AALBORG
UNIVERSITY

A MASTER THESIS REPORT

ON

“STUDY ON IMPACT OF LIGHTNING IN HYBRID CABLE – OVERHEAD LINES”

MASTER’S DEGREE

IN

ENERGY ENGINEERING

Submitted by

SHREYAS SANDEEP SABNIS (20211126)
VISHKHA JALAIK (20212013)

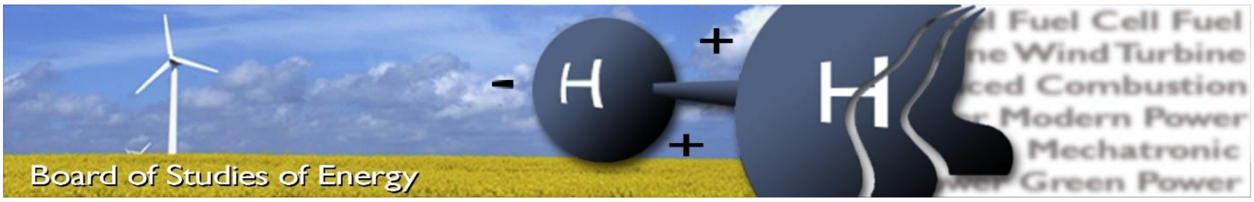
Under the guidance of

Filipe Miguel Faria da Silva
Hanchi Zhang
(AAU Energy)

DEPARTMENT OF ENERGY ENGINEERING

AALBORG UNIVERSITY

2023



Title : **Study on Impact of Lightning on Hybrid Cable – Overhead Lines**
Semester : **10th Semester M.Sc.**
Semester theme : **Electrical High Voltage and Power Systems (EPSH)**
Project period : **01/02/2023 – 02/06/2023**
ECTS : **30 ECTS**
Supervisor : **Filipe Miguel Faria da Silva**
Hanchi Zhang
Project group : **EPSH4 – 1032**

SYNOPSIS: According to historical data, most overhead transmission line faults are caused by lightning strikes. Lightning strikes account for majority of the line outages in many countries. Moreover, the increasing prevalence of hybrid cable – overhead line transmission systems means that lightning strikes on the overhead line can affect the underground cable and create over voltages in the system. To minimize the risk of over voltage in the system, it is important to study the behaviour of lightning transients and the methods to mitigate the impact of the same on the system. One method to do this is to choose an appropriate grounding arrangement for the overhead line and underground cable. The grounding configuration will have a big impact on the lightning performance of the transmission system. The objective of this thesis is to analyse various grounding scenarios for the overhead line shield wire and the underground cable sheath and based on the results draw a conclusion and select the most suitable grounding strategy to improve the lightning performance of the transmission system.

Shreyas

____

[Shreyas Sandeep Sabnis]

Vishakha Jalaik

____

[Vishakha Jalaik]

Pages, total: [60]
Appendix: [1]
Supplements: [0]

By accepting the request from the fellow student who uploads the study group's project report in Digital Exam System, you confirm that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism.

This page has been intentionally left blank

Table of Contents

Table of Contents iii
Preface v
Abstract vi
Nomenclature vii
List of Figures vii
List of Tables ix
List of Abbreviations ix
1 Introduction 1
1.1 A Case Study on the Danish power system 1
1.2 State of the art 2
1.2.1 Overhead Lines (OHL) 2
1.2.2 Underground Cables (UGC) 6
2 Problem Analysis 8
3 Problem Formulation 9
4 Methodology 11
5 Simulation Model 13
5.1 Transmission Line 13
5.2 Tower 14
5.3 Tower footing resistance 15
5.4 Cable 15
5.5 Lightning Source 16
5.6 Model limitations 17
5.6.1 Lightning source impedance 17
5.6.2 Surge impedance of tower 17
5.6.3 Footing impedance 17
5.6.4 OHL insulators 17
5.6.5 Line connector joints 17
5.6.6 Current attenuation in ground 18
6 Hybrid line during lightning on shield wire 19
6.1 Impact on Cable 20
6.1.1 Short circuit grounding method 20
6.1.2 Separate point grounding method 21
6.1.3 Different location grounding method 23
6.2 Impact on Overhead line 24
6.2.1 Short circuit grounding method 24
6.2.2 Separate point grounding method 25
6.2.3 Different location grounding method 25
6.3 Discussion on impact of grounding method on lightning performance 26
6.3.1 Maximum over-voltages 26

6.3.2 Impact of grounding location distance 27
6.3.3 Impact of cross-bonding of cables 29
6.4 Summary 32
7 Hybrid line during lightning on phase conductor 33
7.1 Impact on Cable 34
7.2 Impact on OHL 37
7.3 Discussion on impact of grounding method on lightning performance 39
7.3.1 Impact of grounding configurations on induced cable voltages 39
7.3.2 Impact of grounding configurations on induced OHL voltages 40
7.3.3 Impact of grounding location distance 40
7.3.4 Impact of cross-bonding of cables 42
7.4 Summary 43
8 Conclusion 44
8.1 Project summary 44
8.2 Future work 45
9 References 46
10 Appendix 48
10.1 Appendix A : Table for Expressions of the Striking Distance for different sources 48
10.2 Appendix B : Table for constants 48

Preface

This thesis has been prepared by EPSH – 1032 group of 4th Semester students in the Master's programme in Energy Engineering at Aalborg University. The topic of the project is "Study on Impact of Lightning on Hybrid Cable – Overhead Lines". The modelling, simulation and data analysis work has been carried out with the support of PSCAD.

We would like to express our gratitude to our supervisors at AAU Energy, Filipe Miguel Faria da Silva and Hanchi Zhang for their continuous guidance and assistance throughout this project.

Reading Guide

The reference style utilized in this report is the IEEE method meaning that the references will be marked in square brackets with the description at the end in the section marked "References". If the reference is placed at the end of the paragraph it is meant for the entire paragraph. If the reference is placed at the end of the sentence it refers to only the sentence. All the models, simulations and graphs are developed using PSCAD and Microsoft Excel. This report is submitted in digital PDF format.

Abstract

According to historical data, most overhead transmission line faults are caused by lightning strikes. Lightning strikes account for majority of the line outages in many countries. Moreover, the increasing prevalence of hybrid cable – overhead line transmission systems means that lightning strikes on the overhead line can affect the underground cable and create over voltages in the system. To minimize the risk of over voltage in the system, it is important to study the behaviour of lightning transients and the methods to mitigate the impact of the same on the system. One method to do this is to choose an appropriate grounding method for the overhead line and underground cable. The grounding configuration will have a big impact on the lightning performance of the transmission system. The objective of this thesis is to analyse various grounding scenarios for the overhead line shield wire and the underground cable sheath and based on the results draw a conclusion and select the most suitable grounding strategy to improve the lightning performance of the transmission system.

Nomenclature

List of Figures

Figure 1:1 : Electrical Power System [3] 1
Figure 1:2 : ACSR conductor cross section on the left and ACSR strands on the right [8]....................2
Figure 1:3 : Donau Pylon on the left and Eagle Pylon on the right [9]....................3
Figure 1:4 : XLPE Cable Construction [33]....................6
Figure 1:5 : Cross bonding in UGC [14] 7
Figure 2:1 Lightning in Cable - OHL configurations [6] 8
Figure 3:1 Grounding configuration ‘A’: ‘short circuit‘ 9
Figure 3:2 Grounding configuration 'B': ‘separate points’....................10
Figure 3:3 Grounding configuration 'C': ‘different locations’ 10
Figure 4:1 Lightning performance analysis: Study cases 12
Figure 5:1 Simulation Model....................13
Figure 5:2 Eagle Pylon Tower....................14
Figure 5:3 PSCAD Tower Model 15
Figure 6:1 Current in Shield wire and Sheath in case of fault on Shield wire....................19
Figure 6:2 Induced over voltages in shield wire and cable sheath 19
Figure 6:3 Overvoltage and current in cable: Lightning|Shield wire; Grounding Configuration|Short circuit; Sheath|both-end bonded....................20
Figure 6:4 Overvoltage and current in cable: Lightning|Shield wire; Grounding Configuration|Short circuit; Sheath|cross bonded....................21
Figure 6:5 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| ‘separate points’ ; Sheath| Both end bonded 22
Figure 6:6 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| ‘separate points’; Sheath| cross bonded....................22
Figure 6:7 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| ‘different location’ ; Sheath|Both end bonded 23
Figure 6:8 Ground potential and voltage induced in sheath at junction....................23
Figure 6:9 Sheath voltage and current in cable at the location of grounding in ‘different location’ grounding method 24
Figure 6:10 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire. Grounding method| Short circuit....................24
Figure 6:11 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire. Grounding method| ‘separate point’....................25
Figure 6:12 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire....................25
Figure 6:13 Comparison of maximum phase over voltage in cable at the junction point: Lightning|Shield wire 26
Figure 6:14 Comparison of maximum upper phase over voltage in OHL at tower 2 and 3: Lightning|Shield wire 27
Figure 6:15 Voltage in Shield wire when lightning strikes....................27
Figure 6:16 Impact of grounding location on OHL....................28
Figure 6:17 Impact of grounding location on Cable at Junction....................28
Figure 6:18 Impact of grounding location on Cable....................29
Figure 6:19 Sheath current and voltage change with distance 29
Figure 6:20 Impact of cross-bonding: Grounding method| Short circuit 30
Figure 6:21 Impact of cross-bonding: Grounding method| ‘separate points’....................30
Figure 6:22 Impact of cross-bonding: Grounding method| ‘different locations’ 31

Figure 6:23 Impact of cross-bonding on cable voltages: Grounding method| Short circuit 31
Figure 7:1 Current propagation and induced voltages during lightning strike on phase conductor 34
Figure 7:2 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| Short circuit 34
Figure 7:3 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| 'separate points' 36
Figure 7:4 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| 'different locations'..36
Figure 7:5 Induced over voltages and current at Tower 2 and tower 3 for different grounding configuration: lightning| Phase conductor 38
Figure 7:6 Comparison of maximum phase over voltage in cable at the junction point: Lightning| Phase conductor...39
Figure 7:7 Variation of sheath voltage in different grounding schemes: Lightning| Phase conductor 39
Figure 7:8 Comparison of maximum upper phase over voltage in OHL at tower 2 and 3: Lightning| Phase conductor...40
Figure 7:9 Impact of grounding location distance on OHL induced voltages: Lightning| Phase conductor.40
Figure 7:10 Impact of grounding location distance on cable at junction: Lightning| Phase conductor 41
Figure 7:11 Impact of grounding location distance on cable: Lightning| Phase conductor 41
Figure 7:12 Impact of cross-bonding: Grounding method| Short circuit, Lightning| Phase conductor.......42
Figure 7:13 Impact of cross-bonding: Grounding method| 'separate point' s, Lightning| Phase conductor 42
Figure 7:14 Impact of cross-bonding: Grounding method| 'different location' s, Lightning| Phase conductor 43

List of Tables

Table 5:1 OHL Parameters 13
Table 5:2 Cable Parameters 15
Table 5:3 Lightning Source 16
Table 7:1 Time instance of maximum over voltages 35

List of Abbreviations

ACSR	Aluminium conductor, steel reinforced
BFR	Back flashover rate
BIL	Basic Insulation Level
CFO	Critical flash over
HVDC	High voltage direct current
OHGW	Overhead ground wire
OHL	Overhead Line
SFFOR	Shielding failure flashover rate
SFR	Shielding failure rate
UGC	Underground cable
XLPE	Cross linked polyethylene

This page has been intentionally left blank

1 Introduction

The classic configuration model of power systems (Figure 1:1) consists of networks suited for different levels of application. These levels are generation, distribution, and transmission [1]. The focus of this thesis is primarily on transmission systems. The transmission line is usually shielded by one or more overhead ground wires (OHGWs) also known as a shield wire, at least for a short distance from a substation [2].

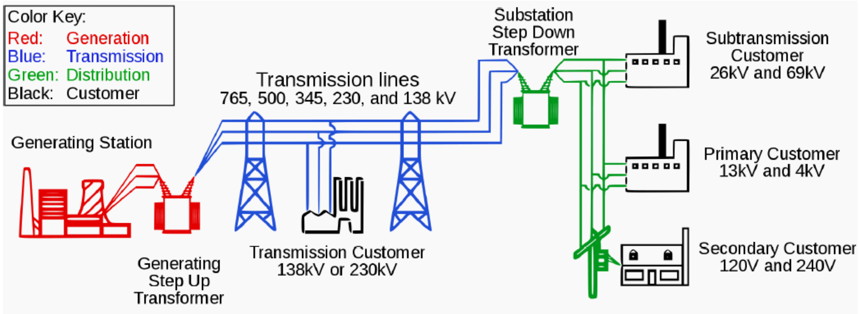


Figure 1:1 : Electrical Power System **[3]**

1.1 A Case Study on the Danish power system

The Danish power system, like other power systems worldwide, is undergoing a transformation from a system dominated by conventional power sources to a system incorporating different power generation sources of various sizes and technologies, including renewable energy sources such as wind power and photovoltaics. The 400 kV transmission grid serves as the backbone of the power system, allowing transportation of large quantities of energy across the country reliably, economically, and efficiently [4].

For this purpose, plans by the Danish National Transmission System Operator, Energinet, are aimed at establishing increasingly more 400 kV transmission lines [5]. However, due to concerns from the Danish Environmental Protection Agency and the local residents from the affected areas regarding the environmental impacts of the projects, various other alternatives were discussed involving the use of underground cables to address the concerns. The overall conclusion was to use a 400 kV system mainly comprising of overhead lines but with a limited extent of underground cabling. This solution gives rise to a hybrid OHL-cable setup in certain areas with such geographical limitations [4].

Alternative solutions such as the use 150 kV or 220 kV cables, HVDC-connections, offshore connections, and gas-insulated transmission lines all involve significant risks and fail to meet Denmark's requirements for energy transport [4]. Thus, these solutions do not constitute alternatives to the implementation of the current projects in Western and Southern Jutland as 400 kV overhead lines [4]. Similar problems regarding choice of power system configuration could also arise in power systems in other parts of the world as hybrid OHL – cable networks are becoming more common.

1.2 State of the art

1.2.1 Overhead Lines (OHL)

Overhead lines are universally used to transmit electrical energy in high-voltage transmission systems [6]. An overhead transmission line consists of conductors, insulators, support structures (also called pylons) and, in most cases, shield wires.

The most common conductor metal for overhead transmission lines is aluminium, which has replaced copper owing to technical, economic, and ecological aspects [7]. The conductors are often stranded together which creates a steel reinforced aluminium conductor, also known as ACSR (Aluminium Conductor, Steel Reinforced) (Figure 1:2). Stranded conductors while easier to manufacture, are also easier to handle as they are more flexible than solid conductors, especially in larger sizes. They are also better for heat dissipation as the thinner wires in stranded conductor contain air gaps and greater surface area with the individual strands and have a high strength-to-weight ratio due to the use of steel strands. Conductors are also often transposed to eliminate unbalanced flux linkages and balance the line by exchanging conductor positions along the line [7]. A 400 kV ACSR conductor would contain 54 number of aluminium strands and 7 number of steel strands [8].

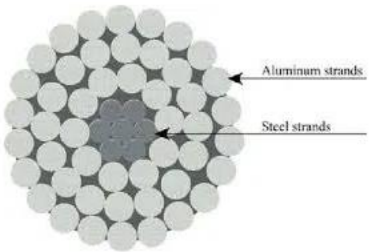


Figure 1:2 : ACSR conductor cross section on the left and ACSR strands on the right **[8]**

Insulators for transmission lines are typically suspension type insulators, that consist of a string of discs constructed of porcelain, toughened glass, or polymer [7]. In order to protect overhead transmission lines against lightning shield wires are used. The shield wires are placed on top of the pylons in order to attract the lightning strokes and prevent the lightning from directly terminating on the phase conductors. The geometry and thereby the placing of the shield wires have significant influence on their capability to protect the phase conductors (shielding effects) and in the overall lightning performance of the overhead line [9].

There can be various types of overhead transmission line pylons. The choice of the pylon can depend on the transmission voltage, better technical solution in terms of lightning performance, or simply design, among other factors [9]. The two common types of pylons used in Denmark are the Eagle and Donau pylon (Figure 1:3).

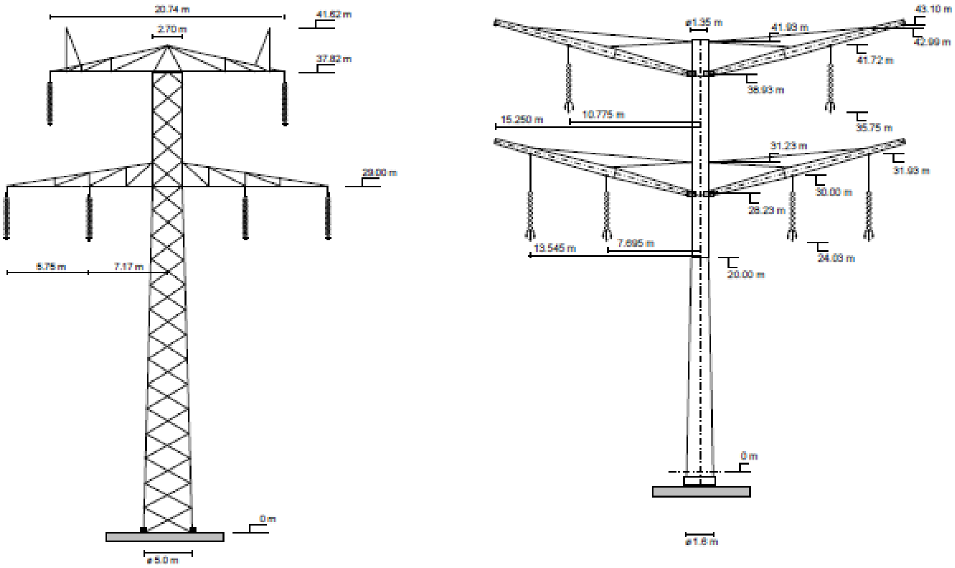


Figure 1:3 : Donau Pylon on the left and Eagle Pylon on the right **[9]**

From an analysis performed for both types of pylons, it was concluded that Eagle Pylon has a better lightning performance than the Donau Pylon. Hence for the modelling of this project, the Eagle Pylon will be used [9]. Also, thereafter overhead transmission lines will be abbreviated as OHL.

1.2.1.1 Modelling of OHL

In order to model an OHL, it is convenient to represent the terminal characteristics by an equivalent model. Traditionally, the transmission line models can be classified into two categories: lumped parameter π section models and travelling-wave models. The most common types of π section models are the nominal – π model and the equivalent – π model. The nominal – π model can be used for medium length lines, typically ranging from 25 to 250 km, by lumping the total shunt capacitance and locate half at each end of the line. The equivalent – π model is used for longer lines [7].

The π section models consider both mutual and self-resistances, inductances and capacitances at a single frequency but do not consider the propagation of the transmission line. For consideration of consider transmission line propagation, travelling wave models, also known as distributed-parameter models are used. The most common types of travelling wave models are constant parameter model and frequency-dependent parameter transmission line models. The first type of model represents the transmission line in the modal domain, and the parameter is calculated at a single frequency, so this model can only be applied within a very limited bandwidth. The most accurate model type for transient simulation is the second type of model which represents the transmission line by considering the frequency-dependence nature when calculating its parameters [10].

Hence for this thesis, to model and simulate the transmission system for lightning transient performance study, the frequency-dependent model of PSCAD will be used.

1.2.1.2 Grounding of OHL

Direct lightning strikes to OHL yields overvoltage across insulator strings that might result in electrical discharges and faults. Lack of shield wires or shielding failure can result in flashover across the insulator [11]. Direct lightning strikes to the shield wire or pylon can also cause a potential rise of the tower to a value where the insulator string can no longer withstand the voltages between the tower and the phase conductor resulting in a back flashover [9]. Tower footing electrodes are an important means of grounding the transmission line and can influence the lightning performance of the OHL. Tower footing grounding impedance plays a major role in the lightning performance and reducing this value is an effective practice to reduce back flashover probability [11]. As considered in [12], for an analysis of 230 kV lines, the reduction of tower footing grounding impedance from 80 Ω to 10 Ω corresponds to a reduction of at least 66% on the amplitude of lightning overvoltage. The grounding impedance can also be reduced by increasing the electrode length. However, grounding impedance gets saturated at a certain electrode length. Effective electrode length increases with increasing soil resistivity and decreasing current front time [11].

1.2.1.3 Lightning Study on OHL

The geometric model is the most common method used to analyse lightning performance of OHL. It is based on the simplified model of the last step of a lightning stroke and was first proposed by C.F. Wagner and A.R. Hileman in 1961. This section describes the methods to calculate the Shielding Failure Rate (SFR), Shielding Failure Flashover Rate (SFFOR) and Back Flashover Rate (BFR).

- *Striking Distance*

The shield wires do not always protect the conductors from a direct stroke, which can result in shielding failure. When a downwards leader is approaching the OHL from a charged cloud, upwards leaders will be launched from ground wires and phase conductors. If an upwards leader from a ground wire reaches the downwards leader, the lightning will terminate on the shield wire. The length of the upwards leader from the conductor is defined as the striking distance [9]. The largest current that can terminate on the phase conductor is defined as the maximum shielding failure current (I_{MSF}), which is as follows [9],

$$I_{MSF} = \left[\frac{\gamma \cdot \frac{h+y}{2}}{A(1-\gamma \cdot sin\alpha)}\right]^{1/B} \qquad \text{Equation 1.2.1}$$

Where, ϒ = Propagation constant (m-1)

h = Height of the shield wire from the ground (m)

α = Angle of the shield wire from the phase conductor

A and B are constants, the values for which can be obtained from Appendix A : Table for Expressions of the Striking Distance for different sources

- *Lightning Ground Flash Density*

The number of lightning strikes to the OHL in a certain area during a period of one year is called its lightning ground flash density.

- *Shielding Failure Rate (SFR)*

SFR is the number of strokes that will strike the line and a phase conductor, resulting in shielding failure.

- *Critical Current*

The critical current (I_c) is the lightning stroke current that will cause a flashover of the insulators. I_c is determined from the characteristic impedance of the line and the critical flashover voltage of the tower insulators and is defined as follows [9],

$$I_c = \frac{2CFO}{Z_c} \qquad \text{Equation 1.2.22}$$

Where, CFO = Critical flashover voltage (V)
Z_c = Surge impedance of the line (Ω)

- *Shielding Failure Flash Over Rate (SFFOR)*

The SFR is the number of strokes that will strike the line and a phase conductor, resulting in shielding failure. This may however mean that not all lightning strikes will cause flashover. The number of strokes that result in flashover of the insulation is called shielding failure flash over rate.

- *Back flashover Rate (BFR)*

When lightning strikes the shield wires or the pylon, a part of the current is forced down the pylon to the ground and the other part is divided into two which enters the shield wires in each direction. The potential of the pylon will rise due to this as compared to the phase voltage and there will be a voltage build up across the insulator. When the potential difference between the pylon and the phase conductor reaches a value that the insulator can no longer withstand, a back flashover can occur [9]. The calculation of the BFR is an iterative process which is beyond the scope of this project and hence will not be discussed further in detail.

1.2.2 Underground Cables (UGC)

Underground cables are commonly used in low- and medium-voltage urban distribution networks. Because of their high cost, and the technical problems associated with the capacitive charging current, high-voltage underground cables are typically only used under special circumstances such as in densely populated urban areas, wide river crossings, undersea transmission, or areas of major environmental concern [6].

The most common type of underground cables used today for power systems with nominal voltages of 110 kV and above are called XLPE (cross-linked polyethylene) insulated cables. The cable conductors are made of either aluminium or copper [13]. Modern XLPE cables consist of a solid cable core, a metallic sheath, and a non-metallic outer covering. The cable core consists of the conductor, wrapped with semiconducting tapes, the inner semiconducting layer, the solid main insulation, and the outer semiconducting layer. These three insulation layers are extruded in one process. The conductors are either round stranded of single wires or additionally segmented in order to reduce the current losses [14]. Hereafter, underground cables shall be abbreviated as UGC.

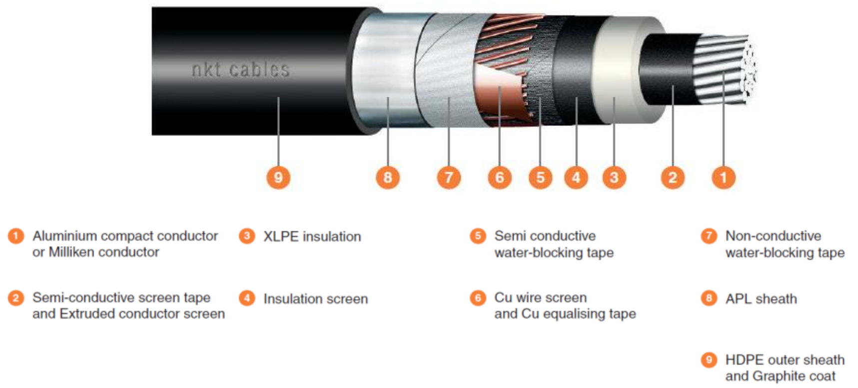


Figure 1:4 : XLPE Cable Construction **[33]**

1.2.2.1 Modelling of UGC

For the modelling of UGC, values of characteristic parameters like shunt capacitance and series impedance can be quite different from OHL. The per-unit-length charging current can also be as high as 30 times more than an OHL, which implies that charging current in the cable becomes a critical parameter which needs to be considered for underground cables. The charging current barrier is the main obstacle for the long length practical application of AC cables in power transmission networks [6] [15].

1.2.2.2 Grounding of UGC

High voltage cables have a metallic sheath, along which circulating current cause a voltage to be induced as a function of the operating current. In order to handle this induced voltage, both cable ends have to be bonded sufficiently to the earthing system. The 3 types of bonding methods are described in the table below [14],

Earthing Method	Typical Application
Single-end bonding	Usually for circuit lengths up to 10 km
Both-end bonding	Substations and short connections
Cross bonding	Long distance connections where joints are required

- Single-end bonding

One end of the cable sheath is connected to the system earth, so that at the other end ("open end") the standing voltage appears, which is induced linearly along the cable length. If the cable length becomes too long there can be an overvoltage at the open end. Since, there is no closed loop in such a bonding, circulating currents can be avoided [14].

- Both-end bonding

Both ends of the cable sheath are connected to the system earth. With this method no standing voltages occur at the cable ends, which makes it the most secure regarding safety aspects. However, since grounding both ends create a closed loop, circulating currents may flow in the metallic sheaths. These circulating currents are proportional to the conductor currents and therefore reduce the cable ampacity significantly [14].

- Cross bonding

A cross bonded system consists of three equal sections with cyclic sheath crossing after each section. The termination points are solidly bonded to earth. This method is applied for long route lengths of cable. Ideally, the three sections are equal and circulating currents in the metallic sheaths are reduced to zero so that no residual voltage occurs. In this method sheath losses can be kept very low without impairing safety. Very long routes can ideally contain multiple cross bonding sections in a row. The figure shows a cross bonded section of an UGC [14].

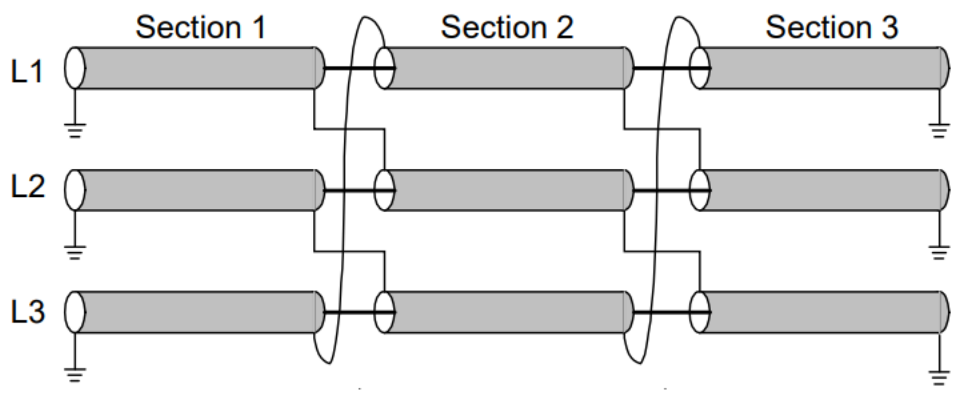


Figure 1:5 : Cross bonding in UGC **[14]**

2 Problem Analysis

According to the historical data, most overhead transmission line faults were caused by lightning strikes. In fact, lightning strikes account for majority of the line outages in different countries of the world like Venezuela [16], Poland [17] [18], China [19], and Malaysia [20]. Therefore, lightning activity is one of the essential parameters which should be considered during overhead transmission line design [21]. Also, considering the fact that construction of new overhead lines is very difficult in many countries due to public opposition, cables are often used for populated zones or areas of high beauty as discussed previously. This results in the hybrid cable – overhead line link where multiple transitions between cable and overhead line may occur. In case of lightning, the lightning surge hitting the shield wire of the tower may propagate from the overhead line into the cable stressing the latter Figure 2:1. The wave propagation speed is dependent upon the geometry of the line.

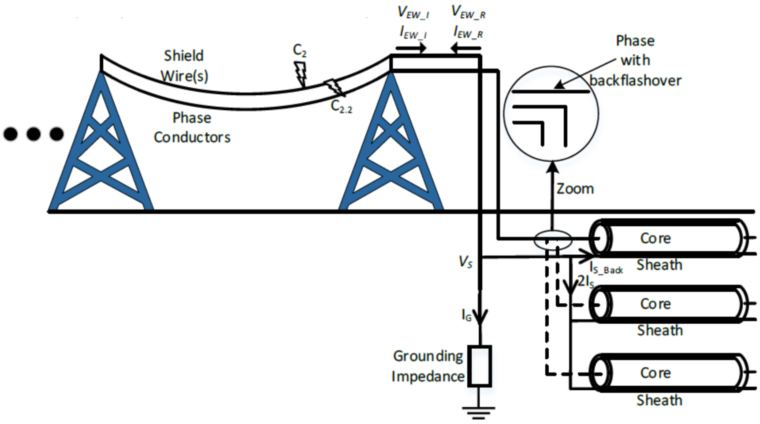


Figure 2:1 Lightning in Cable - OHL configurations **[6]**

In the case of lightning hitting the shield wire of the tower (Case C2 in the Figure 2:1), some of the energy will propagate in the shield wire, some to the ground via towers, some to the cable's sheaths and some to the common cable-tower grounding point. Due to electromagnetic coupling between phase conductor and sheath, voltage gets induced in the phase conductor of the cable. When the wave encounters a discontinuity point in the line i.e., the point where surge impedance changes (for example from OHL to Cable, Cable to OHL etc.), part of the wave travels through and part of the wave is reflected back [22], [23]. These reflected waves rise to the over-voltages in the transmission line.

To minimize the risk of over voltage in the system, it is important to choose an appropriate grounding method for the overhead line and underground cable. The grounding configuration will have a big impact on the lightning performance of the transmission system. Moreover, literature review of existing research suggests that lightning performance study on hybrid transmission lines are lacking in considering different grounding scenarios for grounding of the shield wire and cable sheath [19], [21] [24], [25], [26]. Considering these scenarios and the increasing prevalence of hybrid cable – overhead lines, it is therefore important to bridge this research gap by studying the performance of the hybrid line in case of lightning hitting the ground conductor (shield wire) of the tower and the propagation of the surge considering different configurations alike the ones described previously and based on the results discuss the advantages and disadvantages and suggest guidelines for improvement in the lightning performance.

The analysis of lightning performance on transmission systems is a very broad topic. It involves the study of lightning performance on transmission lines in the case of lightning occurring on the overhead line and well as the event of lightning occurring on the ground which can directly impact the underground cable. However, for the sake of this thesis, the topic is narrowed down to lightning only on the transmission line and the subsequent impact of various grounding systems on the lightning performance of the transmission system.

As discussed previously, due to the increasing prevalence of hybrid cable – overhead line configurations in the transmission system, this thesis also considers a similar transmission system layout for further analysis on how the lightning on overhead lines will affect the underground cable. The grounding of OHL and UGC system will have huge impact on the lightning current propagation in the hybrid line. Furthermore, it will be analysed how using different grounding methods for the tower, shield wire and cable sheath will affect the hybrid line and in what capacity. As current travels through grounding system back into the sheath, the grounding methods would have significant impact on the induced over-voltages. The connection between the overhead line and the cable can be carried out in various configurations. There can be various ways to ground the overhead line and underground cable at junction point. These grounding configurations are briefly explained below,

A. **Short circuit:** In this configuration, both overhead line and cable section are grounded at the junction. The ground wires and cable sheaths are short circuited and grounded at the same location. The method is shown in Figure 3:1, where G1 and G2 are two shield wires and G3 is the short - circuited cable sheath lead.

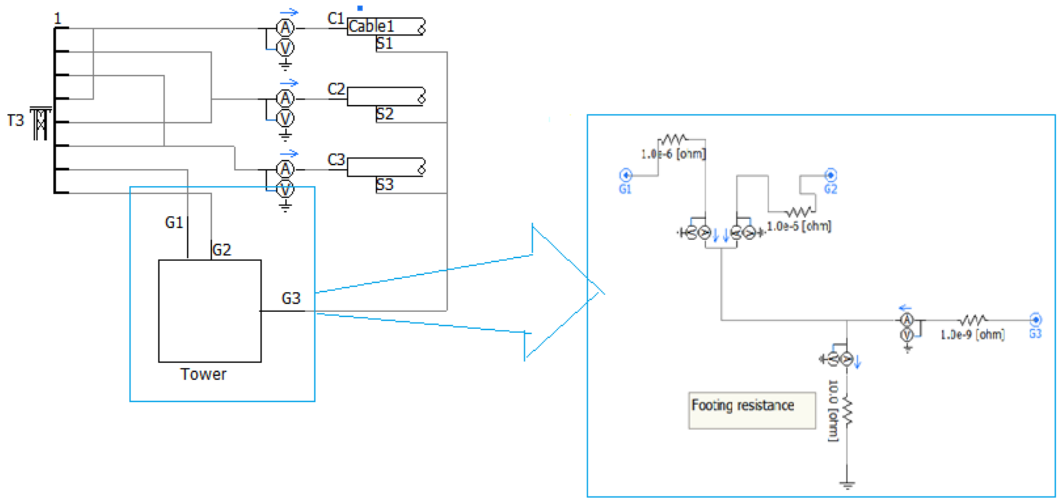


Figure 3:1 Grounding configuration ‘A’: ‘short circuit‘

B. Separate points: In this configuration, both overhead line and cable section are grounded at the junction point as well, but the cable sheath and ground wires are not short circuited. Both are grounded at ‘separate points’ at the junction.

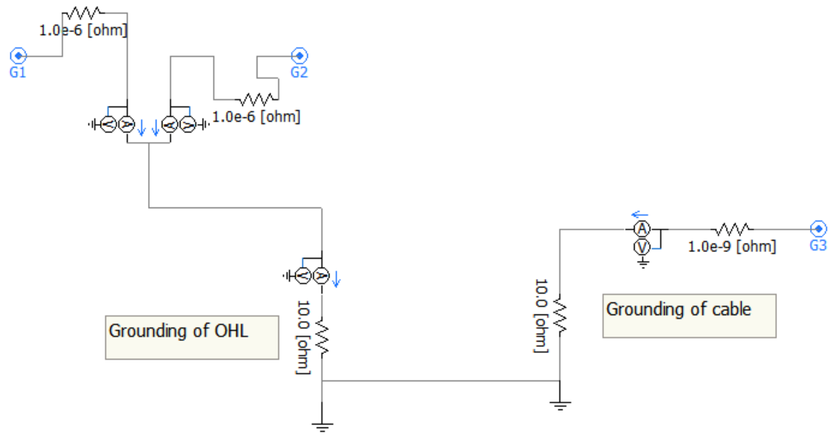


Figure 3:2 Grounding configuration 'B': ‘separate points’

C. Different location: In this grounding configuration, only OHL is grounded at the junction point. Grounding of cable sheath is done at some distance away from the junction point.

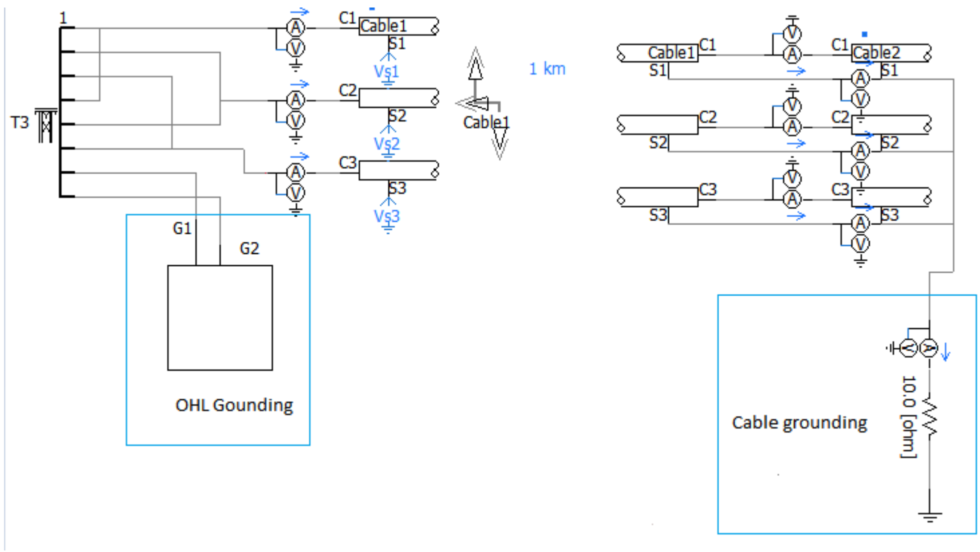


Figure 3:3 Grounding configuration 'C': ‘different locations’

Based on this study, the problem statement for this thesis is formulated as,

“Analysis of grounding configurations and their impact on lightning performance of hybrid cable – overhead lines”

4 Methodology

In the project lightning performance of hybrid OHL-UGC line is analysed based on following three parameters:

- Lightning location
- Cable sheath configuration
- Grounding method

Two type of lightning phenomenon has been considered:

- Lightning on shield wire
- Lightning on phase conductor

Three type of grounding method i.e., *'short circuit'*, '*separate point'* and '*different location'* (refer to Chapter 3) has been considered. The induced voltages and current in the hybrid line are evaluated for each grounding system under the mentioned lightning scenarios and a comparison is drawn among the three different grounding methods to analyse the impact of grounding scheme on lightning performance of the line. Furthermore, two type of models for cable has been used i.e., both-end bonded model and cross bonded model. A comparison is drawn between two models to analyse the impact on lightning performance of the line.

Figure 4:1 shows the various cases that has been studied throughout the course of the project.

Figure 4:1 Lightning performance analysis: Study cases

5 Simulation Model

The simulation has been done in PSCAD software. This section presents the modelling of various hybrid transmission line components in PSCAD. For the course of the project a hybrid line with 300 km overhead line and 20 km cable section has been considered. Figure 5:1 shows the hybrid line model used for simulation.

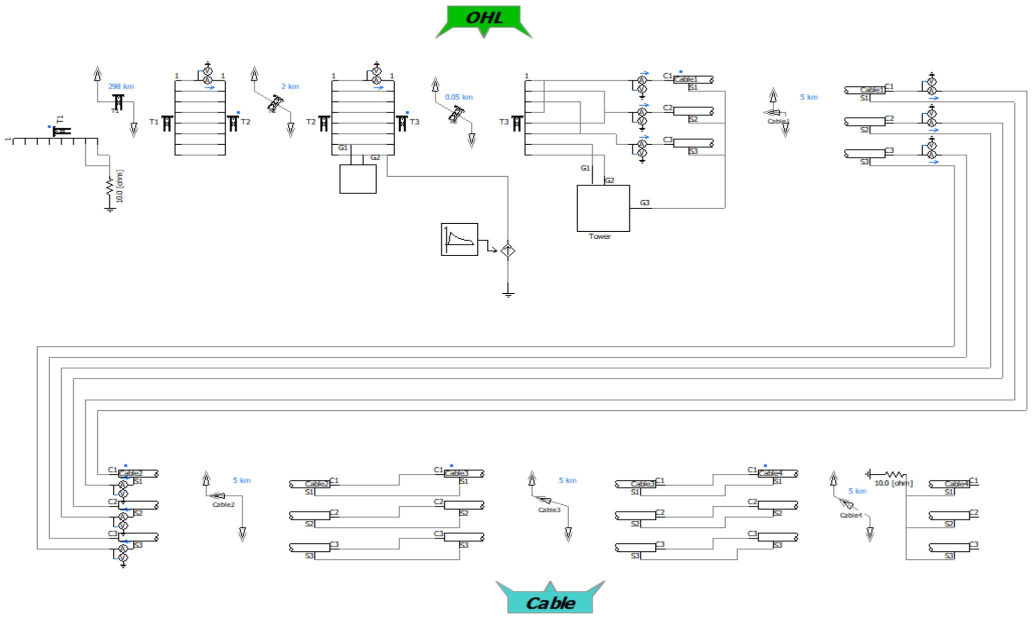


Figure 5:1 Simulation Model

5.1 Transmission Line

A double circuit Overhead transmission line has been modelled using Frequency dependent Model. Table 5:1 presents the parameters of the OHL. The OHL section is divided in to three parts with each part of length 298 km, 2 km, and 0.05 km.

Conductor cross-section	795 Kcmil
Aluminium cross-section	403.77 mm²
Conductor cross-section	431.60 mm²
Number of aluminium wires	45
Diameter of aluminium wires	3.38 mm
Number of steel wires	7
Diameter of steel wires	2.25 mm
Diameter of steel core	6.75 mm
Conductor diameter	27.03 mm
Grease	Optional
Max. DC resistance of the conductor at 20°C	0.0718 Ohm/km

Table 5:1 OHL Parameters

5.2 Tower

For transmission towers, Eagle pylon configuration has been considered as it provides better Lightning performance [9]. Figure 5:2 shows the geometry of the Eagle pylon tower. In PSCAD, tower body has been modelled as transmission line Bergeron model using tower surge impedance and travel velocity. Tower surge impedance has been calculate using Sargent & Daverniza equation [27].

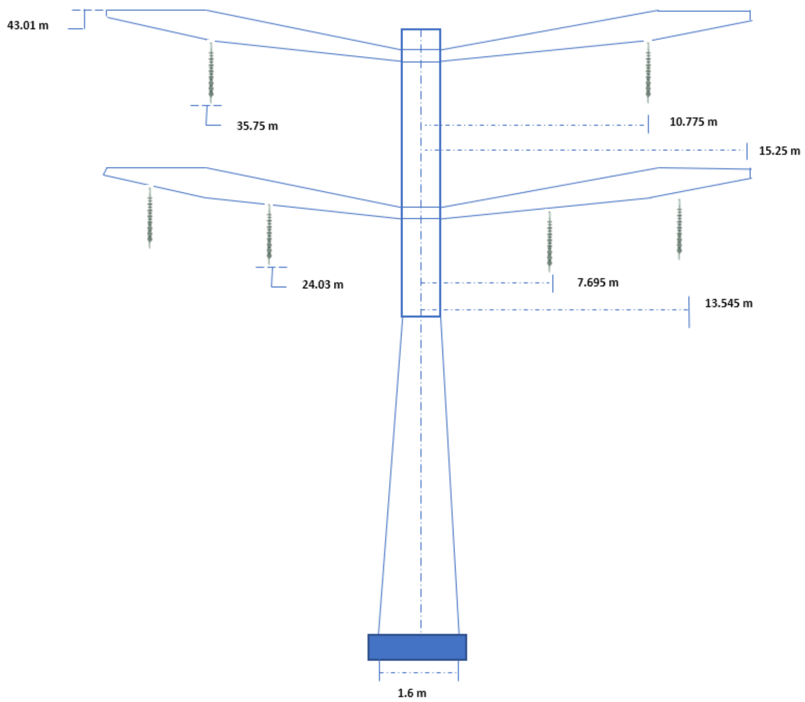


Figure 5:2 Eagle Pylon Tower

The equation is as follows:

$$Z_s = 60 \mathrm{l} \ln\left(\sqrt{2} \cdot \frac{\sqrt{h^2+r^2}}{r}\right) \qquad \text{Equation 5.2.1}$$

Where, h is the height of the tower and r is the radius. The calculated surge impedance is 260 ohms.

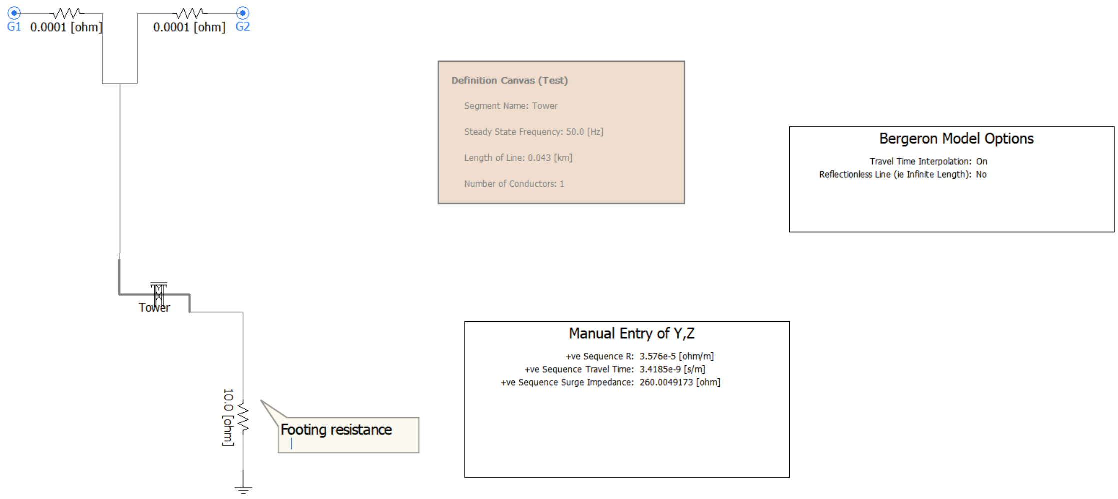


Figure 5:3 PSCAD Tower Model

The propagation speed of wave is considered to be 85% of the speed of light [24]. To take into the account of influence of adjacent towers, tower till 2 km distance away from the strike zone has been modelled, as the tower at later distance does not have significant impact on the over voltages [28].

5.3 Tower footing resistance

The tower footing resistance can be presented as a variable resistance depending on soil ionization and current or as a constant resistance. For this project tower footing resistance has been modelled as constant 10-ohm resistor [29]. The soil resistivity has been considered to be 100-ohm meter [30].

5.4 Cable

The transmission cable has been modelled using Frequency Dependent Model in PSCAD. The cable parameter considered are presented in Table 5:2 [31]. The cable has been modelled as four sections of length 5 km.

Cable configuration - Cable constants Coax cable data	
Input parameters	**Installed values**
Depth of cable	1.3 m
X position of cable	there are 0.3 m between the phases
Cable configuration	C1-I1-C2-I2
	Last metallic layer is not grounded
C1 inner radius	0 m
C1 outer radius	21.6 mm
C1 resistivity	$3.4567 \cdot 10^{-8}\ \Omega m$
C1 relative permeability	1
I1 outer radius	51.02 mm
I1 relative permittivity	2.7588
I1 relative permeability	1.0385
C2 outer radius	53.41 mm
C2 resistivity	$5.66 \cdot 10^{-8}\ \Omega m$
C2 relative permeability	1
I2 outer radius	57.71 mm
I2 relative permittivity	2.5
I2 relative permeability	1

Table 5:2 Cable Parameters

Following two type of cable configuration has been considered for analysis:

- Both ends bonded
- Cross bonded

5.5 Lightning Source

The tower top voltages are highly dependent upon the wave-front parameters of the lightning wave. The maximum voltage across tower occurs when rate of change of lightning current is highest, whereas maximum voltage across ground electrodes is seen at the peak of the lightning current. Thus, accurate wave front modelling is an essential component to determine lightning over voltages in the system. For the course of the project standard lightning has been modelled as a current source with standard IEEE waveform with wave front and tail time of 1.2 and 50 µs [24]. Two types of Lightning scenario have been considered:

- Lightning on shield wire
- Lightning on Phase conductor due to shielding failure

In case of Lightning on shield wire a standard Lightning waveform with peak current amplitude of 150 kA has been considered [32]. In case of shielding failure, lightning current with peak amplitude of 9.6 kA has been considered, which is the maximum shielding failure current for Eagle pylon tower [9].

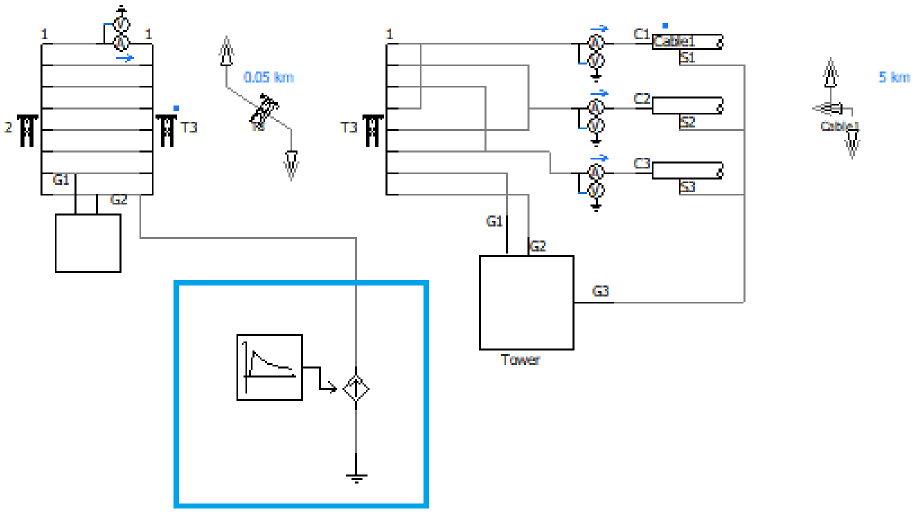


Table 5:3 Lightning Source

5.6 Model limitations

This section presents the limitation of the project owing to the various simplification that has been done in the simulation model. The implications of simplifications on model accuracy have been briefly explained.

5.6.1 Lightning source impedance

The lightning channel impedance has not been considered during modelling and lightning source is modelled as an ideal current source. The lightning channel impedance is dependent on the peak current of the return stroke. The estimated values for channel impedance lies in the range of 460 Ω to 9000Ω [24], which is significantly higher than the grounding impedance of transmission line. Thus, this shall not have major impact on accuracy of the model.

5.6.2 Surge impedance of tower

In the tower model, the surge impedance of the cross arms of the tower has not been considered. As the discontinuity point will be created at tower body and cross arm junction, thus reflected and refracted voltage values shall change. The overall values would be lesser as compared to what is observed in the project.

5.6.3 Footing impedance

Frequency dependency of the footing impedance has not been considered in the model. At high frequencies, impedance can be inductive (impedance increases) or capacitive (impedance decreases) based upon the size and soil parameters. As lightning current reaches the ground, it disperses in the arear around the soil in form of conducting channels, decreasing the soil resistivity. This results in increasing the effective radius of the earth electrodes, which in turns decreases the electrode impedance. Soil resistivity and permittivity values decreases with higher frequencies, thus the ground potential value in the simulation model will be higher than that in real life [24].

5.6.4 OHL insulators

The OHL insulators have not been modelled in the simulation model. The line insulators are generally modelled as capacitors having capacitance values in pF. The presence of insulators has an impact breakdown strength, however in the project back flashover scenario has not been considered. Due to low capacitance values, there shall not significantly impact the voltages observed during lightning scenarios.

5.6.5 Line connector joints

The mid span joints and as well as transition joints has not been modelled. The overall impedance of joints is much lesser than that of line impedance, thus they shall not a significant impact on overall voltage profile during lightning strike.

5.6.6 Current attenuation in ground

In the model, an ideal ground has been considered, which does not consider the distribution of current in ground at different grounding locations. As the current wave reaches the ground it breaks down into various conducting channels, travelling across the grounding electrodes. Thus, grounding current at 'different location' s would have different values. In case of 'separate point' and 'different location' grounding configurations, this impact of wave attenuation has not been considered. Because of this reason the current travelling back into cable sheaths during ''separate point ''and 'different location'' grounding method would be same, when in real life the current in later shall be lower. The actual current reaching the different grounding locations would be lesser than that depicted the simulation model, consequently the induced voltages shall be lower.

6 Hybrid line during lightning on shield wire

In this section lightning performance of hybrid line under lightning on shield wire has been evaluated. The simulation has been performed for three different type of grounding schemes considering both end bonded and cross bonded cable configuration. The induced voltage and current at the OHL-cable junction, ground and consecutive two towers has been observed and a comparison between different grounding schemes has been drawn. The lightning strike is simulated at 50 meters away from tower on shield wire 2. Figure 6:1 shows the current in shield wire and sheath in case of lightning striking the shield wire number 2 (where Ig1 is the current travelling to ground from tower, Ig2 is the current travelling from ground into cable sheath, Isw1 and Isw2 are current in shield wire 1 and 2). As the lightning strikes the shield wire, Lightning currents flows to ground through ground wires. Some of the current travels back into another shield wire and some of the currents goes into cable sheath.

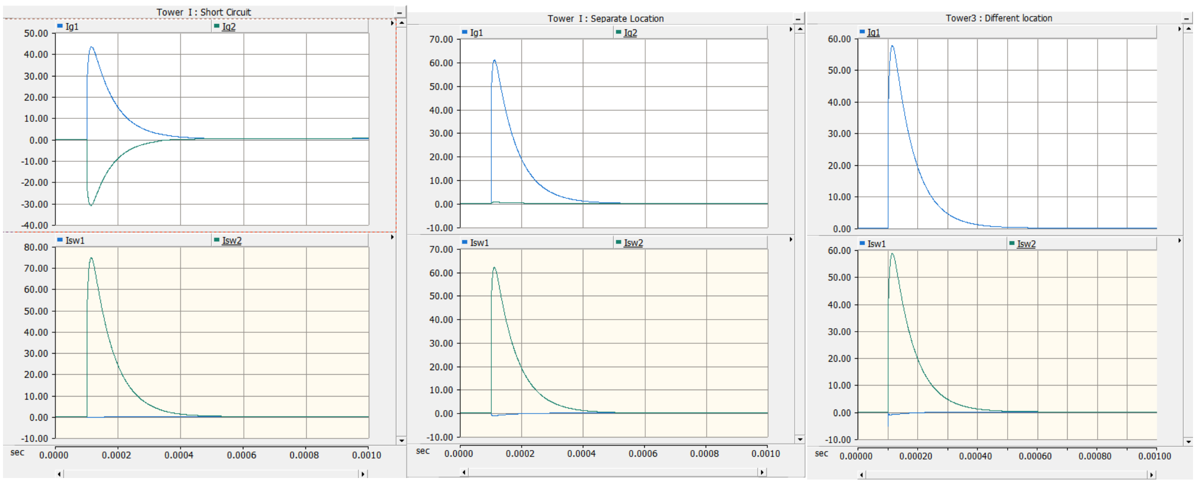


Figure 6:1 Current in Shield wire and Sheath in case of fault on Shield wire

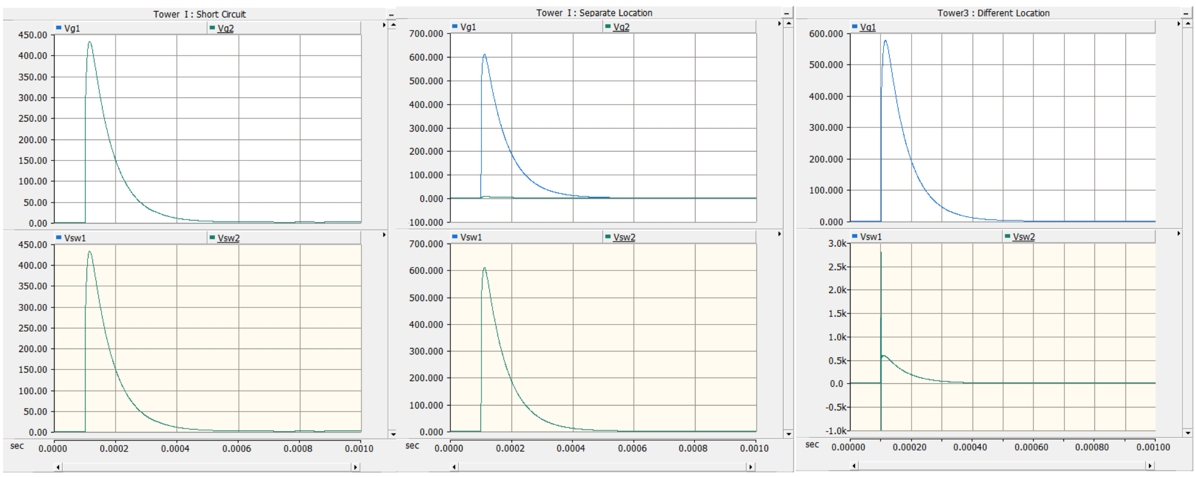


Figure 6:2 Induced over voltages in shield wire and cable sheath

Figure 6:2 shows the induced voltages in ground wire and sheath conductor at junction point.

6.1 Impact on Cable

The induced voltages in cable phase conductor and sheath have been observed at OHL-cable junction and subsequent section (5 km away).

6.1.1 Short circuit grounding method

The induced voltages in case both end bonded and cross bonded system has been compared. Figure 6:3 and Figure 6:4 shows the induced voltages and current at junction and subsequent section in case of both end bonded and cross bonded systems respectively.

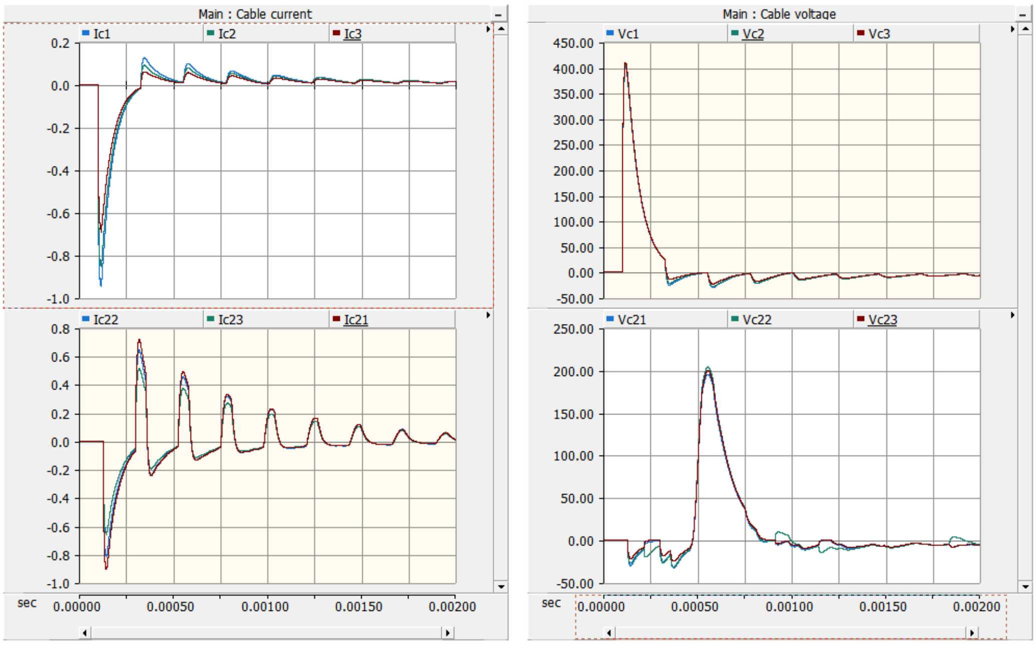


Figure 6:3 Overvoltage and current in cable: Lightning|Shield wire; Grounding Configuration|Short circuit; Sheath|both-end bonded

In figures, Ic1, Ic2, Ic3 and Vc1, Vc2 and Vc3 are the current and voltages at the cable-OHL junction point. Ic22, Ic23, Ic21 and Vc21, vc2 and Vc3 are the current and voltages in Phase 1, 2 and 3 in the subsequent section which 5 km away from the junction.

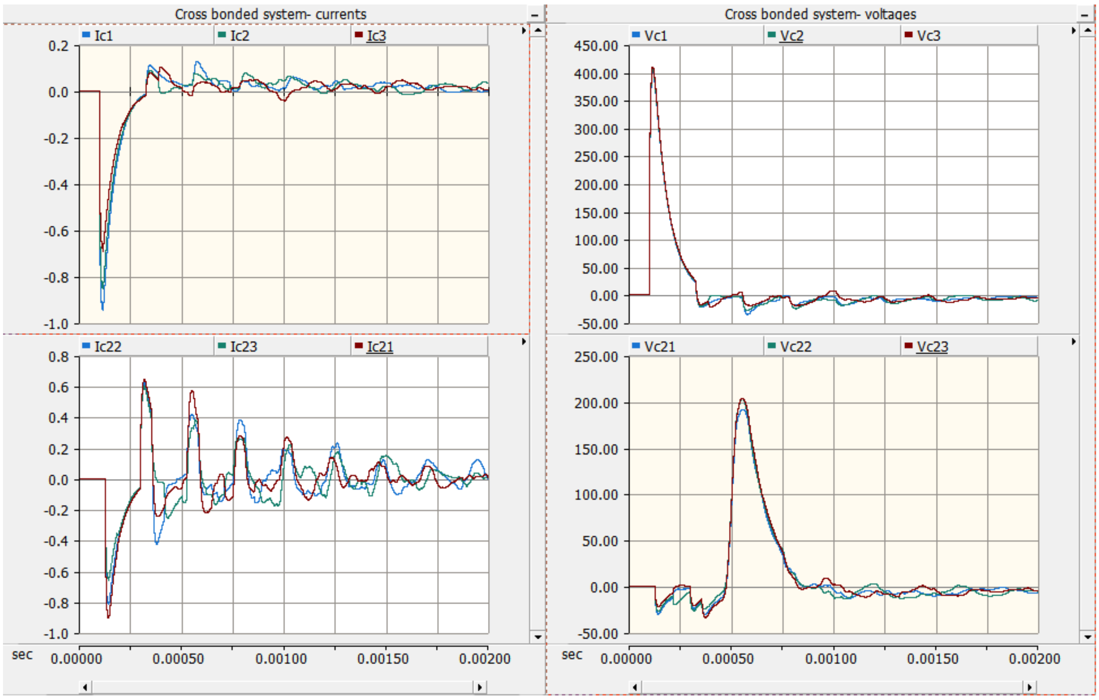


Figure 6:4 Overvoltage and current in cable: Lightning|Shield wire; Grounding Configuration|Short circuit; Sheath|cross bonded

At the junction peak value in both cases is observed at 115 µs. Due to propagation speed of the wave, there is the delay of 15 µs between when lightning strikes and when peak value is observed at junction. At the subsequent section, in case of both end bonded configuration, the peak voltage value is observed at 552 µs, which corresponds to the third reflection. The number of reflections increases in case of cross bonded system, as the cross bonding of sheath results in impedance changes in cable sections thus creating more discontinuity points for the travelling wave [15]. Peak value at subsequent section is observed at third 552.2 µs, which corresponds to fourth reflection.

6.1.2 Separate point grounding method

Figure 6:5 and Figure 6:6 shows the induced voltages and current at junction and subsequent section in case of both end bonded and cross-bonded cable configuration respectively. The peak voltage at junction is observed at 113.7 µs, at second reflection in case of both-end bonded system. In case of cross-bonded system, peak is also observed at 113.7 µs but it corresponds to first reflection. The peak value in subsequent section for both-end bonded system is observed at 368 µs corresponding to third refection. In case of cross bonded system peak occurs at 605 µs, corresponding to 5th reflection.

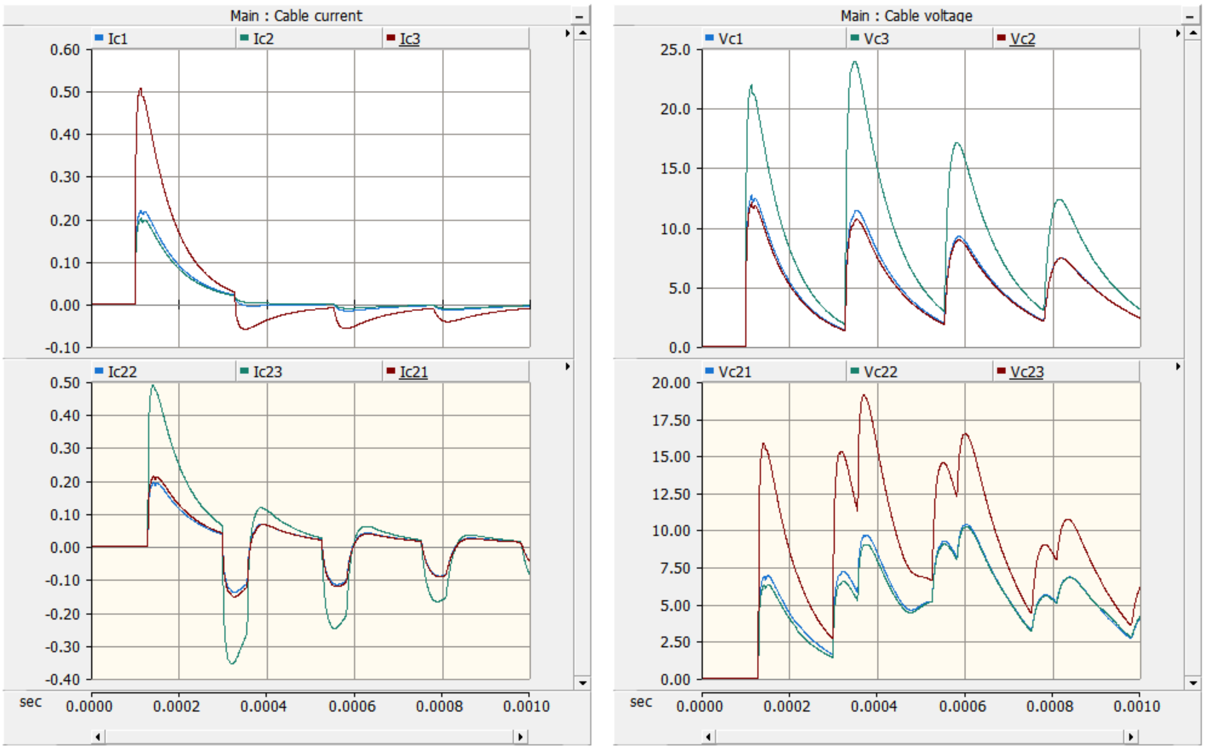


Figure 6:5 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| 'separate points' ; Sheath| Both end bonded

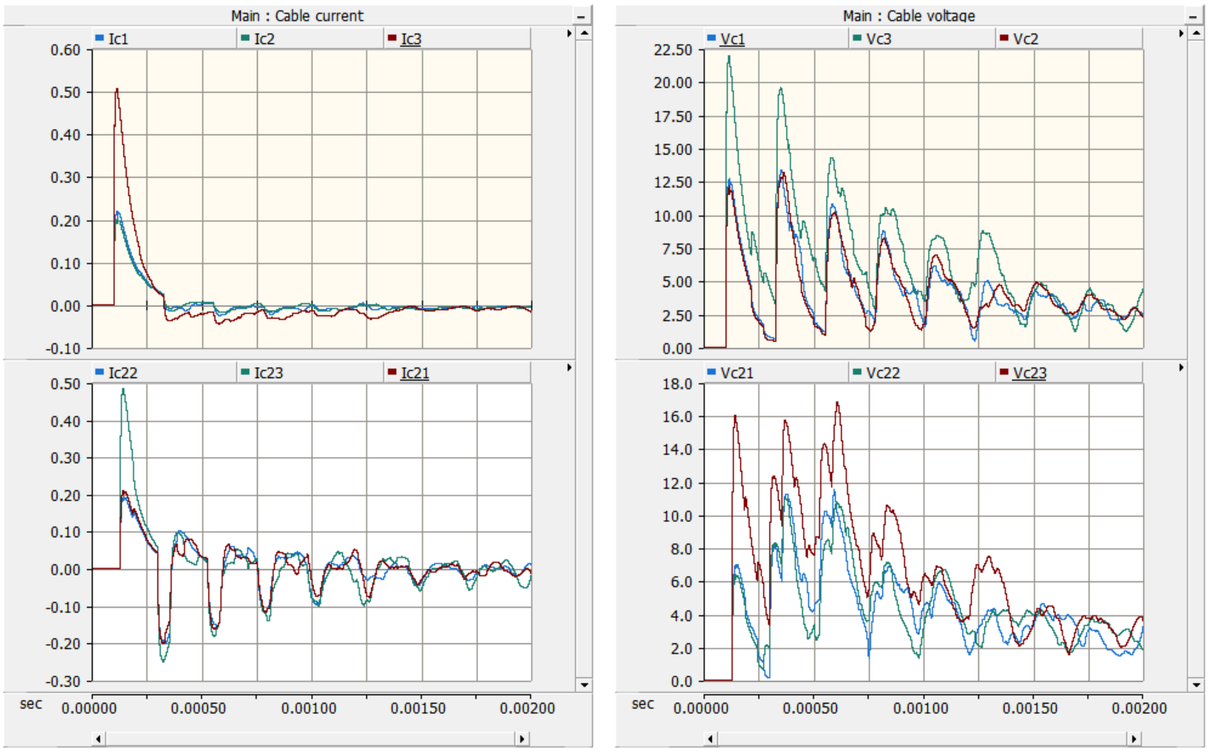


Figure 6:6 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| 'separate points'; Sheath| cross bonded

6.1.3 Different location grounding method

Figure 6:7 shows the induced voltage and current at junction and subsequent cable section in case of 'different location' grounding with both end bonded sheaths. As the sheath at junction are open thus standing voltages are observed at junction point. The maximum voltage in phase conductors at junction is observed at 100.4 µs, just after the lightning strikes the shield wire. This happens because, as the lightning strikes it rases the ground potential, thus voltage appear across the cable sheath, which in turns induces voltage in phase conductor. Figure 6:8 shows the ground potential and sheath voltage at junction. The maximum voltage in case of cross bonded cable configuration also appears at 100.4 µs, however the amplitude is higher than that in both-end bonded configuration.

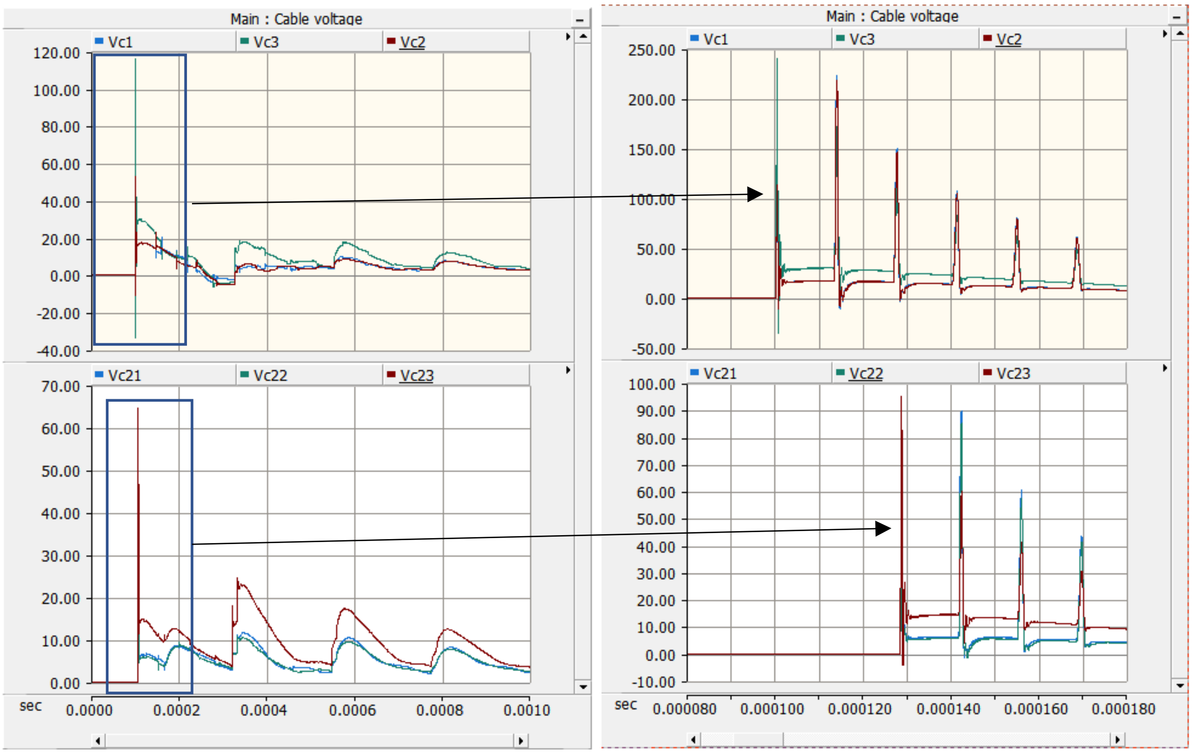


Figure 6:7 Overvoltage and current in cable: Lightning| Shield wire; Grounding Configuration| 'different location' ; Sheath|Both end bonded

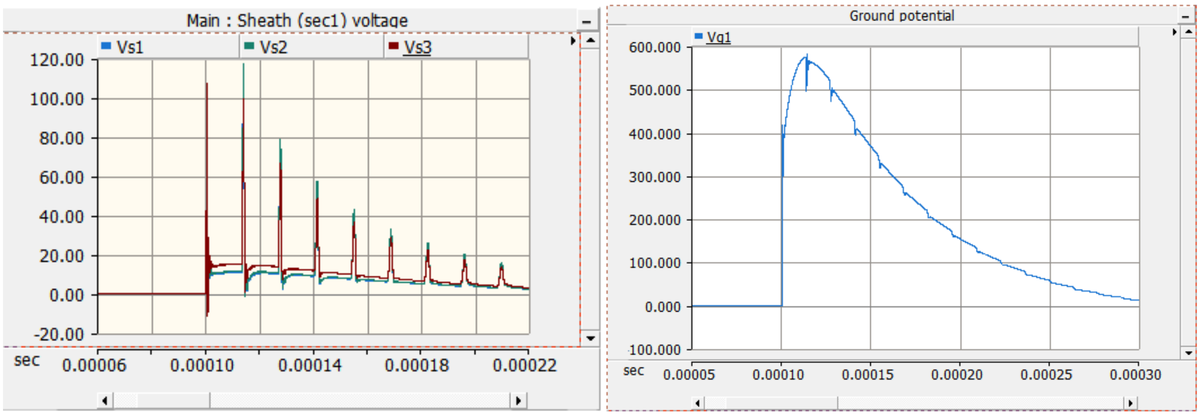


Figure 6:8 Ground potential and voltage induced in sheath at junction

The maximum voltage in subsequent section in cross bonded and both end bonded configuration appears at 106 µs, which correspondent to the time when ground current flows back into the cable sheath. Figure 6:9 shows the sheath current and induced voltage at the location where sheath grounding has been done. The current reaches the location at 106 µs.

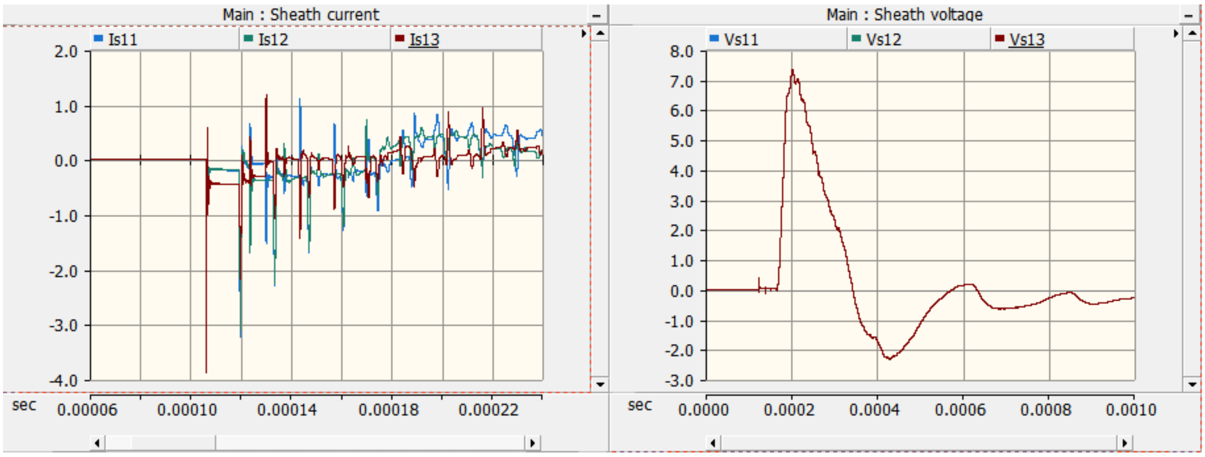


Figure 6:9 Sheath voltage and current in cable at the location of grounding in ‘different location’ grounding method

6.2 Impact on Overhead line

The phase voltage of upper conductor has been analysed at Tower 2 (2km from junction point) and Tower 3 (50 m from junction point).

6.2.1 Short circuit grounding method

Figure 6:10 shows the phase voltage in upper phase of OHL at tower 2 and tower 3. In case both end bonded and cross-bonded cable configurations. The voltage profile shows same behaviour in both cases.

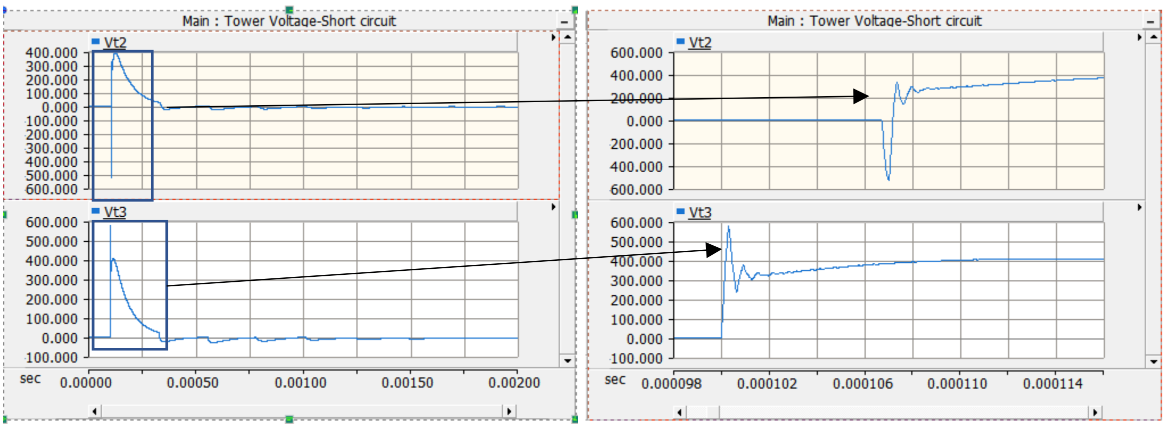


Figure 6:10 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire. Grounding method| Short circuit

The peak value of the voltage in tower 3 (near the lightning strike area) is observed at 100 µs, when the lightning strikes the shield wire. As lightning strikes the shield wire the, there is abrupt rise in voltage in shield wire, which give rise to induced voltage due to electromagnetic coupling in phase conductor, thus the sharp spike is observed in the voltage curve. Peak value at tower 2 is observed at 107 µs. the delay is due the propagation velocity of the wave.

6.2.2 Separate point grounding method

Figure 6:11 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire. Grounding method| 'separate point' presents the upper phase tower voltages in case of the 'separate point' grounding system. The peak voltage value at tower 3 is observed at 100 µs and at tower 2 after some delay due to propagation speed at 107 µs.

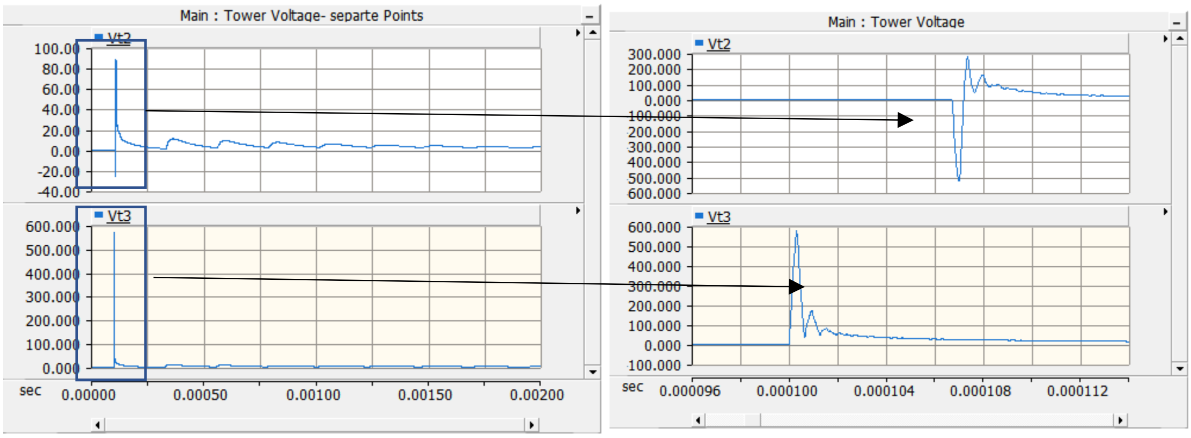


Figure 6:11 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire. Grounding method| 'separate point'

6.2.3 Different location grounding method

Figure 6:12 shows the induced voltages at tower 2 and 3 in case of hybrid line where grounding has been one at two 'different locations'. The peak voltage value at tower 3 is observed at 100 µs and at tower 2 after some delay due to propagation speed at 107 µs. Similar behaviour is observed in case of cross bonded cable configuration as well.

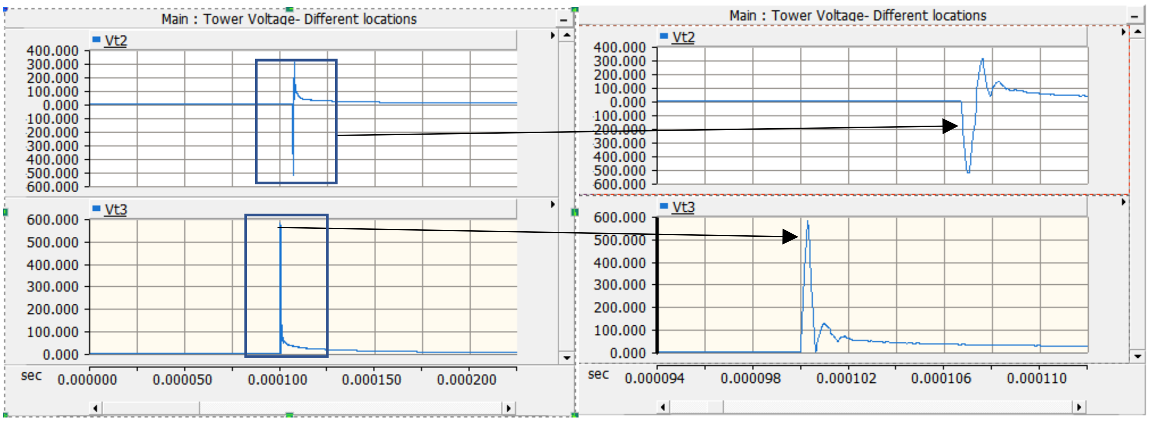


Figure 6:12 Upper phase voltage at Tower 2 and 3 for different grounding methods when lightning strikes shield wire

6.3 Discussion on impact of grounding method on lightning performance

6.3.1 Maximum over-voltages

Figure 6:13 shows the maximum over- voltages in three phases of the cable at the junction for different grounding scenarios. It can be observed the highest over voltages are seen in case of the *'short circuit '*grounding method. The grounding method act as a current division circuit, thus higher impedance implies lower current. Circuit impedance is lowest in case of *'short circuit '*grounding method ('A', refer to chapter 4), thus the current travelling to sheath is highest compared to other two methods, subsequently the induced voltages are much higher as well. The induced voltage at junction in case of 'separate point' method is lesser than that of the 'different location' method. In case of ''different location'' grounding method the cable section between the junction point and the point where sheaths are grounded, is essentially a single end bonded section with open end at junction and standing voltage is induced in the sheath at the junction [14]. The standing voltage in sheath induces higher voltages in phase conductor due to mutual coupling between the sheath and the conductors. Figure 6:13 shows the induced voltages in cable sheath at junction point in case of 'separate point' and 'different location' grounding method. Voltage for later one is higher than the former.

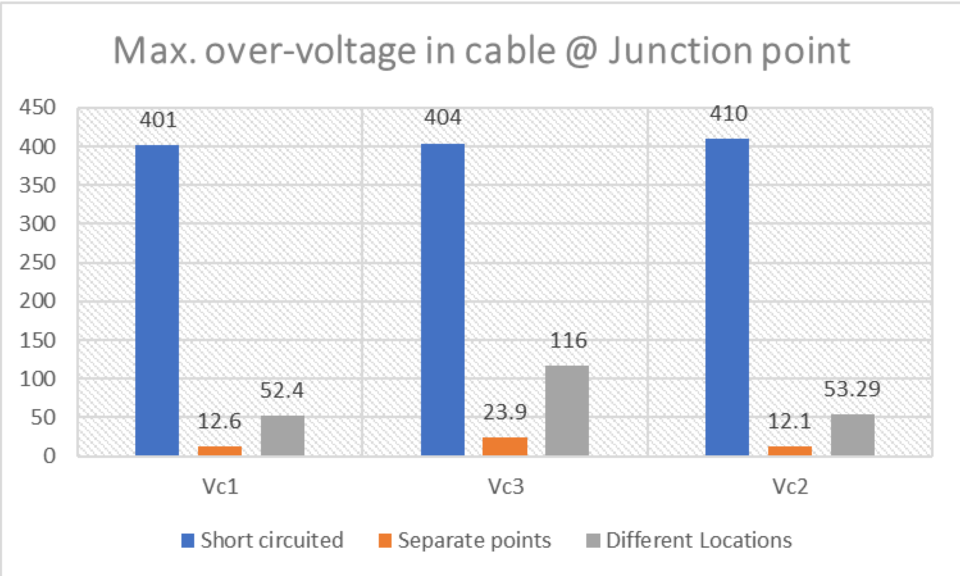


Figure 6:13 Comparison of maximum phase over voltage in cable at the junction point: Lightning|Shield wire

Figure 6:14 shows the comparison of maximum overvoltage experienced by the OHL line in case of different grounding methods (where Vt2 and Vt3 are the upper phase voltages at Tower 2 and Tower 3), which does not depend on the grounding method. The maximum over-voltage in OHL is determined by the induced voltage in shield wire due to lightning current. This over-voltage induces voltages in the phase conductor due to mutual coupling between the shield wire and conductor. The overvoltage when lightning strikes the shield wire is much higher than subsequent reflection refraction voltages. Figure 6:15 shows the overvoltage in shield wire when lightning strikes. Maximum overvoltage at tower 2 is in case of 'different location' grounding method.

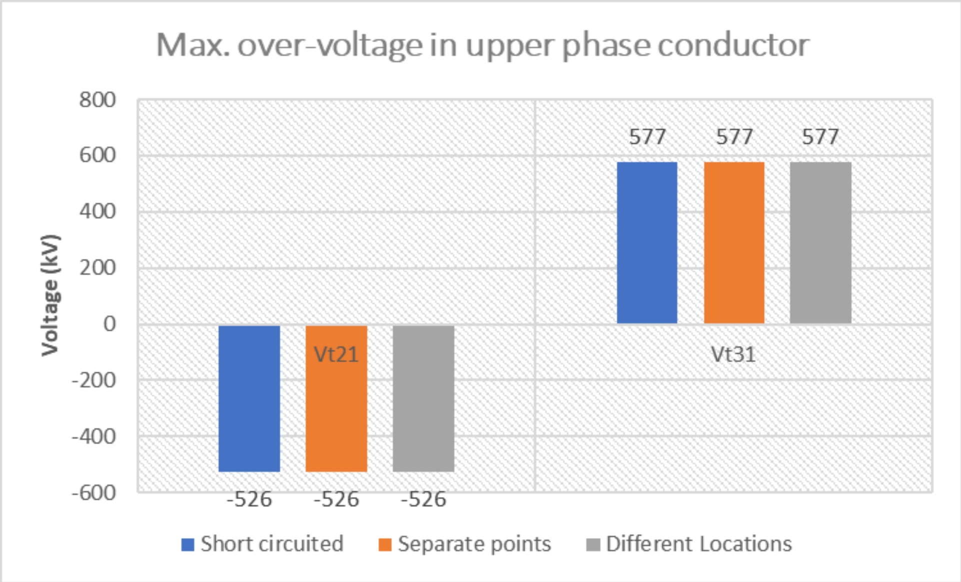


Figure 6:14 Comparison of maximum upper phase over voltage in OHL at tower 2 and 3: Lightning|Shield wire

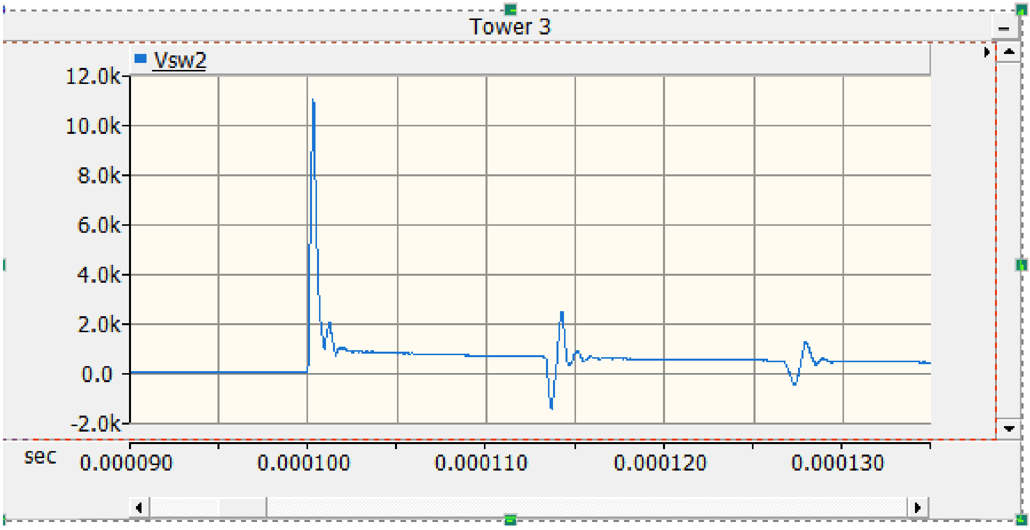


Figure 6:15 Voltage in Shield wire when lightning strikes

6.3.2 Impact of grounding location distance

In this section impact of grounding location distance (Grounding Network method 'C', refer to section 4) from junction point on the lightning performance of the line has been explored. Figure 6:16 shows the maximum over-voltage on upper phase conductor of OHL section (Vt2 at tower 2 and Vt3 at Tower 3) and shield wire (Vsw). As depicted in the figure, grounding location distance does not have an impact on maximum over-voltage values in OHL section, as the maximum value is predominately dependent upon the voltage induces because of electromagnetic coupling between shield wire and phase conductor. However, the Induced voltage reaches 5597 kV in shield wire, which is higher than CFO (2240 kV) [9]. This can cause flashover in the line.

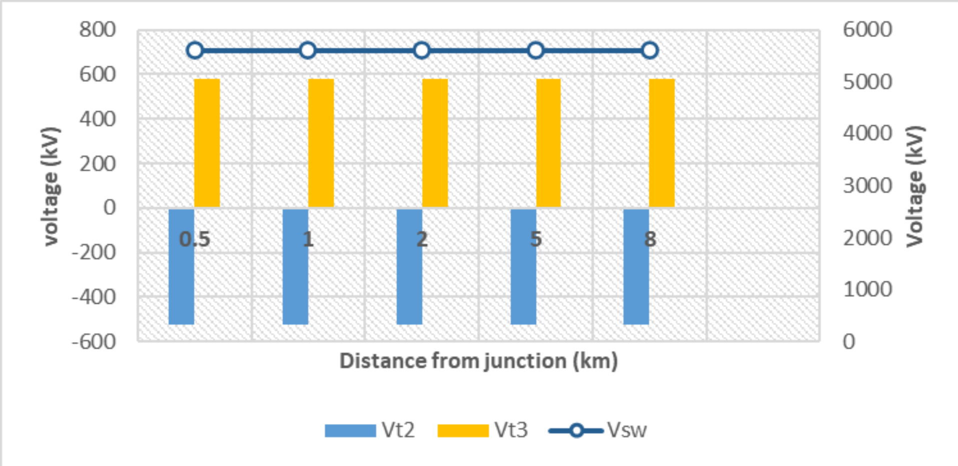


Figure 6:16 Impact of grounding location on OHL

Figure 6:17 presents the maximum voltage observed in three phases of the cable at junction. As evident from the graph, changing the grounding location does not have any impact at junction. As the maximum voltages are observed before the reflection travel back to junction from subsequent section where grounding has been done (refer to section 6.1.3).

Figure 6:17 Impact of grounding location on Cable at Junction

Figure 6:18 presents the maximum voltages observed in the cable phase conductors at the point of sheath grounding. As distance of grounding location is increased, the voltage induced in cable section where grounding of sheath has been done reduces. This happens because the path impedance increases as the distance is increased from the junction point, thus, lesser current flow to the sheath, in turn inducing lesser voltage. Figure 6:19 shows the change in sheath current and induced voltage value at the section where grounding is done, as the grounding location distance increases.

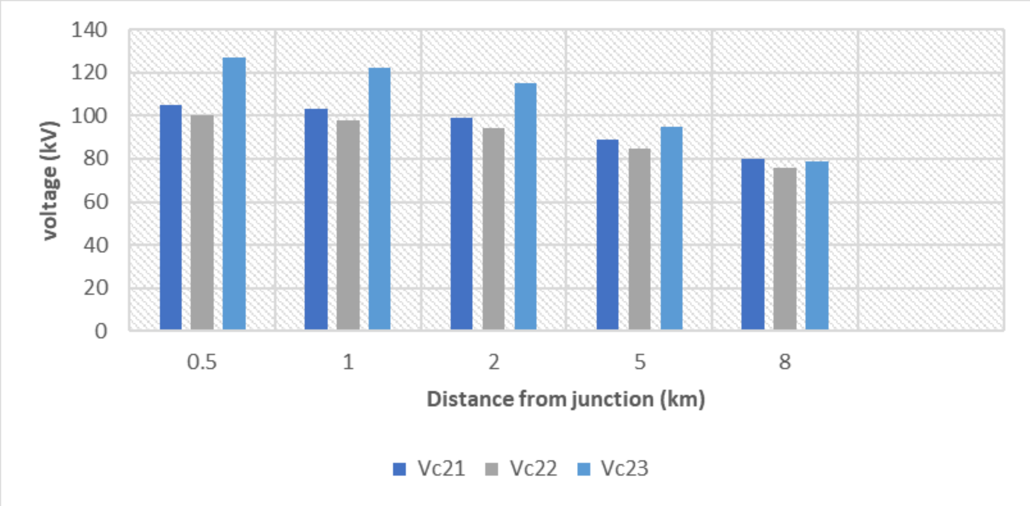


Figure 6:18 Impact of grounding location on Cable

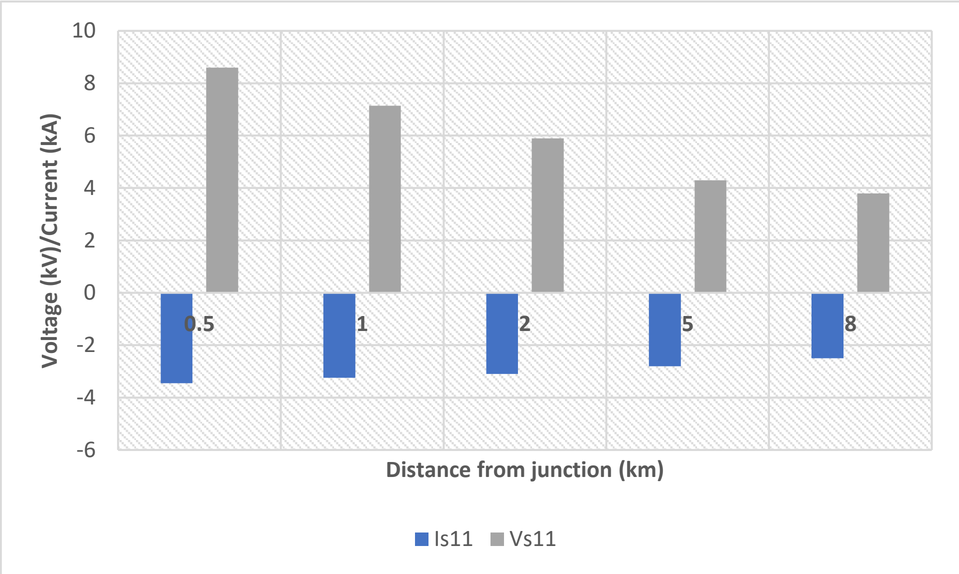


Figure 6:19 Sheath current and voltage change with distance

6.3.3 Impact of cross-bonding of cables

Cable sheath cross-bonding provides a significant improvement in terms of reduction of circulating currents and increasing the ampacity of the cable [14]. This section presents the impact of cross bonding on lightning performance of the hybrid line. For each of the grounding scenarios, voltage and current induced in OHL and cable sections has been studied and a comparison has been made between both end bonded and cross bonded cable sheath connections.

Figure 6:20, Figure 6:21, Figure 6:22 shows the comparison of OHL and UGC over voltages at junction in case of *'short circuit'*, '*separate point'* and '*different location'* grounding method. Cross-bonding have no significant impact. Voltages induced in cable sheath and shield wires remains the same in both cases. The predominant factor in case of OHL is the induced voltages in phase conductor due to mutual coupling. The maximum sheath voltages are dependent upon the current travelling back from ground to sheath in case of *short circuit* 'and '*separate point'* methods. In case of '*different location'*, the standing voltage is predominant factor at junction and reverse current flow from ground at subsequent section. However as seen in Figure 6:23, in case of cross-bonding number of reflections increases as there is wave face more discontinuity points with changing impedance [15].

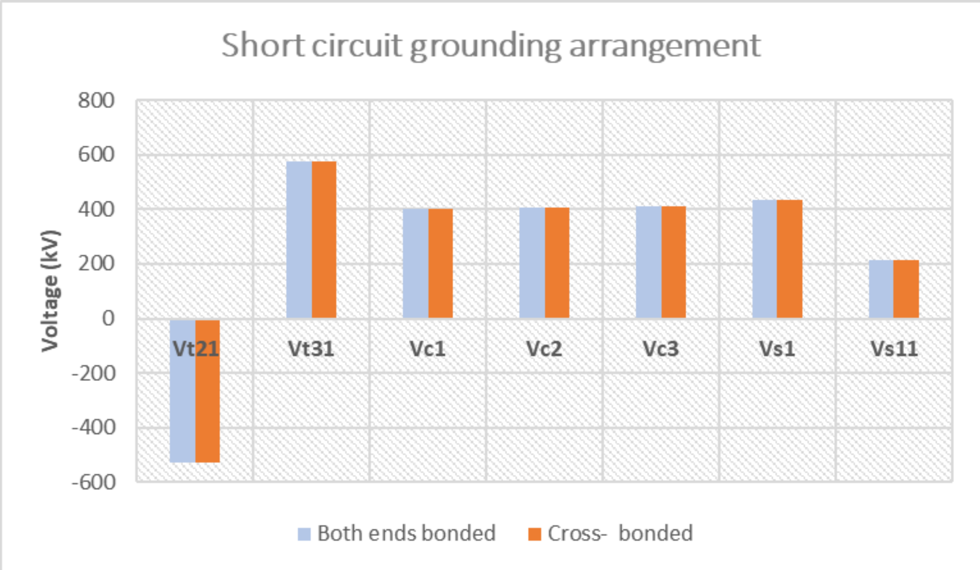


Figure 6:20 Impact of cross-bonding: Grounding method| Short circuit

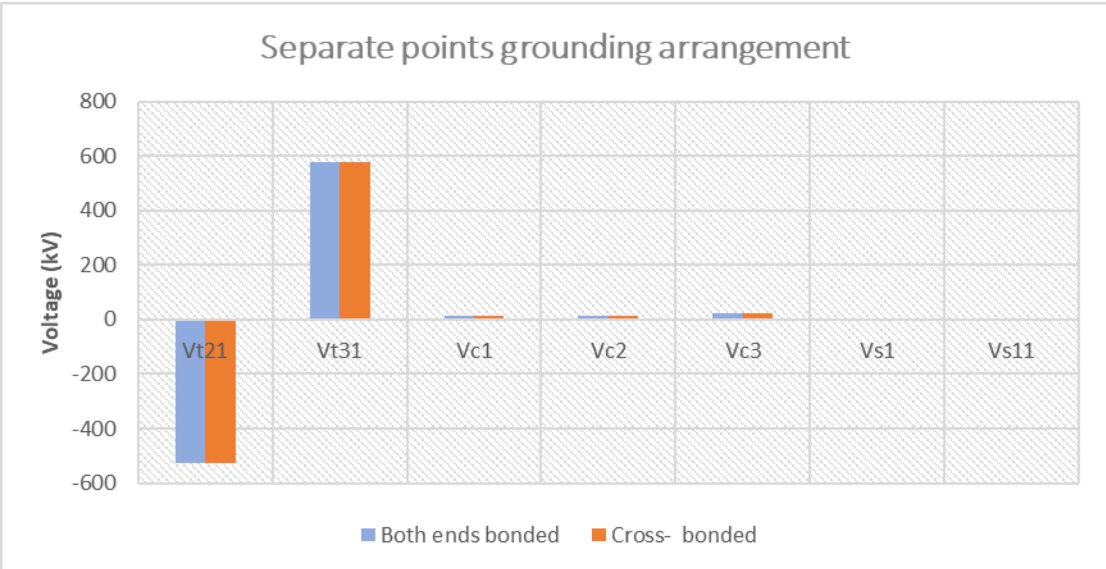


Figure 6:21 Impact of cross-bonding: Grounding method| ‘separate points’

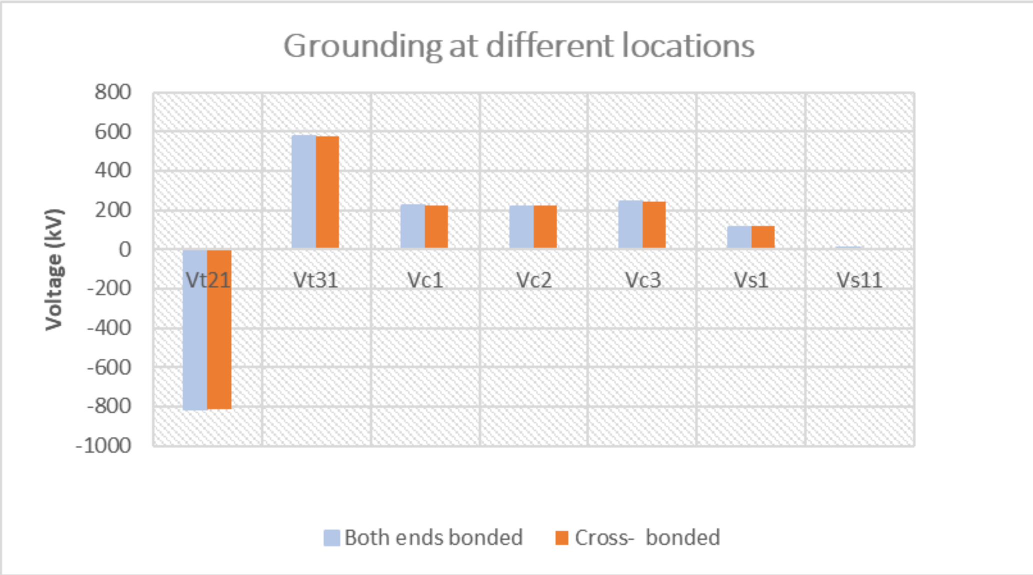


Figure 6:22 Impact of cross-bonding: Grounding method| 'different locations'

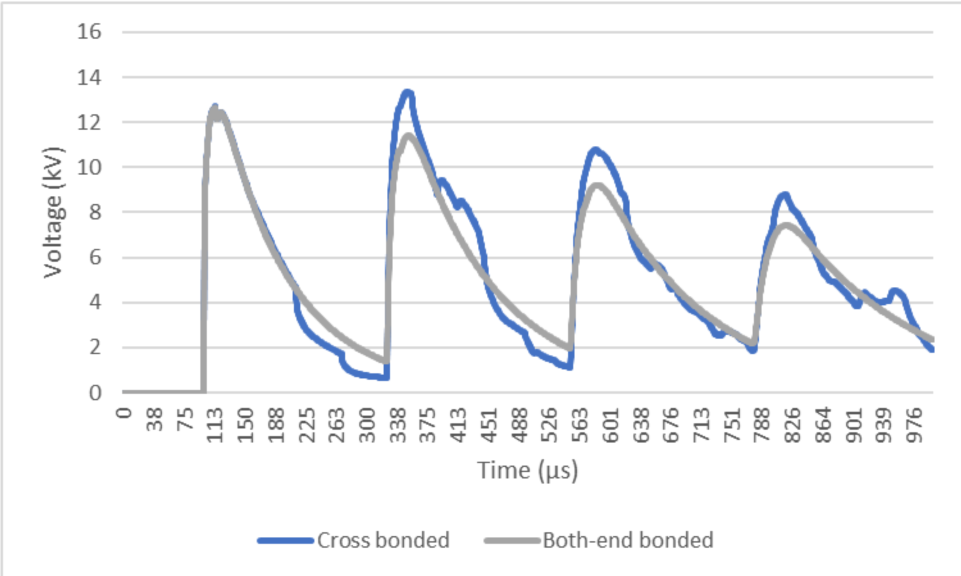


Figure 6:23 Impact of cross-bonding on cable voltages: Grounding method| Short circuit

As per the observations, cross-bonding does not have significant impact on overall maximum voltage in the network.

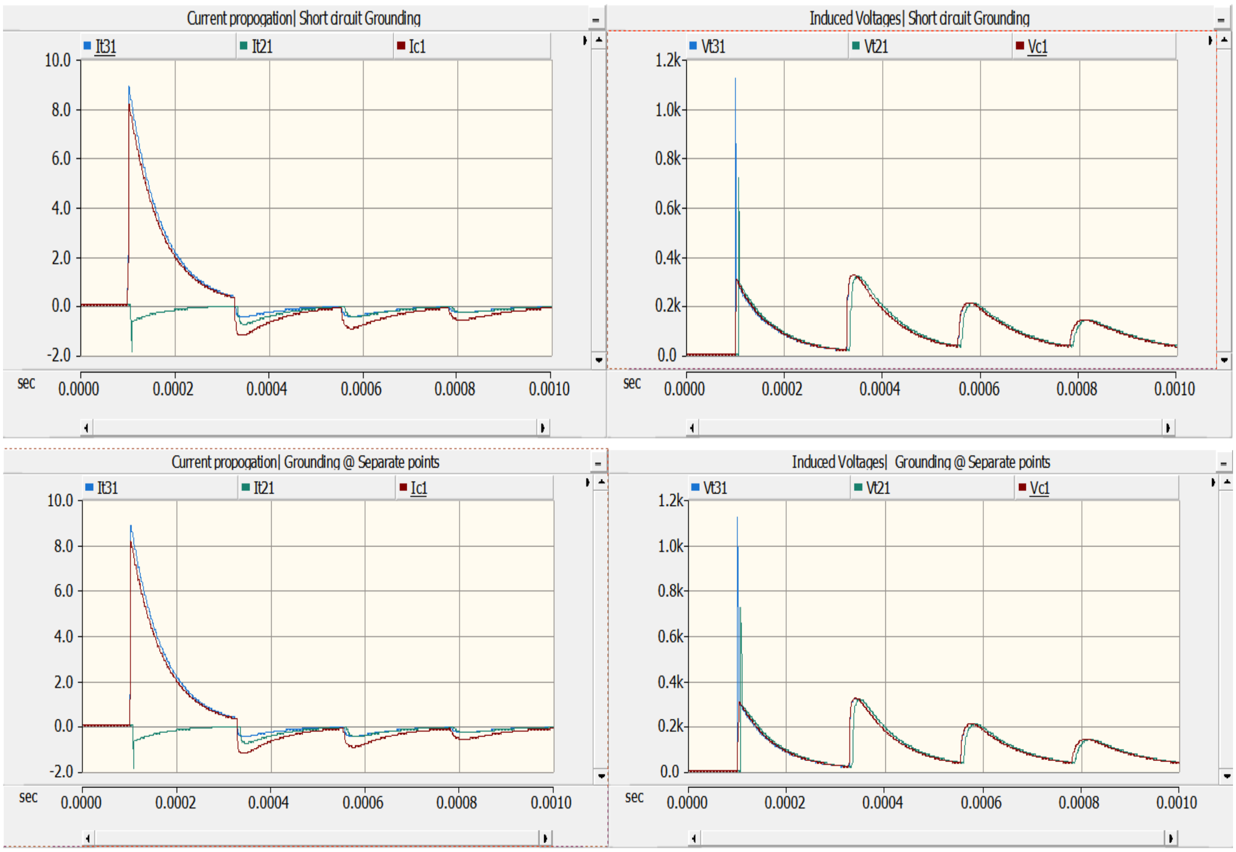
6.4 Summary

In this chapter, lightning performance analysis of the grounding methods in the case where, lightning strike on of the shield wire has been analysed and discussed. For each grounding method, the voltage rises in cable sheaths, cable phase conductors, overhead line segments and shield wires has been evaluated. A comparison has been drawn among the grounding schemes, which shows that 'separate point' grounding method provides the best lightning performance. The maximum induced voltages across cable and OHL are lowest in case of 'separate point' grounding method. In addition to this, a comparison between both end bonded and cross bonded cable sheath connections has been drawn, which shows that cross bonding of cable sheath does not have significant impact on the maximum over voltages seen by the hybrid line. However, in case of cross bonding the travelling waveform is more distorted as compared to the others. Furthermore, in 'different location' grounding method the impact of grounding location from the junction has been analysed. The change in location does not have a significant impact on the over-voltages seen by the OHL and cable section at junction.

7 Hybrid line during lightning on phase conductor

The shielding failure rate for Eagle pylon tower is 0.0353 flashes/year. In case of the shielding failure, lightning will strike the phase conductor, which gives rise to the possibility that flashover might occur. Flashover occurs when the maximum shielding failure current is larger than the critical current (current values for which flashover shall occur). However, in case of Eagle pylon tower, the critical current is higher than the maximum shielding failure current, thus, ideally shielding failure flashover rate for Eagle pylon should be zero [9]. In this section, only lightning strike on phase conductor without any flashover has been analysed. The lightning strike has been simulated on phase conductor 1 at 50 m (Tower 3) from the junction point. Simulation studies for each of the grounding configurations has been conducted and the results has been discussed.

When lightning strikes the phase conductor 1, part of current travels from tower 3 to tower 2 and part of the current propagates towards cable, inducing the voltages in conductors. The reflected and refracted current and voltage values depend upon the surge impedance of the OHL and UGC section [22], [23]. Figure 7:1 shows the lightning current propagation and corresponded induced voltages in cable phase conductor at junction, OHL phase conductor at Tower 3 and Tower 2, considering the three grounding configurations. The surge impedance for OHL is much higher than that of the UGC, thus more current propagates towards cable. As the wave propagates through the hybrid transmission line, it gets refracted and reflected multiple times as it encounters discontinuity points where surge impedance varies, this results in voltage and current spikes visible in the figure below.



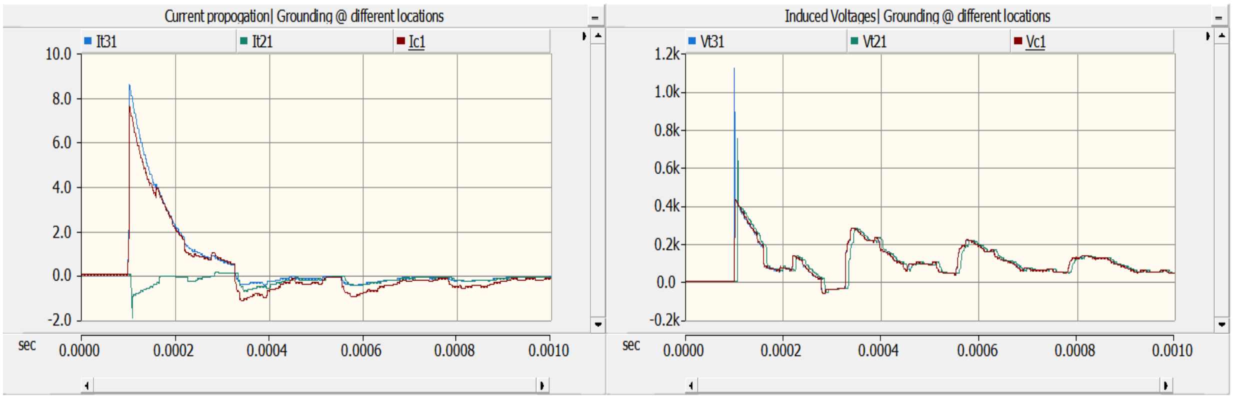


Figure 7:1 Current propagation and induced voltages during lightning strike on phase conductor

7.1 Impact on Cable

In this section over voltages induced in cable in different grounding configurations, when lightning strikes the phase conductor has been discussed. The voltages and currents at junction point and subsequent cable section have been evaluated. Figure 7:2, Figure 7:3 and Figure 7:4 shows the current propagation and induced voltages in cable section under different grounding configurations. As part of lightning current (Ic1) propagates in phase 1 of cable, it gives rise to the voltage Vc1 in phase. Due to electromagnetic coupling among the conductors and sheath of the cable, currents and voltages gets induced in rest of the phases. The spikes in current and voltage waveforms are due to refracted and reflected travelling waves in the transmission line.

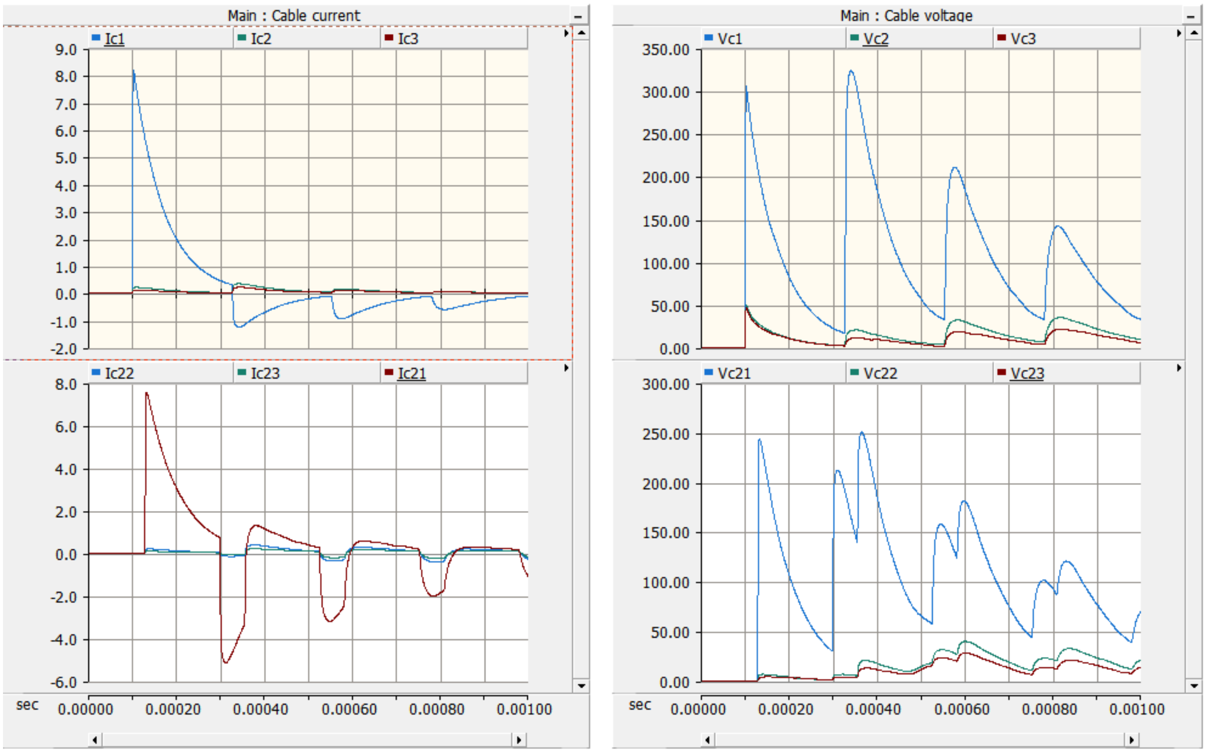


Figure 7:2 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| Short circuit

Waveform in case of 'different location' grounding method (Figure 7:4) is more distorted as compared to the other two grounding methods, this can be attributed to the fact that in case of the former, travelling wave would observe more discontinuities where line impedance changes, as cable sheath grounding is not done at the junction but a later point. By comparing the waveform across the cable length (current and voltages at junction: Ic1, Ic2, Ic3, Vc1, Vc2 and Vc3 and current and voltages at subsequent section: Ic22, Ic23, Ic21 and Vc21, Vc22 and Vc23), it can be seen that, wave does not reach the subsequent section immediately and there is a time lag due to propagation velocity of the wave. The time lag in case of 'different location' method is less as compared to the other two grounding network methods. This happens because voltages are induced across sheath due to rise in ground potential when lightning strikes the shield wire.

Table 7:1 shows the instances when maximum voltages are induced in cable at junction and subsequent cable section.

Grounding	Location	Both ends bonded		Cross-bonded	
		Time (µs)	Reflection number	Time (µs)	Reflection number
Short circuit	Junction	340	2	103	1
Short circuit	subsequent section	363	3	132	1
Separate points	Junction	340	2	102.5	1
Separate points	subsequent section	363	3	132	1
Different Locations	Junction	102.5	1	102.5	1
Different Locations	subsequent section	340	3	108	1

Table 7:1 Time instance of maximum over voltages

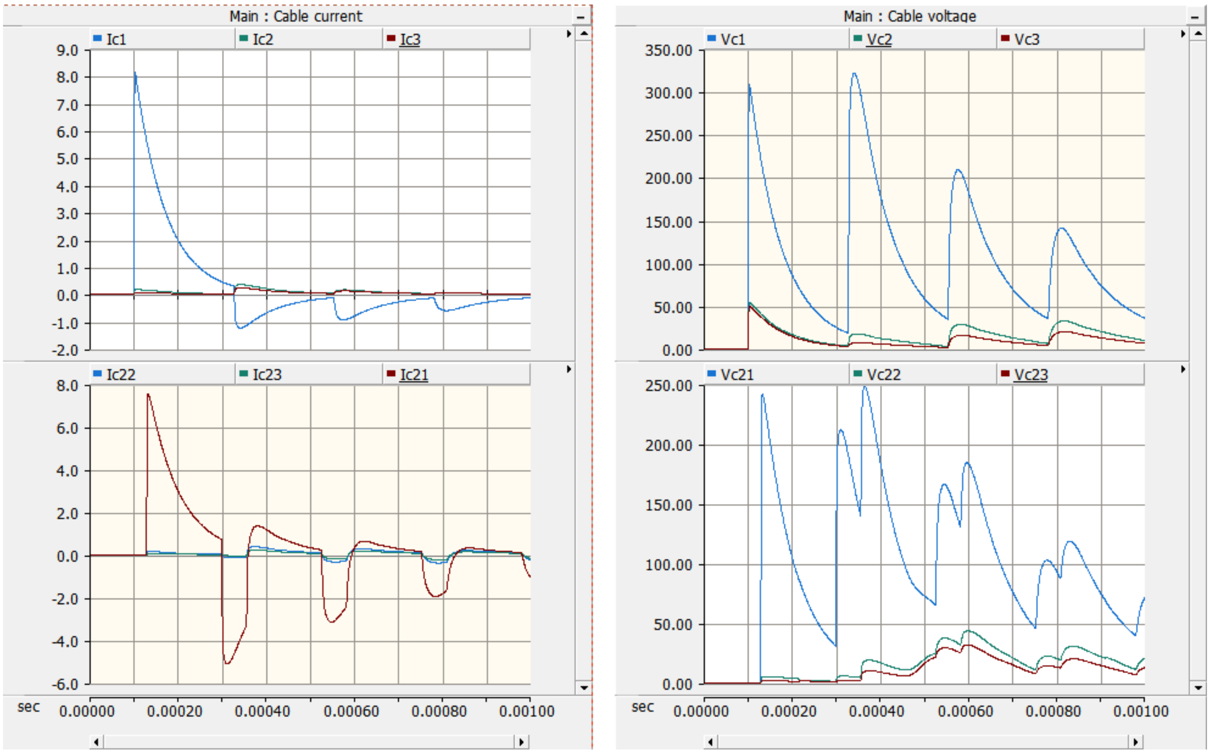


Figure 7:3 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| 'separate points'

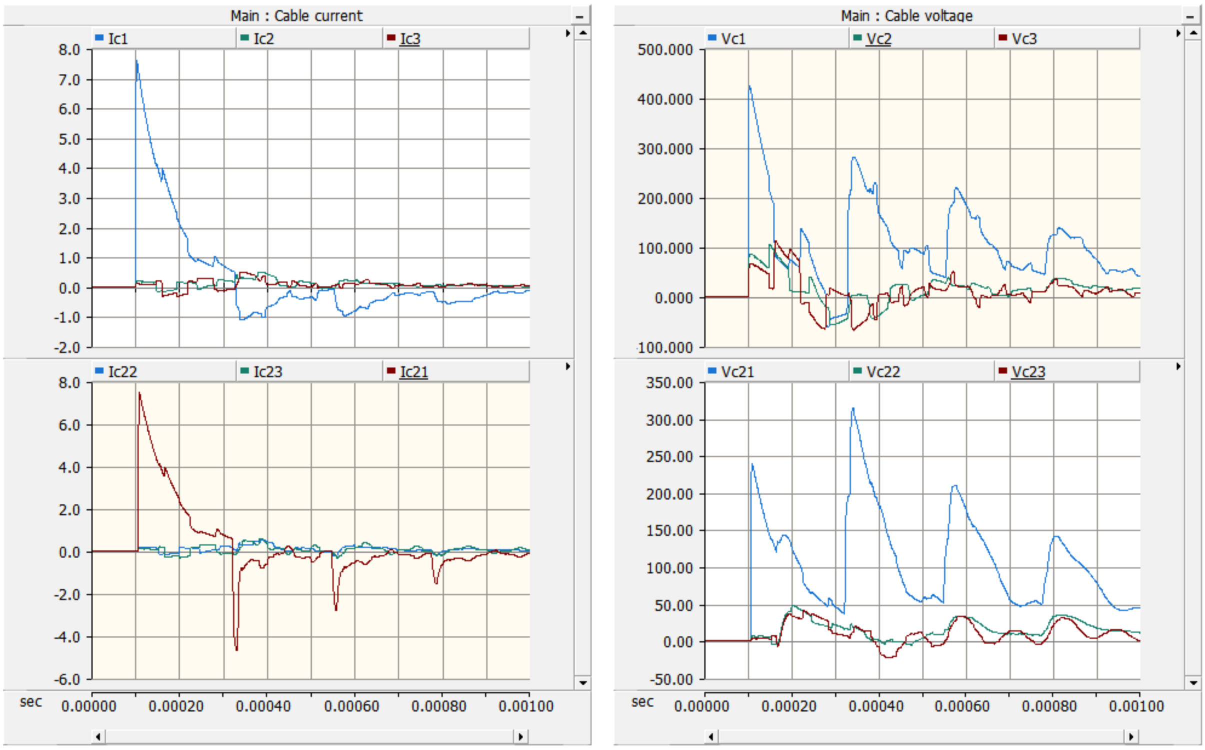


Figure 7:4 Overvoltage and current in cable: Lightning| Phase conductor; Grounding Configuration| 'different locations'

7.2 Impact on OHL

In this section over-voltages induced in OHL section during the lightning strike on phase conductor has been discussed. The induced voltages and current waveforms are observed at Tower 2 and Tower 3. Figure 7:5 shows the induced voltages and current in double circuit overhead line when lightning strikes conductor 1, for different grounding configuration. As the lightning strikes the conductor, transient overvoltage is generated in phase conductor 1. Due to electromagnetic coupling, voltages also get induced in other phases. Induced voltage is higher in the conductors, closest to conductor 1.

The maximum voltage at Tower 3 and 2 is observed at 100 µs and 107 µs. this is so because, the maximum voltage is determined by the tower top voltage, which occurs when lightning hit the conductor. The reflection voltages after the incidence are much lower. The delay in tower 2 maximum voltage is due the propagation velocity of the travelling wave.

Waveform of ‘‘different location‘‘ grounding configuration is more distorted as compared to the other two cases. This happens because, more impedances changes are observed in this configuration owing the two types of sheath connections. By comparing the voltage and current profiles at Tower 2 and tower 3, it can be observed that there is delay in wave reaching Tower 2 owing to the propagation velocity of travelling wave.

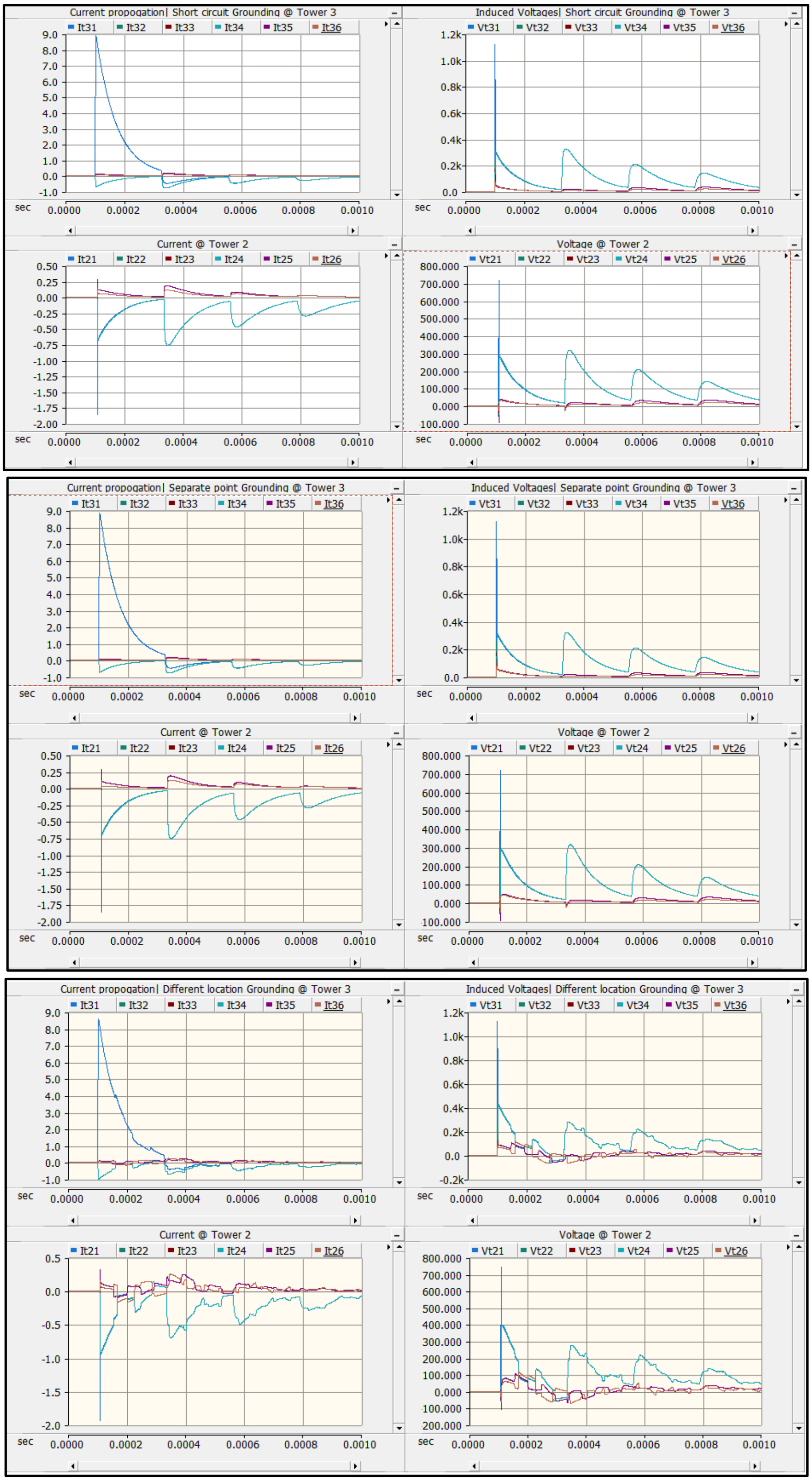


Figure 7:5 Induced over voltages and current at Tower 2 and tower 3 for different grounding configuration: lightning| Phase conductor

7.3 Discussion on impact of grounding method on lightning performance

In this section, a comparison has been drawn between various ground methods to analyse the lightning performance.

7.3.1 Impact of grounding configurations on induced cable voltages

Figure 7:6 shows the comparison of induced voltage at junction, in case of different grounding configurations. It can be observed that the induced voltages in case of ''*short circuit* 'grounding method' is lowest, followed by the ''separate point' grounding method' and highest values are observed in a network method where grounding of OHL and cable are done at 'different location' s. This can be attributed to higher induced sheath voltages, which in turns induces higher phase voltages (refer to Figure 7:7).

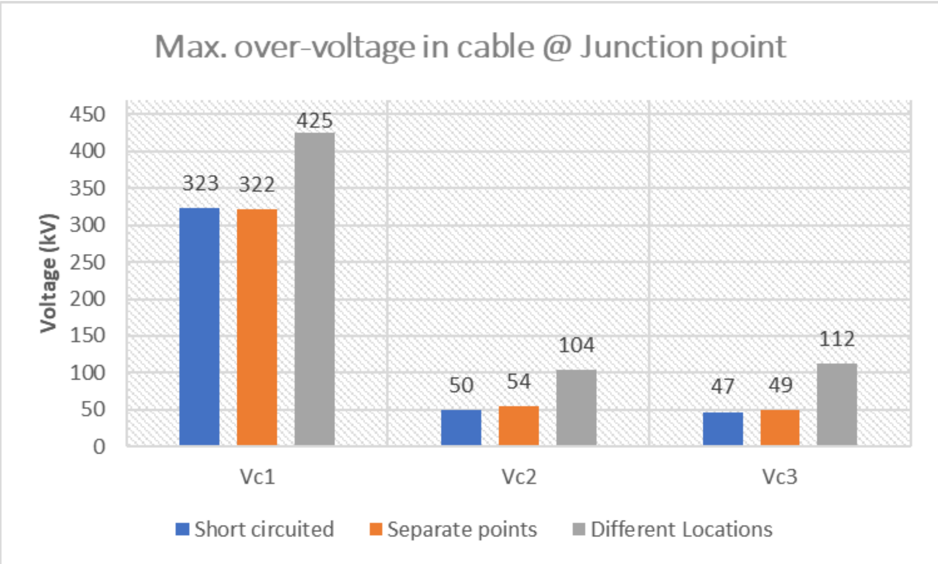


Figure 7:6 Comparison of maximum phase over voltage in cable at the junction point: Lightning| Phase conductor

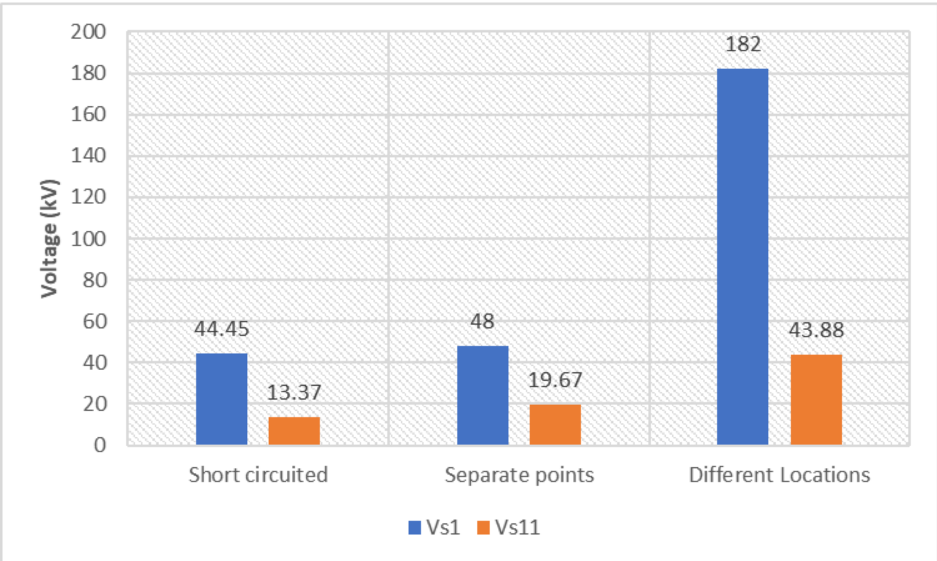


Figure 7:7 Variation of sheath voltage in different grounding schemes: Lightning| Phase conductor

7.3.2 Impact of grounding configurations on induced OHL voltages

Figure 7:8 shows a comparison between maximum over-voltages observed at Tower 2 and Tower 3 in OHL section. The lowest values are observed in 'separate point' grounding method. In case of *'Short circuit '*and 'different location' method the values are really close.

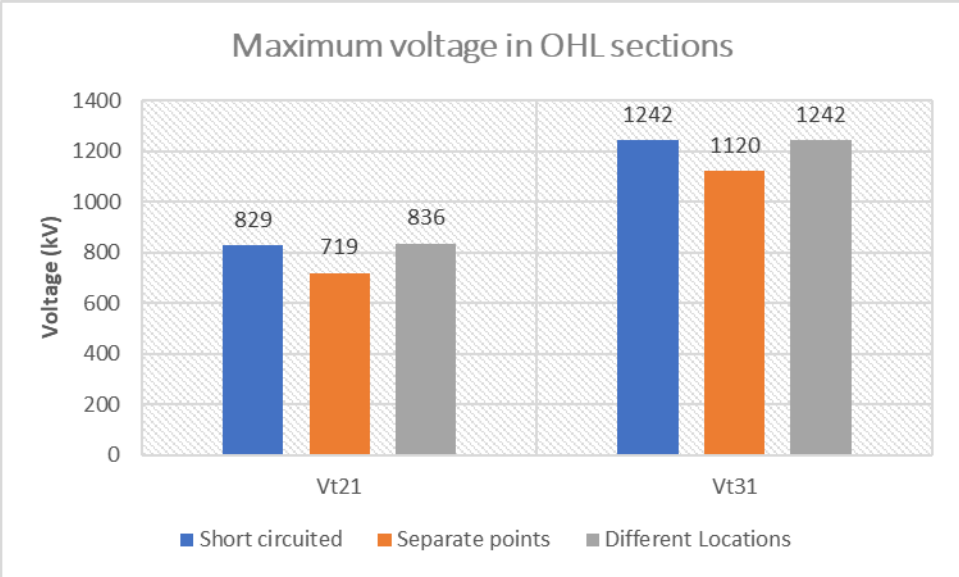


Figure 7:8 Comparison of maximum upper phase over voltage in OHL at tower 2 and 3: Lightning| Phase conductor

7.3.3 Impact of grounding location distance

In this section, the impact of grounding location of cable sheath away from the junction point has been discussed. The cable sheath grounding location is varied between 0.5 to 8 km away from the junction point. From Figure 7:9, it can be seen that grounding location distance does not have an impact on maximum induced voltage in OHL section, because the predominate factor there is the induced voltage due to mutual coupling between phase conductors, when lightning strikes on one of the conductor.

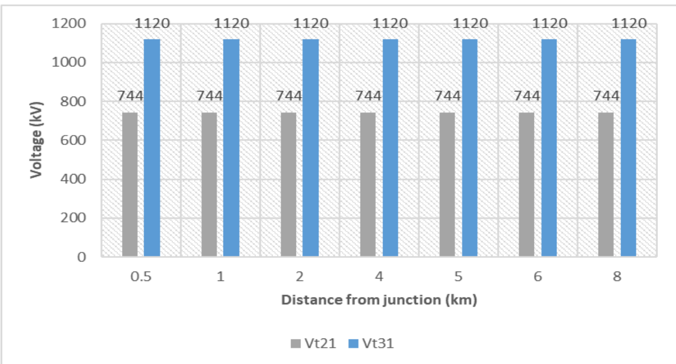


Figure 7:9 Impact of grounding location distance on OHL induced voltages: Lightning| Phase conductor

Figure 7:10 presents the voltage variation in the three-phases of the cable at the junction point. As depicted in the figure, the maximum voltage induced in conductor 1 is not impacted by the change is grounding location distance. Vc1 is mostly influenced by lightning current that propagates to cable from Tower 3. Whereas the voltages in phases 2 and 3 are influenced by the location change and decreases as location is moved further away.

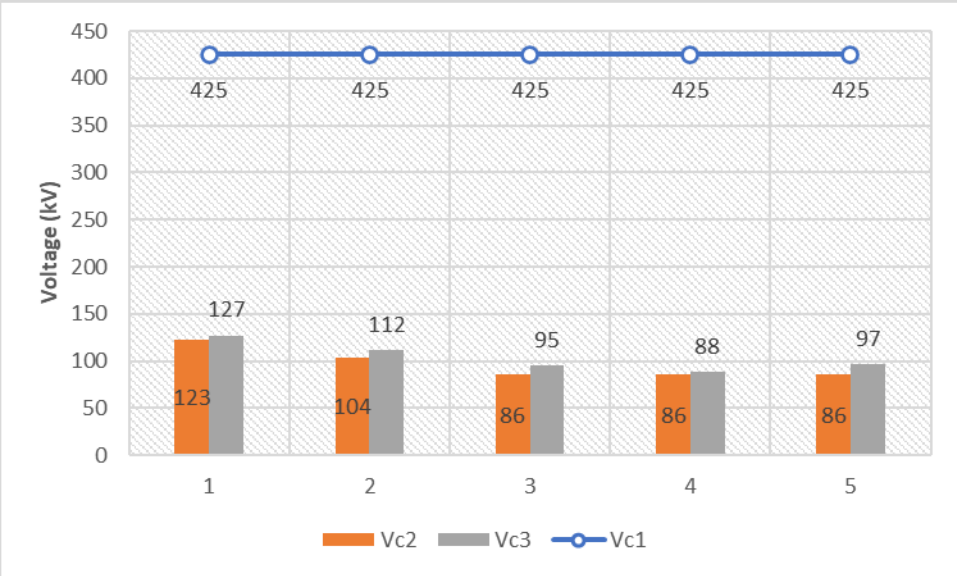


Figure 7:10 Impact of grounding location distance on cable at junction: Lightning| Phase conductor

The voltage variation observed at subsequent section after junction (where sheath grounding is done) along with change in distance. As the distance increase, the voltage value decreases because the path impedance increases and lesser current floes back from earth to the sheath, thus resulting lesser voltages.

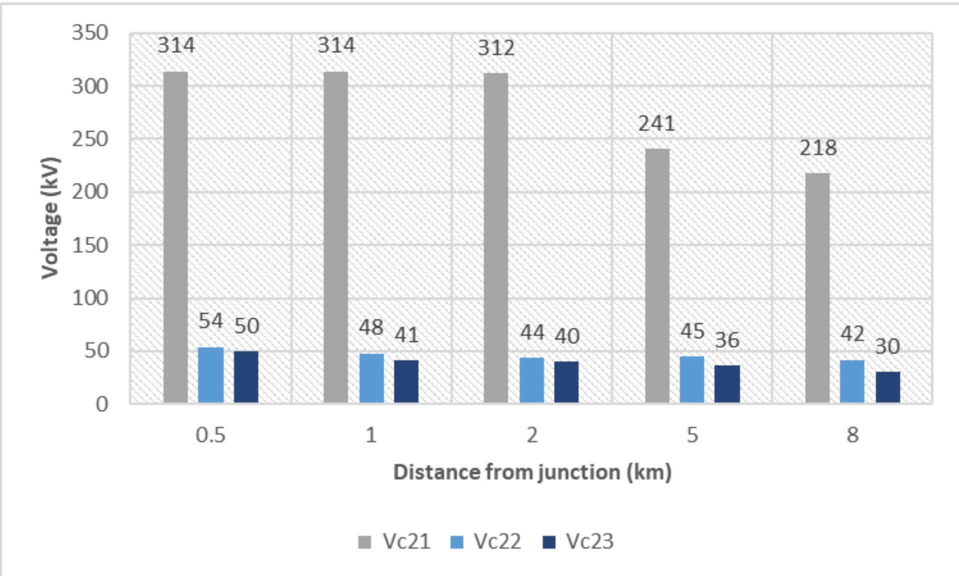


Figure 7:11 Impact of grounding location distance on cable: Lightning| Phase conductor

7.3.4 Impact of cross-bonding of cables

In this section a comparison between cross- bonded and both -end bonded cable connections for three different grounding configurations have been made. It can be seen from Figure 7:12 that, in case of the *'short circuit '*grounding method, cross bonding does not have an impact on maximum induced over-voltages in OHL section.

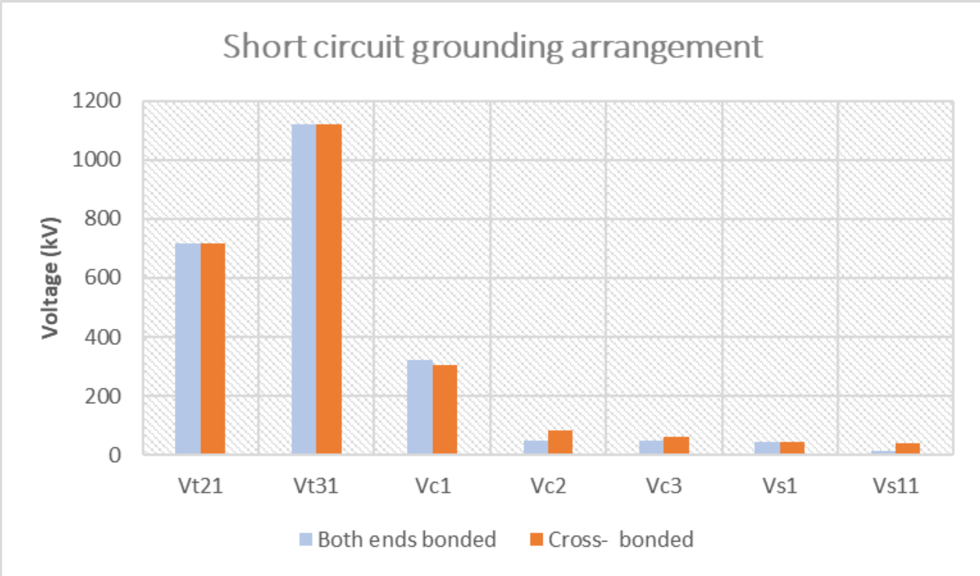


Figure 7:12 Impact of cross-bonding: Grounding method| Short circuit, Lightning| Phase conductor

Figure 7:13 gives an overview of impact of cross bonding in case of ''separate point' grounding configuration. Cross bonding as almost negligible impact on OHL maximum over voltage values. The sheath voltage is higher in case of cross bonded cable.

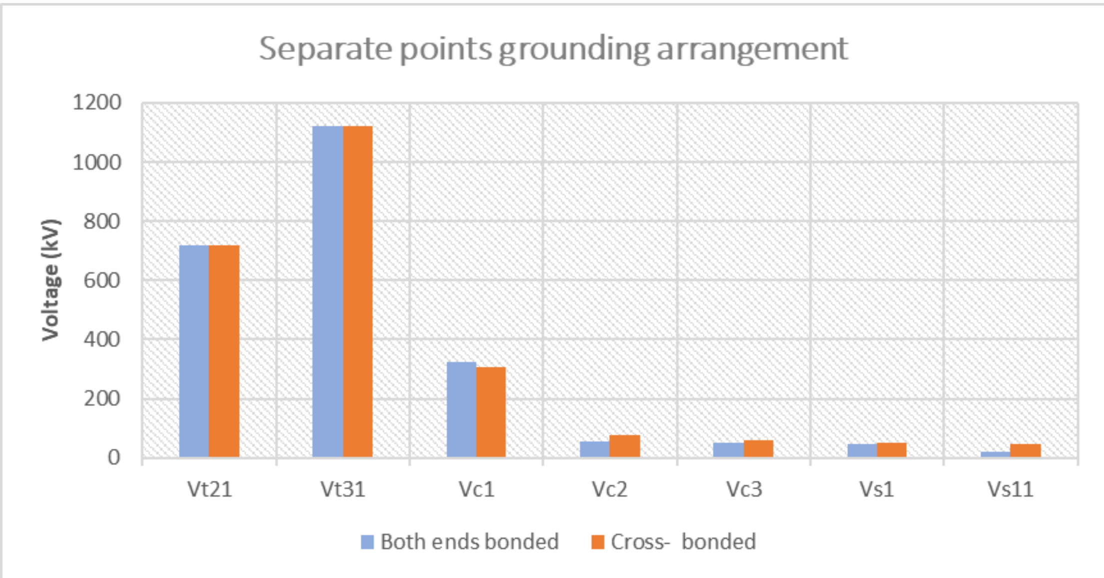


Figure 7:13 Impact of cross-bonding: Grounding method| 'separate point' s, Lightning| Phase conductor

In Figure 7:14, a comparison of maximum induced voltage in OHL and UGC, in case of grounding at 'different location' s has been done. Cross bonding does not impact the maximum voltage at Tower 3. In cable and sheath sections, there is a rise in voltage values.

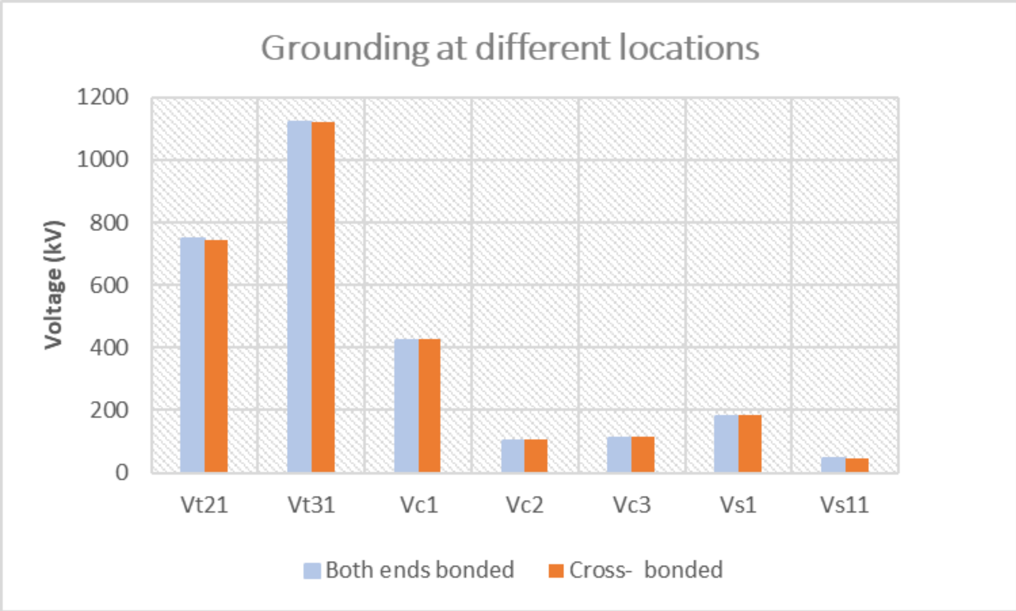


Figure 7:14 Impact of cross-bonding: Grounding method| 'different location' s, Lightning| Phase conductor

7.4 Summary

In this chapter, the impact of the grounding methods on lightning performance of the line, when lightning strikes the phase conductor has been evaluated. The induced over-voltages in the system have been analysed and a comparison has been drawn among the grounding methods. Among the three methods, the induced voltages are mostly lowest in case of 'separate point' grounding arrangement, thus it provides the better lightning performance. The impact of cross bonding has been analysed by drawing a comparison between both end bonded and cross bonded system. It has been summarized that cross bonding does not have a significant impact on the over-voltages seen by hybrid line. However, the wave shape is more distorted in case of cross bonding owing to fact that more discontinuity points are seen by the travelling wave due to impedance changes in cross bonded system. Furthermore, impact of distance of grounding location from the junction has been analysed. The grounding location does not have a significant impact on maximum over-voltages experienced by system.

8 Conclusion

In this chapter, the results, and outcomes of the Master thesis project ‘S*tudy on impact of lightning in hybrid cable – overhead lines’* has been summarized. Thereafter, future research perspective considering the limitation of the current project has been discussed.

8.1 Project summary

The objective of the project has been to analyse the impact of various grounding methods on the lightning performance of the hybrid line. Three types of grounding method namely *‘short circuit’* method where sheath and ground wires are short circuited and grounded at the same point at junction, ‘*separate point’* method where UGC and OHL have different grounding system at the junction and *‘different location’* method where cable is not grounded at junction but at the later location. Each of these methods has been assessed when hybrid line experience two types of lightning scenarios i.e. lightning strike on shield wire and lightning strike on phase conductor. Furthermore, two type of cable sheath connections has been considered i.e. cross bonded cable and cable with both end bonded.

In section 6, hybrid line under lightning where lightning strikes the shield wire has been analysed and discussed. It has been found that ‘*separate point’* grounding method provides the best performance, as the voltages induced in sheath and cable phase conductors is lowest, followed by the *‘different location’* and then *‘shot circuit’* grounding method. If we compare *‘short circuit’ method* with the others, the current travelling back into cable sheath is much higher in this method as compared to others because grounding system act as current divider circuit. However higher voltages are seen in cable at junction in case of *‘different location’* method compared to ‘*separate point’* method, as the cable section between junction and the point where its grounded is essentially a single point bonded system, thus standing voltages are seen in the cable sheath at junction, resulting in higher voltage values. As the distance of this grounding location is increased the current travelling back into sheath decreases, thus reducing sheath voltage at grounding point but this however does not impact the junction voltages. The maximum voltages in case of OHL are dependent predominately on the induced voltages due to coupling between shield wire and phase conductor. The cross bonding does not have significant impact on maximum voltages in case of lightning on shield wire. However, number of reflection voltages increases in cross-bonding as more discontinuity point for impedance are seen by travelling wave,

In section 7, lightning on phase conductor scenario has been analysed and discussed. The highest sheath voltage, cable voltage and OHL section voltages are observed in case of *‘different location’* grounding method followed by *‘short circuit ‘*and then separate location method. This happens due to induced voltages in cable sheath in case of the *‘different location’* method due to standing voltages. Higher sheath voltages are observed in case of the cross bonding of cable sheaths. Changing the location of sheath grounding in case of *‘different location’* method changes the sheath voltage owing to the change in sheath current flowing back from the ground due to change in impedance of grounding circuit. However, these changes do not have impact on the phase where lightning strike has been simulated.

In both the scenarios, '*separate point'* grounding method provides better performance owing to fact that lesser current flows back into cable sheath due higher impedance and since cable is grounded at both ends there are not standing voltages.

8.2 Future work

This project provides a comparison of lightning performance analysis of different grounding schemes under two different lightning scenarios. However, the simulation model can be made more accurate to imitate the real-life behaviour of the system under lightning. The future research perspective can incorporate the following:

- In the model, attenuation of current while travelling in ground has not been considered, a more accurate model for current propagation and attenuation in ground can be developed. This shall provide more accurate results in case of 'separate point' and 'different location' grounding methods.
- The footing impedance model can be improved by incorporating the frequency dependence of the impedance and soil ionization.
- The surge impedance model of the tower can be improved by incorporating the surge impedance of the tower crossarms.
- For the course of the project back flashover due to lightning has not been studied. Impact of different grounding methods on performance of line under back flashover can be addressed in the future work.

9 References

[1] A. Devaraj, K. Papadopoulos, S. S. Sabnis and V. Jalaik, "Automatic Reclosing of Hybrid Transmission Lines (OHL-Cable)," Aalborg University, Aalborg, 2021.

[2] IEEE Standards Board, "IEEE Guide for Improving the Lightning Performance of Transmission Lines," *IEEE Std 1243-1997,* p. 44, 1997.

[3] E. Csanyi, "Electrical Engineering Portal," 9 October 2017. [Online]. Available: https://electrical-engineering-portal.com/electric-power-systems. [Accessed 10 March 2023].

[4] Energinet, "Technical Issues Related to New Transmission Lines in Denmark," 28 September 2018. [Online]. Available: https://energinet.dk/media/g45ft5ay/technical-issues-related-to-new-transmission-lines-in-denmark.pdf. [Accessed 14 March 2023].

[5] Energinet, "Uddrag fra netudviklingsplan 2013 vedrørende 132/150 kv-kabellægningen (Extract from network development plan 2013 regarding the 132/150 kv cabling)," May 2013. [Online]. Available: https://energinet.dk/media/x0hhoec4/netudviklingsplan-2013.pdf. [Accessed March 2023].

[6] J. Machowski, Z. Lubosny, J. W. Bialek and J. R. Bumby, Power System Dynamics, Stability, and Control (Third Edition), New Jersey, USA: Wiley, 2020.

[7] J. D. Glover, T. J. Overbye and M. S. Sarma, Power System Analysis & Design, Boston, USA: CENGAGE Learning, 2016.

[8] Wat Electrical, "WatElectrical.com," 28 November 2020. [Online]. Available: https://www.watelectrical.com/what-is-acsr-conductor-designtypes-properties/. [Accessed 17 March 2023].

[9] T. Ebdrup, D. Olason, C. L. Bak and F. F. D. Silva, "Comparison of Overhead Line Lightning Performance Based on Two Different Tower Geometries," CIGRE International Colloquium on Lightning and Power Systems, Lyon, 2014.

[10] J. L. Y. C. H. D. and Y. Z. , "Development of phase domain frequency-dependent transmission line model on FPGA for real-time digital simulator," Electric Power Systems Research, Winnipeg, Canada, 2021.

[11] S. Visacro and H. F. Silveira, "Lightning Performance of Grounding Systems of Overhead Lines," International Conference on Lightning Protection (ICLP), Shanghai, China, 2014.

[12] S. Visacro, F. H. Silveira and A. De Conti, "The Use of Underbuilt Wires to Improve the Lightning Performance of Transmission Lines," IEEE, 2012.

[13] J. Schlabbach and K.-H. Rofalski, Power System Engineering - Planning, Design, and Operation of Power Systems and Equipment, Singapore: Wiley-VCH, 2011.

[14] Brugg Cables, "Technical user guide of high voltage XLPE cable systems," January 2017. [Online]. Available: https://bruggcables.com/. [Accessed March 2023].

[15] A. a. Ametani, T. Ohno and N. Nagaoka, Cable system transients : theory, modeling and simulation, John Wiley & Sons, 2015.

[16] V. M. Martinez, E. A. Uzcategui and P. R. Jimenez, "Study of Lightning Overvoltages in Valcor-Guanta II 230kV Overhead Transmission Line," IEEE, 2006.

[17] K. Lenarczyk and M. Loboda, "Shutdowns of 220 kV and 400 kV power transmission lines caused by winter lightning strikes in Poland in January 2022," International Conference on Lightning Protection (ICLP), Cape Town, 2022.

[18] M. Laboda and K. Lenarczyk, "Correlation between recorded CG lightning discharges and shut-downs of selected HV overhead power transmission lines in Poland," International Conference on Lightning Protection (ICLP), Shanghai, 2014.

[19] H. Cai, L. Jia, G. Liu, S. Hu, J. Shi, H. He, X. Zhao and J. He, "Lightning performance of EHV and UHV overhead transmission Lines in China southern power grid," International Conference on Lightning Protection (ICLP), Estoril, Portugal, 2016.

[20] I. M. Rawi and M. Z. A. A. Kadir, "Investigation on the 132 kV overhead lines lightning-related flashovers in Malaysia," International Symposium on Lightning Protection (XIII SIPDA), Balneario Camboriu, Brazil, 2015.

[21] B. B. S. Harsono, P. A. A. Pramana and Sriyono, "A Concept for Overhead Transmission Line Performance Evaluation toward Lightning Strikes," *ICT-PEP,* p. 5, 2022.

[22] Junior, F. M. d. Magalhaes and F. V. Lopes., "Mathematical Study on Traveling Waves Phenomena on Three Phase Transmission Lines - Part I: Fault-Launched Waves," *IEEE,* vol. 37(2), pp. 1151-60, 2022.

[23] D. Xinzhou, "Fault Traveling Wave Theory," in *The Theory of Fault Travel Waves and Its Application*, Springer, 2022, pp. 85-154.

[24] W. C4.23, "Procedures for Estimating the Lightning Performance of Transmission Lines – New Aspects," *CIGRE ,* 2021.

[25] F. Massaro, G. Morana and R. Musca, "Transient Behaviour of a "Mixed" Overhead-Cable EHV Line under Lightning Events," IEEE, Palermo, Italy, 2009.

[26] Y. Huangfu, S. Wang and X. Tao, "Transient Lightning Impulse Performance Analysis for Composite Transmission Line Tower," *IEEE,* vol. 57, no. 5, pp. 1103-11, 2015.

[27] H. Zhang, "Transient Lightning Impulse Performance Analysis of a Fully Composite Pylon with an External-grounding Down-lead," Aalborg Universitetsforlag, 2022.

[28] Mestriner, Daniele, R. A. R. d. Moura, R. Procopio and M. A. d. O. Schroeder, "Impact of grounding modeling on lightning-induced voltages evaluation in distribution lines," *Applied Sciences,* vol. 11, no. 7, p. 2931, 2021.

[29] R. S. Rashak and W. S. Majeed, "MODELLING AND ANALYSES OF OVER-VOLTAGE IN 400 KV OVERHEAD TRANSMISSION LINE CAUSED BY LIGHTNING STRIK," *Journal of Engineering and Sustainable Development,* vol. 25, pp. 1-1-204, 2021.

[30] IEEE, "IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System," *IEEE,* 2012.

[31] U. S. Gudmundsdottir, "Modelling of long High Voltage AC Cables in the Transmission System," Department of Energy Technology, Aalborg University, 2010.

[32] IEEE, "IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines," *IEEE,* 2010.

[33] A. R. Hileman, Insulation Coordination for Power Systems, Boca Raton, Florida, USA: Taylor & Francis Group, 1999.

[34] NKT Cables, *HV cables with Longitudinal Water-Blocking System,* Copenhagen: NKT Cables, 2018.

[35] P. S. Kumar and S. Das, "Study of Lightning Phenomena on UG Cable based on Soil Resistivity," IEEE CATCON, Bangalore, India, 2015.

[36] N. Klairuang, T. Khatsaeng and J. Hokierti, "Lightning Electric Field in the Soil and Its Effect to Buried Cables," IEEE.

[37] H.-T. Chang, "Protection of buried cable from direct lightning strike," IEEE, 1980.

[38] R. a. W. S. M. S. Rashak, "MODELLING AND ANALYSES OF OVER-VOLTAGE IN 400 KV OVERHEAD," *Journal of Engineering and Sustainable Development,* vol. 25, pp. 1-1-204, 2021.

[39] D. Gagari, "Ferranti Effect in Transmission Line," *International Journal of Electrical and Computer Engineering,* vol. 2, no. 4, pp. 447-51, 2012.

10 Appendix

10.1 Appendix A : Table for Expressions of the Striking Distance for different sources

Source	r_c		r_g	
	A	B	A	B
Wagner & Hileman	14.2	0.42	14.2	0.42
Young	$\gamma r_g{}^{e}$	0.32	27.0	0.32
Armstrong & Whitehead	6.7	0.80	6.0	0.80
Brown & Whitehead	7.1	0.75	6.4	0.75
Love	10.0	0.65	10.0	0.65
Anderson & IEEE-1985	8.0	0.65	$\beta r_c{}^{a}$	0.65
IEEE-1991 T&D Committee	8.0	0.65	$\beta r_c{}^{b}$	0.65
IEEE-1992 T&D Committee	10.0	0.65	$\beta r_c{}^{c}$	0.65
Mousa & IEEE-1995 Substations Committee	8.0	0.65	8.0	0.65

[a]β = 0.64 for UHV lines, 0.80 for EHV lines and 1.00 for others

[b]$\beta = 22/y$, y = phase conductor height, $0.6 < \beta < 0.9$

[c]$\beta = 0.36 + 0.17 \ln(43-h)$, if $h > 40$ then $h = 40$, h = shield wire height

[d]For masts, Mousa uses an A of 8.8

[e]$\gamma = 444/(462-h)$ for $h>18$m, $\gamma = 1$ for $h < 18$m

Data obtained from reference [33]

10.2 Appendix B : Table for constants

Parameter	Shielding failure domain (I<20 kA)	Backflash domain (I<20 kA)
M	61	33.3
β	1.33	0.605

Data obtained from reference [9]

This page has been intentionally left blank