MODELLING OF LIGHTNING SURGE PROPAGATION IN RAILWAY TRACK AND PROPOSE AN EFFECTIVE PROTECTION SYSTEM

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Degree of Master of Science

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May 2018

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Science in Electrical Installation

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Abstract

The Signalling Network is considered as the brain of the Railway Department, which ensures the safety of the train operations as well as for enhancement of the capacity of trains in the network. The track circuit is the basic logic circuit, which uses in all the other major circuits for selecting and locking routes for trains. Since these track circuits are directly connecting to the rails, it is critically important to protect those track circuits and other expensive equipment connected via track circuits from direct and indirect lightning surges through rails. Rails are the main invasion path of lightning surge into the railway signalling system.

So far, the railway department has not properly standardized the surge protection devices attached to the signalling system and it directly affects the railway operations and train delays, which may cause social disruption.

Since it is among the major concerns of the signal department is struggling with; this thesis addressed the issue by analysing characteristics of the rail and connected circuit components and all possible paths where surges can be entered into the system. Simulation has done by using the rail model prepared using PSCAD software and ground test results were validated with them.

Direct and indirect surge currents were calculated theoretically for 50 kA, 100 kA and 200 kA surges of 10/350 μS and 8/20 μS by applying the calculated surge currents to the above rail model. Induced surge currents of injected rail and induction rail were obtained graphically for different rail lengths.

Finally, by analysing all above results and protection levels of different surge protecting devices, this thesis suggests Category A type surge-protecting device according to IEEE C62.41.2 standard as the best suitable and economical type for including in the track circuits to avoid damages through surge currents via rail lines.

Keywords: *Track circuit, Surge current, Surge Protecting Devices, induced rail, induction rail, rail characteristics, PSCAD*

Acknowledgement

I would like to express my sincere gratitude to my thesis supervisor Dr. Asanka Rodrigo for providing guidance and for his cordial support throughout the thesis. His support and motivations were invaluable driving forces for me for the successful accomplishment of this study. It is for me a great pleasure and a great experience to have worked under such a friendlier supervisor, who is having a broad scientific knowledge related to lightning surges and SPDs.

I am also very grateful to my masters' coordinator Dr. Prasad for his precious advice on thesis writing and for providing useful suggestions for the thesis.

I would like to thank Chief Signal and Telecommunication Engineer Mr. J.I.D.Jayasundara, Deputy Chief Signal and Telecommunication Engineer Mr.K. Thushiyanthan, Signal Engineer Ms.K.A.C. Seneviratne and Signal Engineer Mr.K.S.R.R. Ariyaratne

Furthermore, I would like to thank everybody who has supported me throughout the entire process, both by keeping me harmonious and helping me putting pieces together.

W.I.Jayatunga

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List of Abbreviations

SLSI	SriLanka Standards Institute
IEC	International Electrotechnical Commission
ANSI	American National Standards Institute
IEEE	Institute of Electrical and Electronics Engineers
SPD	Surge Protection Devices
SLR	SriLanka Railway
PSCAD	Power System Computer Aided Design
FE	Feeding End
RE	Relay End
FDTD	Finite Difference Time Domain method
GDT	Gas Discharge Tube
TOV	Transient Over Voltage

CHAPTER 1

INTRODUCTION

Railway signalling system is used to ensure the safe operation of railway traffic. Effective and economical lightning protection system is essential for Sri Lanka railway signalling systems in-order-to minimize interruption to railway operations and train delays due to lightning damage, which may cause social disruption as well. In general, the railway signalling systems are set up by the wayside and directly connected to the rails through cables. Therefore, the rails are the main invasion path of lightning surges to get into the railway signalling system. The effect and the damage of lightning over-voltages are varying with the distance from the origin of the lightning strike to the position of the device as well as the strike current generated due to lightning. From this correlation, the lightning hazard occurrence probability for railway signalling systems can be estimated against lightning conditions.

1.1 International Standards

Since there are no standards stipulated by SLSI for railway systems, we are using international standards as described by IEC, ANSI/IEEE and Australian standards.[1]

1.2 Railway Signalling System

Railway signalling system is needed for ensuring the safe operation in rail traffic. The signal devices are located on the side of the railway line to give information of the state of railway line ahead to train drivers. The efficiency and the safety of the railway network highly depends on the signal system. Failure of the signal system may cause cancellation of trains or in the worst case catastrophic accidents. Therefore, SLR has taken a few actions to keep its signalling system up to the International Standards. However, due to economic limitation and other infrastructure limitations, still SLR signalling system has not achieved the modern international standards. Presently, the signalling system consists of few models starting from an early model of 1960's to the least model in late 2012's. Signalling system consists of early 1990's Electronic system in Colombo – Periyanagavillu line up to

Bangadeniya. Modern signalling system has been installed in Southern line from Kalutara North after Tsunami catastrophe. Northern line is constructed with a modern signalling system. The rest of the network is basically running with old signalling methods.

Failures in signalling system may happen due to few reasons such as human negligence/failures, electrical/electronic failures, sabotage etc. Electrical and Electronic failures may cause mainly due to the breakdown of electrical systems or damages cause on sensitive electronics by high voltage surges. These surges are mainly caused by switching impulses and lightning. Even though there are no any major damages reported by SLR due to failures of signalling system by surges, a considerable number of delays and cancellation of trains have been reported.

A study conducted by IEC (International Electrotechnical Commission) in several countries revealed that the financial loss (cost of damages) due to lightning is the second major reason while negligence in handling equipment tops the list.

Table 1.1: Losses (Cost of Damages) Due to Various Reasons [2]

Cause	Loss as % of Total Loss
Negligence	36.1
Surges	27.4
Burglaries	12.9
Floods/Storms	6.9
Others	16.7

1.3 Reported Damages on SLR Signalling System

Surge protection is a very important part of railway signalling system. Surge generated by lightning or switching impulses may destroy or deteriorate the sophisticated electronic components of the signalling system. In order to minimize the damages, suitable surge protection devices (SPDs) should be installed at appropriate positions. Most of the damages reported by SLR are related to the burning of relays and rectifier circuits which are not severe damages. Since SLR is using a three type of signalling systems, installing of SPDs is a bit complicated process. However, this thesis report has proposed only a general recommendation for surge protection system.

1.4 Research Objectives

Railway signalling system consists of various types of signal, power and control cable lines connected from long distances. Usually, surge protective devices (SPD) are used as lightning protection devices. However, certain types of cable lines cannot have SPDs installed as it is difficult to achieve fail-safe condition with SPD installations. Thus the main objective of this study is to analyse the lightning hazard occurrence probability for railway signalling systems against lightning conditions, developing a model for an effective and economical Earthing system to protect electronic devices in the signalling system, minimize wastage for replacement of expensive equipment and introduce proper standard for railway signal to avoid lightning damages.

1.5 Research Methodology

As the first step to conduct this study, it was required to analyse the magnitude and the frequency of lighting over-voltages on signal cables and rails in railway signalling system while studying the characteristics of different signal cables, rails and other possible paths where surges can be entered into the system. The next step is to build-up a simulation model by using PSCAD with other relevant software applications for the analysis of best mechanism to minimize the impact of lightning strikes to the highly sensitive electronic equipment in the railway signalling system. By introducing surge voltages (direct and indirect) to the real rail and analysed the voltage propagation pattern along the rail for various rail lengths. Same surge voltage is also introduced to the PSCAD model, and it is validated by the model and analysed the voltage propagation through the rail model. Then calculated the probability of damage for one equipment from direct and indirect lightning surges through the rail length and proposed the best category of surge protection device to protect railway signal equipment from lightning surges.

1.6 Thesis Outline

The remaining chapters of the thesis report are organized as follows.

Chapter 2 describes the building up of a rail characteristics model in PSCAD software. Field test conducted for validation of the PSCAD model is described in chapter 3. Chapter 4 describes the Direct Lightning Model using PSCAD. In chapter 5, it describes the results of the simulated rail model. Proposed protection mechanisms are described in chapter 6. Chapter 7 contains the discussion and recommendations. Finally, chapter 8 describes the limitations of the study and future works.

CHAPTER 2

RAIL CHARACTERISTICS MODEL DESIGNED USING PSCAD

2.1 Railway Signal System

The signal system is the brain of the railway department that provides safe movements of trains, locomotives and all other rail running vehicles. The track circuit is the most famous concept for tracking train movements, train occupation and vacancy conditions along the railway network as well as the basic circuit component used for interlocking purposes. Since the whole railway signalling system depends on the track circuit components and the track circuits which are directly connected to the relay interlocking systems, it is important to maintain them in a proper manner to minimize interruptions to the daily train schedules [3].

2.1.1 Track Circuit

The indication of the train movements is taken through track circuits, mainly in the area of the central control system is in operation. The track circuit is a simple circuit, which includes following components and the arrangement of these components is shown in Figure 2.1.

- Track Relay
- Adjustable Resistors
- Rectifier and Power Supply
- Insulated Joints
- Surge Protecting Devices

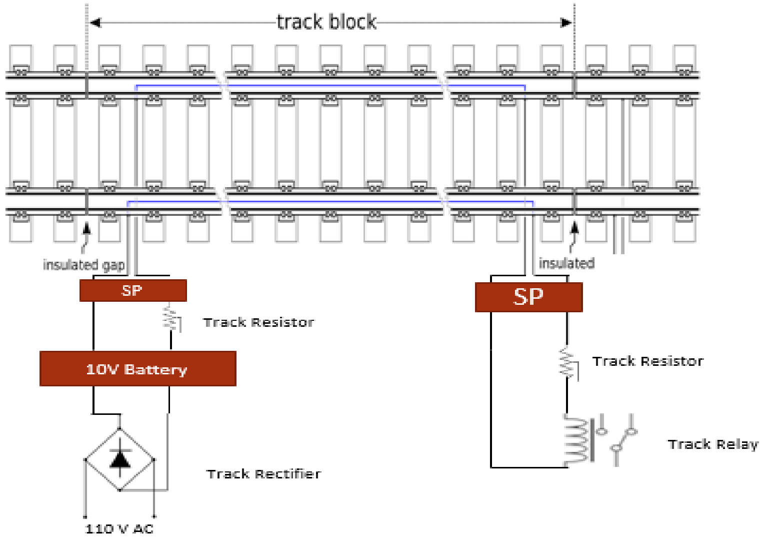

Figure 2.1: Track Circuit Model [4]

2.1.2 Components of Track Circuit

The track circuit is working at the voltage of 6V DC and it is difficult to transmit such a small voltage for a longer distance as the drop is higher. To avoid this, the general practice of railway signal department is enhanced by the transmission voltage to 110 VAC when transmitting to the required location. Then that 110 VAC drops down and converted to 10 VDC for the charging of the batteries at the feeding end of the track circuit. Currently, the railway department is using rechargeable batteries with track feed rectifiers. Variable resistors are used at both receiving and feeding ends of the track circuit for maintaining the relay voltage to 3.5 V at the receiving end.

Each and every adjacent track circuit is insulated by nylon ‘T’ shaped joint to separate them without passing current to the adjoining rail (Figure 2.2).

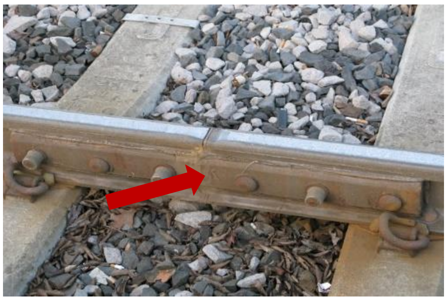

Figure 2.2: ‘T’ Insulator

Surge protectors are used in both ends at the connection point of rail to the circuit equipment.

2.1.3 Working Principle of the Track Circuit

The two ends of the circuit portion are called Feeding End (FE) and Relay End (RE) or Battery End as depicted in Figure 2.3. FE is the voltage source connected end and RE is the Relay connected side.

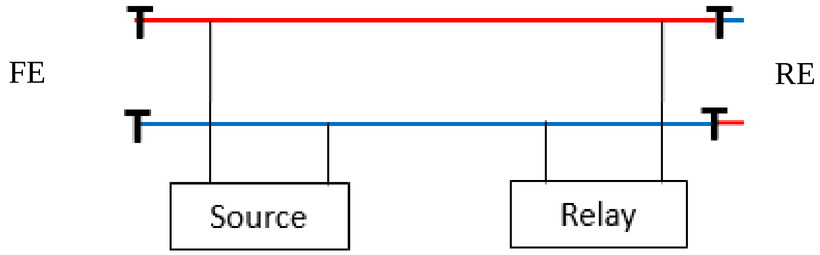

Figure 2.3: RE and FE of a Track Circuit

The track relay is normally in the picked-up condition when there is no occupation of trains on the track circuit portion; the supply voltage from the feeding end through rails to the receiving end as shown in the figure below energizes the relay.

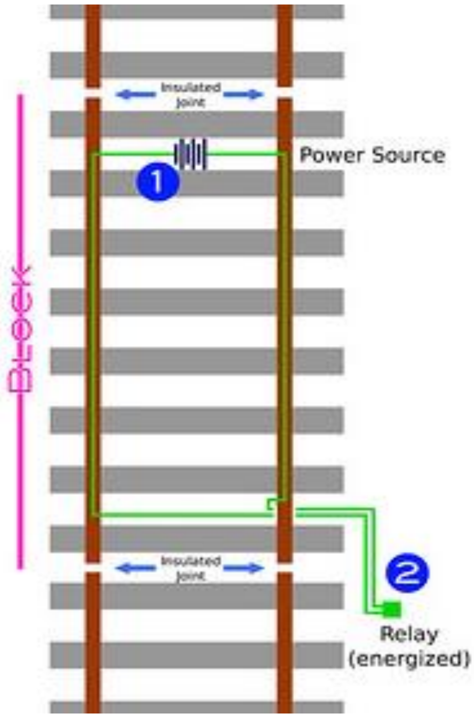

Figure 2.4: Unoccupied Track Circuited Area [5]

When a train occupies the track, the voltage drops across two parallel rails, as the connection become short-circuited through the axel of the wheel where the resistance is very low compared to the rail and then the RE become open circuited. Thus, the relay becomes de-energized and it comes to dropped condition. This has shown in a diagram below as Figure 2.5.

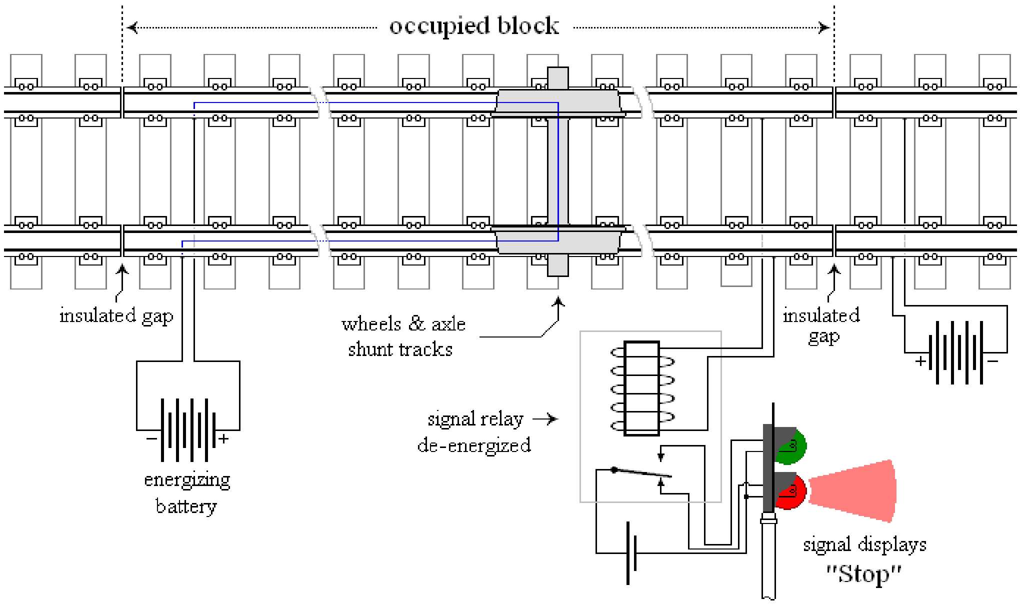

Figure 2.5: Track Circuit when Train Occupied [3]

The relay picked-up condition and the dropped condition are used as logic to identify the occupation and vacancy of the track portion.

2.2 Types of Track Circuits

Track circuits can be divided into two categories based on the status of the track relay.

i. Closed Track Circuit

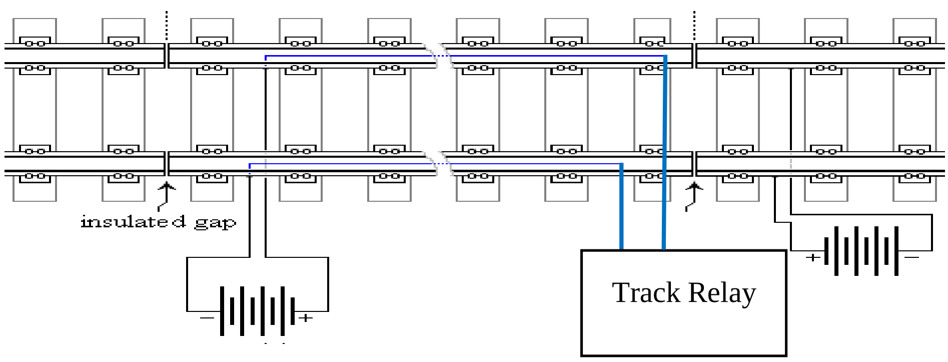

Figure 2.6: Closed Track Circuit [3]

This type of track circuits is used in the Sri Lanka railway network in most of the places. In this type, the track relay is normally in the picked –up condition and when train occupied the relay comes to dropped condition. Since it is considering the dropped condition of the relay as train occupation, route settings through this track portion for other trains cannot be done until the train moves solely from that track circuit. Therefore, in any track circuit failure, the relay is in dropped condition and it ensures the safety because a train cannot enter to that track area by giving signals until the failure of the track circuit is rectified. This known as 'Fail Safe'.

ii. Open Track Circuit

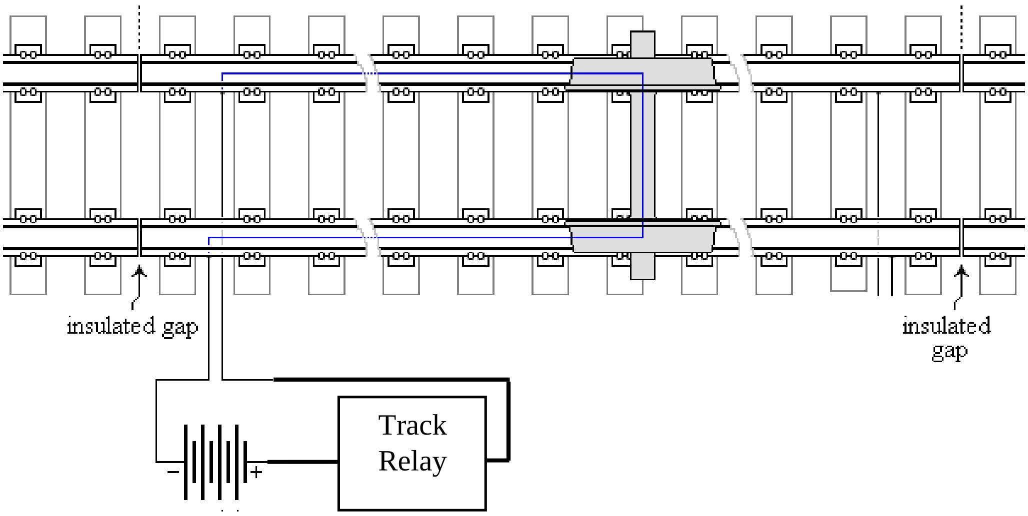

Figure 2.7: Open Track Circuit [3]

In open track circuits, the circuit is opened until the wheels of the rail vehicle come on to the corresponding track. The source and the rack relay is connected to the rail in the single end. The track relay is in dropped condition and when the train occupies, the relay picked up due to short-circuiting of the parallel rails through wheels and axle. Therefore, this method is considered as unsafe because it is unable to track failures in this type of track circuits until the train comes on to it.

Above discussed types are using both parallel lanes to connect the circuit.

iii. Single Rail Track Circuits

The track relay and the source for single rail track circuit are connecting to a single rail and the rail parallel to that is earthed. In this method also the relay is in picked-up condition and it drops when wheels of the train are on that track circuited portion as the current paths shown in green and red colours for both cases.

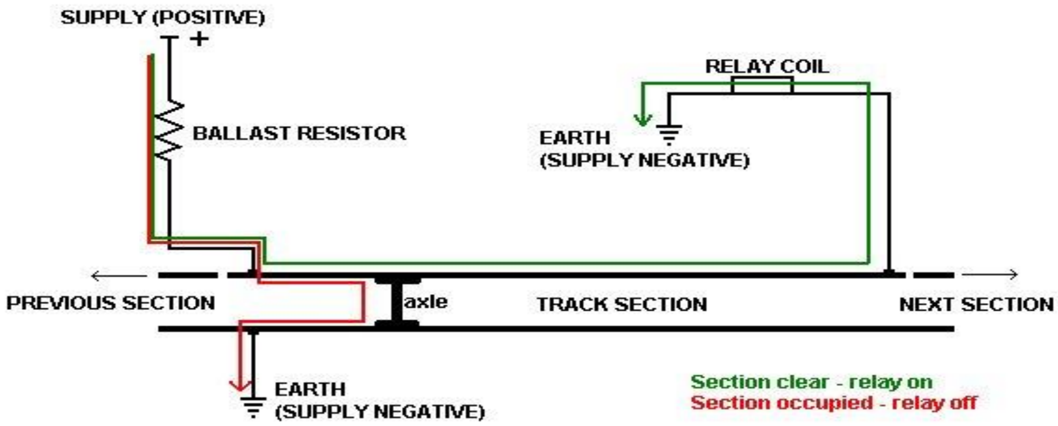

Figure 2.8: Single Rail Track Circuit

2.3 Surge Protecting Devices Used in Track Circuits in Sri Lanka Railway

As mentioned earlier, surge protectors use by the Sri Lanka railway department, mainly to protect expensive wayside equipment from direct and indirect lightning strikes through rails.

Even though the surge protectors are used at both ends of the circuit to protect electrical equipment from the surges strike on rails, so far the railway department has not done any detailed analysis to identify which class of surge arrester is the best to avoid such damages by minimizing the cost to the department. Without analysing various types of surge protection devices of different surge protection categories/levels which are being used in these track circuits at different places and it has become difficult to maintain a signal network free of lightning damages.

The railway department has to bear a large cost for these surge protection devices due to following two reasons;

i. **Using class A SPDs in locations where it is not necessary to use such a higher grade**
ii. **When it uses lower grade SPDs it costs for the department to replace them regularly**

Thus it is important for the railway department to analyse magnitude and impact of surges through rails and to declare a standard for surge protection devices for the use of track circuits, which minimizes unnecessary costs for high-grade surge protecting devices as well as to avoid frequent damages to costly devices attached to the signalling circuits through these track circuits

2.4 Surges and their Effects on Telecom Installations

Surges are a transient phenomenon involving the flow of currents and build-up of potentials of magnitudes several times higher the working currents and voltages, resulting in partial or complete damage of equipment or reduction in life span of components/equipment.

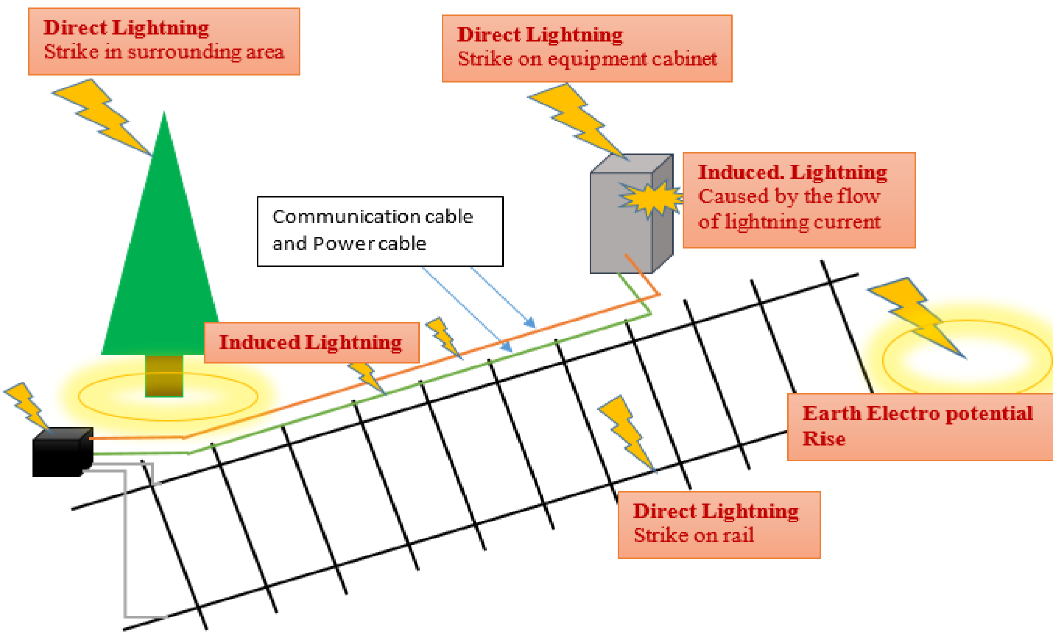

Figure 2.9: Direct and Indirect Lightning Surges on Wayside Equipment Cabinet

Since the equipment rooms are located in open places, they are highly vulnerable to direct strikes. If the instrument room is a metal track-side cabinet, it should be grounded properly. The earth resistance should be kept at low values. For brick or concrete buildings, the structural lightning protection should be done very carefully.

2.5 Literature Review

Lightning damages are often reported in railway signalling systems. This is because higher-voltage that occurs in the lightning has not been quantitatively analysed yet. Prior to this research, a deeper research was conducted regarding the presently available technologies and current research projects which are relevant to this task. Below literature review presents some of the findings. The use of surge protection to the signal and telecom equipment proposed methods to avoid lightning surges to the signal equipment cabinets, most affected areas of the railway lines, mitigation techniques, damage probability due to lightning surges and etc.

According to the research paper "The Lightning Risk Evaluation for Railway Signalling Systems based on Observation of Lightning Over-voltages" [6], the authors have measured lightning over-voltages in railway level crossing systems representing typical examples of wayside electronic signalling equipment at the field. The results enables the estimation of the occurrence probability of lightning damage caused by exceeding the withstand voltage of the level crossing system.

The authors measured lightning over-voltage on railway signalling cables laid on the ground surface, overhead power lines and rails in the field to enable quantitative analysis of the frequency of lightning over-voltage occurrence. The signalling cables, power lines and rails are components of railway signalling systems as shown in Fig. 2.10.

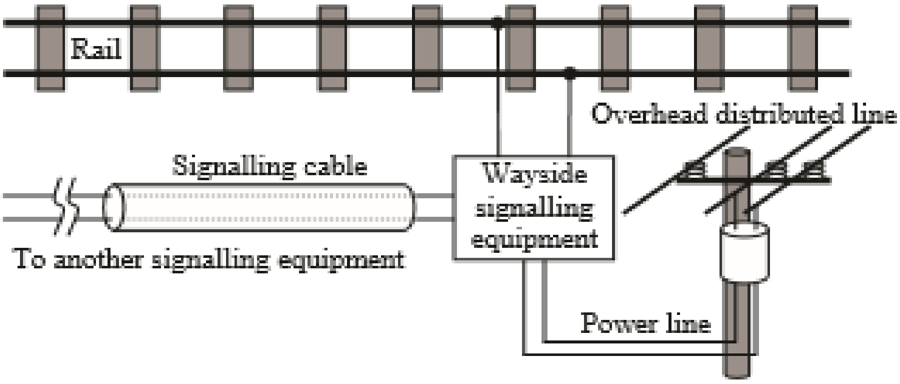

Figure 2.10: Structure outline of railway signalling system

They investigated the correlation of lightning over-voltage on signalling cables, power lines and rails with lightning conditions, such as the stroke current and the strike position (distance from the measuring position). From this correlation, the lightning risk for railway signalling systems against lightning conditions was estimated.

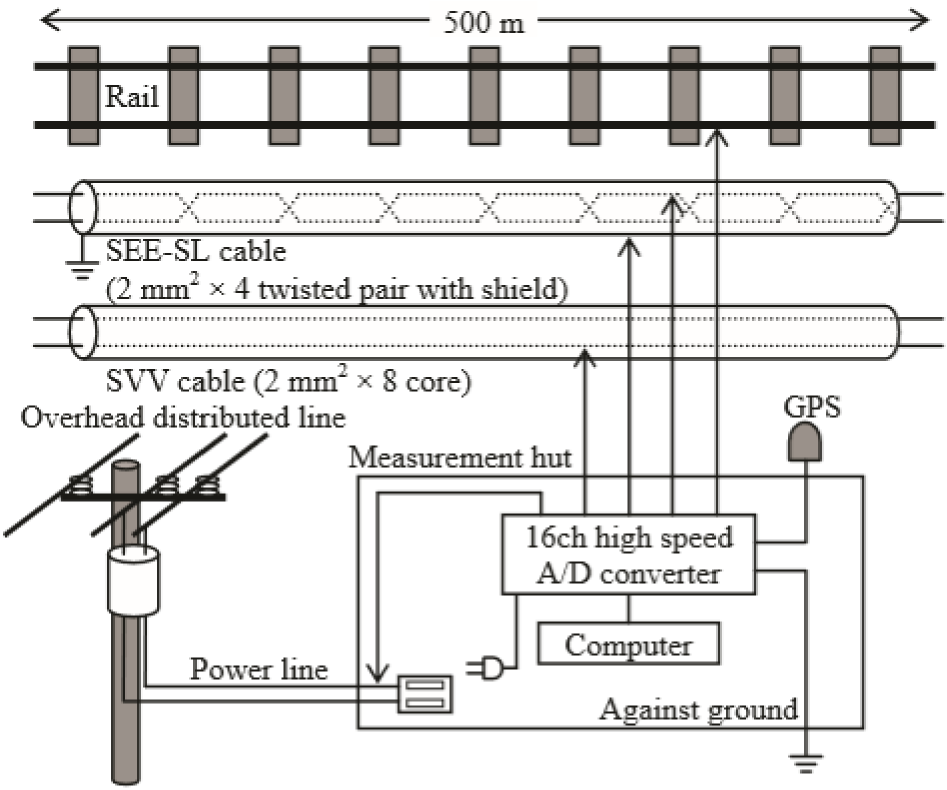

Figure 2.11: Measurement System

This paper describes the lightning risk evaluation for railway signalling systems in by considering the correlation of lightning over-voltage on signalling cables, overhead power lines and rails with lightning conditions, such as the stroke current and the strike position. They proposed the magnitude of lightning over-voltage on overhead power lines is approximately ten times higher than those on signalling cables laid on ground surface and rail. So signal equipment which uses electrical power from overhead cables are need to be protected using lightning protection equipment.

The paper titled “An Example of Lightning-Protection Measures in Railway Signalling Systems” [7] is described the effect of spare cables which are used in railway signal equipment. Railway signalling systems have various types of signal and control cable lines connected to them from long distances. Multi-core cables are used in those lines and usually, surge protective devices (SPDs) are used as a lightning-protection measure. However, certain types of cable lines cannot have an SPD installed on them from the fail-safe perspective, which may result in system failure caused by over-voltage when struck by lightning. As a way to make effective use of spare lines SPD is installed on other unoccupied lines

In this study, they used the FDTD method to examine the amount of over-voltage generated on equipment in the signalling system's equipment room and on the field site to evaluate the effectiveness of the method to mitigate the over-voltage. In this model, when no spare line is used, approximately 20V of over-voltage is generated per 1A of lightning current on the equipment located on the lightning side. Earth resistivity and grounding resistance can influence this voltage significantly: the higher the earth resistivity and grounding resistance, the larger the over-voltage is expected to become. Such over-voltage can be considered as a threat to signalling systems as they are becoming increasingly computerized today. The results of their examination reveal that the method of grounding spare lines at both ends is expected to have an inhibitory effect to mitigate such over-voltage.

As future work, they are planning to introduce other models that are more similar to actual equipment, by inserting a gas discharge tube (GDT) or other objects into spare cable lines, to perform further evaluations in conjunction with experiments.

The research paper “Measurement of current flowing through a rail with the use of Ohm’s method; determination of the impedance of a rail” [8] is described a method of measuring the current flowing through a rail. This method is based on voltage drop measurement.

For this method to be used correctly, it is necessary to know the resistance or impedance of the rail. A laboratory measurement was carried out, in order to determine the resistance and impedance of the rail, and subsequently, a rail substitution diagram was created based on laboratory measurement results. A practical measurement on a railway track was performed to verify this substitution diagram as well as the whole designed measurement methodology.

A pair of rails can be described as a passive circuit with distributed parameters. The following wave equations can be used to describe its behaviour.

$$\begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & -Z_o \sinh \gamma l \\ \frac{-sinh\gamma l}{Z_o} & cosh\gamma l \end{bmatrix} \text{x} \begin{bmatrix} U_1 \\ I_1 \end{bmatrix}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

R= Longitudinal resistance of the pair of rails (Per unit length)

L = Their Inductivity per unit length

C = Capacity per unit length

G = Leakage conductance

The method used to measure the current flowing through rails is based on measuring voltage drop on a segment of a certain length. An equivalent circuit of a rail was created for 50-650 Hz frequencies, as well as for DC current. Parameters of this equivalent circuit were determined on the basis of laboratory measurements performed on a 1m long sample piece of rail. It is verified that the proposed method is applicable on DC current measurement. Further experimentation is needed to be able to determine the applicability of this method on AC current measurements.

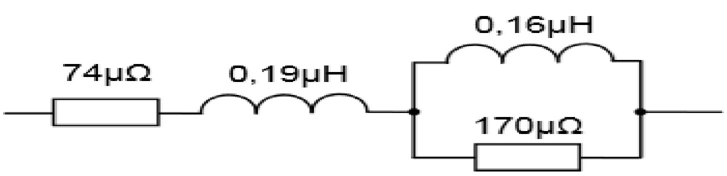

Figure 2.12: Equivalent circuit for determining the impedance of a 1m long rail sample

According to the research paper "Analytical study on lightning over-voltage of rail track and railway signalling equipment" [9] a calculation model is proposed for the surge propagation characteristics along the rails. The results of surge impedance and surge propagation velocity calculated by the proposed model almost verify with the experimental results. Moreover, this paper proposes a calculation model of the lightning over-voltage on the railway signalling equipment. The calculation model consists of the rail model and the equivalent circuit model of signalling equipment. They indicated the validation of the calculation model of the railway signalling equipment with the results of the field test. This model is applicable to the development of lightning protection measures for the railway signalling systems.

They carried out field experiments on the following.

1. Measurement of the surge impedance of the rail and the surge propagation velocity in the rail
2. Measurement of the surge attenuation ratio in the rail

This paper proposes a calculation model of the surge propagation characteristics along the rails. Moreover, this paper proposes a calculation model of the lightning over-voltage on the railway signalling equipment and describes the results of the field tests, the components of proposal calculation model, and the comparison between experimental results and theoretical results.

This paper explains that the experimental results are concerned with the surge propagation characteristics of the rail and the calculation model for surge analysis that can reflect the experimental result. Moreover, this paper proposes a lightning surge calculation model for the level crossing equipment representing typical examples of wayside electronic railway signalling equipment.

This paper proposes a calculation model of the surge propagation characteristics along the rails. The results of surge impedance and surge propagation velocity calculated by the proposed model almost agree with the experimental results. Moreover, the proposed model can ca1culate the surge attenuation along the rails.

Moreover, it is proposed the calculation model of the lightning over-voltage on the railway signalling equipment. The calculation model consists of the rail model and the equivalent circuit model of signalling equipment. The calculation model is applicable to develop the lightning protection measures for the railway signalling systems.

2.6 Lightning Surge Propagation Model along the Rails

The calculation model of the surge propagation characteristics along the rail model is shown in Figure 2.13. As shown in Figure 2.13, the model forms eight divisions of the rail with length 293 m. When the number of partitions is lesser, the admittance component of the rail is added as the concentrated constant against 1 place. If the number of partitions is too small, the model becomes troublesome. The track was non-electrified and the property that equivalent cylindrical body radius is same as usually used in normal tracks.

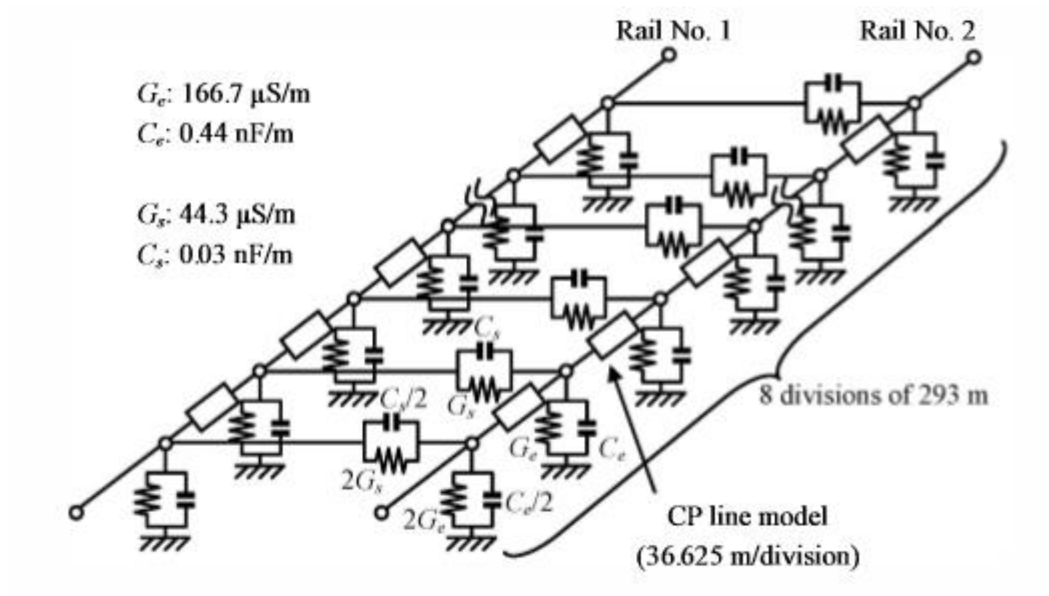

Figure 2.13: Rail Model for Surge Propagation [9]

2.7 Modelling the Real Rail line in PSCAD Software

By using PSCAD software version 4.5.0.0 real rail line was modelled according to the Figure 2.13. The steep-front current was injected to the simulated model for analysing the voltage characteristics of the rail.

C_s = 0.03 µF/m	G_e = 166.7 µS/m	$R_1=3.3\times10^{-3}\Omega$	$R_2=3.4\times10^{-3}\Omega$
G_s = 44.3 µS/m	C_e = 0.44 µF/m	$L_1=3.0\times10^{-6}$H	$L_2=3.0\times10^{-6}$H
$R_3=1.48\times10^{-3}\Omega$			

Where G_e is the conductance between the rail and the ground (S/m), Gs is the conductance between rails (S/m), C_e is the capacitance between the rail and the ground (F/m), C_s is the capacitance between rails (F/m)

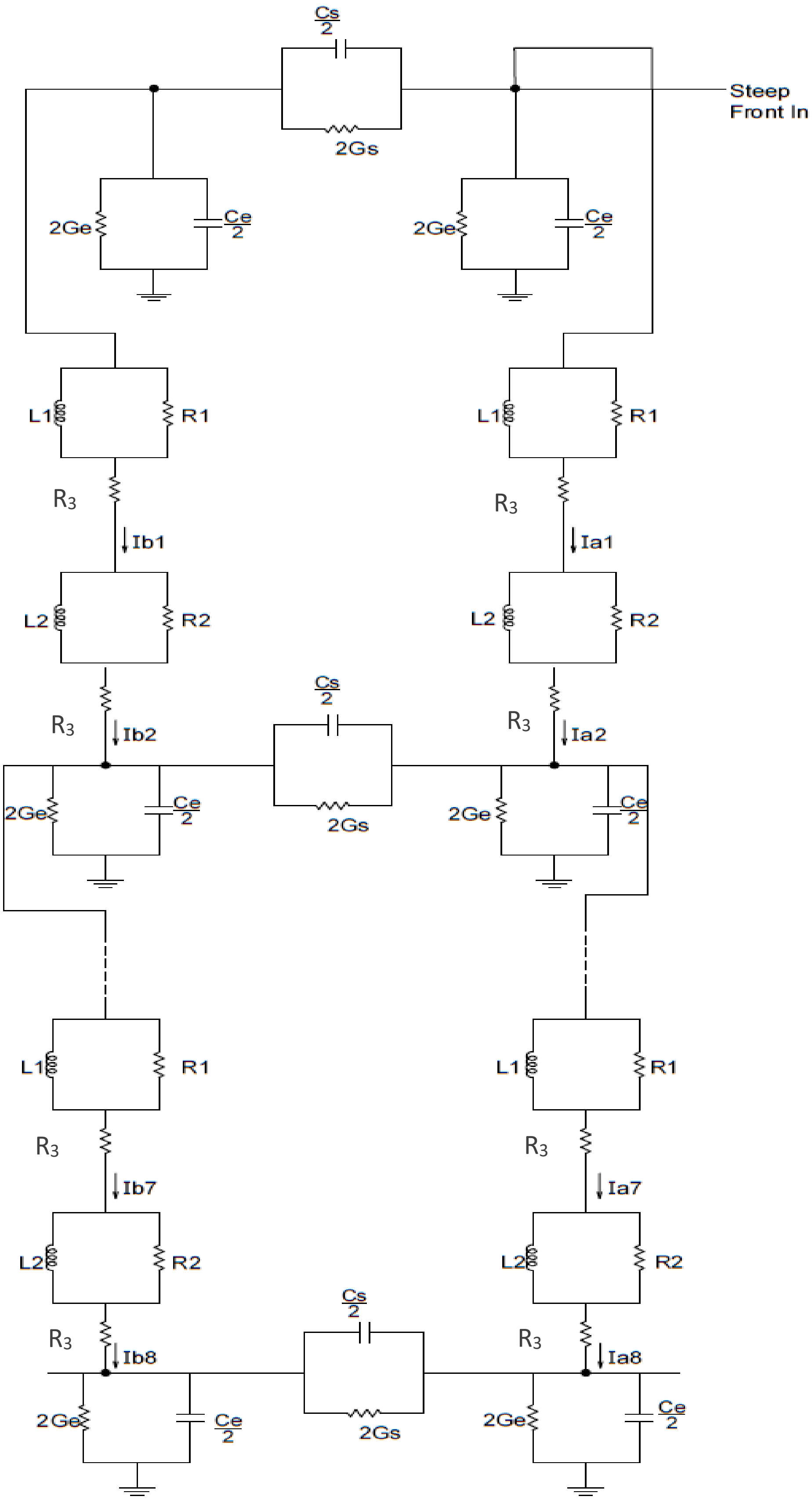

Figure 2.14: Railway Track Steep Front Analysis

CHAPTER 3

VALIDATION OF THE PSCAD RAIL MODEL

3.1 Lightning over-voltage analysis by real rail model

The rail used in conventional lines in Sri Lanka, which is called the 90N, has the property of equivalent cylindrical body and measured ground resistivity of 534 Ωm. The validity of the proposed calculation model is analysed by comparing the results of the field test.

- As shown in Figure 3.1, In an actual railway line, the given setup was arranged and measured the voltage drop along the rail. By using the signal generator and power supply, 10V with the 1/100 µs pulse was given into the actual rail and PSCAD model for validating the rail. Then measured the voltage drop along each rail portion and measured the peak-to-peak voltage for both cases.

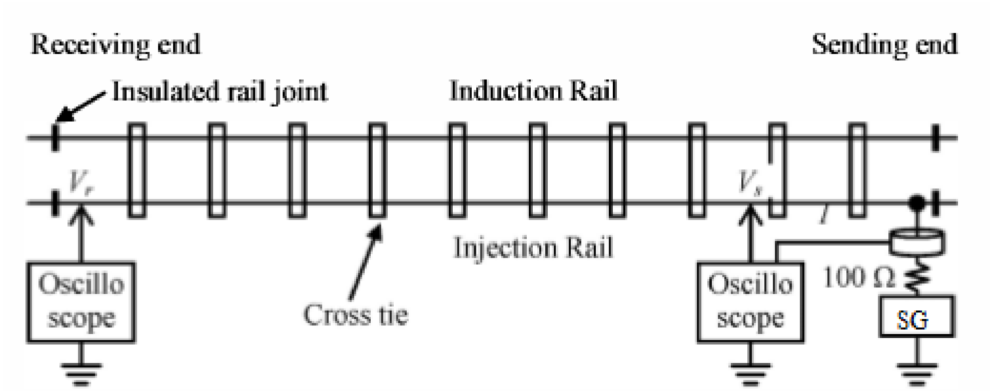

Figure 3.1: Outline of Field Test

Obtained output voltage values are tabulated and a graph is drawn for each value along the real rail. The total length of the real rail line is 293 m and it is divided into eight equal rail portions and measured the output voltage in each length. 'T' insulation joints are used to separate them into portions and isolate them. And 'U' bonds used to connect them.

Observations are tabulated below by obtaining maximum voltage drop along the real rail.

Table 3.1: Maximum voltage drop along the real rail line

Rail Length (m)	Max: Voltage drop along the real Rail (V)
0	10.000
36.625	8.459
73.250	8.211
109.875	7.762
146.500	7.435
183.125	7.113
219.750	6.864
256.375	6.512
293.000	6.121

3.2 Comparison between real rail model and PSCAD model obtained results

Same conditions were created to both real rail and obtained PSCAD model. Then applied the same voltage levels to both conditions. After that compared the real rail value data and simulation results data and compared obtained results by calculating error percentage values.

Table 3.2: Results comparison between real rail model and PSCAD model

Rail Length (m)	Maximum voltage drop along the real rail (V)	Maximum voltage drop along the PSCAD model (V)	Error with real rail line (V)	Percentage error %
0	10.000	10.0	0	0
36.625	8.459	9.60	1.141	13.49
73.250	8.211	9.20	0.989	12.04
109.875	7.762	8.80	1.038	13.37
146.500	7.435	8.40	0.965	12.98
183.125	7.113	8.00	0.887	12.47
219.750	6.864	7.60	0.736	10.72
256.375	6.512	7.20	0.688	10.57
293.000	6.121	6.80	0.679	11.09

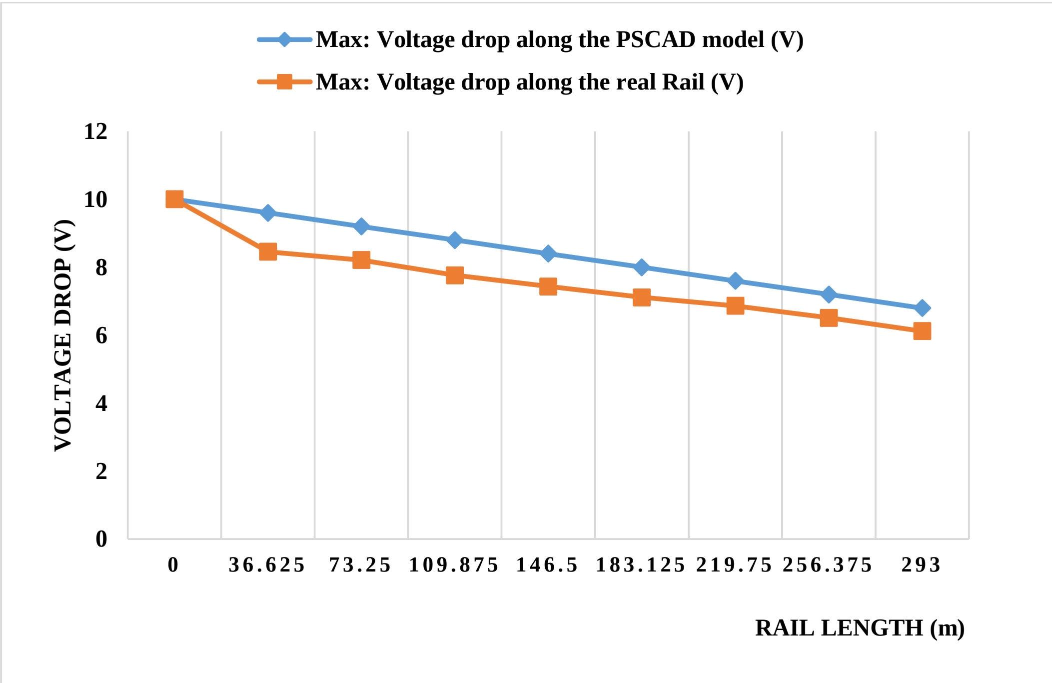

Figure 3.2: Voltage propagation pattern along the real rail line and PSCAD model

The voltage propagation along the PSCAD model railway line has small deviation compared to the voltage propagation along the field test values.

This can happen due to field condition, ground condition and properties of sleepers used in Sri Lanka. By varying parameters, the error percentage of the model was minimized to bring it closer to the actual parameters of the real rail model.

Table 3.3: Results comparison between real rail model and PSCAD model

Rail Length (m)	Maximum voltage drop along the real rail (V)	Maximum voltage drop along the PSCAD model (V)	Error with real rail line (V)	Percentage error %
0	10.000	10	0	0
36.625	8.459	9.2	0.741	8.75
73.250	8.211	8.8	0.589	7.17
109.875	7.762	8.5	0.738	9.50
146.500	7.435	7.9	0.465	6.25
183.125	7.113	7.5	0.387	5.44
219.750	6.864	7.3	0.436	6.35
256.375	6.512	6.8	0.288	4.42
293.000	6.121	6.5	0.379	6.19

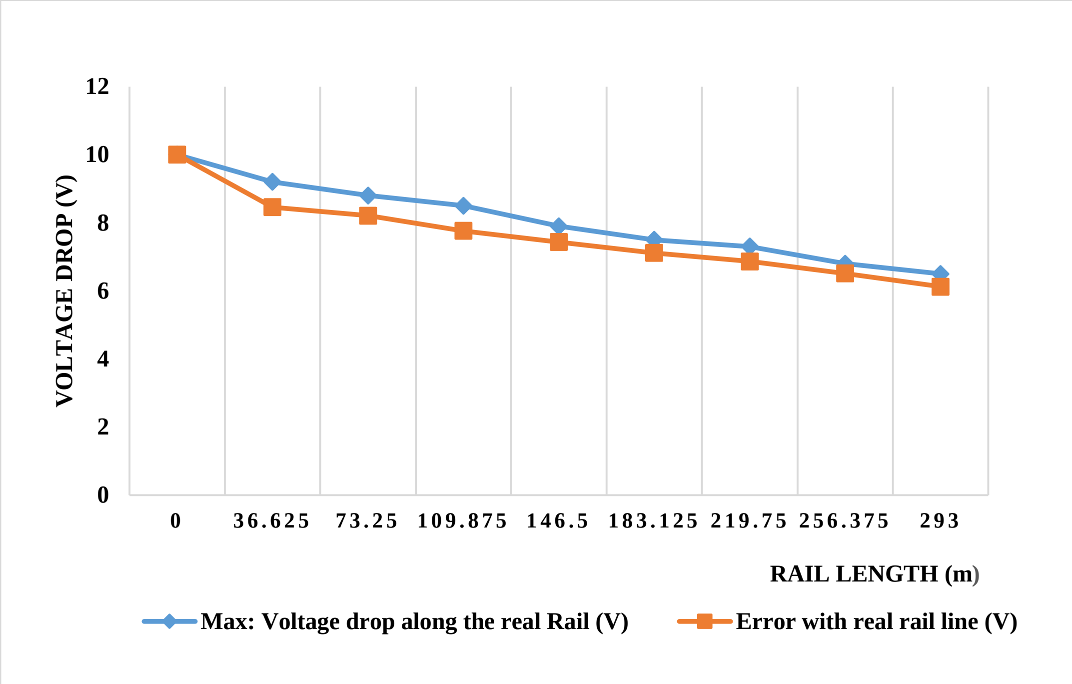

Figure 3.3: Voltage propagation pattern along the real rail line and PSCAD model

Table 3.4: Results comparison between real rail model and PSCAD model

Rail Length (m)	Maximum voltage drop along the real rail (V)	Maximum voltage drop along the PSCAD model	Error with real rail line (V)	Percentage error %
0	10.000	10	0	0
36.625	8.459	8.7	0.241	2.84
73.250	8.211	8.5	0.289	3.51
109.875	7.762	8.2	0.438	5.64
146.500	7.435	7.8	0.365	4.91
183.125	7.113	7.5	0.387	5.44
219.750	6.864	7.3	0.436	6.35
256.375	6.512	6.8	0.288	4.42
293.000	6.121	6.5	0.379	6.19

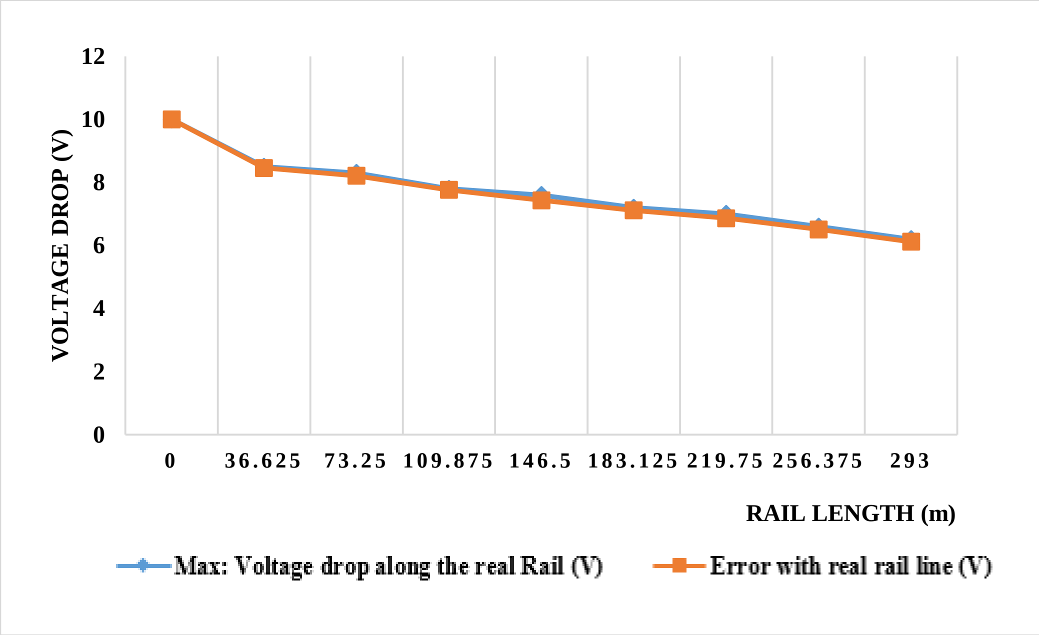

Figure 3.4: Voltage propagation pattern along the real rail line and PSCAD model

Table 3.5: Results comparison between real rail model and PSCAD model

Rail Length (m)	Maximum voltage drop along the real rail (V)	Maximum voltage drop along the PSCAD model (V)	Error with real rail line (V)	Percentage error %
0	10.000	10	0	0
36.625	8.459	8.5	0.041	0.48
73.250	8.211	8.3	0.089	1.08
109.875	7.762	7.8	0.038	0.49
146.500	7.435	7.6	0.165	2.22
183.125	7.113	7.2	0.087	1.22
219.750	6.864	7	0.136	1.98
256.375	6.512	6.6	0.088	1.35
293.000	6.121	6.2	0.079	1.29

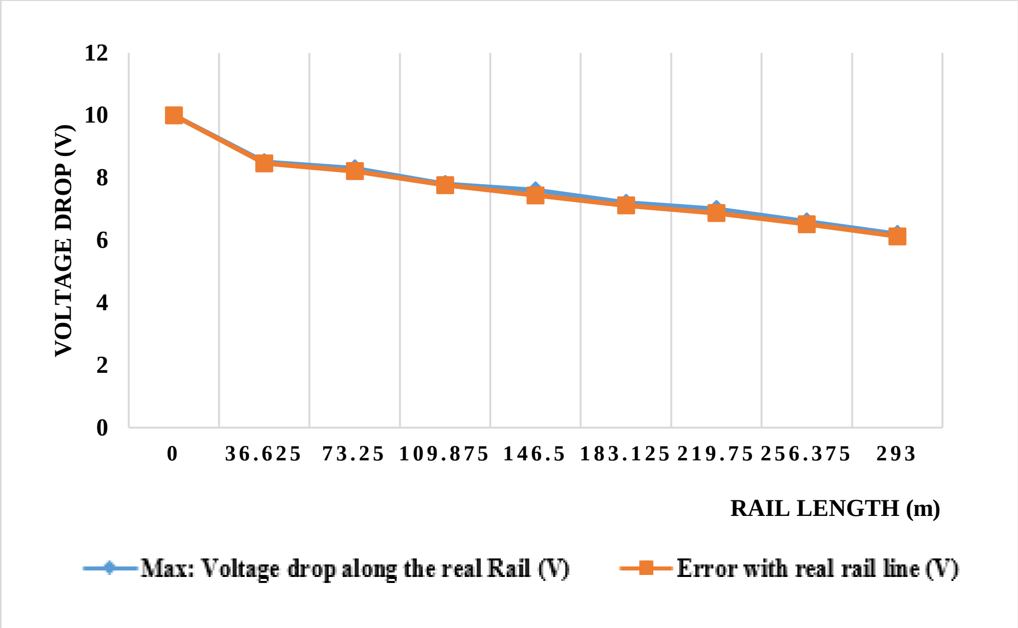

Figure 3.5: Voltage propagation pattern along the real rail line and PSCAD model

Now both output values of the PSCAD model and real rail line model are approximately equal. By using trial and error method, new values are introduced and finally got the approximately equivalent output values and built up a new model for the rail line.

Corrected values for the new model.

$C_s = 0.03\ \mu F/m$	$G_e = 159.7\ \mu S/m$	$R_1=3.3\times10^{-3}\Omega$	$R_2=3.4\times10^{-3}\Omega$
$G_s = 44.3\ \mu S/m$	$C_e = 0.51\ \mu F/m$	$L_1=3.0\times10^{-6}H$	$L_2=3.0\times10^{-6}H$
$R_3=1.48\times10^{-3}\Omega$			

It was required to verify these new values with the current model. For that another voltage level is introduced to the current model and validated the proposed model is approximately equivalent to real rail model.

Table 3.6: Results comparison between real rail model and PSCAD model

Rail Length (m)	Maximum voltage drop along the real rail (V)	Maximum voltage drop along the PSCAD model (V)	Error with real rail line (V)	Percentage error %
0	20	20	0	0
36.625	18.42	18.58	0.16	0.87
73.250	17.65	17.97	0.32	1.81
109.875	16.11	16.24	0.13	0.81
146.500	15.23	15.55	0.32	2.10
183.125	14.62	14.89	0.27	1.85
219.750	13.99	14.23	0.24	1.74
256.375	13.79	13.91	0.12	0.87
293.000	13.21	13.51	0.30	2.27

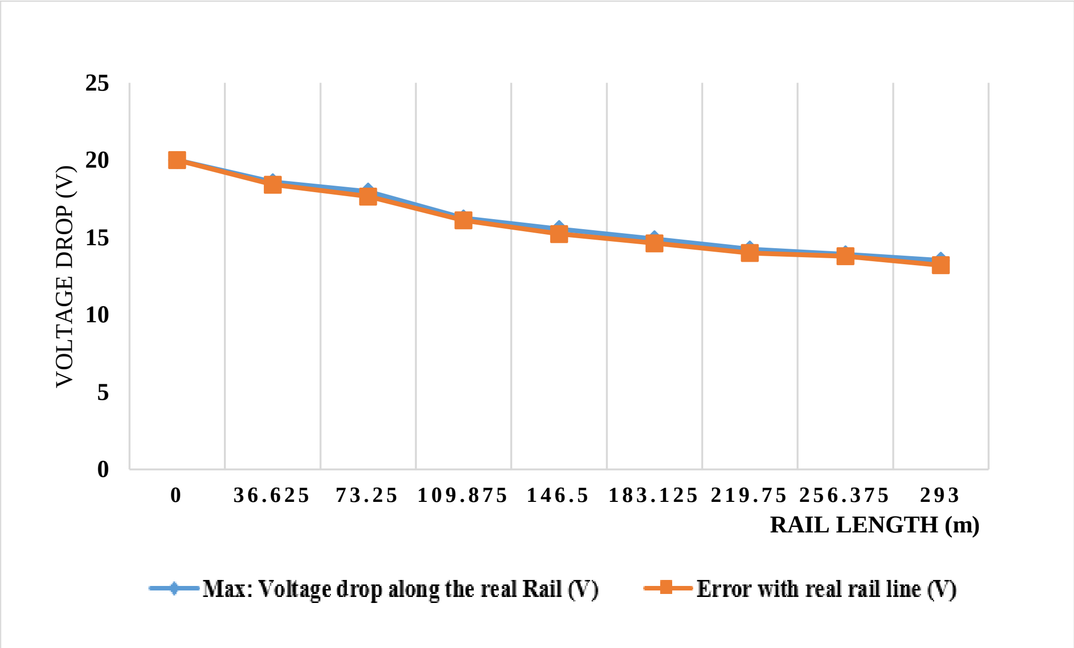

Figure 3.6: Voltage propagation pattern along the real rail line and PSCAD model

Validation of PSCAD model with the real rail line was challenging due to the ground conditions. Same rail characteristics were used to model the PSCAD model but it was difficult to match the ground condition of the real rail. So to match with the real rail conditions to the PSCAD model, the ground condition parameters were changed and re-simulated the model. By comparing voltage drop along the real rail and PSCAD model it was approximated to the real rail line by varying ground condition values in several steps. In the first stage, applied voltage matches both for the real rail line and the PSCAD modelled rail line. To confirm those values, applied another voltage level to those two models and calculated the percentage error. Both values have given approximately same percentage error values hence validated the model for further requirements.

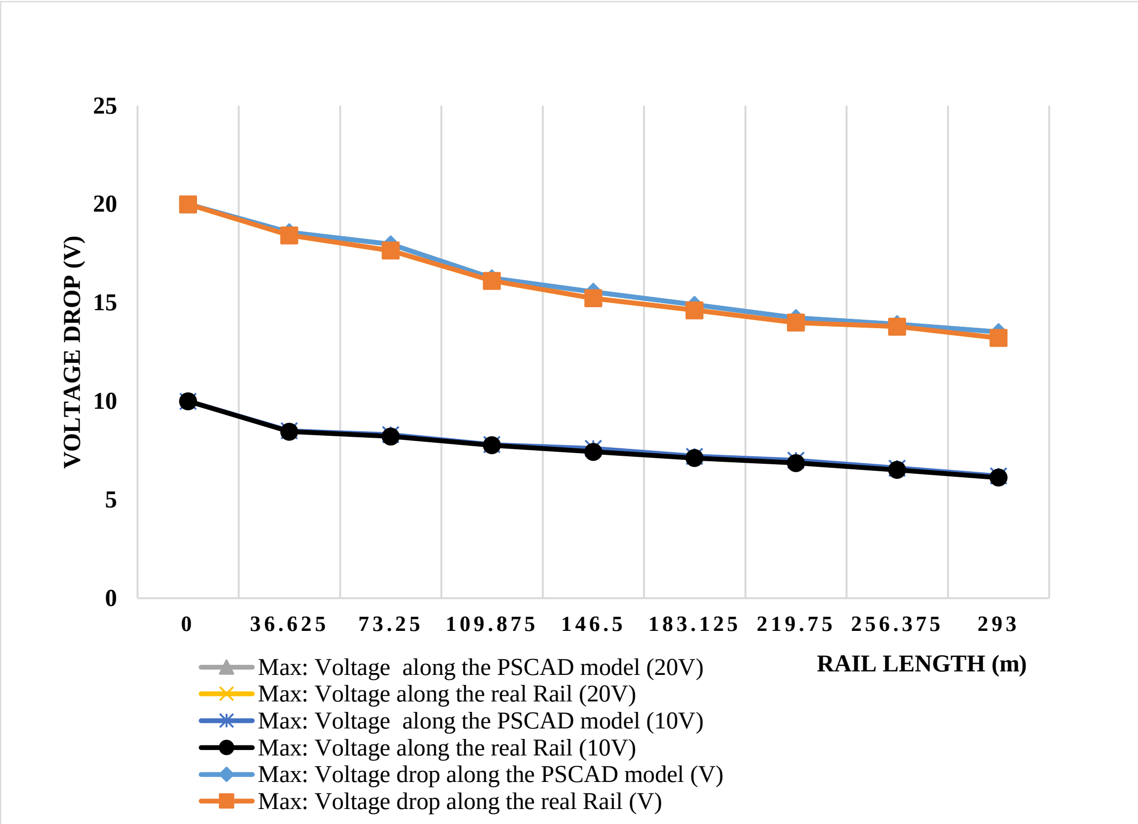

Figure 3.7: Voltage Drop with Rail Length for both 10 V and 20 V voltages

Also, it was very difficult to test with real surge values due to the dangerous situation and it was hard to apply those high voltage values in practically. To compensate for that surge current values were converted to the applicable value by changing the time duration with the voltage value.

CHAPTER 4

DIRECT LIGHTNING MODEL DESIGNED USING PSCAD

The switching surge arrester model available in the Master Library is modelled as a piece-wise-linear resistance where volt-amp characteristic is to be entered by the user. (Or a default characteristic can be applied). It is suitable for designing switching surge Transient Over Voltage (TOV) protection.

4.1 Determining Fast Front Model Parameters

The current injected into the surge arrester should be the same magnitude and wave shape to the current applied by the manufacturer to determine the switching surge discharge voltage. Inject the switching surge test current and examine the resulting peak voltage.

The current impulse I_{test} is approximated by two exponential functions.

$$I_{test} = I\,(e^{-at} - e^{-bt})$$

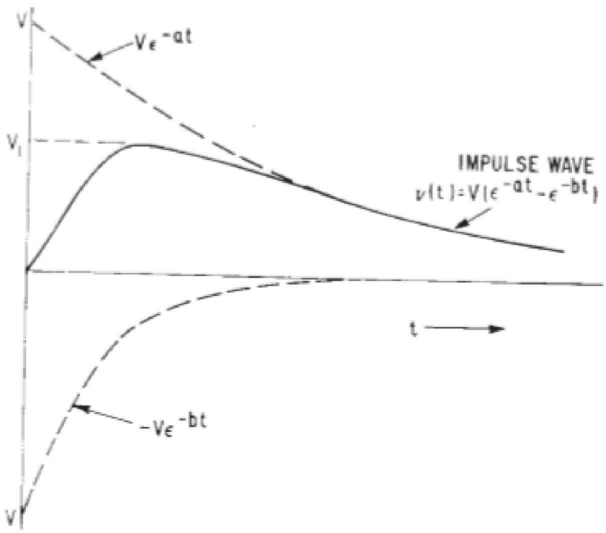

Figure 4.1: Impulse wave shape expressed as the sum of two exponential functions [10, p. 31]

The values of I, “a” and “b” of the above equation may be determined for the impulse wave if the crest value I_1 and the time to crest t_1 and time to half settle on the tail t_2 are known. This relationship is approximated using of curves.

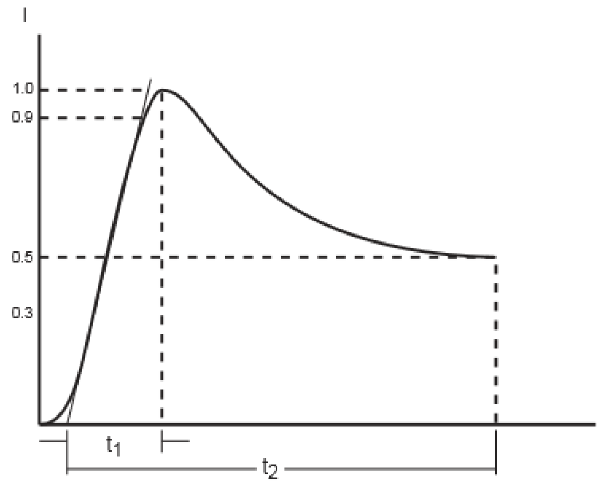

Figure 4.2: Impulse Wave Specifications [10, p. 31]

Determining parameters for impulse wave expressed by $I_{test} = I\ (e^{-at} - e^{-bt})$.

Step 01: Calculate the value of t_2/t_1 for the impulse waveform.

Step 02: According to the Figure 4.3 get the value of b/a for calculated t_2/t_1

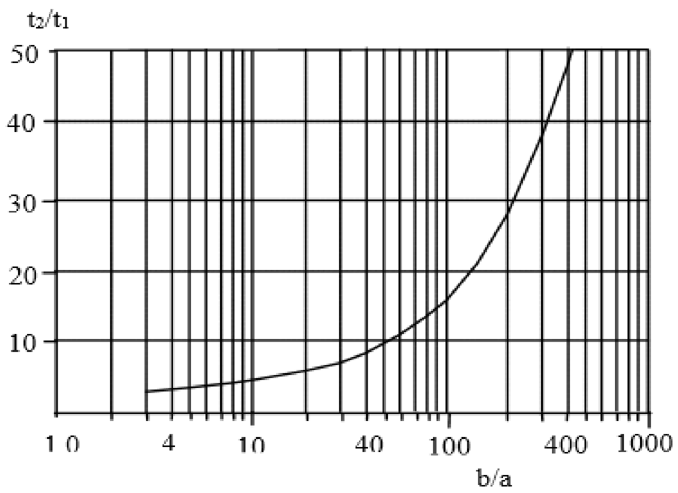

Figure 4.3: Standard curve for determining b/a [10, p. 32]

Step 03: After obtaining the b/a value from step 02 obtain the at_1 value from Figure 4.4

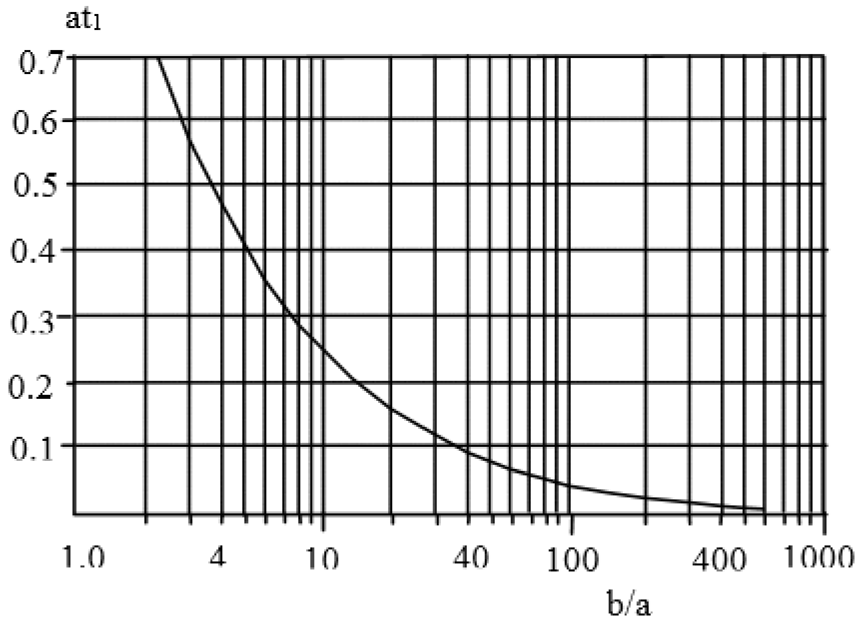

Figure 4.4: Standard curve for determining at_1 [10, p. 32]

Step 04: After obtaining the b/a value from step 02 obtain the I_1/I value from Figure 4.5

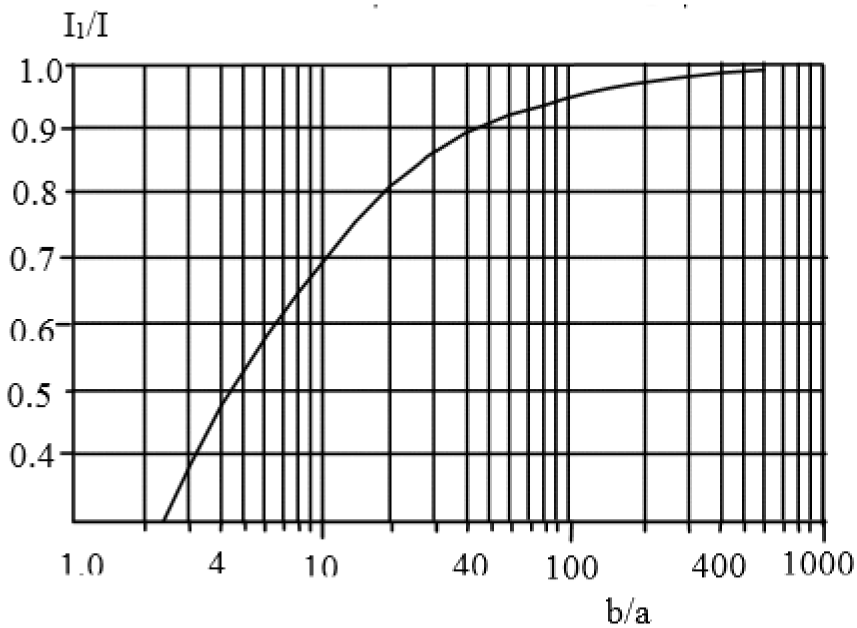

Figure 4.5: Standard curve for determining I_1/I [10, p. 32]

4.2 Direct Lightning Surge Calculation

4.2.1 50 kA Direct Lightning Surge of 10/350 μs

Step 01: Consider synthesizing a 10/350 μsec impulse.

$$\frac{t_2}{t_1}=35$$

Step 02 : $t_2/ t_1 = 35$ → $b/a = 250$

Step 03 : $b/a = 250$ → $at_1 = 0.02$

Step 04 : At $b/a = 250$,

$$\frac{I_1}{I} = 0.97$$

According to the 10/350μs impulse,

$$t_1 = 10\ \mu s$$

From the above graph

$$at_1 = 0.02$$

$$a = 2 \times 10^3$$

From equation $b/a = 250$

$$b = 5 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.97$$

$$I_1 = 0.97 \times 50kA$$

$$I_1 = 48.5\ kA$$

By using same algorithm determined the parameters for impulse waveform expressed by $I_{test} = I(e^{-at} - e^{-bt})$ for direct lightning currents.

Table 4.1: Direct Lightning Surge Current Equations

Surge Current (kA)	Equation for Direct Lightning Current
50	I_{test}= 48.5 ($e^{-2\ e5\ t}$-$e^{-5\ e5\ t}$)
100	I_{test}= 97 ($e^{-2\ e5\ t}$-$e^{-5\ e5\ t}$)
200	I_{test}= 194 ($e^{-2\ e5\ t}$-$e^{-5\ e5\ t}$)

4.3 In Direct Lightning Surge Calculation

By using the same algorithm, the parameters for impulse waveform expressed by $I_{test} = I(e^{-at} - e^{-bt})$ for 50 kVA, 100 kVA and 200 kVA in-direct lightning currents were determined.

Table 4.2: Direct Lightning Surge Current Equations

Surge Current (kA)	Equation for In direct Lightning Current
50	I_{test}= 12.5 ($e^{-0.866e5\ t}$-$e^{-1.732\ e5\ t}$)
100	I_{test}= 25 ($e^{-0.866e5\ t}$-$e^{-1.732\ e5\ t}$)
200	I_{test}= 50 ($e^{-0.866e5\ t}$-$e^{-1.732\ e5\ t}$)

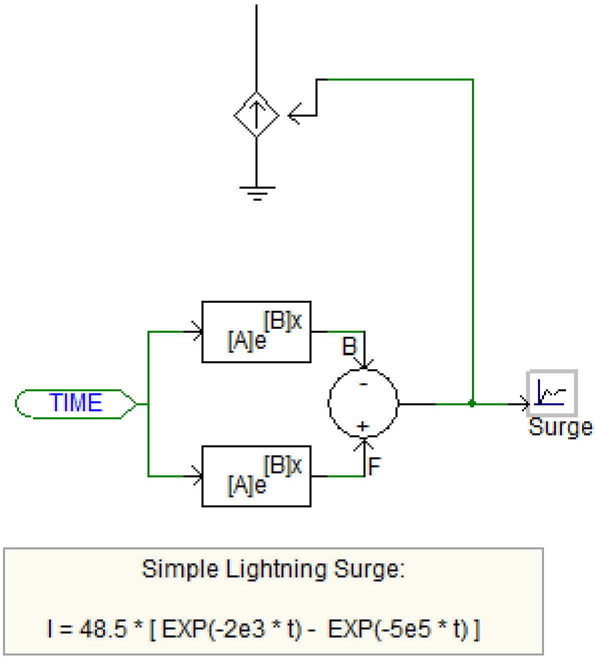

Figure 4.6: Direct Lightning Surge PSCAD Simulation Model

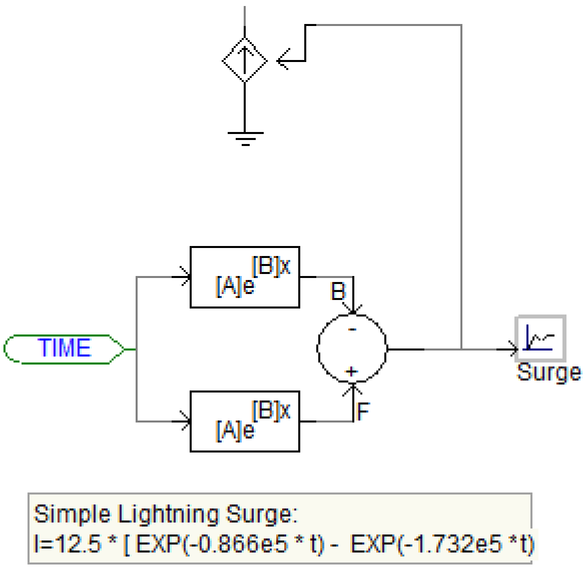

Figure 4.7: In-Direct Lightning Surge PSCAD Simulation Model

CHAPTER 5

EVALUATION OF RESULTS OF THE SIMULATION RAIL MODEL

5.1 Results of the PSCAD Model for 50 kA Direct Lightning Surge

By using the simulation model as described in chapter 3 and 4, graphical results were obtained by varying the rail track length for Injected and Induced surge currents. Peak surge current values are tabulated below.

Table 5.1: Tabulated Results for 50 kA Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	40.357	0.256
73.25	39.748	0.255
109.875	26.951	0.164
146.5	25.951	0.155
183.125	13.476	0.086
219.75	12.964	0.085

5.1.1 Obtained Graphs for above-Tabulated Values

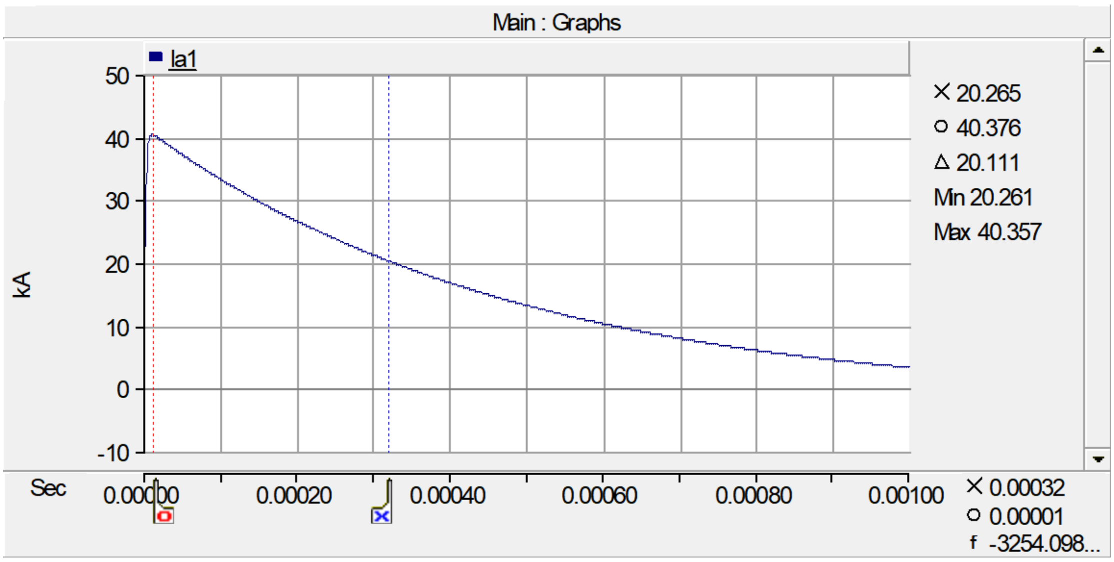

Figure 5.1: Induced Surge Current of Injected Rail at 36.625 m Rail Length

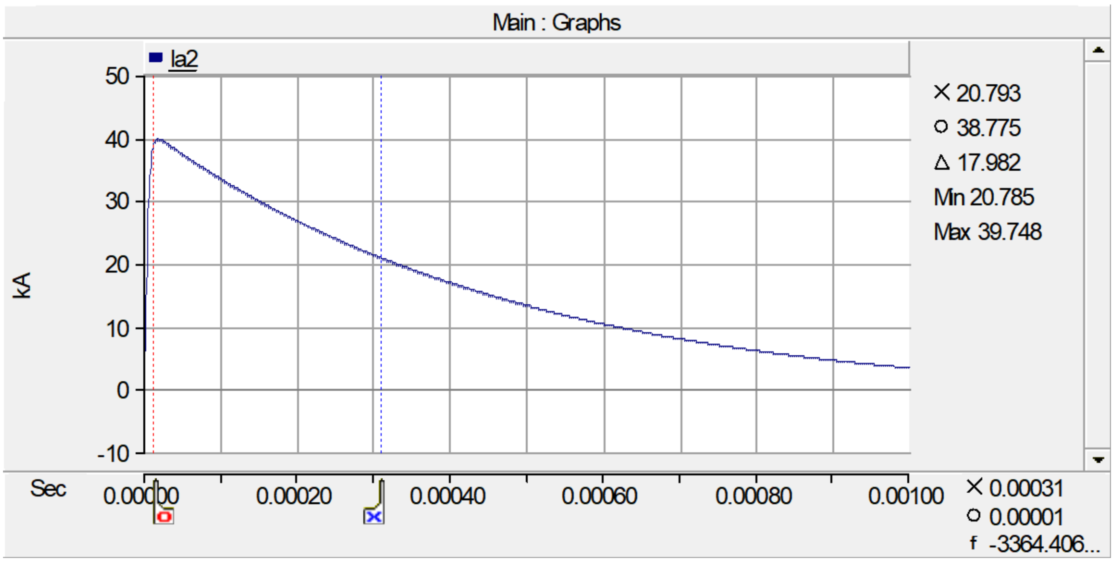

Figure 5.2: Induced Surge Current of Injected Rail at 73.250 m Rail Length

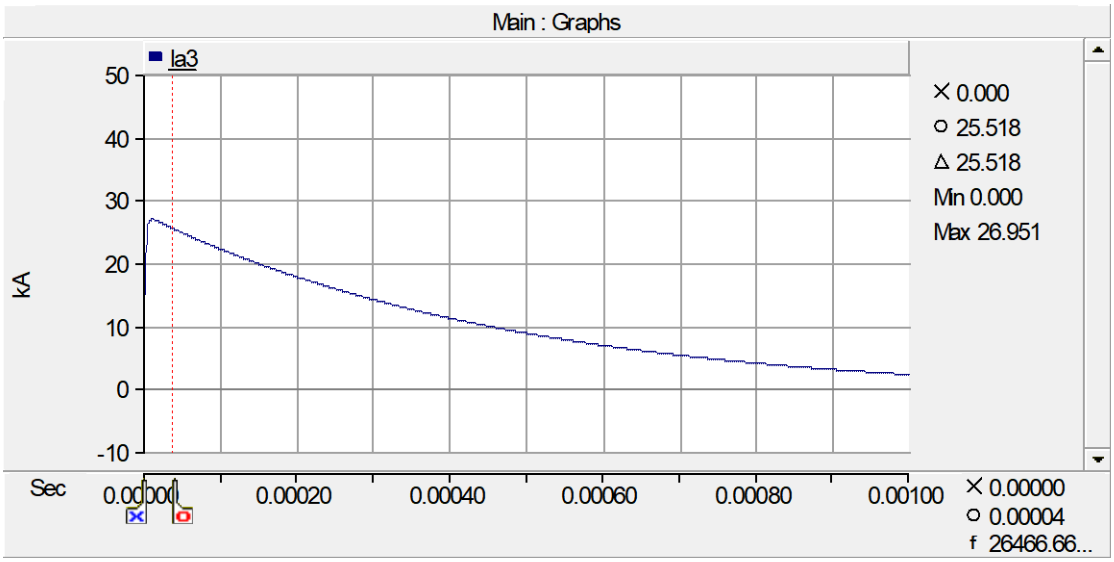

Figure 5.3: Induced Surge Current of Injected Rail at 109.875 m Rail Length

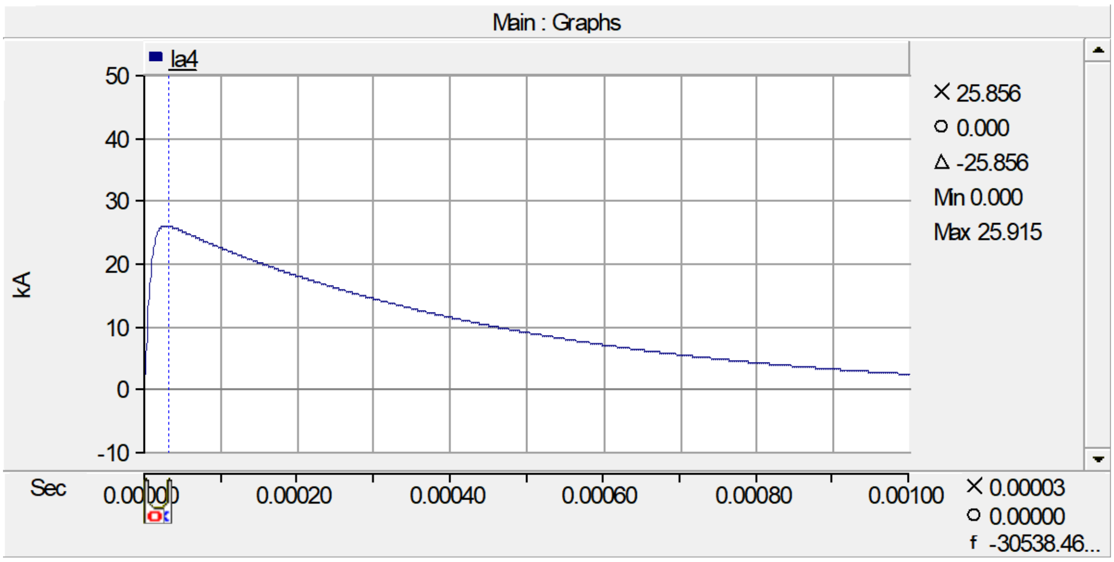

Figure 5.4: Induced Surge Current of Injected Rail at 146.5 m Rail Length

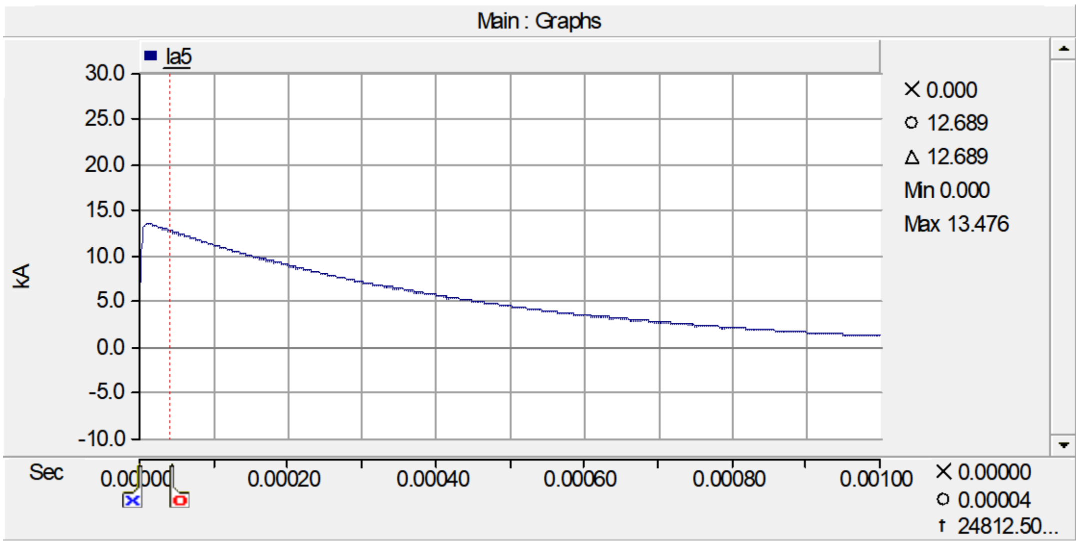

Figure 5.5: Induced Surge Current of Injected Rail at 183.125 m Rail Length

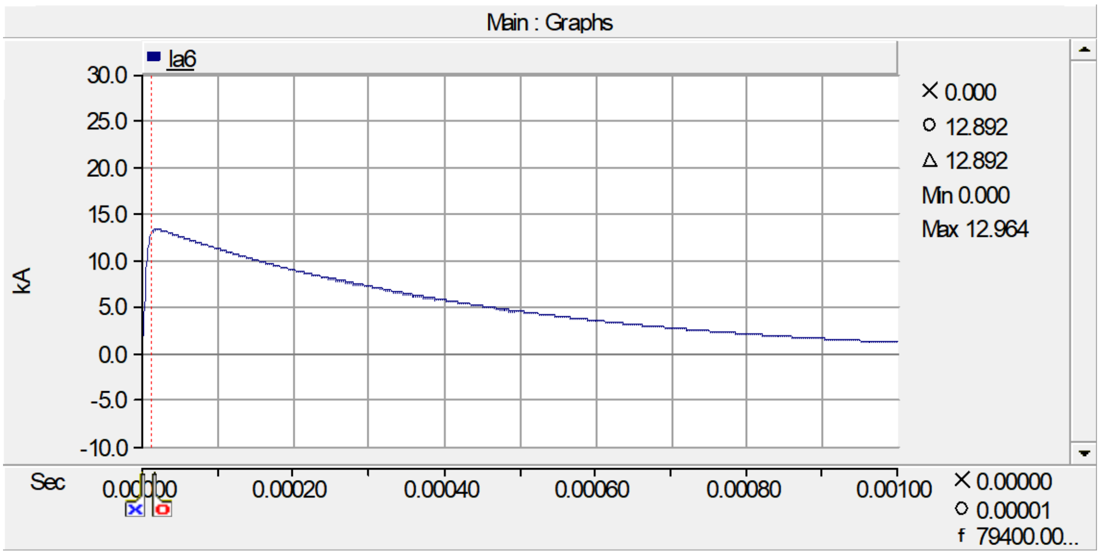

Figure 5.6: Induced Surge Current of Injected Rail at 219.75 m Rail Length

After introducing the PSCAD model for the real rail line, induced surge currents were measured both injected rail and induction rail. These values were obtained along the rail track and tabulated results were used to analyse characteristics of the model through each portion of the rail. According to the tabulated data, maximum induced surge current of the injected rail graphs was obtained by using PSCAD software.

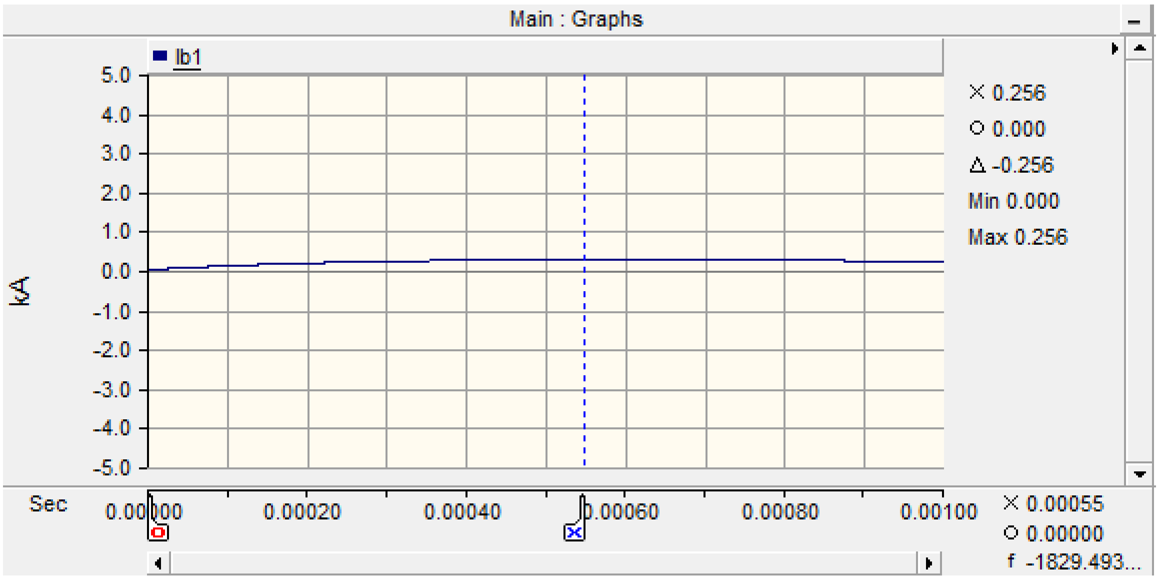

Figure 5.7: Induced Surge Current of Induction Rail at 36.625 m Rail Length

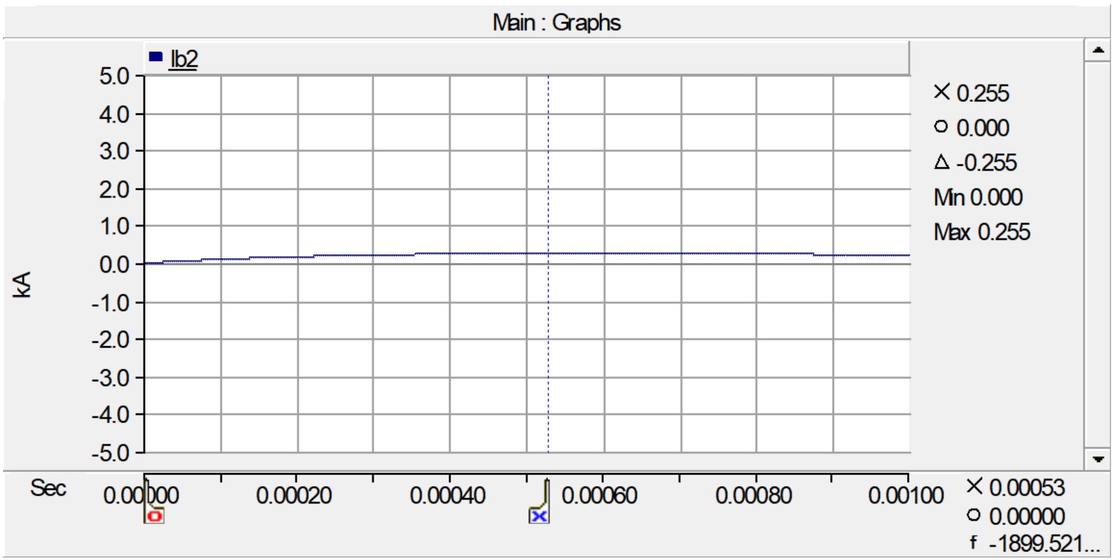

Figure 5.8: Induced Surge Current of Induction Rail at 73.250 m Rail Length

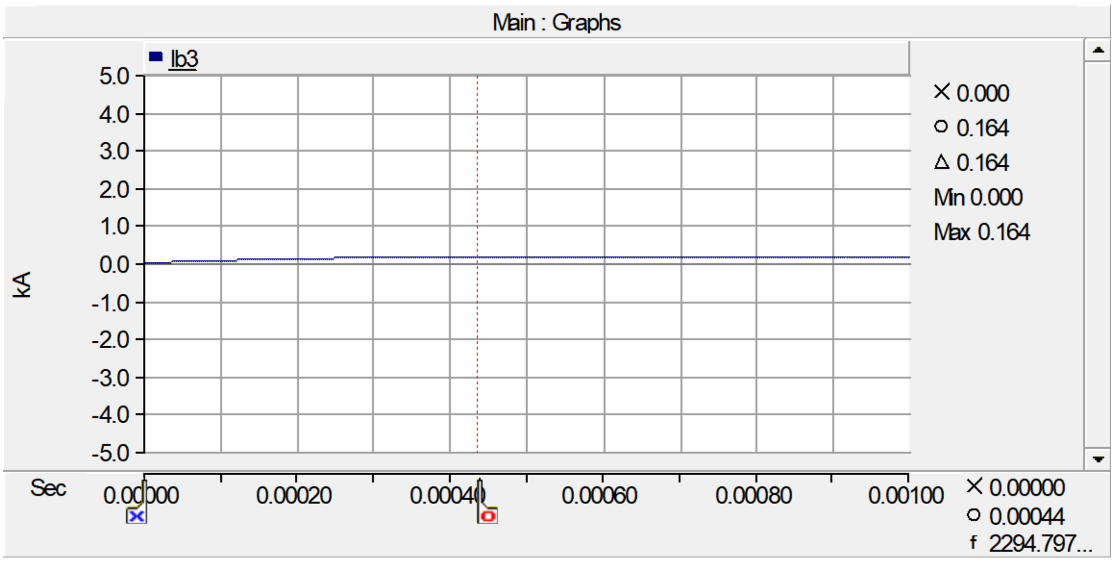

Figure 5.9: Induced Surge Current of Induction Rail at 109.875 m Rail Length

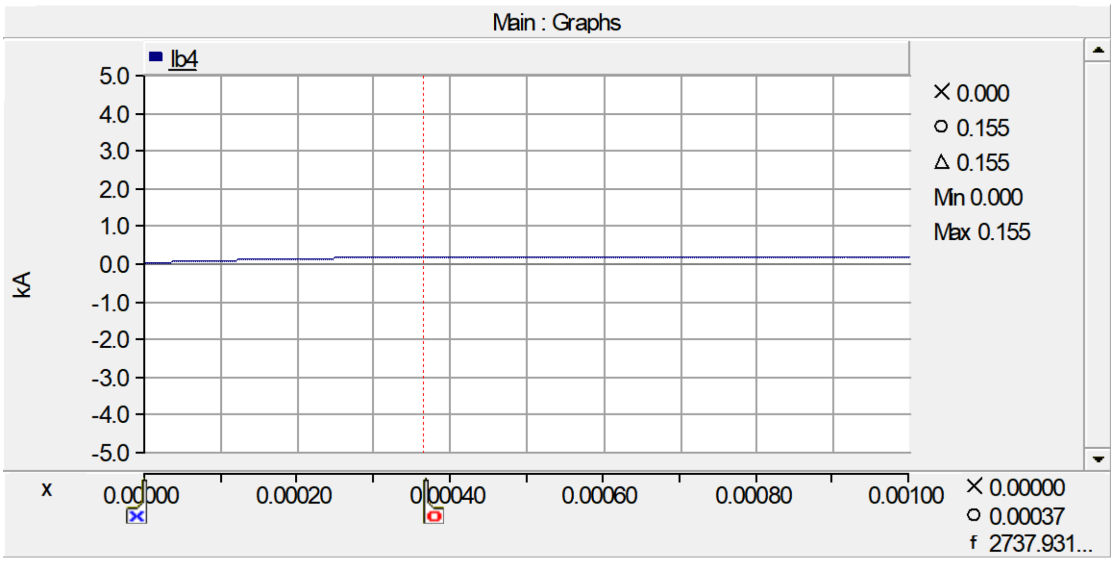

Figure 5.10: Induced Surge Current of Induction Rail at 146.500 m Rail Length

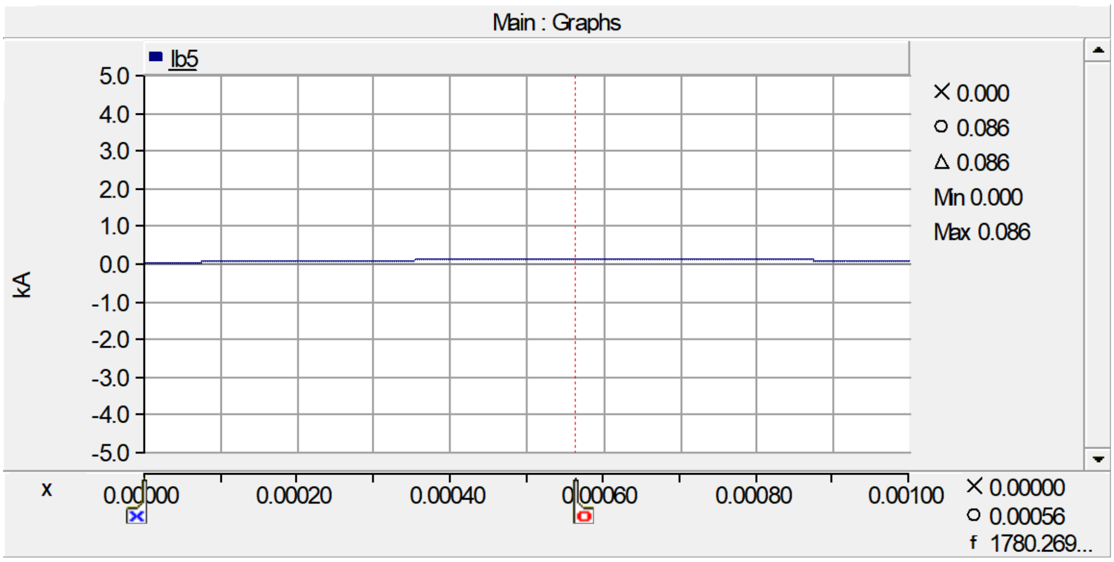

Figure 5.11: Induced Surge Current of Induction Rail at 183.125 m Rail Length

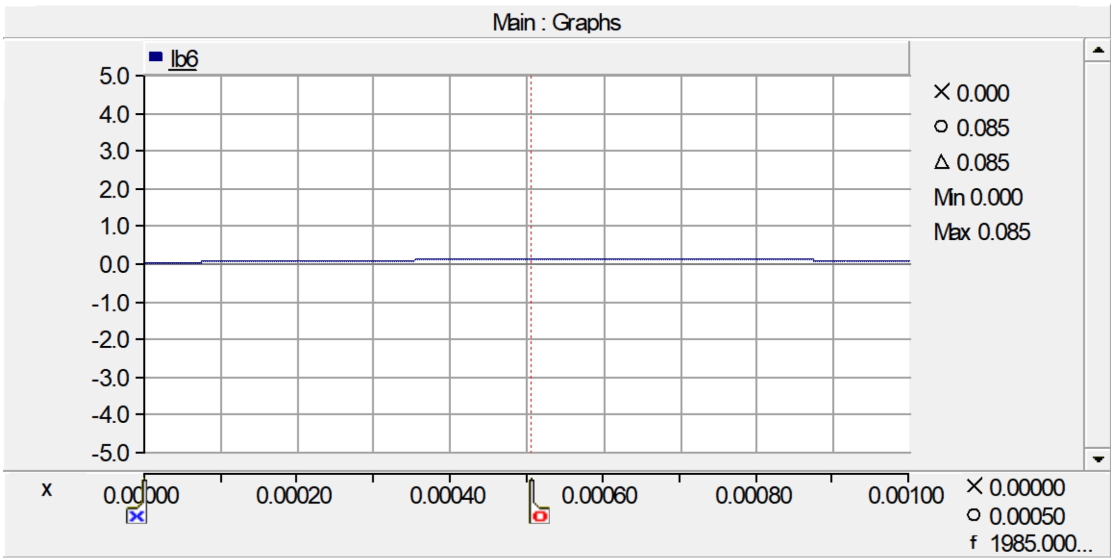

Figure 5.12: Induced Surge Current of Induction Rail at 219.750 m Rail Length

Induced surge currents in the second rail (not directly open to the direct surge) also obtained by using PSCAD software and maximum induced surge currents of the induction rail, graphs were obtained. Tabulated in the same table for comparing the rail characteristics of the 50 kA direct lightning surge.

Similarly obtained both induction and injection rails induced surge currents for 100 kA and 200 kA surge values in graphical mode by using PSCAD software.

5.2 Results of the PSCAD Model for 100 kA Direct Lightning Surge

Table 5.2: Tabulated Results for 100 kA Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	80.85	0.513
73.250	79.52	0.509
109.875	53.91	0.337
146.500	52.87	0.321
183.125	26.95	0.198
219.750	25.84	0.185

5.3 Results of the PSCAD Model for 200 kA Direct Lighting Surge

Table 5.3: Tabulated Results for 200 kA Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	161.71	1.024
73.250	160.68	1.009
109.875	107.81	0.671
146.500	106.59	0.658
183.125	53.91	0.232
219.750	52.87	0.211

5.4 Results of the PSCAD Model for 50 kA In-Direct Lightning Surge

Table 5.4: Tabulated Results for 50 kA In - Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	2.68	0.002
73.250	2.59	0.002
109.875	1.79	0.001
146.500	1.65	0.001
183.125	0.89	-
219.750	0.78	-

5.5 Results of the PSCAD Model for 100 kA In-Direct Lightning Surge

Table 5.5: Tabulated Results for 100 kA In - Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	5.35	0.003
73.250	5.21	0.003
109.875	3.57	0.002
146.500	2.98	0.002
183.125	1.78	0.001
219.750	1.69	0.001

5.6 Results of the PSCAD Model for 200 kA In-Direct Lightning Surge

Table 5.6: Tabulated Results for 200 kA In - Direct Lightning Surge

Rail track length (m)	Induced Surge Current in Injected Rail (kA)	Induced Surge Current in Induction Rail (kA)
36.625	10.7	0.007
73.250	9.98	0.006
109.875	7.14	0.004
146.500	6.89	0.004
183.125	3.57	0.003
219.750	2.89	0.003

5.7 Direct Surge Propagation Pattern Analysis

Table 5.7: Tabulated Results for50 kA, 100 kA and 200 kA Direct Lightning Surge

Rail Length (m)	Measured surge current for 50 kA	Measured surge current for 100 kA	Measured surge current for 200 kA
36.625	40.357	80.85	161.71
73.25	39.748	79.52	160.68
109.875	26.951	53.91	107.81
146.5	25.951	52.87	106.59
183.125	13.476	26.95	53.91
219.75	12.957	25.84	52.87

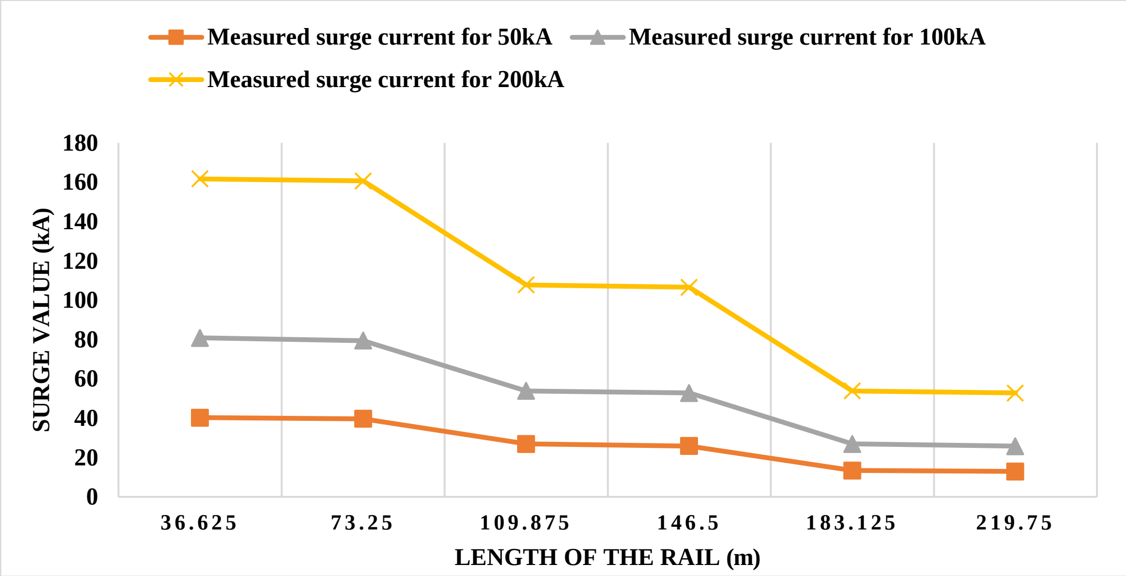

Figure 5.13: Direct Surge Propagation against the Track Length

5.8 In - Direct Surge Propagation Pattern Analysis

Table 5.8: Tabulated Results for 50 kA, 100 kA and 200 kA In- Direct Lightning Surge

Rail Length (m)	Measured surge current for 50 kA	Measured surge current for 100 kA	Measured surge current for 200 Ka
36.625	2.68	5.35	10.7
73.25	2.59	5.21	9.98
109.875	1.79	3.57	7.14
146.5	1.65	2.98	6.89
183.125	0.89	1.78	3.57
219.75	0.78	1.69	2.89

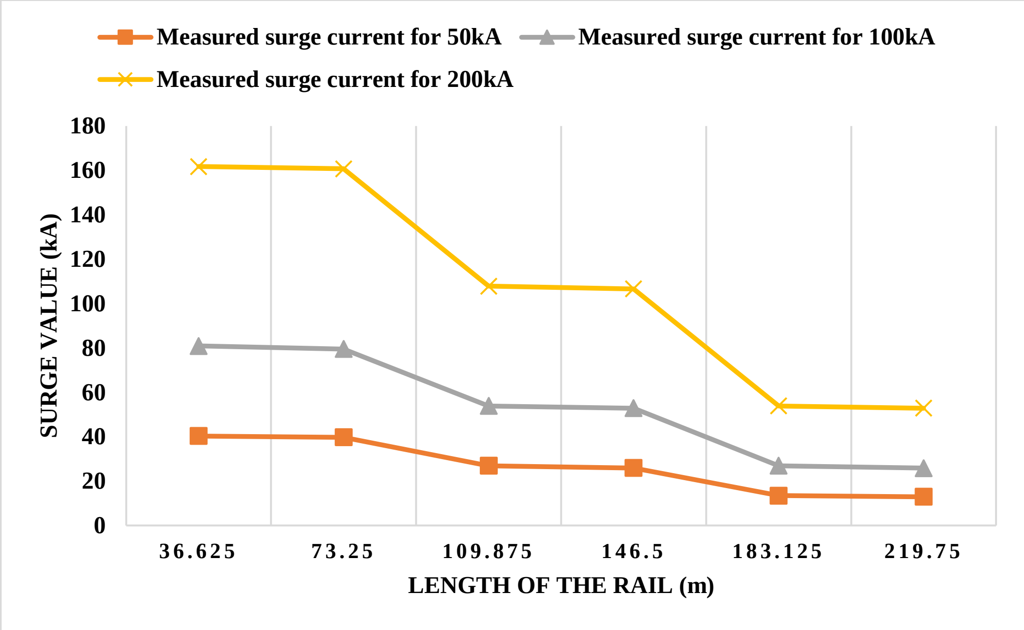

Figure 5.14: In - Direct Surge Propagation against the Track Length

5.9 Summary of the Observations

- Direct and Indirect current through rail is reduced **along the length** of the rail from the surge injecting point
- Compared with the current along the **Injecting rail**, the surge current along the **Induction rail** is negligible
- The surge current along the rail is **drastically reduced** by the **current grounded through sleepers**
- The magnitude of **Direct surge** current through the Injecting rail is closely **proportional to the Actual current of the surge**

For 10/350 µS Direct Surge Current Model Results at 36.625 m Rail Length simulation results indicate that, as the distance from surge stroke location increases, the over-voltage is getting decreased.

Table 5.9: Tabulated Results for Actual Surge Current with Direct Surge Current through Injecting Rail

Actual Surge Current (kA)	50	100	200
Direct Surge Current through Injecting Rail (kA)	40.43	80.85	161.71

5.10 Calculate Discharge Voltages in Wayside Cabinets

By assuming wayside equipment cabinet contains

- Track Rectifiers
- Track relays
- Battery charger units
- Transformers
- Communication equipment

The common total resistance through the equipment in wayside cabinet is 581 ohms

5.11 Direct and In-Direct Transient Discharge Voltages in Wayside Equipment Cabinets

By considering above equipment in the wayside cabinets, common total resistance through the equipment in wayside cabinet is 581 ohms and according to the above-obtained results, the generated voltage for direct and indirect transient voltages was calculated. Simply by using Ohms law can be calculated total generated voltage. Obtained results are tabulated the results for both direct and indirect transient current values for 50 kA, 100 kA and 200 kA Surge Currents.

5.11.1 Direct Transient Voltages for 50 kA, 100 kA and 200 kA Surge Currents

Table 5.10: Generated Direct Transient Voltages in Rail Length

Rail Length (m)	Generated Voltage (V) for 50 kA surge Current	Generated Voltage (V) for 100 kA surge Current (V)	Generated Voltage (V) for 200 kA surge Current (V)
36.63	23447.417	46974	93954
73.25	23093.588	46201	93355
109.9	15658.531	31322	62638
146.5	15077.531	30717	61929
183.1	7829.556	15658	31322
219.8	7528.017	15013	30717

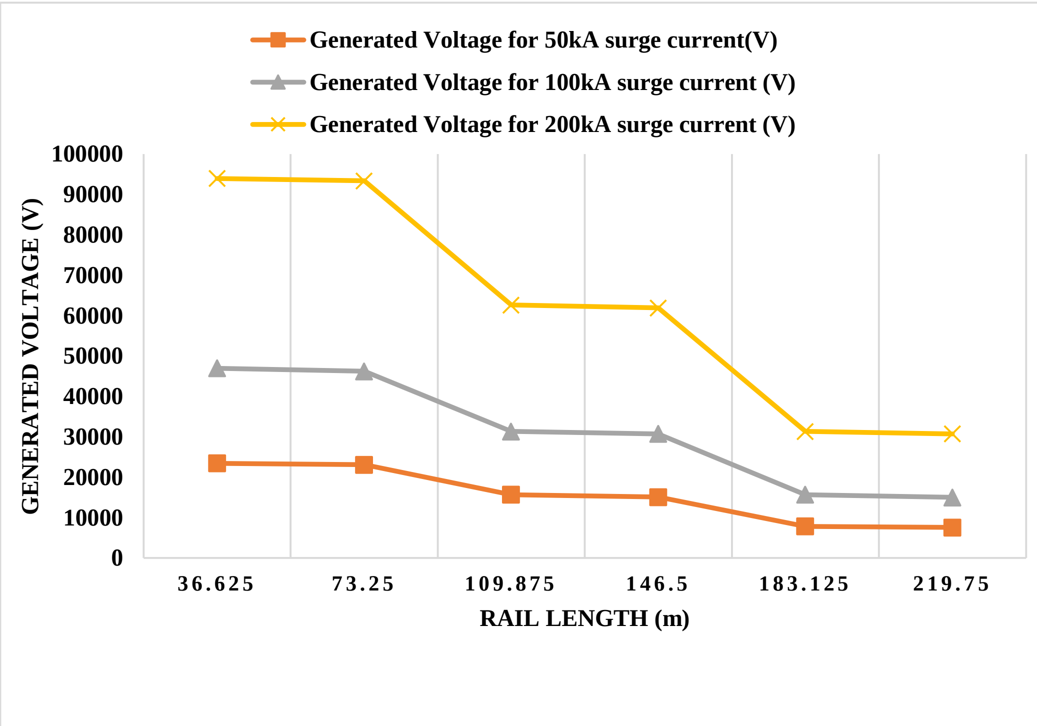

Figure 5.15: Generated Voltages for Each In-Direct Surge Current

5.11.2 In - Direct Transient Voltages for 50 kA, 100 kA and 200 kA Surge Currents

Table 5.11: Generated In-Direct Transient Voltages in Rail Length

Rail Length (m)	Generated Voltage (V) for 50 kA surge Current	Generated Voltage (V) for 100 kA surge Current (V)	Generated Voltage (V) for 200 kA surge Current (V)
36.63	1557	3108	6217
73.25	1505	3027	5798
109.9	1040	2074	4148
146.5	958.7	1731	4003
183.1	517.1	1034	2074

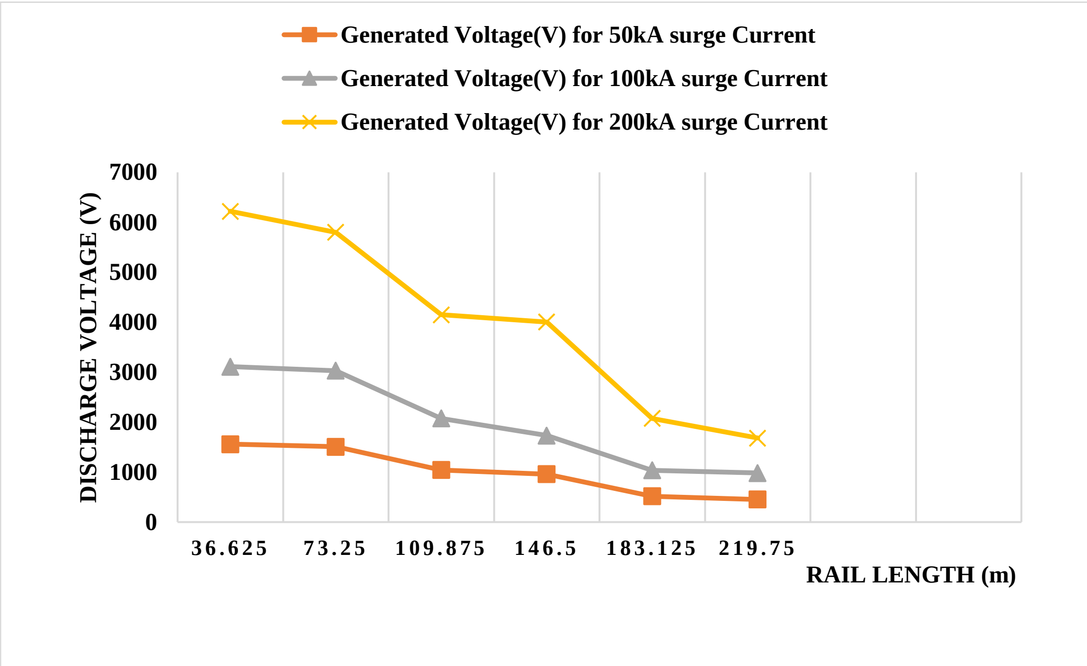

Figure 5.16: Generated Voltages for Each In-Direct Surge Current

By using fast front model parameters, direct lightning surge PSCAD simulation model is built and applied to the modelled rail line. The modelled rail line consists of two rails, and the current was injected to one rail line and measured at several points in each length. And also, it was measured the induced surge current in induction rail. By using the direct lightning surge PSCAD simulation model, direct and indirect lightning surge currents were applied to the simulated rail model. Rail track length was divided into eight equal portions and measured the output current values in both injected and induction rails. Along the rail, the surge current was decreased and drastically reduced through concrete sleepers. By using the past research paper values, the probability of the direct and indirect surges through the rail line to the equipment cabinet was calculated. The calculated values are show that there is no effect of the direct lightning surge to the equipment cabinet through the rail line, and can be neglected by comparing with indirect surge currents to the rail line.

CHAPTER 6

PROPOSED PROTECTION MECHANISM

All traction vehicles and rolling stocks run on the rail line according to the signal. To avoid large amount of money wastage from lightning surges it is required to implement a reliable protection system.

6.1 Classes of SPDs

Classes of protection are depended on the class of SPD. According to the IEEE C62.41.2 standard basically, three categories are included.

Category C – Basically, install in service entrance. More severe environment; 10 kV and 10 kA surge

Category B – Ground stream and less severe environment cases are used. Greater than or equal to 30 feet away from Category C, 6 kV and 3 kA surge

Category C – Further ground stream environment. Greater than or equal to 60 feet away from Category C, 6 kV and 0.5 kA surge

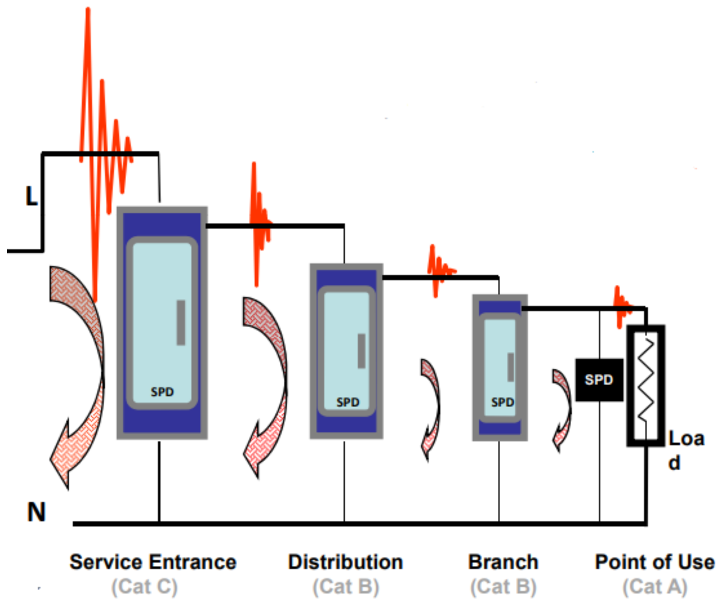

Figure 6.1: Surge Protection Categories

Rule of Thumb: The higher the kA rating on the product, the better its withstand capability and overall robustness. For each level of protection (cascading) cut the kA rating by half.

6.2 Probability of damaging a signaling equipment due to a surge through a rail

The estimation method can be used to assist decisions on whether or not to introduce lightning protection measures to signaling equipment. An important factor which is needed to decide whether lightning protection measures should be taken to protect signaling equipment is the lightning strike risk assessment which justifies if the measure will be effective or not in reducing damage. Nonetheless, today there is no quantitative method to determine the probability of lightning damage occurrence based on lightning current and distance to strike location.

According to;-H.Arai, Y.Ono, H.Fujita "**The Lightning Risk Evaluation for Railway Signaling Systems based on Observation of Lightning Over-voltages"** in: Lightning Protection (ICLP), Austria, 2012 measurements were taken over a long period of time of the power surges caused by lightning strikes in signaling equipment ground signaling cables, overhead power line and rails.

6.2.1 Method of finding the probability

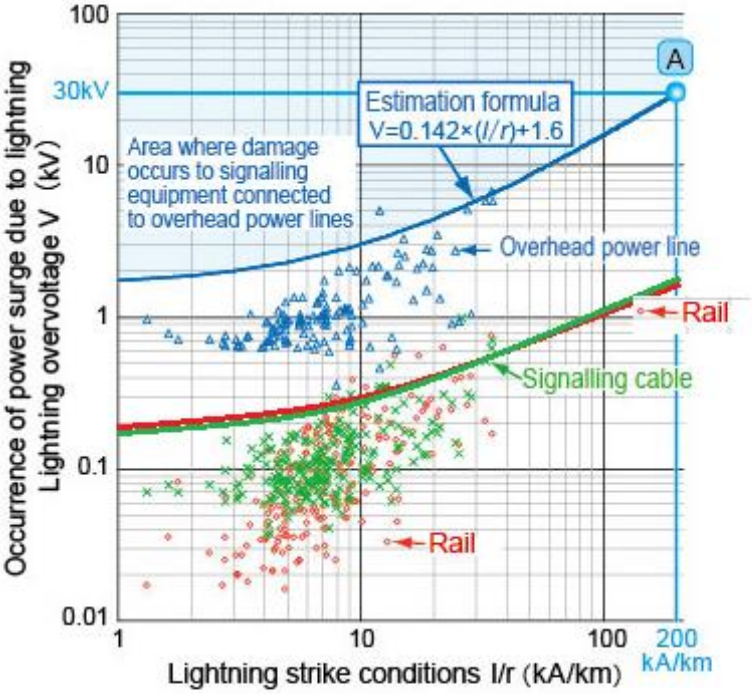

Figure 6.2: Estimation of lightning strike conditions which may lead to lightning damage [11]

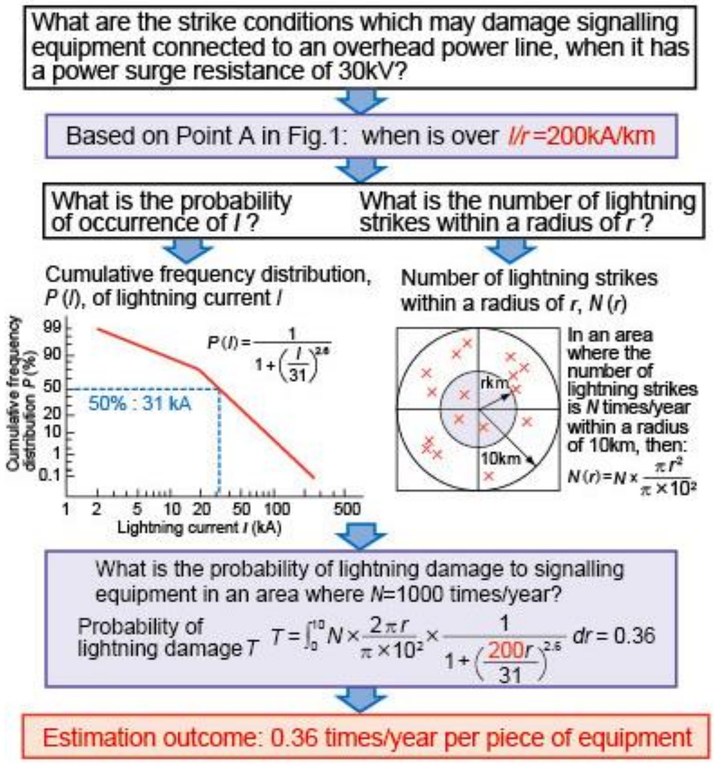

Figure 6.3: Probability of lightning damage to signalling equipment [11]

Using the estimation formula in Figure 6.2, it is possible to identify which lightning strike conditions can provoke lightning damage to signalling equipment as well as by considering the probability of occurrence of lightning strike conditions; it is possible to estimate the probability of lightning damage to signalling equipment according to Figure 6.3.

According to the below equation, it can be estimated the direct and indirect lightning probabilities to the rail for different surges and different places in the rail.

The lightning over-voltage on rails V=0.0134 x (I/r) + 0.19[11]

By considering the above graph in Figure 6.2, the probability of occurring direct lightning surges to the rail can be neglected. So introducing surge protection devices for the direct lightning surges for the signal equipment cabinets is practically not required. The probability of damage per piece of equipment from indirect lightning surges are tabulated in below table and it is assumed that the 1000 numbers of the lightning strikes for an area of 10 km radius when calculating the probability.

The probability of Lightning Damage (T)

$$T = N \int_{0}^{10} \frac{2\pi r}{\pi \, x \, 10^2} \, x \, \frac{1}{1 + \left(\frac{Hr}{31}\right)^{2.6}}$$

H – Lightning Condition

N – Number of Lightning strikes within radius r

Probability of damage per piece of equipment from in-direct lightning surges tabulated in Table A of Appendix A.

6.3 Recommendation for suitable and economical surge arrestor

It is recommended to install relevant surge protective devices only for indirect lightning surges from the railroad by considering the surge voltage build-up in the equipment cabinet. Since this thesis only considered and studied about direct and indirect lightning effect to the signal equipment from the rail track; by considering that surge comes only through the railway track it is proposed to use Category A surge protective devices for the signal equipment cabinet as per the standards of **IEEE C62.41.2**

Also, it is recommended to consider other invasion methods of lightning surges (from outside overhead cables, underground cables etc.) to the signal equipment cabinets, and install surge protective devices by designing the best option to protect signal equipment for future studies.

6.4 Validation of Proposed surge protection category Using PSCAD model

From the graph shown in Figure 6.2; the occurrence of power surge due to lightning over-voltage value need to manage below 0.2 kV to reduce the probability of lightning damage occurrence. For that, it is needed to maintain the surge voltage from the rail to equipment cabinet below 0.2 kV. Thus the surge protection device should be with **Category A** properties of **0.5 kA, 6kV** according to **IEEE C62.41.2** standard which needs to be used to protect equipment.

6.5 Surge Arrester Model

By introducing this (Figure 6.4) surge arrester model to the above rail model the behaviour of the rail when the surge is applied to the rail is observed.

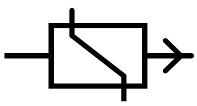

Figure 6.4: Surge Arrester Model

6.6 PSCAD Simulation Results for the Model with Proposed SPD

According to the IEEE C62.41.2 standard Category A type SPD is installed parallel with respect to the load. Surge arrestor model is installed to the above-proposed PSCAD model and results were obtained for each case. The probability of damage per piece of equipment from indirect lightning surges is calculated.

Table 6.2: Tabulated Results for Indirect Surges after Installing SPDs in PSCAD Model for 50 kA, 100 kA and 200 kA Surge Currents

Rail Length (m)	Measured Surge Current (kA) after installing the SPD	Calculated Surge Voltage (kV) after intalling the SPD
36.625	0.374	217.294
73.25	0.296	171.976
109.875	0.224	130.144
146.5	0.219	127.239
183.125	0.125	72.625
219.75	0.111	64.491

6.7 Output Characteristics for 50 kA Surge Current after installing the SPD

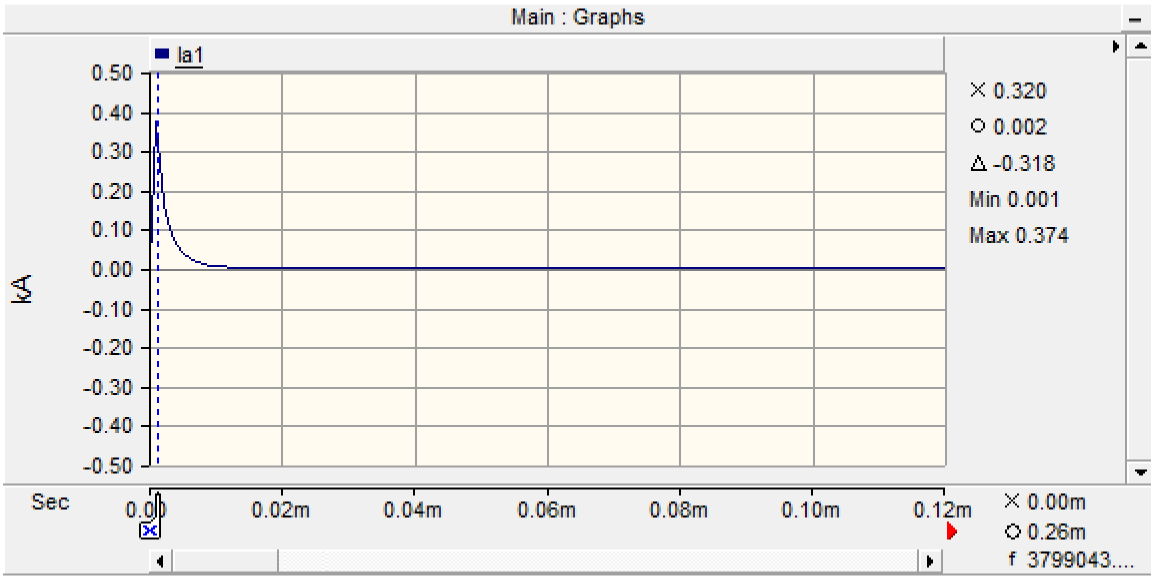

Figure 6.5: Output Characteristics for 36.625 m Rail Length

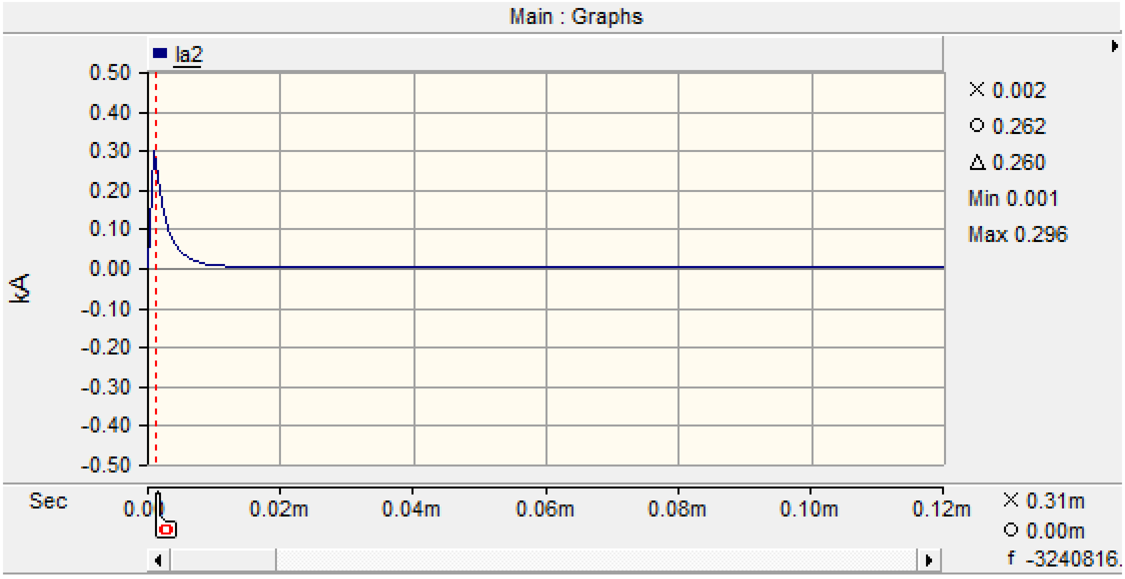

Figure 6.6: Output Characteristics for 73.25 m Rail Length

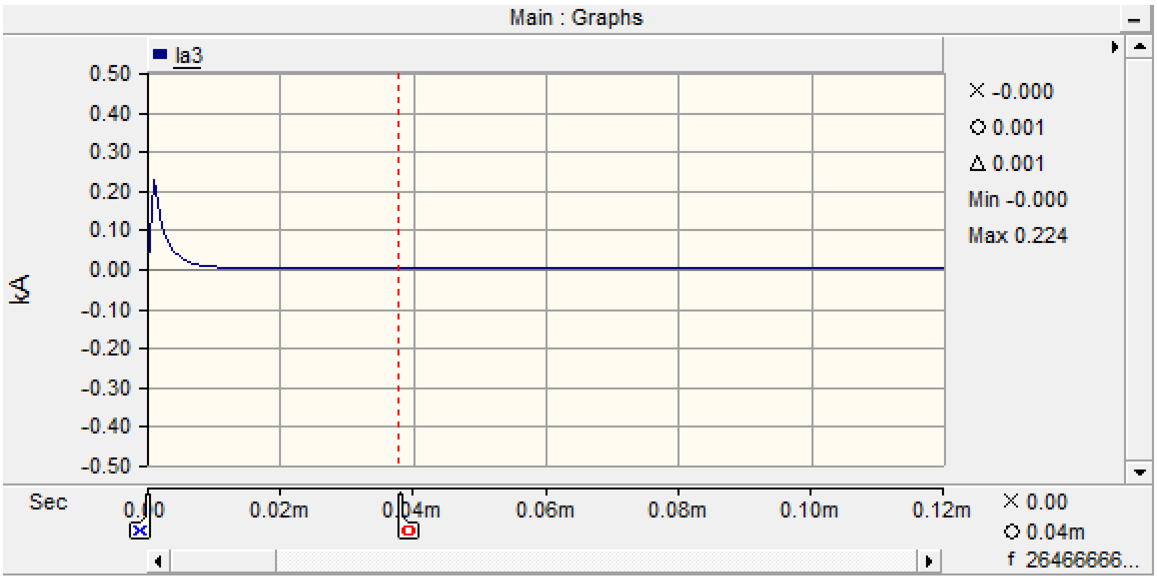

Figure 6.7: Output Characteristics for 109.875 m Rail Length

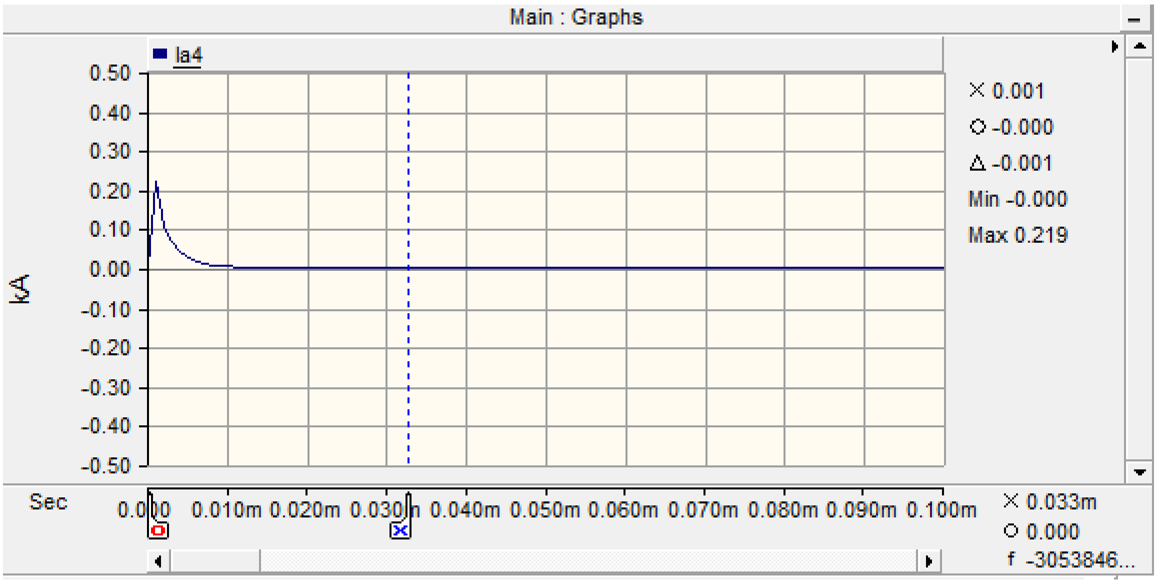

Figure 6.8: Output Characteristics for 146.500 m Rail Length

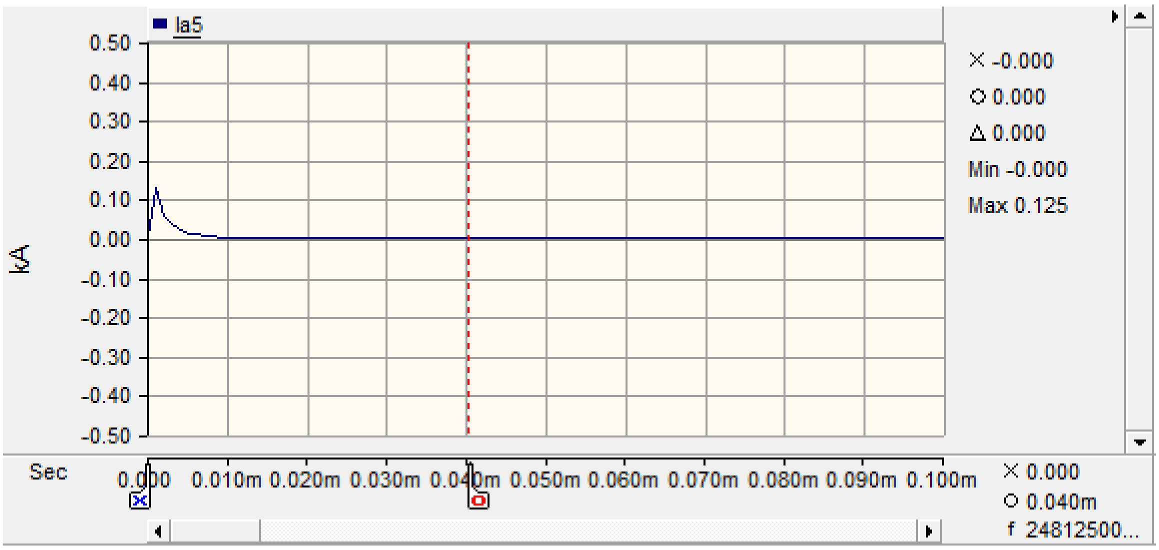

Figure 6.9: Output Characteristics for 183.125 m Rail Length

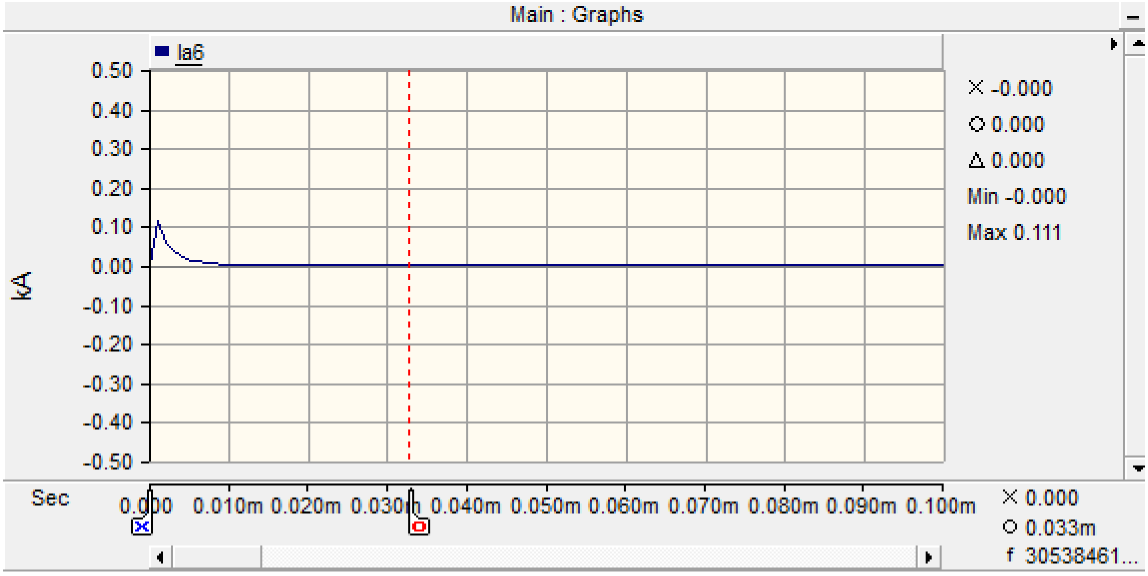

Figure 6.10: Output Characteristics for 219.750 m Rail Length

Above results are obtained for 50 kA, 100 kA and 200 kA surge currents injected to rail and induction rail measured surge currents are approximately "0" A. According to the Figure 6.2 Lightning Strikes Conditions I/r (kA/km) value is approximated to value "1" and by considering Figure 6.3 the probability of lightning damage is approximately zero for both injection rail and induction rail. Finally, surge arrester model was introduced to the PSCAD role model and same surge current values were applied to the model. Surge arrester model parameters were changed by using the PSCAD software. According to the model parameters can be introduced the best ratings for surge protection devices to reduce the lightning over-voltage damages to the signal equipment cabinets only through the rail.

CHAPTER 7

LIMITATIONS AND FUTURE WORKS

The goal of this research was to the development of the effective and economical protection system to the railway signal equipment cabinets because of the lightning damages caused disruptions for the railway transportation system.

7.1 Limitations

In terms of conductivity, a pair of rails can be described as a passive circuit with distributed parameters. However, both the rail's resistance and impedance are slightly different in different cases. There are several standardized rail sizes, but none of these types have identical parameters all the time. This thesis considered only one rail size. And also there can be narrow gauge and broad gauge rail lines. In addition, in the course of time, all rails get worn out, which reduces their cross-section and consequently increases their resistance. Due to above reasons above obtained results are limited to the measured type rails only.

7.2 Assumptions

In the practical scenario assumed that the proposed rail characteristics model parameters are fully matched with the rail line. Cross section area of the whole rail is constant and resistance variation is neglected along the rail. When calculating the probability of occurrence, it is assumed by using the equation,

$$T = N \int_{0}^{10} \frac{2\pi r}{\pi \; x \; 10^2} \; x \; \frac{1}{1 + (^{Hr}/_{31})^{\;2.6}}$$

According to the above equation, it is assumed that the 1000 numbers of lightning strike for a 10 km distance area when calculating for the probability of occurrence.

In the equipment cabinet, there can be various equipment and total resistance value could change accordingly. For this research total resistance value is calculated by using only,

- Track Rectifiers
- Track relays
- Battery charger units
- Transformers
- Communication equipment

And those equipment total resistances might not be constant. The values can vary with equipment to equipment and also with the temperature. In this analysis is assumed the total resistance is not changed and always used only the above equipment.

According to the above analysis, the lightning surges have come only through the rail to the equipment cabinet. The direct lightning strikes to the equipment cabinet doors, the potential rises near to the equipment cabinet floor, direct and indirect lightning strikes through the overhead cables and various scenarios should be taken to the calculations. Unless the proposed solution has not become optimum.

7.3 Future Works

The effect of overhead cables and signal cables is need to be considered when proposed optimum solution to the lightning protection system to the signal equipment cabinets. So a total system analysis should be conducted to find total effect to the equipment cabinet from all the external sources. For that, all the power cables, communication cables which are used in overhead lines and buried in the ground are needed to be modelled.

Introduction of a proper lightning protection standard method to Sri Lanka Railway Signalling equipment cabinets should be done once analysis of all the conditions are being done.

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Appendix A

Table A: Probability of damage per piece of equipment from indirect lightning surges

Rail Length (m)	Lightning Over-voltage (kV)	Lightning Strike Condition I/r (kA/km)	Probability of Lightning Damage Occurance	Lightning Over-voltage (kV)	Lightning Strike Condition I/r (kA/km)	Probability of Lightning Damage Occurance	Lightning Over-voltage (kV)	Lightning Strike Condition I/r (kA/km)	Probability of Lightning Damage Occurance
	50kA			100kA			200kA		
36.625	1.56	150	1.41	3.11	0.00	0.00	6.22	0.00	0.00
73.25	1.50	150	1.41	3.03	0.00	0.00	5.80	0.00	0.00
109.875	1.04	100	3.10	2.07	0.00	0.00	4.15	0.00	0.00
146.5	0.96	99	3.16	1.73	180.00	0.99	4.00	0.00	0.00
183.125	0.52	30	29.79	1.03	100.00	3.11	2.08	0.00	0.00
219.75	0.45	28	33.76	0.98	99.00	3.16	1.68	170.00	1.11