STUDY OF LIGHTNING GROUND FLASHES INTERACTION WITH RAILWAY LINES

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Special dedication

I dedicate this work to my beloved mother, father,wife,brother and son.

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All praises is to ALLAH Subhanahu wa ta’ala for bestowing me with health, opportunity, patience, and knowledge to complete this research. May the peace and blessings of ALLAH Subhanahu wa Ta’aala be upon Prophet Muhammad (Sallallahu alayhi wa sallam).

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Thank you.

ABSTRACT

Railway signaling systems on conventional lines of Malaysian railway companies have been damaged from lightning, especially in 2010. Therefore, effective and economical lightning protection measures are necessary for railway signaling systems because suspended operation or train delays due to lightning damage may cause social disruption. For analyzing lightning risk and making study for countermeasures against lightning damage, must measure the lightning overvoltage on railway signaling cables, which were laid at the ground surface and overhead, and rails in the field to enable quantitative analysis of the frequency of lightning overvoltage occurrence. Moreover, we investigated the correlation of lightning overvoltage (V) on signaling cables and rails with lightning conditions, such as the strike current (I) and the strike position (distance from the measuring position). From this we deduced the correlation between the lightning overvoltage (V) and (I), expressed as a linear expression. From this correlation, the lightning risk for railway signaling systems against lightning conditions can be estimated. In addition, it is possible to calculate the possibility of lightning damage to railway signaling equipment.

ABSTRAK

Railway sistem pada talian konvensional syarikat keretapi di Malaysia isyarat telah rosak dari kilat, terutamanya pada tahun 2010. Oleh itu, langkah-langkah perlindungan kilat berkesan dan ekonomi yang perlu untuk sistem isyarat kereta api kerana operasi atau kereta api digantung kelewatan akibat kerosakan kilat boleh menyebabkan gangguan sosial. Untuk menganalisis risiko kilat dan membuat kajian untuk langkah balas terhadap kerosakan kilat, mesti mengukur voltan lampau kilat di kereta api isyarat kabel, yang telah dibentangkan di permukaan tanah dan overhed, dan landasan keretapi di lapangan untuk membolehkan analisis kuantitatif kekerapan berlakunya kilat voltan. Selain itu, kami mengkaji korelasi voltan lampau kilat (V) pada isyarat kabel dan landasan dengan keadaan kilat, seperti mogok semasa (I) dan kedudukan mogok (jarak dari kedudukan pengukur). Dari sini kita disimpulkan hubungan antara voltan lampau kilat (V) dan (I), dinyatakan sebagai ungkapan linear. Dari korelasi ini, risiko kilat untuk sistem isyarat kereta api terhadap keadaan kilat boleh dianggarkan. Di samping itu, ia adalah mungkin untuk mengira kemungkinan kerosakan kilat untuk peralatan kereta api isyarat.

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LIST OF SYMBOLS AND ABBREVIATIONS

MLS	Multiple lightning stroke
FLF	Flash Lightning Flatlands
MV	Mega voltage
LF	Leader Formation
CC	Cloud-to-cloud
BL	Ball lightning
GC	Ground-to-cloud
E	Electrical fields
V	Propagation speed
RS	Railway System
R	Resistance
L	IInductance
G	Conductance
Γ	Propagation constant
RLs	Railway lines
BTs	Booster transformers
ATs	Autotransformers
EMI	Electromagnetic interferenc
α	Refection Coefficient
β	Transmission Coefficients
A	Equivalent Attractive area
b	Effective width
Ra	Equivalent Attractive distance
BLD	Bewley lattice diagram
Z	Impedance

Y	Admittance
SG	Railway track S and ground
SRG	Railway track S and Railwaytrack R and ground
MTLs	Multiple transmission lines

CHAPTER 1

INTRODUCTION

1.1 Project Background

Lightning is an important meteorological process, it is a dangerous natural phenomenon which causes disturbances in our life, and it has a bad effect on mankind. So a great attention has been taken towards this phenomenon. From railway point of view, these rails should be protected against this phenomenon, where large parts of the railway exposed to lightning. System components can be exposed to lightning-induced overvoltage's; this overvoltage have high magnitude comparing with any voltage level of the distribution network, so flashover is generated causing damage to the equipment when insufficient protection against this phenomenon is used. This directly effects on system reliability for railways. Of all lightning discharges only around 25% of the lightning bolt reaches the ground. Lightning being an intense power source (although of short duration), has the potential to cause significant damage to life and property [1].

Attempts to understand the phenomena (being most spectacular in nature but destructive), has been a great challenge and forms one of the well-researched area. In spite of enormous research efforts, when it comes to the question of “how likely is it that lightning will strike an object and cause damage?” deterministic answers are not possible yet [2]. For such questions one needs to heavily depend upon the lightning statistics. The other variables on which the CG discharges depend are terrain, tall structures & trees, their relative spatial spread, shape and composition of the structures, and soil resistivity (which has bearing on dampness and its type), to name a few important ones [3]. Lightning CG discharges have many destructive effects, as is widely known. The more damaging effects have come to the fore due to its indirect effects on modern electronic gadgets, which are susceptible to surge voltages and currents. The effort here is to bring out the salient features of lightning with specific reference to indirect effects. The lightning is the main cause of problems in railway in the world [4] [5].

1.2 Problem Statement

Lightning strikes are atmospheric phenomena which have adverse effects on railway. Lightning strikes damaged rail infrastructure an average of 192 times each year between 2010 and 2013, with each strike leading to 361 minutes of delays. In addition, 58 trains schedules a year were cancelled due to lightning related faults. Predicting the geographical and temporal distribution of the lightning strike densities through modeling can help railway designers to improve the protection of the existing and new railway. When lightning strikes a rail, the high voltage can damage this sensitive electronic signaling equipment. As our signaling system fails safe, when a component is damaged all signals in the area turn red and trains must stop. In order to compare the results of the model simulations to the physical data, characterization is required. The distribution of the lightning strike densities generates patterns which are highly nonlinear and no stationary. Nowadays simulation technique is implemented to improve traditional techniques, where the results can be obtained instantaneously after it analyzes the input data of the railway such as currents (i) and voltages (v). In this project MATLAB SIMULINK is used to simulate railway system and analyze the result.

1.3 Project Objectives

This project proposes the analysis simulation of lightning strike in railway using MATLAB program, the objectives of the work are:

i) To design railway model through direct and indirect lightning strike using MATLAB tools and analyze the step by step the voltage and current curves.

ii) To analyze the scenario of propagation currents and voltages and the travel waves that cause the system instability in railway according to Bewley Lattice diagram after the lightning stroke.

iii) To test of railway track model with a single lightning impulse voltage and AC voltage in the laboratory.

1.4 Project Scope

The project primarily concerned with lightning ground flashes interaction with railway lines .the scope of this project are:

(i) The Malaysian railway transport system will be studied and the case study is based on Kluang railway station.
(ii) Simulation of the lightning-induced surge propagation along the railway lines will be done using Bewley Lattice method of analysis.
(iii) Modeling and simulation analysis study will be also involve with the use of MATLAB software and laboratory test.
(iv) In the project simulation execution ,the flashing lightning strike modes be focused :
  a) Single lightning stroke.
  b) Multiple lightning stroke (multiplicity level up to 2).
  c) Multiple and Simultaneous lightning stroke (multiplicity level up to 2).
(v) In the laboratory test the lightning impulse voltage is more than 2 kV.

1.5 Thesis Outline

This thesis is separated into 5 chapters. In the first chapter focuses on outlines the main idea of this project. The would explained about lightning phenomenon, motivation methods and principals locating of lightning strikes, and literature reviews of previous researchers this in the second chapter. The following describe the methodology of the project, including the tools and equipment's, procedure and processes involved for the hardware and software development of the entire project. And in forth chapter discussed on the results obtained from the lightning detection system. Finally in chapter 5 is about conclusion and recommendations that can be used for further research related to this topic in future would be included.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Lightning is a sudden high-voltage discharge of electricity that occurs within a cloud, between clouds, or between a cloud and the ground and external of the cloud. Globally, there are about 40 to 50 flashes of lightning every second or nearly 1.4 billion flashes per year. These electrical discharges are extreme deadly and devastative. Lightning is a giant spark of electricity in the atmosphere between clouds, the air, or the ground. In the early stages of development, air acts as an insulator between the positive and negative charges in the cloud and between the cloud and the ground. When the opposite charges builds up enough, this insulating capacity of the air breaks down and there is a rapid discharge of electricity that we know as lightning. The flash of lightning temporarily equalizes the charged regions in the atmosphere until the opposite charges build up again [6].Lightning can occur between opposite charges within the thunderstorm cloud (intra-cloud lightning) or between opposite charges in the cloud and on the ground (cloud-to-ground lightning).Lightning is one of the oldest observed natural phenomena on earth. It can be seen in volcanic eruptions, extremely intense forest fires, surface nuclear detonations, heavy snow storms, in large hurricanes, and obviously, thunderstorms. Lightning strike comes about every day in the world. The lightning strike towards the surface on earth has been estimated at 100 times every second. Thus, almost every governments suffer major loses because of this phenomenon every year. It also would cause horrific injury and fatality to humans and animals. The lightning may affect almost every organ system as the current passes through the human body taking the shortest pathways between the contact points. There are 25.9% of lightning strike occurrences for victims who took sheltered under trees or shades, whereas 37% at open space area. Head and neck injury are two common areas which have an effect on the lightning strike victims with 77.78% and 74% respectively. Only 29.63% of the cases presented with ear bleeding [7].United State National Lightning Safety Institution reported that Malaysia has highest lightning activities in the world whilst the average-thunder day level for Malaysia's capital Kuala Lumpur within 180 - 260 days per annum [8, 9]. The isokeraunic level is approximately 200 thunderstorm days a year. The lightning ground flash density is

2.2 Mechanism of Lightning to railway.

Lightning is an electric discharge in the form of a spark or flash originating in a charged cloud. It has now been known for a long time that thunder clouds are charged, and that the negative charge center is located in the lower part of the cloud where the temperature is about - 50 C, and that the main positive charge center is located several kilometers higher up, where the temperature is usually below - 200 C. In the majority of storm clouds, there is also a localized positively charged region near the base of the cloud where the temperature is 00 C. Figure 2.1 shows such a cloud located above an overhead transmission line.

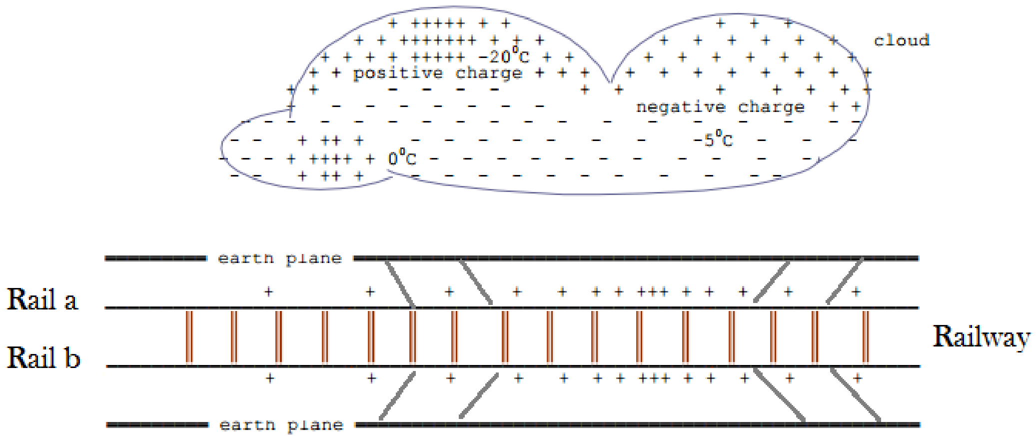

Figure 2.1: Induced charges on railway.

Fields of about 1000 V/m exist near the Centre of a single bipolar cloud in which charges of about 20 C are separated by distances of about 3 km, and indicate the total potential difference between the main charge centres to be between 100 and

1000 MV. The energy dissipated in a lightning flash is therefore of the order of 1000 to 10,000 MJ, much of which is spent in heating up a narrow air column surrounding the discharge, the temperature rising to about 15,000 0 C in a few tens of microseconds. Vertical separation of the positive and negative charge centres is about 2 - 5 km, and the charges involved are 10 - 30 C [10]. The average current dissipated by lightning is of the order of kilo-amperes. During an average lightning storm, a total of the order of kilo-coulombs of charge would be generated, between the 00 C and the -40 0 C levels, in a volume of about 50 km^3 [11].

2.3 Effects of lightning discharges in the railway.

The physics of lightning is still a mystery. CG discharges can be quite destructive, particularly when grounded objects are not protected. The number of lightning related deaths in humans is small when compared to other causes of accidents. Livestock on the farms is most susceptible, particularly four legged animals with large spans between legs; e.g. cattle’s. Lightning plays an important role in forest fires and associated damages. Interaction of CG discharges with railway can disrupt power lines can causing power failures [12]. The effects of CG discharges can be broadly classified into two categories, namely: (i) direct (direct strokes), and (ii) indirect (indirect strokes). Indirect effects can be further viewed as those due to: (a) conductive, inductive and capacitive coupling, and (b) radioactive coupling [13].

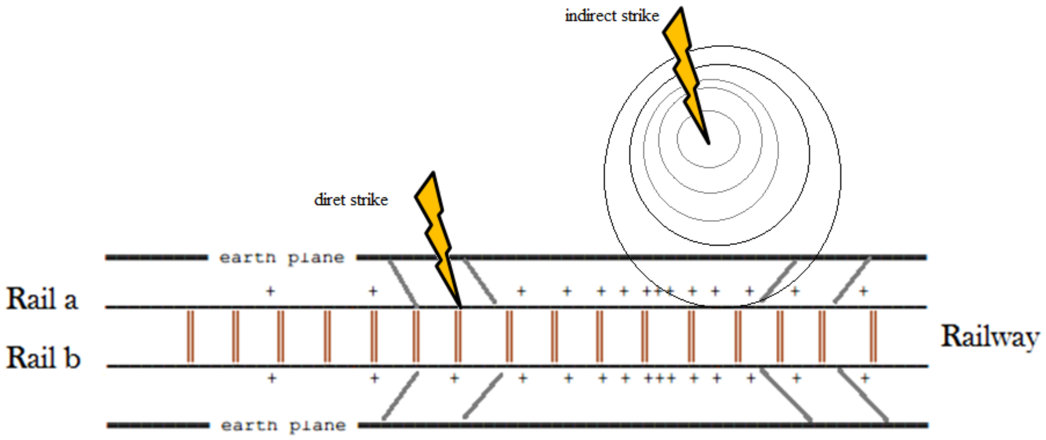

Figure 2.2: Categories of Lightning discharges.

2.3.1 Direct strokes.

A lightning CG discharge, strikes an object directly, such as power-line or building, and it can result in significant damage. Direct effects generally result in physical damage and have associated fire hazards. In the case of buildings it can result in cracks in the masonry work. The injected voltages and currents associated with direct strokes being much higher compared to indirect strokes, will have the ability even to damage power and distribution equipment and cut railway [14]. Most often the electrical motor insulations associated with the irrigation pump becomes the victim of a direct stroke. Other common examples are welding of contactors of the motors starters and explosion of power distribution transformers. The protections in the form of lightning rods and ground overhead wires can significantly reduce the chances of direct strokes. Having averted the direct strokes if one has to successfully reduce the probable secondary effects an appropriate grounding and bonding system is a must [15].

2.3.2 Indirect effects.

Even if the lightning rods and ground overhead wires effectively shield the buildings, power lines, railways, and other objects, Once the lightning CG discharges are to the ground rod and railway lines, the charges tend to flow to the ground through the associated grounding system., the system needs grounding with zero ground impedance, ideally. In actuality the ground impedances are neither zero nor stable due to many of the soil properties and its associated parameters. There are guidelines related to the threshold permissible values of earth resistances depending on the criticality of the system being protected [16].

2.4 Railway system.

As show the figure 2.3 Rail composed of a set of sections connected by junctions long the section about 100m.

Figure 2.3: Railway track joint.

The line profile of the rail track at the test section is shown in Figure. 2.13 a rail track consists of rails, cross ties, a rail bed, and a track bed.

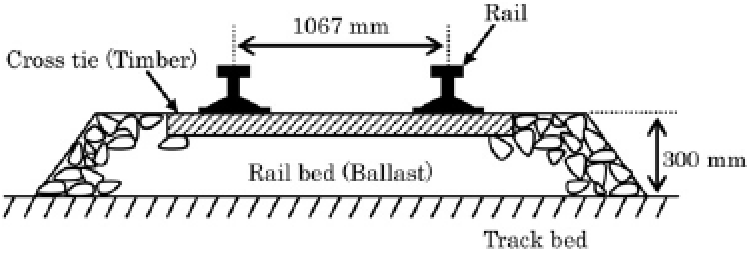

Figure 2.4: Profile of the railway track.

2.4.1 Lightning surge parameters of railway track [17].

The surge impedance and the surge propagation velocity are important parameters as the surge characteristics of a rail. We investigated the surge impedance and the surge propagation velocity between the rail and the ground due to measuring the injection current to the rail and the induced voltage on the rail when the steep-front current was injected into the rail. The outline of measuring method is shown in Figure2.5.

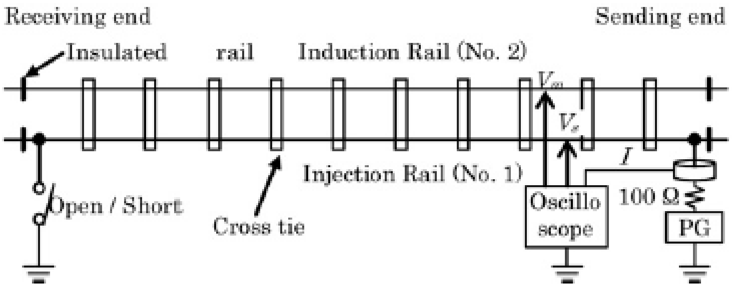

Figure 2.5: Outline of measuring surge parameters of railway track.

2.4.2 Surge attenuation ratio in the railway track.

The surge attenuation caused by traveling along the rail is important parameters as the surge characteristics of a rail. We investigated the lightning surge attenuation ratio due to measure the voltage waveforms between the rail and the ground at the Sending end and the receiving end Surge.

2.4.3 Electric circuit for the railway.

The electric circuit, which is formed between sending end and receiving end of rail showing in Figure 2.6 can be considered a two-port circuit composed from the distributed-parameter line such as rails. We investigated the frequency-dependent four-terminal parameters (resistance R, inductance L, conductance G and capacitance C) of the rails to estimate the distributed parameter adopted in the calculation model due to measure the open circuit impedance and the short circuit impedance by non-grounding or grounding at the receiving end of rail, respectively. In the same way, open/short circuit impedance between rails [18].

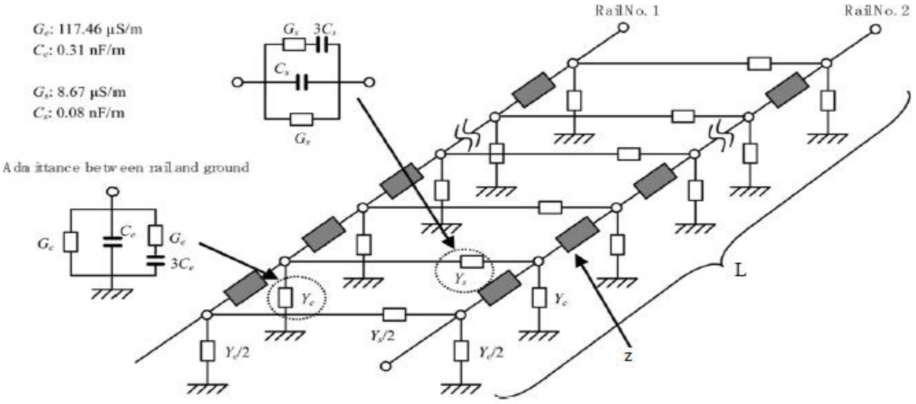

Figure 2.6: Railway tracks electric model propagation of surges.

2.5 Kluang single-track railway.

A photograph of the railway line in Kluang station is shown in Figure 2.7 it shows the distribution of MRLs. Both the tracks and ground conductors are considered as MRLs under the ground and are assumed to be infinite in either direction, which mal (2.6) problem two-dimensional. The schematic of MRLs model for double -track electrified railway system commonly found in Kluang is shown in Figure 2.15, the associated conductor systems are described in Table 2.1. The different mediums that would be of interest for the wave propagation studies are shown in Table 2.2. The typical values shown in Table 2.2 are taken; further, they are nominal and do not correspond to some extreme conditions of climate or temperature.

Figure 2.7: Railway tracks in Kluang station.

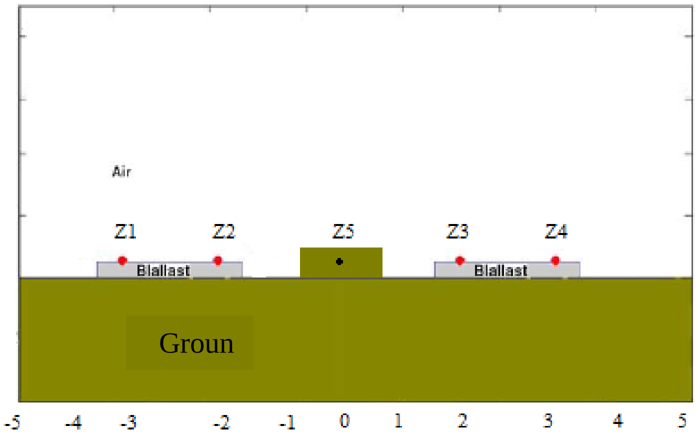

Figure 2.8: Schematic of double-track railway system (axes are in metres).

Table 2.1: Conductor nomenclature of Kluang tracks.

Conductor nomenclature	Conductor with bundle
S_1-rail	Z_1
R_1-rail	Z_2
S_2-rail	Z_3
R_2-rail	Z_4
Cable	Z_5

Rail and ballast .include the conductor's Z_1 and Z_2 are the rail1. $Z_3$and Z_4 are the rail$_2$. Z_1 and Z_3 are called the S-rail and is continuous and forms one of the reference/return conductors.Z_2 and Z_4 are the I-rail, which is broken every 1.02 km and is used for the signaling purpose. The track circuits are connected across the S-rail and I-rail and across which a constant potential of 7V exists. This voltage collapses to zero once the locomotive is on this section of the rails in the normal case.

Then relay units are also connected across the tracks. These serve the purpose of train positioning and signaling systems. Z_5 is the cable underground, which feeds the light. The Kluang railway system works at 10 kV and 16(2/3) Hz [19].

Table 2.2: Material properties of MTLs.

Mediums/conductor Systems	Relative permittivity	Relative permeability	Conductivity (S/m)
Air	1.0	1.0	1.0e-11
Ballast	10.0	1.0	1.0e-5
Ground	10.0	1.0	4.0e-4
Z_1,Z_2,$Z_3$and Z_4	1.0	20.0	4.40e-6

2.6 Modeling direct Lightning Strikes for Railway Systems with Lumped Components.

A model with most common devices connected along the multiconductor transmission line (MTL) system of railway, i.e., booster transformers (BTs), autotransformers (ATs), and track circuits, for evaluating the voltage and current propagation due to lightning and switching transient sources was developed by the authors [20]. As the potential between above ground wires and poles may exceed the insulator impulse withstand voltage levels, flashovers occur and hence needs to be implemented in the model [21].

2.6.1 Induced Voltages Across Lumped Devices Along The Track System in Railway And Transmissions Lines.

The electromagnetic interference (EMI) source used in the calculations is representative of a subsequent lightning return stroke. The lightning is simulated to strike at a 50-m perpendicular distance from the midpoint of the system. The lightning channel base-current wave shape, at time *t*, is expressed by the sum of two functions expressed as (1), with the parameters as stated in Table 2.3 [22].With these parameter values, the base current peak is about 12 kA. This current is assumed to propagate upward in the lightning channel in accordance with the modified transmission-line model with linear decay [23]. The field-to-line coupling model adopted in the calculations is the Agrawal et al. model. In this model, the electromagnetic fields are represented as series- and shunt-connected voltage sources along the lines of the MTL system [24]. In the analysis, an MTL system, representative of the catenary track system of electrified single-track railway system, as shown in Figure. 2.9, is considered. As seen, this 6-km long MTL system consists of five overhead wires, S-rail, I-rail, catenary, return conductor/negative feeder (called as return conductor), and auxiliary wire. All lines are terminated to the finitely conducting ground (ground resistivity 1000 Ω/m) by their self-characteristic impedance. The conductor radii and characteristic impedances are given in Table 2.4. Characteristic impedances are calculated for ideal ground, and are only approximate for finitely conducting ground. The telegraphers' equation for the 5-conductor transmission line system above finitely conducting ground is given as follows [25]:

Table 2.3: Base-current parameter values.

I_{01}	τ_{11}	τ_{21}	n_1	I_{02}	τ_{12}	τ_{22}	n_2
(kA)	**(μs)**	**(μs)**		**(kA)**	**(μs)**	**(μs)**	
10.7	**0.25**	**2.5**	**2**	**6.5**	**2.1**	**230**	**2**

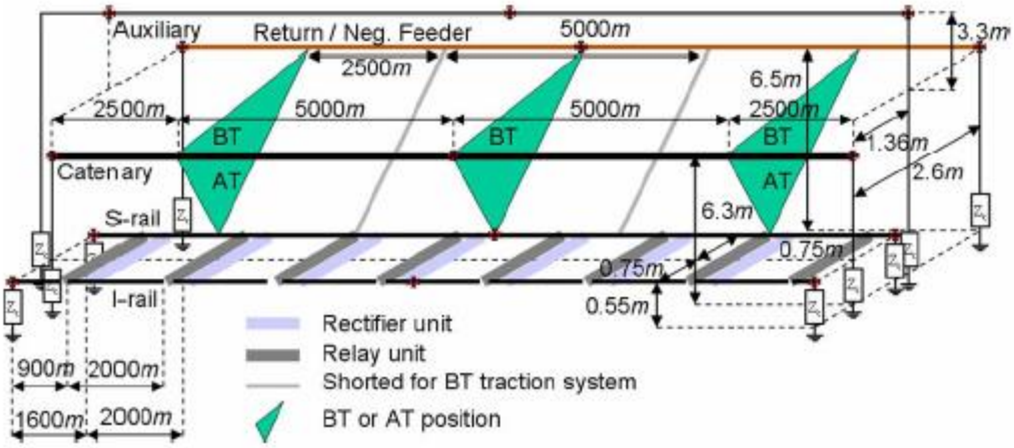

Figure. 2.9: MTL system representative of a typical railway traction conductor feeding system.

Table 2.4: Conductor radii and characteristic impedances for Figure 2.16.

	S-Rail	**R-Rail**	**Catenary**	**Return/ Neg.feeder**	**Auxiliary wire**
Radii(mm)	**49.5**	**49.5**	**50.6**	**8.2**	**5.6**
$Z_c(\Omega)$	**186**	**186**	**331**	**442**	**490**

In Figure 2.17. It shows the complex distribution of MTLs. In the simulation, we have taken only a single-track system. However, an analysis with the double-track system would be similar as described here but with more conductors. Both the tracks and overhead conductors are considered as MTLs above the ground and are assumed to be infinite in either direction [26].

Figure 2.10: Railway track showing the complexity of MTLs.

Figure 2.11: Railway track showing of MTLs in Malaysia

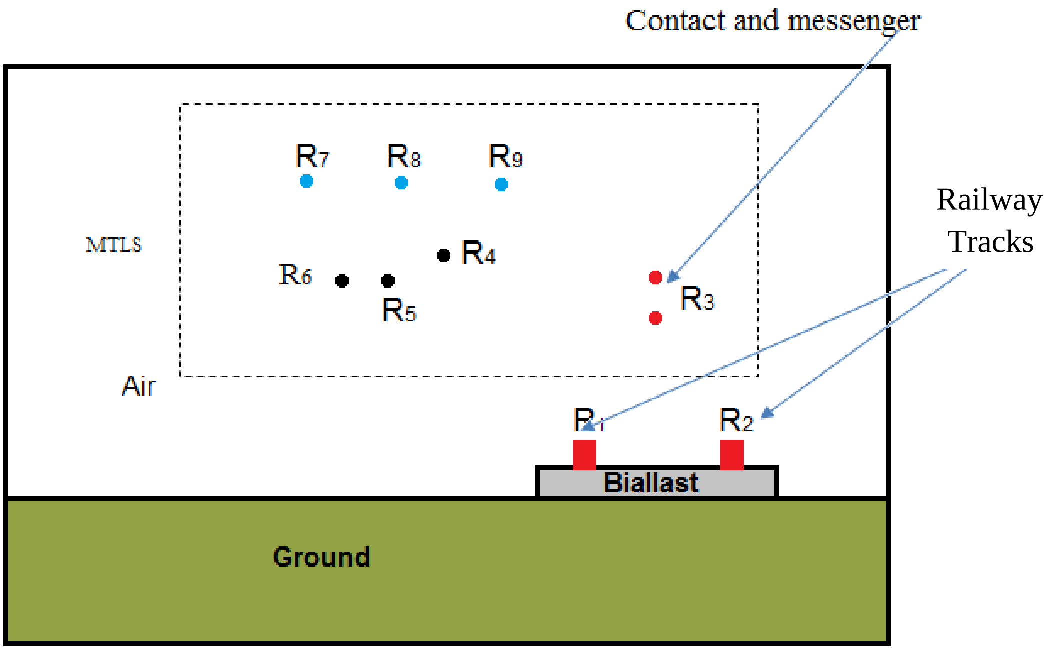

Figure 2.12: Schematic of single-track railway system (axes are in meters).

Table 2.5: Conductor nomenclature.

Conductor nomenclature	Conductor with bundle
S-Rail	R_1
R-Rail	R_2
Contact and messenger	R_3
Reinforcement	R_4
Return	R_5 and R_6
help	R_7-R_9

2.6.2 The electrified railway system.

A normal single-track electrified railway system can consist of as many as ten above ground conductors, and one buried communication cable along the track, not shown in the cross sectional view of the MTL system. The contact and messenger cables, both noted as *R3* in the cross-sectional view of Figure. 2.17, are interconnected at every 7-10 *m* and these conductors can, in accordance with the principle of bundled conductors [27], be combined into a single conductor.

Table 2.6: Conductor nomenclatures and properties in a typical single-track electrified railway system.

Conductor nomenclature	Conductor notation	Conductivity (S/m)
S-Rail	R_1	4.4×10^{-6}
R-Rail	R_2	4.4×10^{-6}
Contact and messenger	R_3	5.8×10^{-7}
Reinforcement	R_4	3.5×10^{-7}
Return	R_5 and R_6	3.5×10^{-7}
help	R_7-R_9	3.5×10^{-7}

Names, notations and conductivities of the overhead conductors of Figure 1.1 are presented in Table 2.6. The conductors forming the MTL system consist of the following:

- Two rails; the S-rail, R_1, is continuous though out the entire railway system and used as a return path for the traction current and the I-rail, R_2, has 45 insulated gaps at regular intervals and is used for signaling purposes.
- The bundled R_3 conductor, also known as the catenary wire, is used for feeding power to the locomotive through the pantograph located on the locomotive roof with 15 kV, 16.67 Hz.
- An electrical reinforcement wire, R_4, is running in parallel with the catenary and it is connected to it every 200-300 m. This wire is present for reducing the catenary system impedance.
- Return conductors, R_5 and R_6, are used for returning the traction currents to the feeding stations.
- Auxiliary power wires, R_7, R_8 and R_9, operating at 22 kV, 50 Hz are used to supply power to trackside equipment after a step down to 400/230 V. The communication cables used in the Swedish railway systems are buried or put in trenches at a depth of 0.5-0.75 m and about 1-2 m away from the tracks on the pole side. There are different kinds of communication cables used on different track sections based on current demand and future planning. A communication cable frequently used by Banverket is the Ericsson made BV ECLALPLE 1S1.2 + 28P 0.9 [28], a cross sectional view of this cable is shown in Figure 2.13. This multiconductor communication cable consists of 60 copper conductors split in three layers, pair-wise twisted arrangement, enclosed by a stranded aluminum shield and a steel armor [29].

Figure 2.13: Ericsson BV-ECLALPLE 1S1.2 + 28P 0.9 cable, a typical communication cable used in the railway systems.

In double-track railway systems the tracks run in parallel and the overhead conductors are mirrored, with a distance of 4.4-10 m between the centers of the lines, with auxiliary wires only present at one side of the track [30].

2.7 Pole insulator flashover and ionization at the pole footing.

2.7.1 The interconnection between the conductors.

Interconnections between conductors play an important role in surge current distribution. The return conductors (R5 and R6) and S-rail (R1) are connected together at every 5 km. This situation is shown in Figure. 2.21 (dashed line). The interconnection is assumed to be at the middle of the line being simulated, where the lightning is assumed to strike at the top of conductor R7. The termination matrix at this junction point on the middle of the line is a sparse conductance matrix with its elements corresponding to short and open circuit resistances. Note that in all the simulations, this junction is assumed to be in the middle of the two pole locations. The distance between the two poles is 60 m.

2.7.2 Pole insulator flashover and soil ionization at the pole footing.

The poles support the conductors through insulators, which have different impulse with stand voltages as shown in Table 2.7.

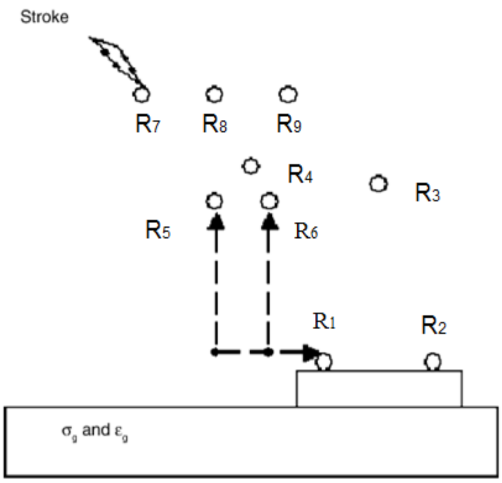

Figure 2.14: Interconnection between R_5, R_6 and R_1.

The other terminations to the ground from the conductors are due to the insulator flashovers on the poles and pole’s footing ionization/static resistance as the case may be. Determining the equivalent termination resistance at the pole is a bit complex and depends on the ionization characteristics at the pole footing and insulator flashover behavior. The S-rail (R1) is connected to the pole footing directly and all the other conductors excepting I-rail (R_2) are connected to the pole through the insulators, the schematic of which is shown in Fig. 2.22 The resistance (*R*g) due to soil ionization at the pole footing is calculated using the method proposed by the IEEE standard [31],*R*0 is the footing resistance measured with low current (dc), *I*R the lighting current through the footing resistance and *I*g is the current required to produce a voltage gradient, *E*0, at which soil breakdown occurs which is about 400 kV/m. The termination resistance is calculated using the equivalent circuit based on the schematic diagram shown Figure 2.15.

Table 2.7: Impulse withstand levels for the insulators.

Conductor nomenclature	Ceramic insulator type	Impulse withstand voltage (kV)
R_3	Rod or composite	225
R_4	Lie post	170
R_5 and R_6	Spool	60
R_7–R_9	Pin	140

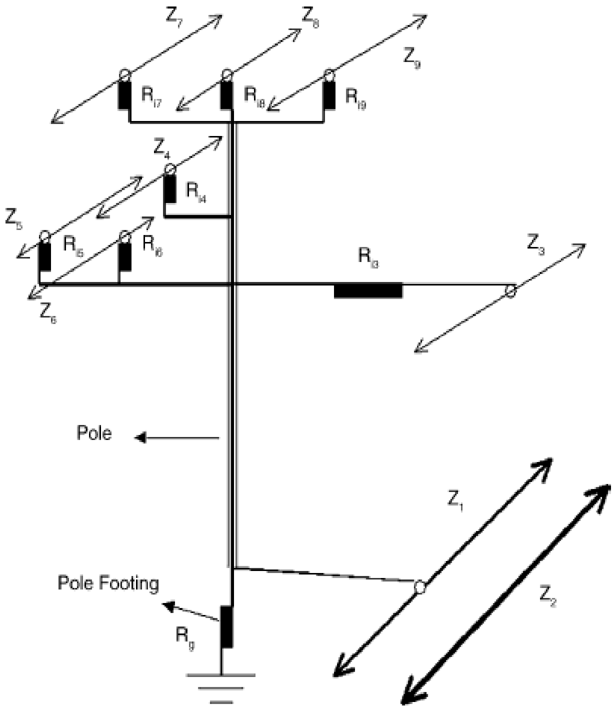

Figure 2.15: Insulators, connections and pole footing resistance in a single track railway system.

At every 60 m along the MTL system there are poles. These are not only used for grounding points for the S-rail, but also to hold the overhead wires in the air along the system, as shown in Figure. 2.22. The above ground wires are connected onto this pole by insulators of different materials and impulse withstand over voltages, as shown in Table 2.7.

2.8 Waves on railway lines.

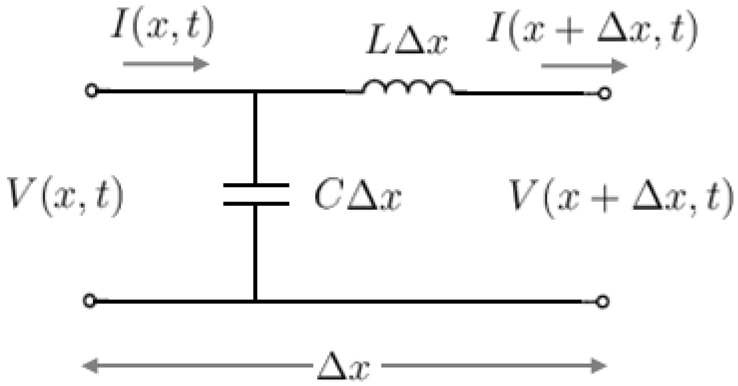

Figure 2.16: Travelling wave in railway Line model.

Considering the above railway line in the sinusoidal steady state. Assuming series impedance per meter and shunt admittance per meter to neutral are:

$$Z = r + j\omega l \tag{2.1}$$

$$y = g + j\omega c \tag{2.2}$$

From figure 2.16 V_1 and I_1 are per phase terminal voltages and currents at left and V2, I2 are per phase terminal voltage and current at right. Considering a small section of line length dx .Taking the series impedance and the shunt admittance of dx are zdx and ydx respectively. The receiving end at the right side is located at x=0 and the sending end at the left side is at x=L. Applying Kirchhoff's voltage law and Kirchhoff's current law to dx.

$$\gamma = \sqrt{ZY} = \alpha + j\beta \tag{2.3}$$

γ is a complex quantity which is known as the propagation constant. Where Z is the characteristic impedance of the line and is given by:

$$Z = \sqrt{\frac{R+L\frac{\partial}{\partial t}}{G+C\frac{\partial}{\partial t}}} \tag{2.4}$$

$$Z = \sqrt{\frac{L}{C}} \tag{2.5}$$

This is the characteristic impedance of the line. This implies that the voltage and current waves travel down the line without changing their shapes.

$$\frac{\partial^2 u}{\partial^2 x^2} = Lcu \tag{2.6}$$

Equation (2.6) is the so called travelling wave equation of a loss less railway line. The solutions of voltage and current equations reduce to

$$u(x,t) = A_1(t)e^{\frac{x}{v}} + A_2(t)e^{\frac{-x}{v}} \tag{2.7}$$

$$i(x,t) = -\frac{1}{Z_0}[A_1(t)e^{\frac{x}{v}} - A_2(t)e^{\frac{-x}{v}}] \tag{2.8}$$

Where v is the travelling wave propagation speed defined as:

$$V = \frac{1}{\sqrt{LC}} \tag{2.9}$$

2.8.1 Reflection and refraction of travelling waves (Bewley Lattice diagram)

When the wave propagates along a railway line with certain characteristic impedance, there is a fixed relation between the voltage and current waves. The line is defined as:

$$\alpha = \frac{Z_R - Z_0}{Z_R + Z_0} \tag{2.10}$$

Where Z_0 is a characteristic impedance of the line and Z_R is the railway impedance [32]. Similar coefficients can be obtained for the currents, but the current reflection coefficient equals the negative of the voltage reflection coefficient value.

$$\beta = \frac{Z_0 - Z_R}{Z_R + Z_0} \tag{2.11}$$

As a special case, termination in a short circuit results in $\alpha = -1$ for the voltage signals and $\beta = 1$ for current signals. If the termination is an open circuit, Z_R is infinite and $\alpha = 1$ *in* the limit for the voltage signal and $\beta = -1$ *for* the current signal. For a travelling wave while propagating through the railway, the railway (refraction) coefficient can be calculated as:

$$\beta = \frac{2Z_R}{Z_R + Z_0} = \alpha + 1 \tag{2.12}$$

Therefore, for a line terminated in a short circuit, the voltage of the backward (or reflected) wave is equal and opposite to the voltage of the forward (or incident) wave. The bounce diagram, also known as the lattice diagram, provides a systematic way of tracing the wave propagation on a railway line in a graphical manner. This methodology is called the bounce diagram since it represents the travel waves that bounce back and forth at the impedance discontinuities of the railway line. Figure 2.17 shows the typical voltage bounce diagram [33] that represents the transient voltage at the total railway length with an incidental voltage signal of V+.

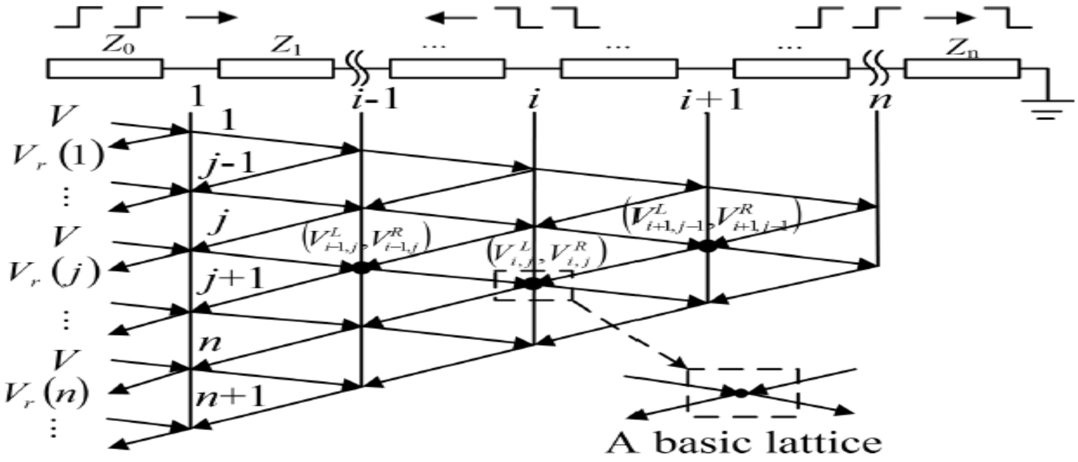

Figure 2.17: Bewley Lattice diagram that illustrates the injected voltage traveling back and forth in railway line.

$$V_{i,j}^{L} = \beta_{i-2,i-1} V_{i-1,j}^{L} + \alpha_{i-1,i-2} V_{i-1,j}^{R} \tag{2.13}$$

$$V_{i,j}^{R} = \alpha_{i,i+1} V_{i+1,j-1}^{L} + \beta_{i+1,i} V_{i+1,j-1}^{R} \tag{2.14}$$

Where *Ti;i*+1 and *Ti*+1*;i* are the transmission coefficients $\alpha_{i,i+1}$ and $\alpha_{i+1,i}$are the refection coefficients between *Zi* and *Zi*+1. $\beta_{i,i+1}$, $\beta_{i+1,i}$, $\alpha_{i,i+1}$ and $\alpha_{i+1,i}$ are defined as follows [34].

$$\alpha_{i,i+1} = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \tag{2.15}$$

$$\alpha_{i+1,i} = \frac{Z_i - Z_{i+1}}{Z_{i+1} + Z_i} \tag{2.16}$$

$$\beta_{i,i+1} = 1 + \alpha_{i,i+1} \tag{2.17}$$

$$\beta_{i+1,i} = 1 + \alpha_{i+1,i} \tag{2.18}$$

2.8.2 Propagation the waves in Bewley Lattice diagram method.

Figure 2.18 show how the voltage propagation in one section and determined peak voltage in end the line.

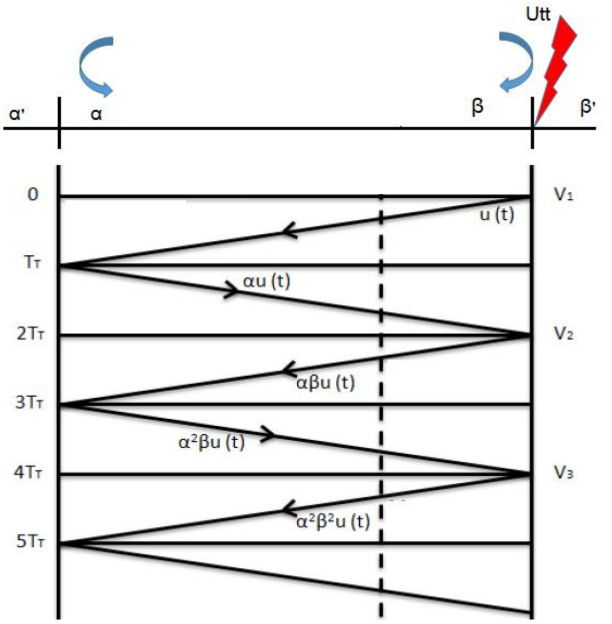

Figure 2.18: Bewley Lattice diagram for one section in railway line.

The following equations explain how to get the peak voltage in the strike point.

$V1=u\ (t) \qquad t=0$ (2.19)

$V2= (\alpha+ \beta\alpha) \qquad t=2TT$ (2.20)

$V3= (\alpha^2\beta+\alpha^2\beta^2)\ u\ (t) \qquad t=4TT$ (2.21)

$V4= (\alpha^3\beta^2+\alpha^3\beta^3)\ u\ (t) \qquad t=6TT$ (2.22)

$UTT=V1+V2+V3+V4$ (2.23)

$UTT\ (t) = ut(t)+ \alpha ut(1- \beta)\ (t-2TT) +\alpha^2\ \beta u(t-4TT) +\alpha^2\ \beta^2\ u(t-4TT) +\alpha^3\ \beta^2\ u(t-6TT)$

$+\ \alpha^3\ \beta^3\ u(t-6TT)$. (2.24)

$= ut(t) +\alpha\ (1- \beta) +ut\ (t-2TT) +\alpha^2\ \beta^3\ (1-\beta)\ u(t-4TT) +\alpha^3\ \beta^2\ (1-\beta)\ u(t-6TT)$

$= ut(t) +\alpha\ (1+\beta)[\ ut\ (t-2TT) +\alpha\ \beta\ u(t-4TT)+ (\alpha+\beta)^2\ u(t-6TT)]$. (2.25)

2.9 Lightning risk evaluation for railway signalling systems.

The lightning overvoltage on signalling cables

$V = 0.0145 \times (I / r) + 0.17$ (2.26)

The lightning overvoltage on rails

$V = 0.0134 \times (I / r) + 0.19$ (2.27)

We can estimate the lightning conditions at the case of lightning damage occurrence caused by exceeding the withstand voltages of railway signalling systems according to (2.25) – (2.26). We can evaluate the occurrence frequency of lightning risk for railway signalling systems to the occurrence probability of lightning conditions as shown in Figure 2.19. If the railway signalling systems leading overhead power lines have a withstand voltage of approximately 30 kV where countermeasures for protection against lightning are taken, These lightning conditions correspond to the case that 31 kA of lightning strikes within a 0.155-km radius. 31 kA of lightning stroke current is 50 % value of cumulative occurrence frequency distribution of the peak value of lightning current. [35].

$$P(I) = \frac{1}{1+(\frac{I}{31})^{2.6}} \tag{2.28}$$

Where P (I) is the cumulative occurrence frequency distribution of the peak value of lightning current [%]. *Iis* the lightning stroke current [kA]. At the region where is *N* [times/year] of lightning stroke within a 10-km radius, the number of lightning stroke within r/km radius can be calculated by (2.28).

$$N(r) = N \times \frac{\pi r^2}{\pi \times 10^2} \tag{2.29}$$

Where *N*(*r*) is the number of lightning stroke within a r-km radius [times/year] [36]. *R* is the radius [km]. *N* is the number of lightning stroke within a 10-km radius [times/year]. for example of the region where is *N* = 1,000 times/year, we can evaluate that occurrence frequency of lightning damages of railway signalling systems leading overhead power lines is 0.36 times/year/equipment.

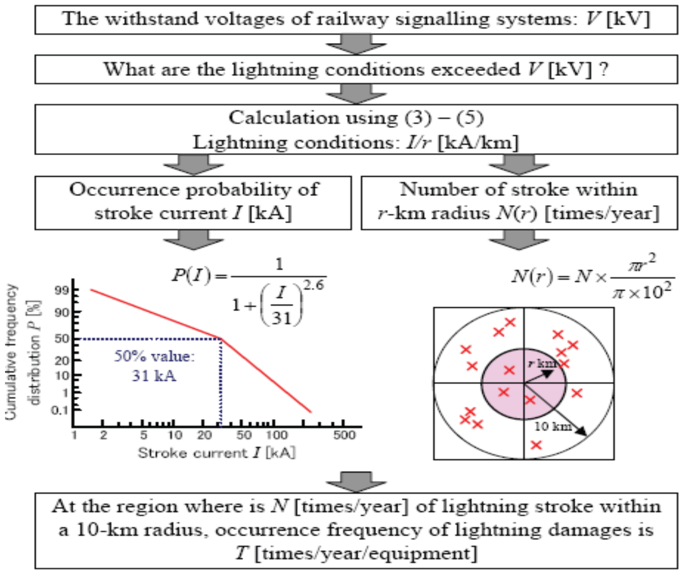

Figure 2.19: Evaluation flow of lightning risk for railway signaling systems.

2.10 Devices along Electrified Railway Systems.

The most common devices connected along electrified railway systems consist of trackside transformers; BT and AT, and track circuits; relay and rectifier units. There are also interconnections between the overhead conductors in the railway system, depending on which feeding system that is used. In the single-track electrified railway system with ten overhead conductors there are not only the contact, messenger and reinforcement wires that are interconnected as explained before. The return conductors are also interconnected, and for BT systems these are also connected to the S-rail at the midpoint between two consecutive transformers. In double track railway systems the S-rails of the different tracks are interconnected at every 300 m. At every pole position the S-rail is shorted to the pole footing. The pole footing is in turn grounded, but due to the phenomenon of soil ionization [37] not to ideal ground. This can be accounted for by connecting series non-linear resistors between every pole footing and the reference ground.

Components and devices connected to the auxiliary wires are not considered in this work.

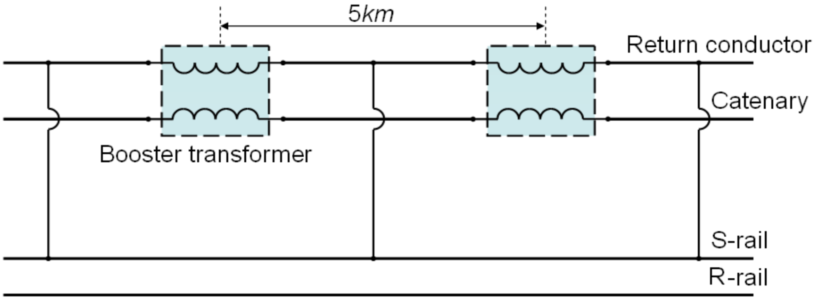

Figure 2.20: Transformer connections in BT feeding systems.

2.10.1 Trackside Transformers.

There are mainly two types of trackside transformer used in the Swedish electrified railway system, BT and AT. Both these are 1:1 transformers with the same purpose, i.e. to force the traction current to return through the designated return conductors (or negative feeder) to the traction supply to reduce stray currents which may cause EMI with electrical systems in the vicinity of the railway system. There are differences between the transformers, the primary and secondary coils of a BT are connected in series with the catenary and return conductor, and the coil of an AT is connected as shunt between the catenary and negative feeder and the midpoint of this coil is

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