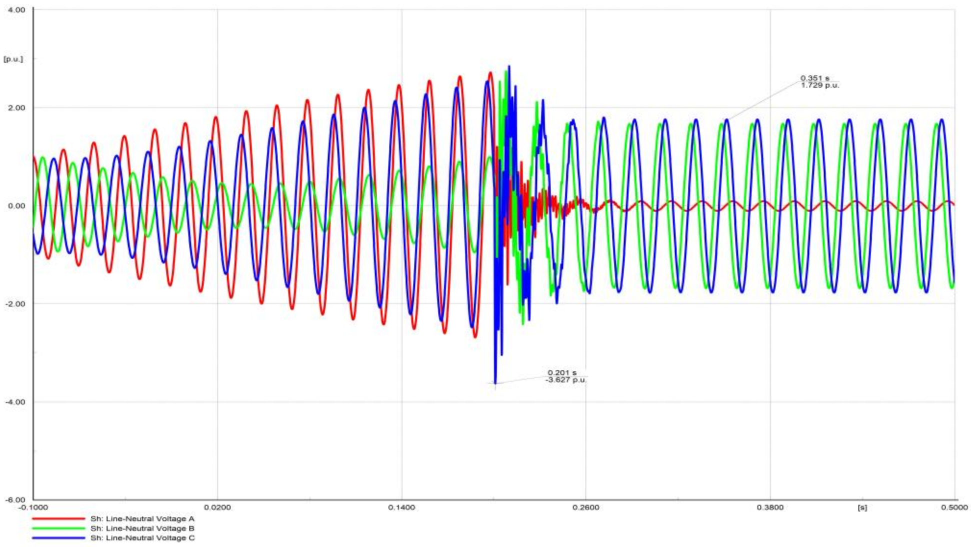


Figure 65: Bus Sh Line-Neutral voltage for centralized Peterson coil grounding (fault at middle of a radial line).

The result shows an unbalance in the voltages of the phases before the short circuit event and the recorded overvoltage and fault current are as seen in table 21.

Table 21: Overvoltage and fault current for centralized Peterson coil grounding (fault at middle radial line).

Overvoltage (p.u)	Fault current (kA)
1.729	0.006

Fault current table is shown in Appendix table B7

6.1.2 Single-line to ground fault at the end of a radial study network 1.

The overvoltage measured at bus Sh for a single-phase to ground fault at the end of a radial line bus BD is shown in figure 66.

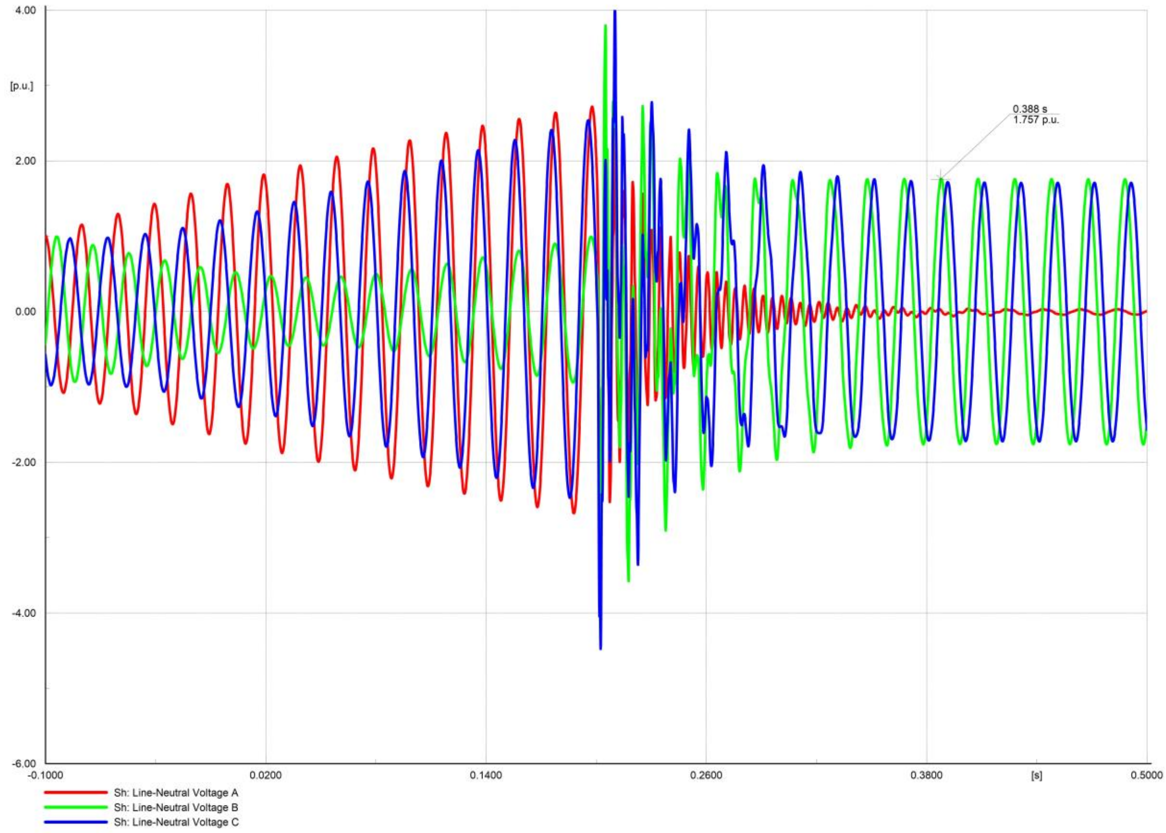


Figure 66: Bus Sh Line-Neutral voltage for centralized Peterson coil grounding (fault at end of a radial line).

Overvoltage (p.u)	Fault current (kA)
1.757	0.006

A fault that occurs at the end of a radial line of an un-transposed transmission line gives a higher overvoltage of 1.757p.u relative to 1.729p.u when a fault was at the middle of the radial line with a fault current of 0.006kA of Appendix B6.

6.1.3 Single-line to ground fault at the end of the mesh study network 2.

The simulation result is shown below, however unsymmetrical line increases the earth fault current (0.008kA) for faults at the end of a mesh network as seen in Appendix table B7 with an overvoltage of 1.732pu

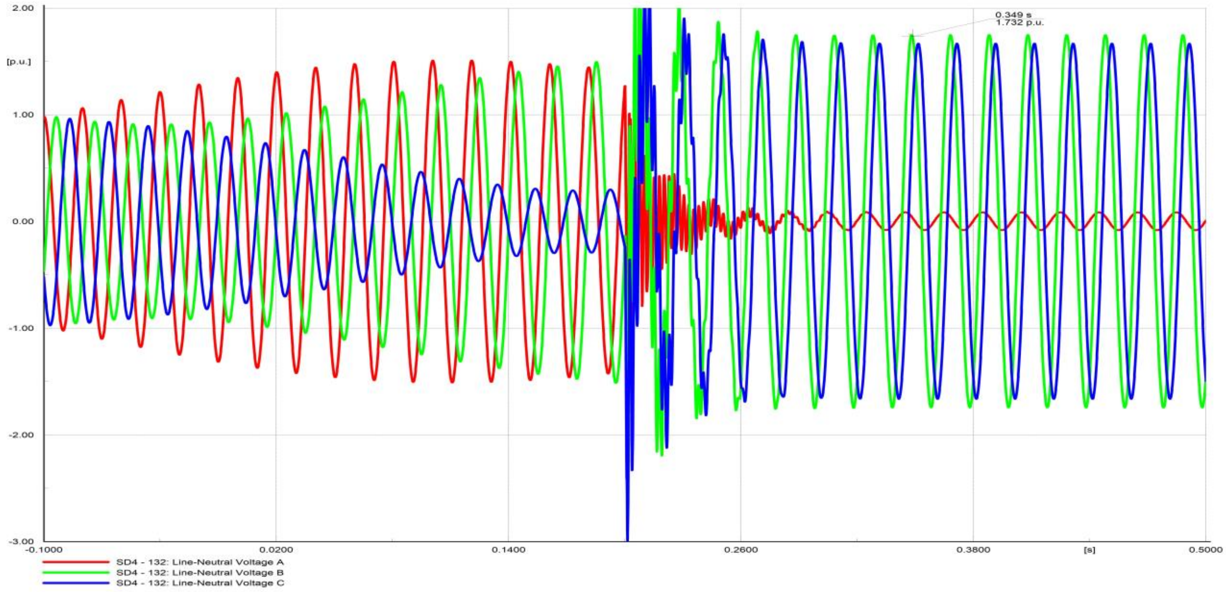


Figure 67: Bus SD4-132 of study network 2 (fault at end of mesh line).

6.2 Overvoltage in a distributed compensated Peterson coil grounding.

Distributed compensation with Peterson coil simulation for an unsymmetrical line is achieved as shown in the diagram below.

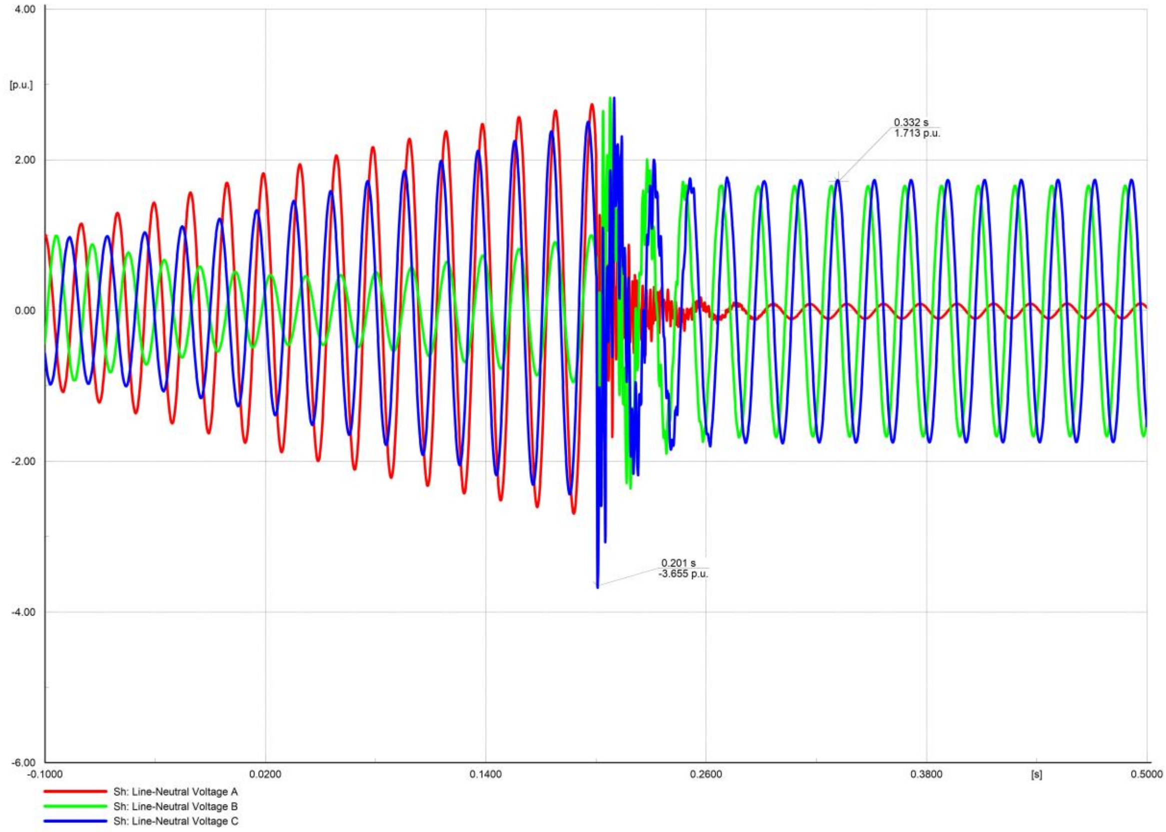


Figure 68: Bus Sh Line-Neutral voltage for distributed compensated Peterson coil.

Distributed Peterson coil reduces the Overvoltages on the healthy phase irrespective of the Network being transposed or not however, the major difference between the transposed and un-transposed is that the unsymmetrical transmission lines double the earth fault current of a compensated Peterson coil grounded system.

6.3 Overvoltage in a directly grounding located at the central transformer.

The result simulation is as shown in figure 69, with only the main transformer station directly grounded in the event of a single line to ground fault at the end of the line 6 feeder.

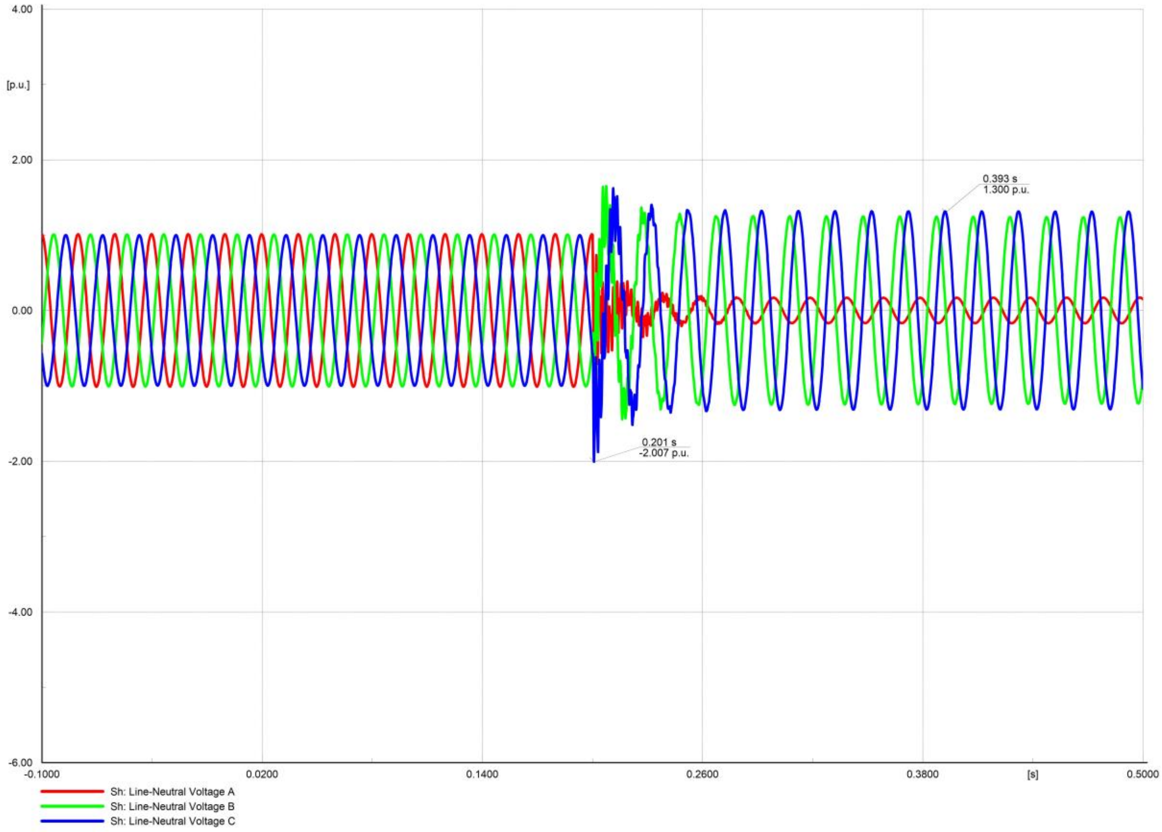


Figure 69: Bus Sh Line-Neutral voltage for un-transposed direct grounding located at the central transformer.

From figure 42 above, it is evident that there is not any unbalance in the phase voltages before the fault when the network is directly grounded. There is also a reduced overvoltage when the system is directly grounded compared to compensated Peterson coil grounding. In addition to the above-mentioned advantages of using direct centralized grounding for an un-transposed transmission line, the earth fault current is 1.136kA compared to the 1.126kA earth fault current recorded when the electrical network is directly grounded in the central transformer for a transposed line. See Appendix table B4 and table B8. That is to say that the effect of a non-symmetry transmission line has a minimal effect on the earth fault current when directly grounded compared to compensated grounding, where the earth fault current is doubled.

6.4 Overvoltage in a directly grounding distributed in a radial system.

Two transformer stations were directly grounded in a radial system to achieve a distributed direct grounding during a single-phase to ground fault at line6. The bus Sh voltages at the end of the simulation for 0.5 seconds are shown in figure 70 below.

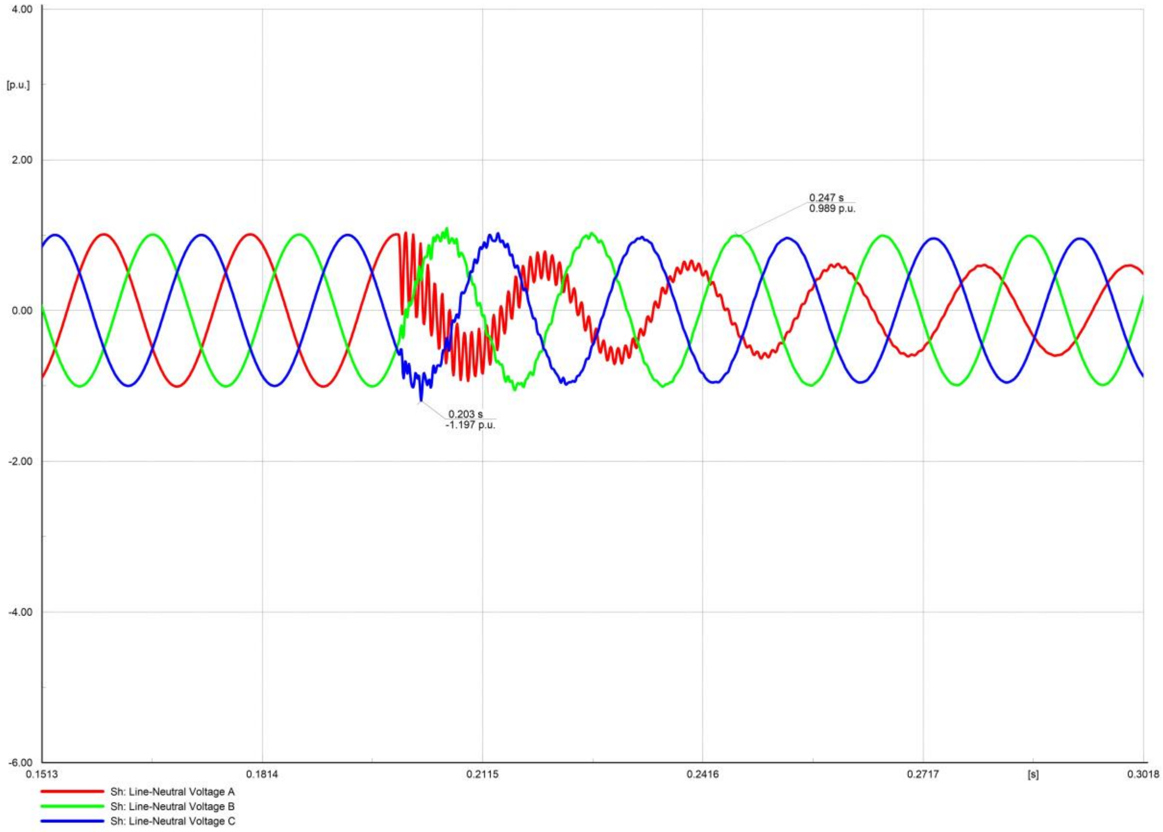


Figure 70: Bus Sh Line-Neutral voltage for un-transposed direct grounding distributed in a radial network.

The result indicated that there is no overvoltage in the healthy phase for a direct grounding distributed in a radial network.

7 Discussions

To maintain robustness and operational safety of the Vestfold and telemark region, there is a need to strengthen the grounding systems of the transmission/distribution network. This chapter discusses the impact of an additional load on compensated Peterson coil grounding and Direct grounding in terms of the following:

7.1 Overvoltage and fault current.

The overvoltage and fault current in simulation results of chapters 5 and 6 are analyzed for both transposed and un-transposed transmission lines.

7.1.1 Centralized compensated Peterson coil versus Centralized Direct grounding (transposed line).

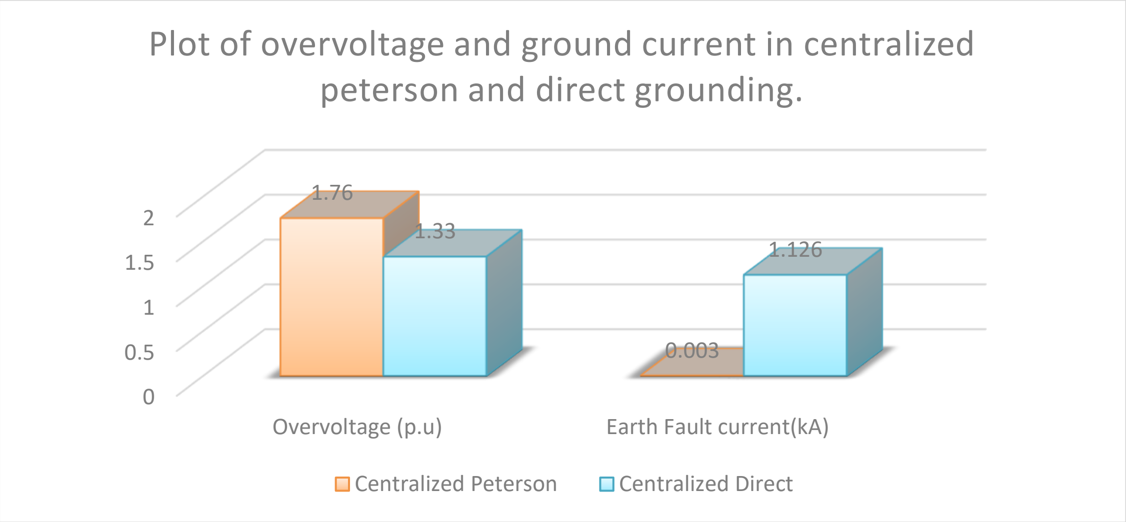


Figure 71: Overvoltage and earth fault current plot for both centralized Peterson coil and direct grounded.

The research result shows that a compensated Peterson coil shows a higher overvoltage increase of about 80% line to the neutral voltage on the heathy phases, which is close to the worst-case scenario of 1.8p.u that can be recorded with Peterson coil grounding, with a reduced fault current of 0.003kA whereas a centralized direct grounded overvoltage increases of about 30% with an increased fault current of 1.126kA as shown in figure 71 above. It is presumed that at 50 Hz, the capacitance in parallel with the coil provides a zero-sequence impedance that is theoretically limitless[34]. For a reduced network of ours, there is a possibility of extinguishing the fault arc and fault isolated by distance protection within the shortest time $< 200ms$. Another advantage of resonant grounding using Peterson coil over the direct grounding method is that the line voltages of the healthy phases B and C are maintained at 132.723kV and 132.717kV respectively, as seen in Appendix Table B2. Thus, there will be a continuous operation of the network load between 1-2 hours. However, for an earth fault current of 50A and above in a large network, this may be dangerous for both personnel and system components if the fault is not isolated within the shortest time.

7.1.2 Distributed compensated Peterson coil versus distributed Direct grounding (transposed line).

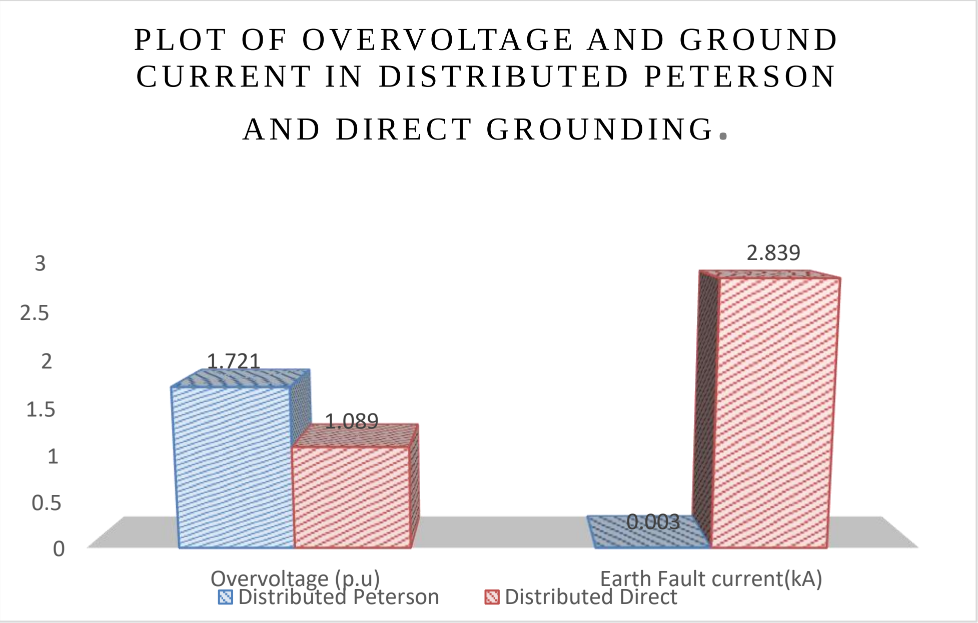


Figure 72: Plot of overvoltage and ground current in distributed Peterson and direct grounding.

Distributing direct grounding to two transformer stations increased the fault current by two with no overvoltage on the healthy phase, whereas the overvoltage on healthy phases as well as the fault current for a compensated system was reduced, as seen in figure 47. This is to say that the fault current value of a distributed direct grounding is directly proportional to the number of transformer stations. Disconnection of any compensation coil in the network will not affect the performance of the entire network; however, this can lead to an increase in the cost of maintenance and installation of such a network. To limit the earth fault current in distributed direct grounding, it is advised to reduce the number of directly grounded transformer stations.

7.1.3 Comparison between centralized compensated Peterson coil grounding and distributed compensated Peterson grounding (radial transposed line).

The result analysis of table 22 indicates that distributing Peterson coil grounding to one or more transformer stations has a minimal significant effect on the overvoltage with no effect on the fault current. Similarly, the short circuit power tends to reduce when the Peterson coil is distributed. The reduced value of the short circuit power Sk''(MVA) could be to the reduction in the active and reactive earth fault currents and active losses due to the increase in length of the cable in a radial network. Centralized compensation poses a problem to increase in active losses as the cable length increases. To solve this challenge, distributed compensation is preferred, perhaps comparing the smaller test networks (1 and 2) to a more realistic network model would have revealed more significant differences, and such a survey could be used as part of future research.

Table 22: Centralized Peterson coil grounding versus Distributed Peterson coil grounding.

	Overvoltage (p.u)	Fault current (kA)	Short circuit power (MVA)
Centralized	1.760	0.003	0.244
Distributed	1.735	0.003	0.234

7.1.4 Comparing centralized compensated Peterson coil(transposed) with centralized compensated Peterson coil (un-transposed line).

This capacitive and inductive unbalance for the un-transposed transmission line is most visibly in a compensated Peterson coil grounding. The plot below shows the result analysis of the earth fault current for both transposed and un-transposed lines for compensated Peterson coil.

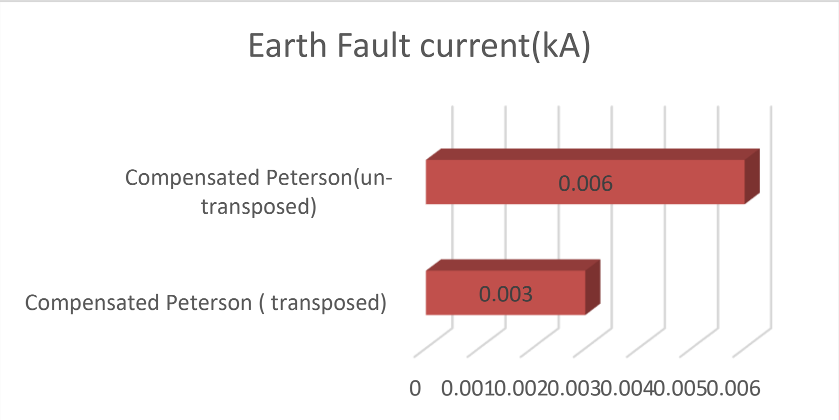


Figure 73: Compensated Peterson coil grounding(transposed) versus compensated Peterson coil grounding(un-transposed).

The fault current doubles for a compensated Peterson coil when the transmission lines are un-symmetrical to when the lines were transposed.

7.1.5 Comparing centralized direct grounding (transposed) with centralized direct grounding (un-transposed line).

An un-symmetrical line creates no voltage unbalance for a directly grounded system but shows a small increase in fault current as in table 23. This could be because of the absence of inductive/capacitive reactance effect in direct grounding.

Table 23: Overvoltage and fault current for both direct grounding (transposed and un-transposed).

	Overvoltage (p.u)	Fault current (kA)
Transposed	1.307	1.126
Un-transposed	1.300	1.136

7.1.6 Overvoltage at the middle of a radial line verses end of a radial line for a compensated Peterson coil (transposed line).

Overvoltage at the end of the radial line for a resonant grounded system is lower than that at the middle of the radial line, as shown in table 24.

Table 24: Overvoltage and fault current (fault at middle and end of radial line).

	Overvoltage (p.u)	Fault current (kA)
Middle of radial line	1.760	0.003
End of the radial line	1.712	0.003

Capacitance tends to increase with an increase in the length of the transmission line, which in turn reduces the line to neutral voltages at the end of the radial line.

7.1.7 Overvoltage at the end of a mesh network for a compensated Peterson coil grounding (study case 2 transposed line)

The overvoltage for fault at the end of a mesh network is seen to be higher than that at the end of a radial network in table 25, with a high fault current value of 0.007kA compared to that at the end of the radial line in table 24.

Table 25: Comparison between overvoltage and fault current (for fault at end of mesh and radial lines).

	Overvoltage (p.u)	Fault current (kA)
End of a mesh network	1.726	0.007
End of a radial network	1.712	0.003

7.2 Touch and Step Voltages.

These voltages play a very important role in the designing of the grounding system due to the rise in earth potential during ground faults. The earth's potential is a product of the resistance to the ground and the earth's current. The tower impedance determines the grounding system's resistance to ground in the case of steel towers [27]; thus, a reduced earth current and resistance to the ground will invariably reduce the touch and step voltages.

The potential ground rise of a compensated Peterson coil grounding in chapter 5 for a fault at line 6 feeder of tower type D gave a maximum ground current of 0.003kA, assuming the ground resistance to be 12Ω.

$$\text{GPR} = I_{Gmax} \times R_G \tag{7.1}$$

$$\text{GPR} = 0.003\text{kA} \times 12 = 36\text{volts}$$

Similarly, the Ground potential for a directly grounded system of chapter 5 will give a GPR value of:

$$\text{GPR} = I_{Gmax} \times R_G$$

$$\text{GPR} = 1.126\text{kA} \times 12 = 13{,}512\text{volts}$$

Comparing the two, compensated Peterson grounded system has a lower touch and step voltage after being compensated with the Peterson coil and can only last for the time duration of seconds. The direct grounded system shows a high touch/step voltage which can last for more than 10seconds if not isolated within the shortest time. This poses a danger to both personnel and the system equipment within the vicinity. Touch- and step-voltages can be lowered by putting extremely resistive surface layers on the ground around towers, such as bedrock, or by properly connecting the tower footing to highly conductive soil layers with ground electrodes, lowering the total neutral to ground impedance [27].

Tower D of a single circuit with double earth wire has multiple parallel resistance to ground and will give rise to a reduced total equivalent resistance to ground. This has a more reduced touch/step voltage compared to towers G, H, C, and K.

7.3 Fault detection.

Lower fault currents below 50A can easily be disconnected using a distance relay by comparing the total line impedance with the measured total positive sequence impedance. For a compensated Peterson coil of a small network like ours, the fault current of 3A will easily be detected by the distance relay and overcurrent relay without the tripping of the circuit breaker within the shortest time duration for fault currents that are less than the load current. However, a permanent ground-fault current of 50A and above will remain until the fault is isolated manually by the control center. Assuming a tower line without a ground wire, it will be difficult for the distance relay to operate. Tripping. In direct grounding, the fault current is cleared with the help of non-directional and directional overcurrent relays.

7.4 Compensation Degree.

Changes in network topology, on the other hand, alter total shunt capacitance and capacitive earth fault current; therefore, coil inductance should be changeable to maintain the compensation degree constant [39]. The degree of compensation (K) can be mathematically stated in the equation 7.2.

$$K = \frac{I_L}{I_c} \tag{7.2}$$

Where:

K = Degree of compensation

I_L= Inductive current of the Peterson coil in Amperes

I_c= Capacitive current component of the fault current in Amperes

K $> 1 = overcompensation.$

K$< 1 = undercompensation.$

K = 1 = Resonance, so to avoid overvoltage that can lead to system breakdown due to oscillation between the inductance and capacitance, K $\approx 1 \pm 5\%$.

The degree of compensation affects the residual earth's current value. Analysis of this is shown in table 26 and graph plot of figure 74.

Table 26: Degree of compensation verses fault current (transposed and un-transposed).

% Compensation	Fault current for transposed line (A)	Fault current for un-transposed line (A)
100	9	15
101	8	16
102	7	17
103	5	18
104	4	19
105	3	20
106	2	20
107	1	21
108	0	22
109	1	23
110	2	24

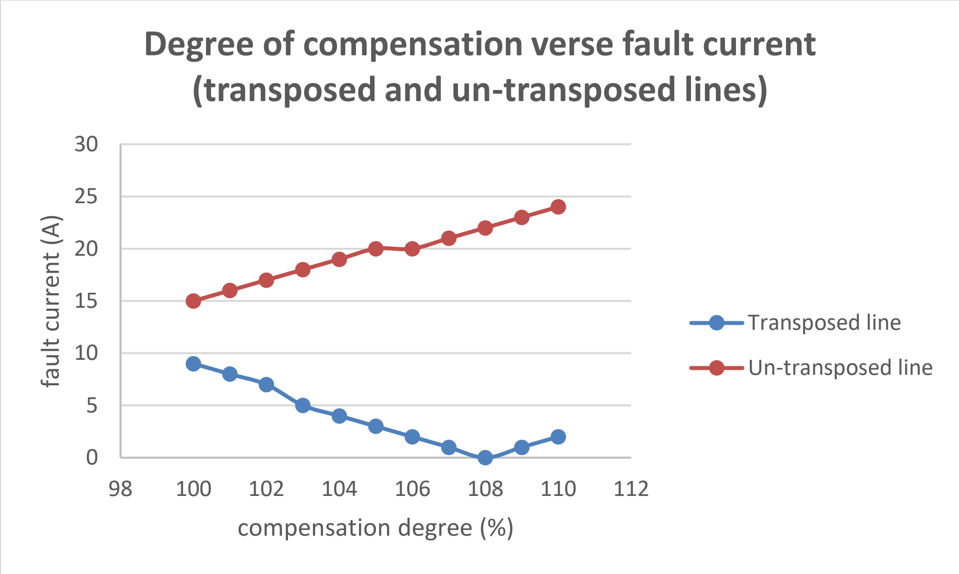


Figure 74: Compensation degree plot against earth fault current.

The analysis supports that the residual earth current of a transposed line decreases as the degree of compensation increases, and this can affect the touch and step voltage if not being checked. At 8%, the Peterson coil compensates all the capacitive current of infinite zero sequence impedance to result in zero amperes of fault current, which is contrary to what we know about resonance at 100 % compensation; the fault current is zero given symmetrical capacitances. However, this shift in resonance maybe because of power losses of 13.30MW in the system and the impact of the zero-sequence impedance of the transformer with reference to [40]. Based on this development, the operating compensation through the calculations of the designed 132kV network is:105 % / 108 % = 97,2 %. For an un-transposed line, the fault current increases as the compensation degree increase invariably. This will be a treat to both personnel and system equipment if not checked.

8 Conclusion

A summary of the research analysis done on the 132kV network has proven the following point:

- That a centralized Peterson coil grounded, the system shows a higher overvoltage of 1.76, which is the line RMS voltage over ground potential during single-phase fault when the impact from capacitances is neglected and reduces the fault current drastically than a centralized direct grounded system of 1.30 overvoltage with an increased fault current.
- The fault current value of a distributed direct grounding is directly proportional to the number of transformer stations.
- Distribution of compensated Peterson coil to two or more transformer stations shows a minimal effect on the overvoltage with no effect on the fault current.
- Un-transposition of the transmission line doubles the earth fault current of a centralized Peterson coil grounding with little or no effect on overvoltage and fault current in a directly grounded network.
- Overvoltage recorded at the middle of a radial line in a compensated Peterson coil grounding is higher than that at the end of the radial line considering the capacitance-voltage relationship for a transposed line.
- A mesh network shows an increased fault current of 7A compared to that of a radial line of 3A.
- Peterson coil resonant grounding has a lower touch and step voltage and can only last for a time duration of seconds, while the Direct grounded system shows a high touch/step voltage which can last for more than 10seconds for fault currents less than 50A.
- Detection of fault in compensated resonant grounding is always difficult due to the reduced fault current, unlike in the direct grounded network.
- Overcompensation in a Peterson coil resonant grounding reduces the earth current for transposed transmission lines, whereas the case is different for an un-transposed line.

8.1 Further work

The following has been proposed as further work on this topic based on some limitations:

- The overvoltage effect on the proposed Network for other frequency harmonics should be considered for further research.
- Safety issues and impacts from system grounding (resonant and direct) onto operational security should be investigated.
- The overvoltage impact on both distributed and centralized Peterson coil grounding should be investigated using a more realistic network model.
- Shift in resonance at 100% compensation in resonance grounding should be investigated for networks with and without losses.

References

[1] T. Safwat Kabel and M. Bassim, "Literature Review of Renewable Energy Policies and Impacts," Aug. 2019.

[2] "GWEC_Global_Wind_2018.pdf." Accessed: Feb. 23, 2022. [Online]. Available: https://indianwindpower.com/pdf/GWEC_Global_Wind_2018.pdf

[3] "Natural gas and wind forecast to be fastest growing sources of U.S. electricity generation - Today in Energy - U.S. Energy Information Administration (EIA)." https://www.eia.gov/todayinenergy/detail.php?id=41333 (accessed Feb. 23, 2022).

[4] "NERC-CAISO_VG_Assessment_Final.pdf." Accessed: Feb. 24, 2022. [Online]. Available: https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC-CAISO_VG_Assessment_Final.pdf

[5] "Fault Current Contributions from Wind Plants." https://resourcecenter.ieee-pes.org/publications/technical-reports/PESTR0026.html (accessed Feb. 24, 2022).

[6] A. Cerretti, F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and G. Valtorta, "Temporary overvoltages due to ground faults in MV networks," in *2009 IEEE Bucharest PowerTech*, Jun. 2009, pp. 1–8. doi: 10.1109/PTC.2009.5282140.

[7] E.-E. E. Portal, "Where Do We Use Arc Suppression Coil (Petersen Coil)? | EEP," *EEP - Electrical Engineering Portal*, Jun. 06, 2016. https://electrical-engineering-portal.com/arc-suppression-coil-petersen-coil (accessed Feb. 25, 2022).

[8] J. Endrenyi, "Analysis of Transmission Tower Potentials During Ground Faults," *IEEE Trans. Power Appar. Syst.*, vol. PAS-86, no. 10, pp. 1274–1283, Oct. 1967, doi: 10.1109/TPAS.1967.291904.

[9] "What is Electrical Fault? Definition, Types & Harmful Effects of Fault on Power System," *Circuit Globe*, Aug. 10, 2016. https://circuitglobe.com/electrical-fault.html (accessed Jan. 18, 2022).

[10] C. D. Gozon, "Power Systems Modelling and Fault Analysis..Theory and Practice-Nasser Tleis", Accessed: Feb. 26, 2022. [Online]. Available: https://www.academia.edu/38173740/Power_Systems_Modelling_and_Fault_Analysis_Theory_and_Practice_Nasser_Tleis

[11] "A review on fault classification methodologies in power transmission systems: Part—I | Elsevier Enhanced Reader." https://reader.elsevier.com/reader/sd/pii/S2314717217300065?token=1BA3B58D90E5A759DF36769137AB52AF42FE63D50BA4A8EDCF9F7D9343A97865A6CC3FBD6AFE4C406A4EB326990E44C0&originRegion=eu-west-1&originCreation=20220118210652 (accessed Jan. 18, 2022).

[12] Francisco Gonzalez-Longatt, *Class 3 Unsymmerical Faults*, (Mar. 26, 2020). Accessed: Jan. 19, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=1k10O3Gt8h4

[13] Francisco Gonzalez-Longatt, *Class 3. Symetrical Components an Sequence Networks PART I*, (Mar. 25, 2020). Accessed: Jan. 19, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=yvjnJ0tfMzM

[14] "Symmetrical Components." https://www.allumiax.com/blog/symmetrical-components (accessed Jan. 19, 2022).

[15] H. Kazan, "Chapter 7: Symmetrical Components and Representation of Faulted Networks Chapter 7: Symmetrical Components and Representation of Faulted Networks Overview", Accessed: Feb. 27, 2022. [Online]. Available: https://www.academia.edu/40853927/Chapter_7_Symmetrical_Components_and_Representation_of_Faulted_Networks_Chapter_7_Symmetrical_Components_and_Representation_of_Faulted_Networks_Overview

[16] "Analysis of Faulted Power Systems - Paul M. Anderson.pdf - Free Download PDF." https://kupdf.net/download/analysis-of-faulted-power-systems-paul-m-andersonpdf_5a4bd20ae2b6f5146bc199c4_pdf (accessed Mar. 03, 2022).

[17] "Transmission Lines: Parameters, Types & Theory | Electrical4U," *https://www.electrical4u.com/*. https://www.electrical4u.com/transmission-line-in-power-system/ (accessed Mar. 03, 2022).

[18] "cosas_lineas.pdf." Accessed: Apr. 17, 2022. [Online]. Available: https://www.unioviedo.es/pcasielles/uploads/proyectantes/cosas_lineas.pdf

[19] C. D. Gozon, "Power Systems Modelling and Fault Analysis..Theory and Practice-Nasser Tleis", Accessed: Feb. 24, 2022. [Online]. Available: https://www.academia.edu/38173740/Power_Systems_Modelling_and_Fault_Analysis_Theory_and_Practice_Nasser_Tleis

[20] "myCableEngineering.com > Impedance." https://mycableengineering.com/knowledge-base/impedance (accessed Mar. 05, 2022).

[21] "IEEE Std 81-2012, IEEE Guide for Measuring Earth R.pdf." Accessed: Apr. 25, 2022. [Online]. Available: http://bentoros.com/wp-content/uploads/2019/07/IEEE-81.pdf

[22] "IEEE Std 81-2012, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System," p. 86.

[23] M. K. Sachin Ranjit, "Survey on sequence impedance and distance protection in subtransmission system', 2018," University of southeast Norway.

[24] "info_iec60909-1{ed2.0}en_d.pdf." Accessed: Mar. 06, 2022. [Online]. Available: https://webstore.iec.ch/preview/info_iec60909-1%7Bed2.0%7Den_d.pdf

[25] "IEEE-Guide-for-Safety-In-AC-Substation-Earthing-Grounding.pdf." Accessed: Apr. 29, 2022. [Online]. Available: https://www.powerandcables.com/wp-content/uploads/2017/12/IEEE-Guide-for-Safety-In-AC-Substation-Earthing-Grounding.pdf

[26] "EMF-Portal | Effects of current on human beings and livestock - Part 1: General aspects." https://www.emf-portal.org/en/article/41979 (accessed Apr. 06, 2022).

[27] M. Lauglo, "Ground Fault Protection of Transmission Lines," p. 134.

[28] A. C. B. Alves, B. Alvarenga, and E. G. Marra, "On the Calculation of the Reduction Factor for Ground Resistance of Foot," p. 6.

[29] L. Šroubová, R. Hamar, and P. Kropík, “Arrangement of phases of double-circuit three-phase overhead power lines and its influence on buried parallel equipment,” *Trans. Electr. Eng.*, vol. 4, no. 3, pp. 80–85, 2015.

[30] S. Alyami, “Grid Grounding Calculations for a 132-KV Substation Using Soil Backfilling,” *IEEE Access*, vol. PP, pp. 1–1, Aug. 2019, doi: 10.1109/ACCESS.2019.2932447.

[31] “Electrical Grounding Requirements OSHAcademy Free Online Training.” https://oshatrain.org/courses/pages/electrical_grounding_requirements.html (accessed Jan. 17, 2022).

[32] “LTH-IEA-7216.pdf.” Accessed: Mar. 13, 2022. [Online]. Available: https://www.iea.lth.se/publications/Reports/LTH-IEA-7216.pdf

[33] A. L. Fredriksen, “Earth fault protection in isolated and compensated power distribution systems,” p. 124.

[34] M. Loos, “Single Phase to Ground Fault Detection and Location in Compensated Network’,” PhD Thesis, PhD thesis, Université Libre de Bruxells, 2014.

[35] “Resonant Grounding or Arc Suppression Coil Grounding,” *EEEGUIDE.COM*, Jun. 25, 2018. https://www.eeeguide.com/resonant-grounding/ (accessed Mar. 14, 2022).

[36] J. J. Kolak, “The Basics of Personal Protective Grounding,” *EC&M*, Jun. 01, 2010. https://www.ecmweb.com/maintenance-repair-operations/article/20900286/the-basics-of-personal-protective-grounding (accessed May 13, 2022).

[37] “Amokabel Norway AS,” *amokabel*. https://amokabel.com/en/a/amokabel-norway-as (accessed Apr. 20, 2022).

[38] “(18) (PDF) Transmission line transposition,” *ResearchGate*. https://www.researchgate.net/publication/224091506_Transmission_line_transposition (accessed Apr. 01, 2022).

[39] P. Kangasluoma, “MEDIUM VOLTAGE NETWORK RESIDUAL EARTH FAULT CURRENT ESTIMATION METHODS,” p. 97.

[40] J. Roberts, D. H. J. Altuve, D. D. Hou, and W. Usa, “REVIEW OF GROUND FAULT PROTECTION METHODS FOR GROUNDED, UNGROUNDED, AND COMPENSATED DISTRIBUTION SYSTEMS,” p. 40.

Appendices A

132kV Network Configurations - Given by Gunne J.Hegglid

Example Network .

Main Grid - 420 / 300 kV.

Bus MG420 - Short circuit infeed capacity 20 kA / Sk3 = 15.000 MVA.
Bus MG-300 - Short circuit infeed capacity 10 kA / 5000 MVA.

Transformers.		MVA	Un1	Un2	Ez (%)	Nup	Ndwn	dN	Loads	Un kV	MW	cosfi
MG420 bus 1	SD1-132 bus 3	600	420	132	14	16	16	1%	B	132	200	0.97
MG420 bus 1	MG300 bus 2	2000	420	300	5	0	0	0		300	150	0.97
MG300 bus 2	SD2-132 bus 8	200	300	132	13	16	16	1%	R-A	132	150	0.97
MG300 bus 2	SD3-132 bus 13	400	300	132	13	16	16	1%	R-B	132	200	0.97
MG300 bus 2	SD4-132 bus 19	250	300	132	13	16	16	1%	H	132	75	0.97

Lines			Un	Type	L	Q (FeAl) or conductor wire	Grd W or earth wire
1	SD1-132	FI	132	H	86	329	
2	FI	BD	132	H	25	253	No
3	SD1-132	KS	132	H	4	329	FeAl 150
4	KS	Mn	132	K	6	253	FeAl 120
5	Mn	SD2-132	132	D	14	150	FeAl 50
6	SD2-132	Ng	132	D	22	120	St 50
7	Ng	GfA	132	D	30	120	St 50
8	GfA	Åf	132	D	5	120	St 50
9	Åf	Sh	132	D	42	120	St 50
10	SD3-132	ÅmA	132	G	65	131	95
11	ÅmA	Ha	132	C	10	253	120
12	Ha	ÅmB	132	C	10	253	120
13	ÅmB	GfB	132	D	18	150	No
14	SD3-132	Nd	132	C	54	150	95
15	Nd	GfB	132	C	13	150	95
16	SD4-132	Kb	132	D	20	253	2 x 95
17	Kb	GfB	132	D	26	253	2 x 95

Data power plants.

	Transformer					Generator			
	Sn	Un1	Un2	ek	Connection	Sn	Un	xd'	Pmax
	MVA	kV	kV			MVA	kv	pu	
Fi 4	200	132	11	11%	Ynd	200	11	0.25	150
Åf 11	27	132	11	11%	Ynd	27	11	0.25	23
GfB 17	37	132	11	11%	Ynd	37	11	0.25	32
Ha 15	150	132	11	11%	Ynd	150	11	0.25	120
Nd 18	150	132	11	11%	Ynd	150	11	0.25	130
Kb 20	100	132	11	11%	Ynd	100	11	0.25	80
Sh 12	70	132	11	11%	Ynd	70	11	0.25	60

Appendices B

132kV Network Model

Grid: Summary Grid

Generation	=	520.00 MW	20.99 Mvar	520.42 MVA
External Infeed	=	268.30 MW	246.22 Mvar	364.15 MVA
Inter Area Flow	=	0.00 MW	0.00 Mvar	
Load P(U)	=	775.00 MW	194.23 Mvar	798.97 MVA
Load P(Un)	=	775.00 MW	194.23 Mvar	798.97 MVA
Load P(Un-U)	=	0.00 MW	0.00 Mvar	
Motor Load P	=	0.00 MW	0.00 Mvar	0.00 MVA
Losses	=	13.30 MW	72.97 Mvar	
Line Charging	=		-33.55 Mvar	
Compensation ind.	=		0.00 Mvar	
Compensation cap.	=		0.00 Mvar	
Installed Capacity	=	595.68 MW		
Spinning Reserve	=	75.68 MW		
Total Power Factor:				
Generation	=	1.00 [-]		
Load/Motor	=	0.97 / 0.00 [-]		

Figure B 1:Grid Summary

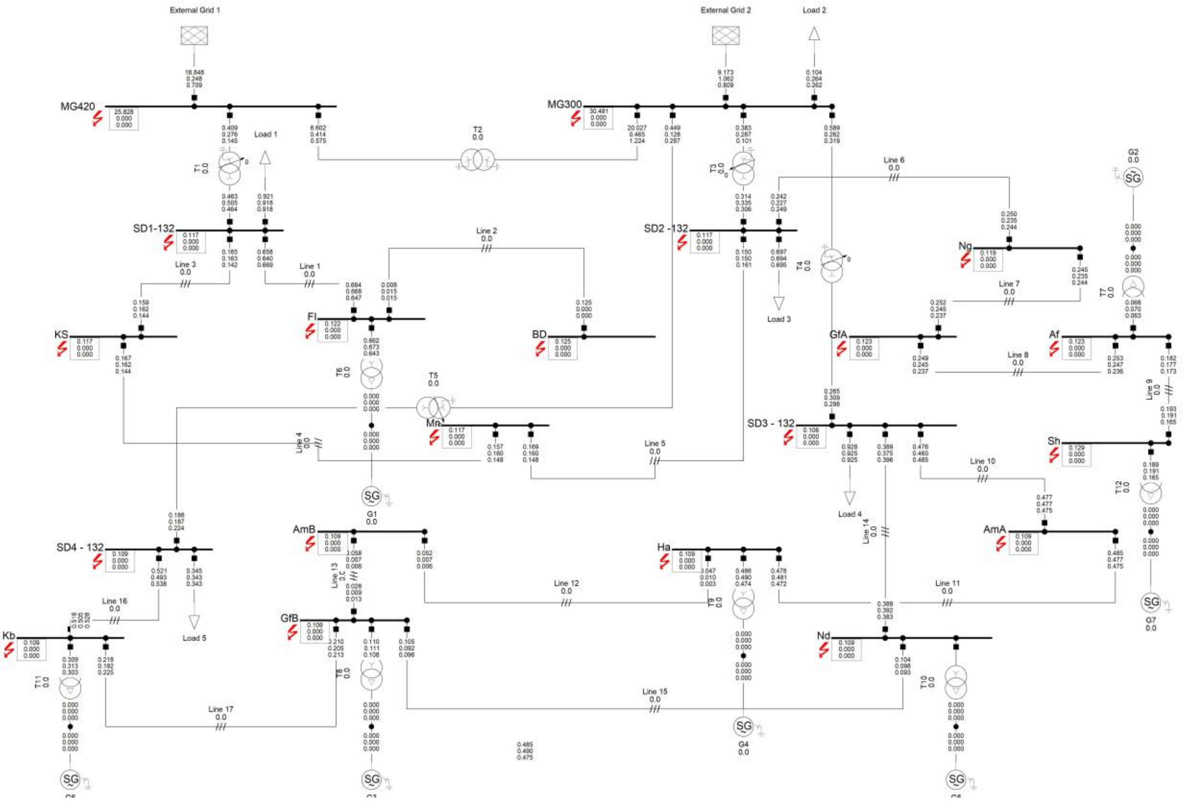


Figure B 2: Short circuit calculation

Table B 1: Maximum fault current of study network 1(red color) and study network 2 (green color).

Project(1) study Case, Complete'/ Max. Short-Circuit Currents

Break Time	Fault Clearing Time (Ith)
0.10 s	1.00 s
Resistance, Rf	Reactance, Xf
0.00 Ohm	0.00 Ohm

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
Af	Grid		132.000	A	0.000	0.000	1.000	9.388	0.123	91.512	0.123	91.501	0.272	0.123	0.202
				B	133.403	-148.384		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	134.028	152.703		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 - 132	Grid		132.000	A	0.000	0.000	1.000	8.282	0.109	91.394	0.109	91.394	0.290	0.109	0.252
				B	130.865	-148.490		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.933	151.851		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	9.797	0.129	93.219	0.129	93.195	0.297	0.129	0.296
				B	135.562	-146.334		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	136.360	155.199		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 2: Fault current after centralized compensated Peterson coil (radial network).

Project	Project(1)	
Study Case	Study Case	
Method	complete	
Single Phase to Ground	/ Max. Short-Circuit Currents	
Short-Circuit Duration	Break Time	Fault Clearing Time (Ith)
	0.10 s	1.00 s
Fault Impedance	Resistance, Rf	Reactance, Xf
	0.00 Ohm	0.00 Ohm

Use Selection

	Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)
58	Sh	Grid		132.000	A	0.000	0.000	1.000	0.243	0.003	-78.081
59					B	132.723	-145.245		0.000	0.000	0.000
60					C	132.717	154.716		0.000	0.000	0.000

Table B 3: fault current after centralized Peterson coil compensation (mesh network).

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
KS	Grid		132.000	A	0.000	0.000	1.000	8.932	0.117	88.565	0.117	88.565	0.305	0.117	0.206
				B	130.142	-151.385		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.200	148.829		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 - 132	Grid		132.000	A	0.000	0.000	1.000	0.540	0.007	87.428	0.007	87.428	0.019	0.007	0.016
				B	130.264	-148.308		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.272	151.714		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	9.797	0.129	93.219	0.129	93.195	0.297	0.129	0.296
				B	135.562	-146.334		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	136.360	155.199		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 4: Short circuit power of a distributed compensated Peterson coil.

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD1-132	Grid		132.000	A	0.000	0.000	1.000	0.218	0.003	-79.985	0.003	-79.985	0.008	0.003	0.006
				B	129.812	-151.178		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	129.813	148.818		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD2 -132	Grid		132.000	A	0.000	0.000	1.000	0.218	0.003	-80.996	0.003	-80.996	0.007	0.003	0.006
				B	128.782	-151.969		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	128.783	148.024		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	0.234	0.003	-75.167	0.003	-75.167	0.007	0.003	0.007
				B	132.724	-145.247		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	132.722	154.714		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 5: Fault current for a centralized direct grounding at the middle of the radial line.

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD3 -	Grid		132.000	A	0.000	0.000	1.000	8.088	0.106	90.140	0.106	90.139	0.281	0.106	0.236
				B	129.286	-149.864		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	129.349	150.374		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 -	Grid		132.000	A	0.000	0.000	1.000	8.282	0.109	91.394	0.109	91.394	0.290	0.109	0.252
				B	130.865	-148.490		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.933	151.851		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	85.843	1.126	-68.196	1.116	-68.148	2.604	1.117	2.584
				B	103.867	-137.900		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	108.079	144.533		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 6: fault current of a distributed direct grounding.

Terminal	Grid	Operation Scenario	Rated Voltage	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD3 - 132	Grid		132.000	A	0.000	0.000	1.000	8.088	0.106	90.140	0.106	90.139	0.281	0.106	0.236
				B	129.286	-149.864		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	129.349	150.374		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 - 132	Grid		132.000	A	0.000	0.000	1.000	8.282	0.109	91.394	0.109	91.394	0.290	0.109	0.252
				B	130.865	-148.490		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.933	151.851		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	216.354	2.839	-76.437	2.778	-76.138	6.562	2.783	6.465
				B	77.084	-110.476		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	71.093	122.237		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 7: fault current for an un-transposed network 1for a centralized Peterson coil grounding.

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD2 -132	Grid		132.000	A	0.000	0.000	1.000	0.435	0.006	-7.790	0.006	-7.790	0.014	0.006	0.012
				B	128.584	-151.914		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	128.785	147.916		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	0.459	0.006	-7.212	0.006	-7.212	0.014	0.006	0.014
				B	133.195	-145.368		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	132.676	154.876		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 8:fault current for a single ground fault at the end of a mesh study network 2(Unsymmetrical).

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD2 -132	Grid		132.000	A	0.000	0.000	1.000	9.088	0.119	85.189	0.119	85.189	0.297	0.119	0.249
				B	129.134	-152.115		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	129.465	148.031		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD3 - 132	Grid		132.000	A	0.000	0.000	1.000	0.620	0.008	68.360	0.008	68.360	0.022	0.008	0.018
				B	128.962	-149.720		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	128.832	150.308		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 - 132	Grid		132.000	A	0.000	0.000	1.000	0.647	0.008	69.068	0.008	69.068	0.023	0.008	0.020
				B	130.039	-148.270		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.309	151.609		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B 9: fault current for a directly grounded at the central station. (unsymmetrical).

Terminal	Grid	Operation Scenario	Rated Voltage (kV)	Phase	Fault Voltage (kV)	Fault Voltage Angle (deg)	c-Factor	Sk" (MVA)	Ik" (kA)	Ik" Angle (deg)	Ik. (kA)	Ik. Angle (deg)	ip (kA)	Ib (kA)	ib (kA)
SD3 - 132	Grid		132.000	A	0.000	0.000	1.000	8.150	0.107	88.986	0.107	88.985	0.284	0.107	0.238
				B	129.361	-149.851		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	129.287	150.394		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD4 - 132	Grid		132.000	A	0.000	0.000	1.000	8.334	0.109	89.898	0.109	89.898	0.292	0.109	0.254
				B	130.638	-148.453		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	130.975	151.747		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sh	Grid		132.000	A	0.000	0.000	1.000	86.603	1.136	-68.281	1.126	-68.241	2.627	1.127	2.606
				B	104.921	-138.166		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
				C	107.253	144.101		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000