ELECTROMAGNETIC COMPATIBILITY ANALYSIS OF SRI LANKAN RAILWAY NETWORK: COMPATIBILITY OF RAILWAY SIGNALING SYSTEM FOR RAILWAY ELECTRIFICATION

Makuralage Rasika Kumudu Kumari Koongahavita
(149287 R)

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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(Dr. Asanka S. Rodrigo)

ABSTRACT

Efficiency of the transportation system is an indicator which shows the development of the country. In Sri Lanka 20 percent of passengers use train transportation. Recently demand for rail transportation systems has been increased with the increment of rail transportation facilities. As more than 40 percent of employees use rail transportation passenger transportation is the main target of Sri Lanka Railways than the good transportation.

Railway signaling system is to cater the traffic requirements by utilizing the limited resources like trains and tracks. The loss due to failure of signal system is uncountable as human lives and human hours loss except to the loss of damages to properties.

Train detection is a main input for reliable signaling system. DC track circuits are used in Sri Lanka Railway signaling system to detect train on rails. In this scenario the current flow through rails is in milliamphere range.

Induced voltages due to external forces could be affected to change the current value and direction of power flow. This postgraduate research thesis describes the effect of electromagnetic interference on track circuit due to transmission lines and further effect due to electrification systems.

Electromagnetic interference level was measured under the different transmission lines and suitable model was selected to further calculations. Safe margin levels was introduced to keep with tracks for rated current flows.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

AC	- Alternating current
CEB	- Ceylon Electricity Board
CLS	- Color Light System
DC	- Direct current
ECTC	- Electronic Centralized Traffic Control
EMF	- Electro Magnetic Field
MFD	- Magnetic Flux Density
OHE	- Over Head Equipment
TSR	- Train Shunt Resistance
TSS	- Traction Sub Station
SLR	- Sri Lanka Railways
VPI	- Vital Processing Interlocking

Chapter 1

Introduction

1.1 General and Background

Initially the railway system of Sri Lanka has developed only for transporting plantation products from estates to ports for exporting. Due to the increasing population and the higher demand for longer distance travelling, passenger transportation became more popular lately. This is where the rail transport became more passenger oriented. Today railway is the main transportation medium used by the middle class people in Sri lanka, transporting over 400,000 passengers daily. Considering about high energy consumption, high emission, high delay times and less passenger comfort in the existing system, it has been proposed to electrify the existing railway system. As the first phase of the project, it has been decided to electrify from Panadura to Veyangoda through Colombo Fort.

In this scenario contribution of railway signaling system is very important to maximize the utilization of trains and train lines and to minimize the travel time of passengers. Signaling normally comprises an array of inputs detecting the current state of railway, high-integrity processing, and an array of outputs to authorize or inhibit the movement of trains. Apart from that it also helps to control other devices, such as points, which may affect the safety of train movements.

Sri Lanka Railway (SLR) is using a mechanical signal system and an electrical signal system as authority to train movements. Semaphore arms and Call on signals are used in mechanical signal type with compromise safety with lever frames. With compared to mechanical system, electrical signal system is having several types of signals according to field data acquisition and commands to field. In proposed electrification area, it is going to use two separate interlocking systems as VPI (Vital Processing Interlocking) system from Panadura to Maradana and ECTC (Electronic Centralized Traffic Control) system from Maradana to Veyangoda.

VPI system acquires data from wayside equipment, process the data and gives commands to wayside equipment accordingly. ECTC system has inherent relay interlocking and commands to wayside given through written codes. Method of acquiring field data and final output command to field is common for both VPI and ECTC systems and only difference is processing data.

Safe and reliability of signaling system depend on validity and accuracy of the data received from field. Availability of train in concern route, possibility of moving points along signal direction, acquiring conflicting routes during operating time are mainly considered before initiating a route signal.

SLR is using track circuits to check the track occupation and point condition. Power is fed to track from one side of track and collect it from other end using track relay. Relay condition is checked for track occupation. Point relays energized through the contact to identify the point in normal or reverse condition. Length of track circuits depend on the location that is used.

Since the safety of the entire signaling process depends on the data of track circuits, accuracy of track circuit data is very important for reliable signal system. As track relays have 1.5V and 103 mA pick up values, validating is necessary for the safety of the signal system.

In Sri lanka, power transmission line and rail line share same corridor often. In some places, both lines runs parallel and line is crossed with different angles at some places. Power transmission lines induce oscillating Electro Magnetic Field (EMF) nearby. The strength of the EMF depends on the current, voltage, conductor structure, type of conductor, phase angle and sag. Induced voltage due to EMF depend on the strength of the EMF level at considering point and this varies with the distance to EMF source.

Main research issue in concern is that to identify the effect of EMF on rail track due to transmission lines and check the effect of electrified system on existing track circuits and introduce safe margin distance to keep with the rail track.

1.2 Research Initiating Statement.

Operating department including train controllers and station masters are complaining that they are unable to give signal to trains due to track failures without any trains on the track and that failure automatically recover and also given signals become to danger position without signal passing by a train. That kind of failures are noted in server data and it recover within few seconds. This situation is caused to delay trains and it is unable to rely on signals due to automatically change of signal without any cause of failure. This unacceptable situation initiate the research to find out effect of transmission line on track circuits and to find out the effect in future with electrified train system.

1.3 Objectives

- To investigate the electromagnetic fields on track circuit due high voltage transmissions lines of 220kV, 132kV and 33kV and thereby, analyze the possibility of changing the conditions of track relays.
- To prepare a statement of safe distances to maintain with transmission lines and to introduce safety precautions with electrified train system.

1.4 Methodology

i. **Study the track circuit arrangement, track relay operation and power transmission data**

   Study the track circuits and feed voltages and track relay specifications used by Sri Lanka Railway department and Power transmission voltages, structures, rated current used by Ceylon Electricity Board (CEB) and power feed arrangement of electrified train system.

ii. **Literature survey**

   Do a literature survey on the Electro Magnetic Field around transmission line, induced voltage due to EMF, models to calculate Electro Magnetic Interference along transmission lines.

iii. **Taking physical measurements and compare values with models**

   Measure the magnetic field physically under the transmission lines for different voltages and structures using standard measuring meters with real time voltage and current values and compare those values with models used in literature reviews to validate a model for further calculations.

iv. **Calculate the induced voltage due to magnetic fields**

   Calculate the maximum possible induced voltage and current at relay end in the presence of electric fields using rated current values of the transmission lines.

v. **Safe Distances to keep with parallel transmission lines**

   Prepare a statement of safe distance levels for safe margin operations of track circuits for different voltages and transmission line configurations for parallel paths.

vi. **Mitigation methods for crossed transmission lines**

Prepare a statement for safety angle range when cross the rail track and possible methods to mitigate the induce voltage.

1.5 Results & Dissemination

- Electromagnetic field intensity profiles and impact level for different voltages and formations for transmission lines and electrified train system.
- Statement of safe distance to keep with parallel transmission lines and safe angular range for crossing lines.
- Statement safe distance to keep with electrified train system
- Induced voltage mitigation proposals using track circuit length and reverse electrified system for parallel transmission lines
- Induced voltage mitigation proposals using track length for crossed transmission lines.

Chapter 2

SLR Color Light Signal System, Track Circuit and Electrified train system

2.1 Signal Systems in Railway

Signals used in railways are categorized as audible and visual. For Audible signals detonators, voice or whistle are used. Audible signals are mainly used to warn a caution ahead stop the train. Red and green movable flags are used to indicate to reduce the speed or to stop the train. Train driver identify the signal according to the way of flag waving.

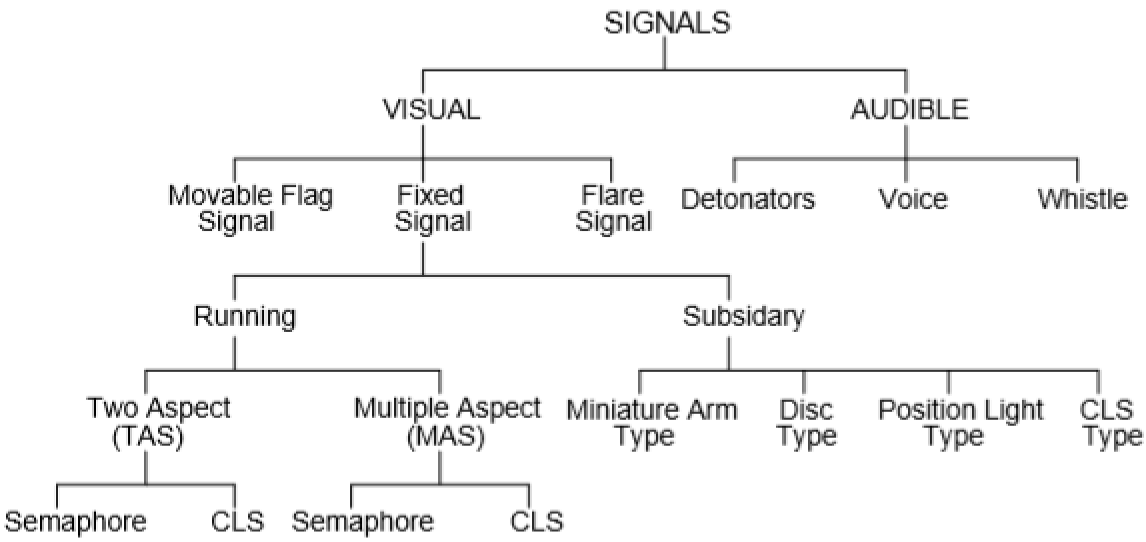


Figure 2.1: Signals used in railway

2.1.1 Semaphore signals

Two aspect lower quadrant semaphore signals are used in SLR. Semaphore signal operation done through mechanical lever frames and levers connected with mechanical inter locking. Semaphore arms are painted with red and white strips. Only two aspects are shown by lower quadrant semaphores. Stop dead indication is shown using horizontal aspect and proceed indication is shown using midway movement of semaphore arm. To improve the visibility at night, red and green lamps are used.

Figure 2.2: Semaphore arms in mechanical signaling

Semaphore signal system is moving off from the SLR due to

- Signals operating angle (90^0 and 45^0) is changed with the temperature. During day time the operating angle varies in between 90^0 to 45^0 and night time operating angle vary below 45^0 and need to adjust signal cables for day and night time
- Indicate only two aspects
- High maintenance due to moving parts
- Cannot change the visibility for different atmospheric conditions
- Mounting is difficult
- Operating time depends on operator’s skill

As Color Light System (CLS) eliminates above disadvantages SLR has moved to CLS with different technologies.

2.1.2 Color Light Systems

For the easiness and to improve the efficiency of signal system color light signaling systems are used in SLR. Electric power is used in this system for operation rather than mechanical power used in semaphore based system.

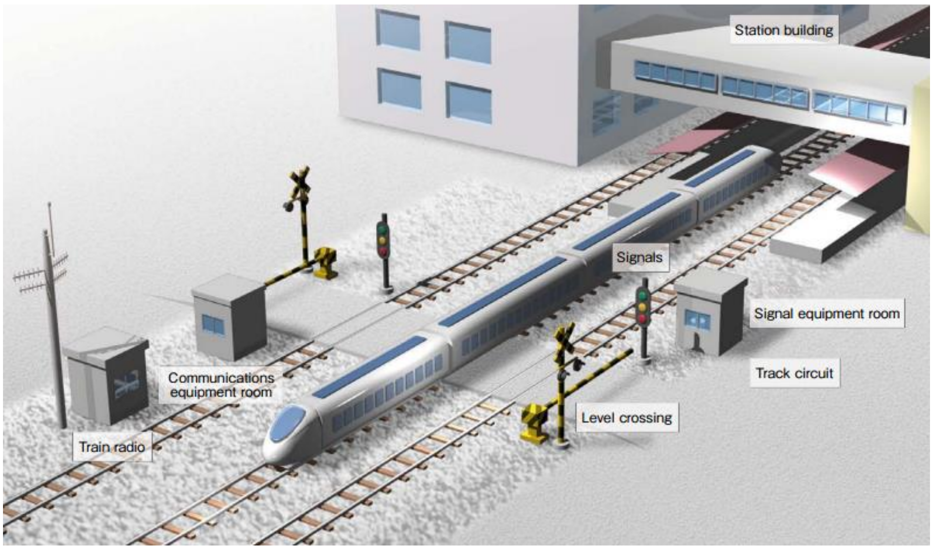


Figure 2.3: Wayside equipment of signal system [4]

Command is given by the controller and interlocking system checks the feasibility of processing command. If there is no any objection, system gives command to way side equipment.

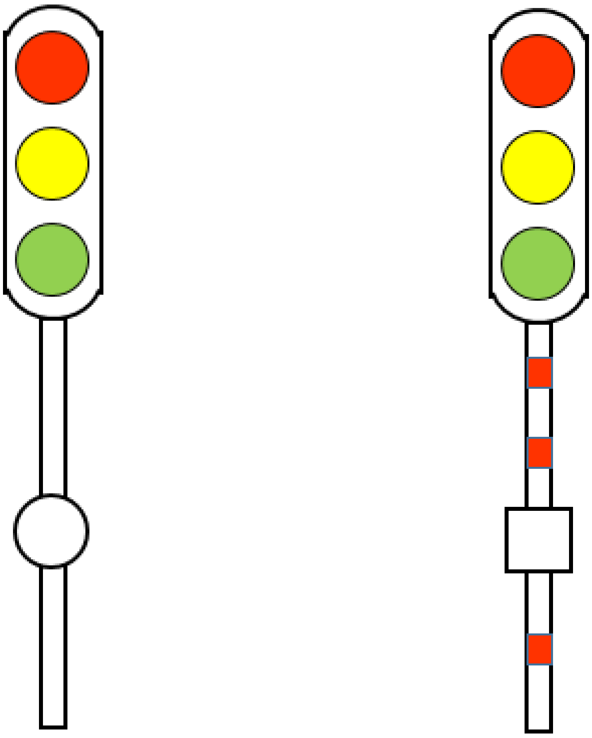
Two types of color light systems are used in SLR as Control and Automatic signals. Control and automatic signals are light up only when a train approach to a section. Control signal are controlled by station master or control officer while automatic signals gives signal after checking the front signal condition. Automatic signals are provided between controlled signals in order to split the section into short block sections and increase capacity of trains in particular section.

Automatic signals are of two types as Automatic Block Signals and Automatic Approach Signals. Three aspects are consisted in Automatic Block System and Red at the top, Amber at the middle and Green at the bottom of the signal post.

Automatic Approach signals are placed immediately in rear of controlled signals and comprised of two units. One unit is mounted on a tall post with Red, Amber and Green aspects. Second unit is placed below the main unit and consist only Amber and Green aspects.

High controlled signals and Dwarf controlled signals are the two types of control signals. Two or three aspects mounted in short post are consisted in Dwarf Controlled signals.

Two units of three aspects placed in vertical line are consisted in High Controlled signals. Third units are consisted in some High Controlled Signals to indicate points having more than one turn outs. Each unit is referred to separate route or routes having same speed restrictions. Straight road is indicated by top unit and high speed deviation is indicated by second unit route traversing one or more deviations over which a speed of 16 kmph is indicated by the bottom unit.



a. b.

Figure 2.4: a. Automatic signal b. Control Signal

Behind the signals that give permission to enter the next section, there is a complex system that get the orders from controller, check the feasibility to give signals and give orders to relevant lights to lit. NMA, ECTC, Indian and Automatic are the different controlling methods used in SLR and VPI and Relay to relay interlocking are the interlocking methods used in SLR CLS to process the order given by controller.

Vital Processing Interlocking

Vital field data is taken to processor as inputs. Track occupancy through track relay condition, point direction, signal conditions and command from controller are the vital inputs. Conflicting and overlapping signals and routes are checked through the processor and provides command as vital output.

Relay to Relay interlocking

Track occupation, point position and signal conditions are taken through relays. Commands are taken through relays and by picking up separate relay it is checked conflicting and overlap route, points and signals conditions through relays. Command is given to signal also done through relays. Number of relays are consisted in this system.

Track occupation is very important factor in both VPI and relay interlocking system for safe signal operation. Basically there are two main train detection methods as track circuits and axel counters. SLR using track circuit train detection method to prove the availability of train on track.

2.2 Track Circuits

To detect the presence of locomotive in interest portion of rail, train detection methods are used. Train detection applications are used at the berthing tracks, point zones, level crossings, block sections, automatic block sections and intermediate block sections.

In track circuit, portion of rail track isolate from adjoining rails and isolated portion energized through track relays. Rail track occupation is identified by the condition of track relays. The length of track circuit confined to the ballast resistance, relay type, speed of train and usage location of track circuit.

According to the supply source track circuits categorize as Direct current, Audio Frequency and Alternating current. DC track circuits with two configurations as open and closed track circuits.

2.2.1 DC Track Circuits

DC track circuits are powered by batteries or direct current sources. Power fed to the circuit from one end and taken out through relay from other end. According to the relay condition during normal operating time, DC track circuits are divided into two categories as open track circuits and closed track circuits.

Open track circuit relays are normally in drop condition and circuit is completed through relay with the presence of shunt train only. Even though energy consumption of open track circuits are low as energy consumes with occupation of train, this type of track circuits are not used in SLR since any failure of the circuit is not identified until train arrives.

Closed track circuit relays normally in pickup condition and drops during shunt conditions. This system consumes more energy than open system, but ahead in safety. Therefor closed track circuits are used in SLR signaling system.

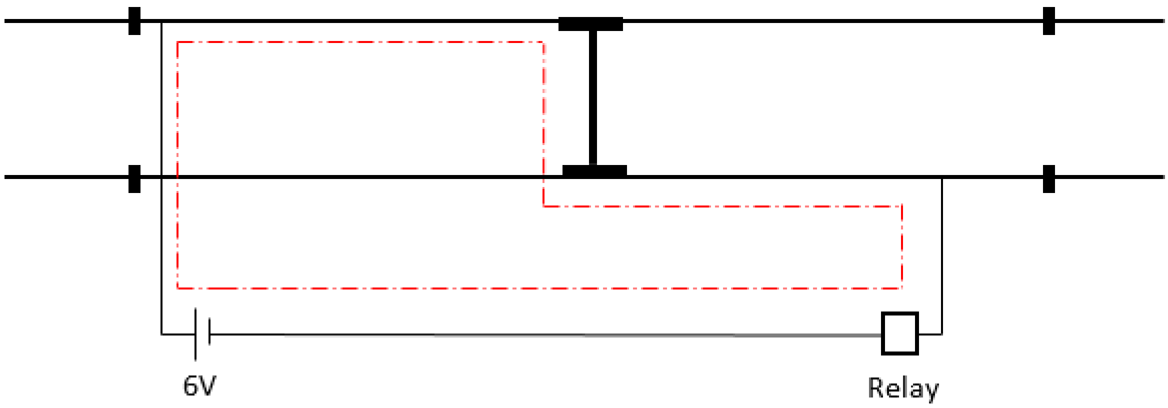


Figure 2.5: Open track circuit

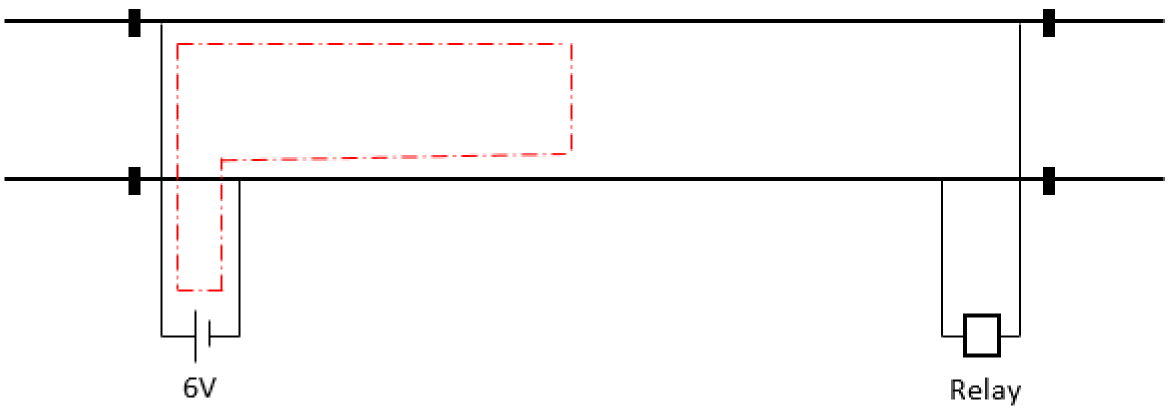


Figure 2.6: Closed track circuit

Components of DC track circuits,

- Battery
- Adjustable Resistance
- Track relay
- Track lead cable

- G.I. wires to connect rail
- Continuing rail bonds
- Insulation joints

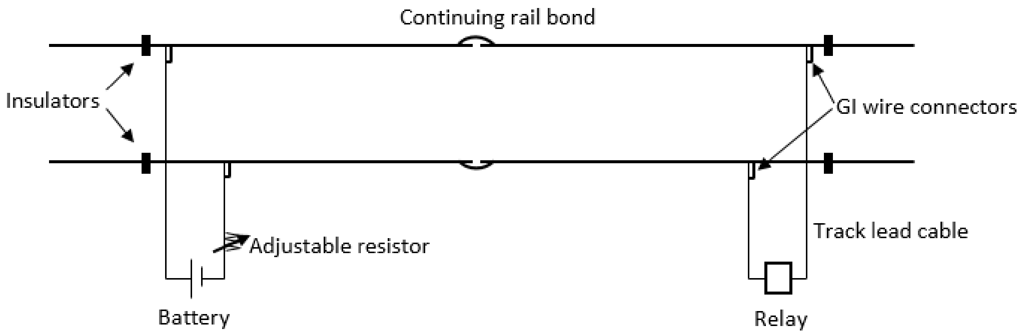


Figure 2.7: Component of closed track circuit

In closed track circuits feed is given from the one end and relay is connected to other end. The relay drops when shunted by train or due to discontinuity of rail. Adjustable resistor is used to alter the feed end voltage and to protect the feed equipment when the track is shunted. Power supply is fed at one end and it is collected through the track relay. During track vacant time, power flows through relay coil and relay contacts are picked up.

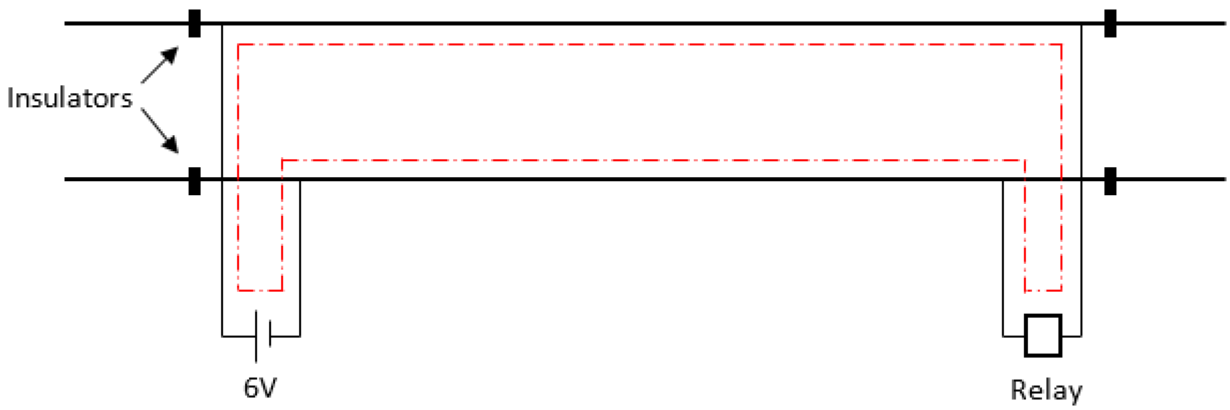


Figure 2.8: Power flow during normal time

When track shunted by train power flow through the traction as train traction resistance is very low compared to lead resistance and relay resistance.

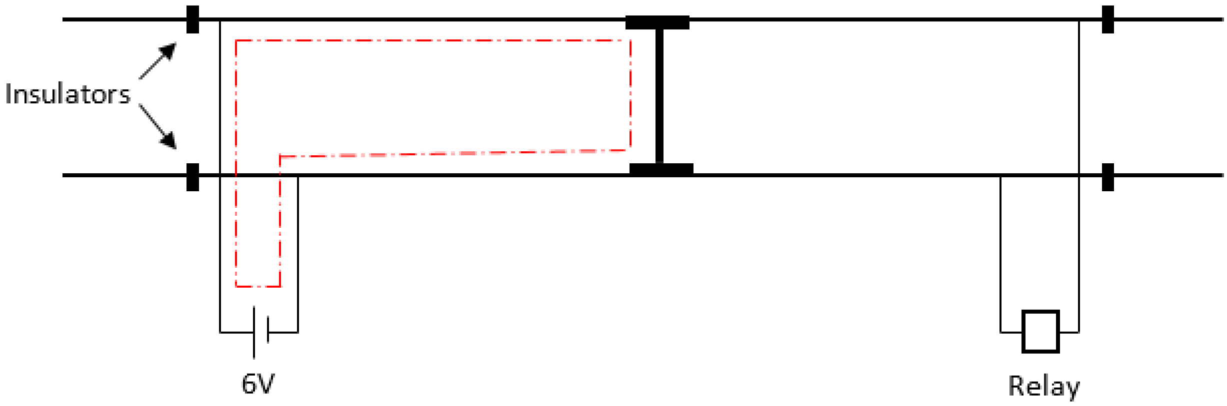


Figure 2.9: Power flow during shunt time

Staggered polarities are practiced in adjoining rails to detect failure in rail joints. Any failure of rail joints will cause to series the feed and parallel the relays. Higher circulating current and higher voltage drop across the regulating resistance due to relay paralleling result to drop one relay or both relays.

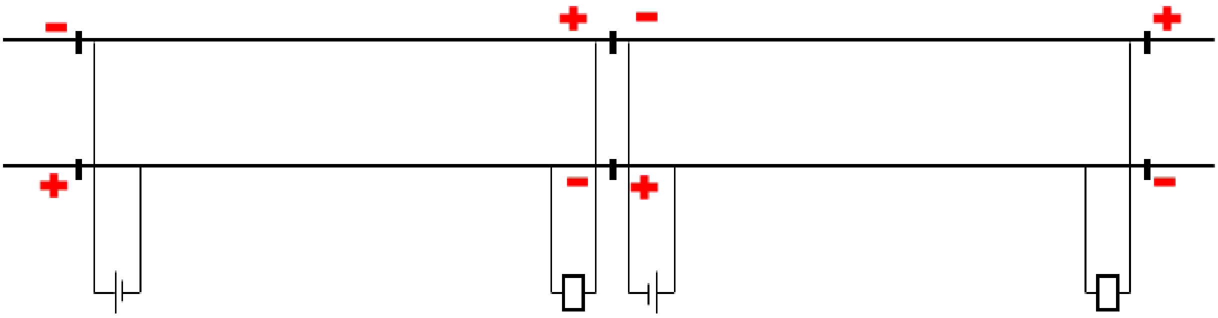


Figure 2.10: Staggered polarities

2.2.2 Parameters of DC track circuits

Considering circuit parameters that effected to the current of DC tack circuits are mainly feed end voltage and internal resistances. Internal resistances influence with track circuits can be eliminated as follows.

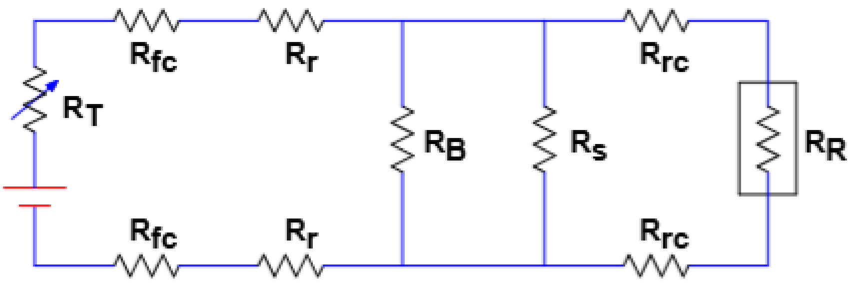


Figure 2.11: DC track circuit parameters

R_T – Regulating resistance, use to adjust the relay end voltage and current with series to fixed battery end

R_B – Ballast resistance, net resistance offered by the ballast and sleepers. Low ballast resistance caused to leakage the rail current and ballast resistance vary with the moisture content of the ballast and sleepers

R_r – Rail resistance, resistance of the rail and the continuing bonds. Rail resistance is negligible under normal condition and bond resistance vary with the condition of the bond

R_R – Relay resistance, fixed value for relay

R_S – Shunt resistance, resistance offered by shunting vehicle axle. Shunt resistance varies with the rail top, weight of train and the speed. Highest resistance can apply though rail, which caused to drop the relay is called as Train Shunt Resistance (TSR)

R_{fc} – Feed end cable resistance,

R_{rc} – Relay end cable resistance [9]

2.3 Electrified Train System

Number of coaches of a train, power consumption and efficiency of a train is restricted with the loco engine used. With the electrified train efficiency, productivity can be increased and power loss is less. Improving the acceleration and deceleration within short distance, fuelling and watering is no longer needed, less environment pollution and noise are also engage with electrified trains. Considering above advantages, SLR also stepping up for electrified train systems.

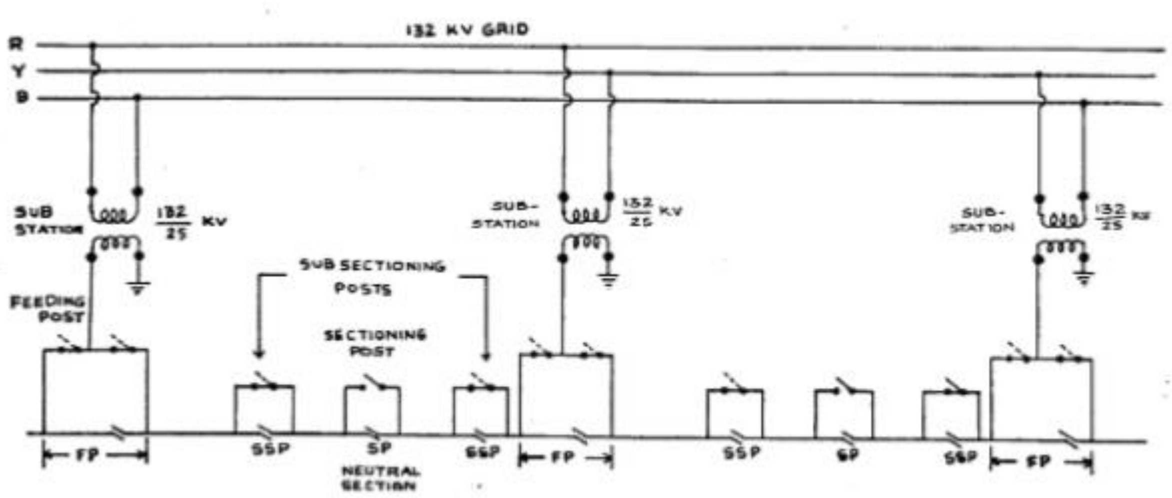


Figure 2.12: Electrified train power feeding system

Electrified system is derived 25kV, 50Hz single phase supply from grid system through transformers installed at Traction Sub Stations (TSS). Stepped down 25kV supply is fed to the Over Head Equipment (OHE). Sectioning and Paralleling posts are used to provide neutral regions to avoid bridging two phases and Sub Sectioning and Paralleling post are used for isolation of OHE. Contact wire dropped the power from catenary wire and using pantograph power is fed to loco vehicle.

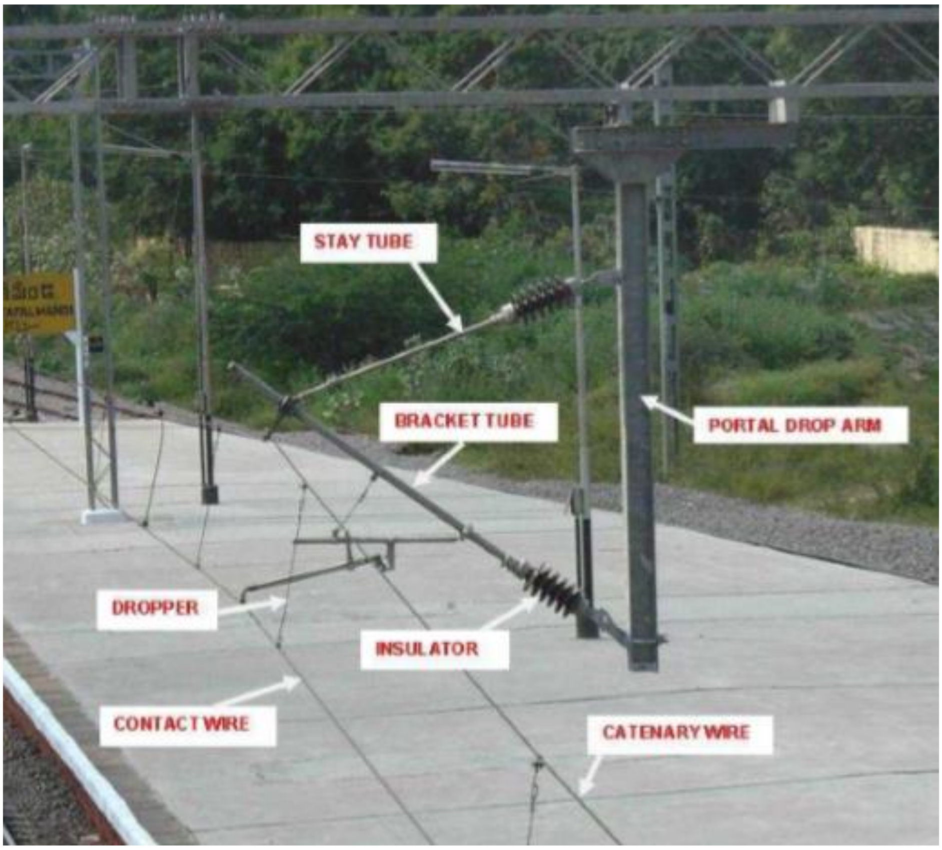


Figure 2.13: Power feeding components

Chapter 3

ELECTROMAGNETIC FIELD AROUND TRANSMISSION LINE AND MATLAB MODELS

3.1 Transmission line data

The Sri Lankan commercial electric power system use several voltages in power transmission and distribution circuits. 220 kV, 110 kV and 33kV are used in transmission circuit and 11 kV 230 V are used in distribution circuit with different structures. Power system operates at a frequency of 50 Hz, or cycles per second, meaning that the field increases and decreases its intensity 50 times per second. The interactions of the fields emanated from transmission lines also oscillate at the same frequency. The electromagnetic field levels in the proximity of a high voltage transmission line depends on a number of variables, including but not limited to the voltages, currents, overall geometry of the structures holding the conductors, the type of conductors, phase spacing, sag and earth wires used. Hence, in the modeling and calculation process, each voltage level of the transmission lines has been considered separately and calculated independently for the specific structure geometry and conductor type used.

The strength of an EMF increases significantly with decreasing distance from the source. The strength of an electric field is proportional to the voltage of the source. Thus, the electric fields beneath high voltage transmission lines far exceed those below the lower voltage distribution lines at the same distance. The magnetic field strength, by contrast, is proportional to the current in the lines, so that a relatively low voltage line with a high current load may produce a magnetic field that is as high as those produced by some higher voltage transmission lines.

Transmission line data, like the minimum clearance from ground, height of conductors at the tower level, the length of the basic span, distance of conductors from the tower center, number of conductors, conductor spacing in the bundle and the conductor diameter were considered in developing the model. Data for Three tower types, TDL, TDL+6 and TDL+12 used in Sri Lanka are given in Table 3.1 and 3.2 for 132kV and 220kV lines.

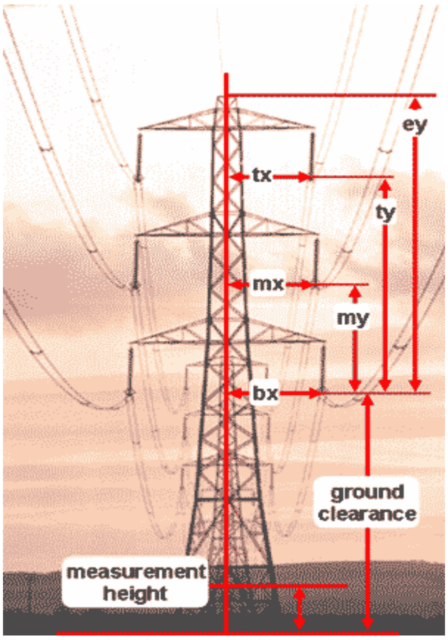


Figure 3.1: Transmission line parameters [4]

Table 3.1: Tower dimensions for 220 kV

Dimension		code on diagram	Voltage	tower type			Units
conductor	**Direction**			**TDL**	**TDL+6**	**TDL+12**	
earth wire	horizontal from tower centre	Double EW	220kV	6720	6720	6720	mm
	vertical above bottom phase	ey		19925	19925	19925	mm
top phase	horizontal from tower centre	tx		6720	6720	6720	mm
	vertical above bottom phase	ty		11375	11375	11375	mm
middle phase	horizontal from tower centre	mx		6900	6900	6900	mm
	vertical above bottom phase	my		5800	5800	5800	mm
bottom phase	horizontal from tower centre	bx		7800	7800	7800	mm
	Ground to Bottom Phase	-		17710	23710	29710	mm
	Minimum Ground Clearance			7010	13010	19010	mm
conductor bundle	Number of conductors			2	2	2	
	Spacing			200	200	200	mm
	Diameter			28.62 (ACSR, Zebra)			mm

Table 3.2: 132kV double circuit transmission line data

Dimensions		Code on diagram	Voltage	tower type			units
Conductor	Direction			TDL	TDL+6	TDL+12	
Earth wire	horizontal from tower centre	Double EW	132kV	3660	3660	3660	mm
	vertical above bottom phase	ey		14290	14290	14290	mm
Top phase	horizontal from tower centre	tx		3660	3660	3660	mm
	vertical above bottom phase	ty		8530	8530	8530	mm
Middle phase	horizontal from tower centre	mx		3705	3705	3705	mm
	vertical above bottom phase	my		4230	4230	4230	mm
Bottom phase	horizontal from tower centre	bx		4010	4010	4010	mm
	Ground to Bottom Phase	-		15235	21235	27235	mm
	Minimum Ground Clearance			6700	12700	18700	mm
Conductor in bundle	number of conductors			2	2	2	
	Spacing			200	200	200	mm
	Diameter			28.62 (ACSR, Zebra)			mm

Table 3.3: 33kV Double circuit transmission line data

33kV Vertical Double Circuit Dimensions		Max.	Min.	units
Conductor	Direction			
Top phase	horizontal from tower centre	3.0	2.5	m
	vertical to bottom	3.0	2.4	m
middle phase	horizontal from tower centre	3	2.5	m
	vertical to bottom	1.5	1.2	m
Bottom phase	horizontal from tower centre	3.2	2.7	m
	vertical to ground	13	6.5	m
conductor	number of conductors	1	1	
	Diameter	12.3/19.6		mm
	vertical to ground	13	6.5	m

Table 3.4: 33kV horizontal configuration line data

Dimensions for Horizontal Formation		**Max.**	**Min.**	**Units**
Conductor	**Direction**			
Right phase	horizontal from tower centre	0.95	0.95	m
	vertical to ground	13	5	m
middle phase	horizontal from tower centre	0	0	m
	vertical to ground	13	5	m
Left phase	horizontal from tower centre	0.95	0.95	m
	vertical to ground	13	5	m
conductor	number of conductors	1	1	
	Diameter	12.3		mm

Table 3.5 : 33kV triangular configuration line data

Triangular Formation Dimensions		**Max.**	**Min.**	**Units**
Conductor	**Direction**			
Top phase	horizontal from tower centre	0	0	m
	vertical to lower phase	2.0	2.0	m
Lower left phase	horizontal from tower centre	1.6	1.6	m
	vertical to ground	13	6.5	m
Lower right phase	horizontal from tower centre	1.6	1.6	m
	vertical to ground	13	6.5	m
Conductor	number of conductors	1	1	
	Diameter	12.3		mm

Average conductor height above ground

The input for field calculation requires an "average conductor height" - which is determined by ground clearance (at certain load conditions) and sag (at the same set of conditions).It is assumed that the ground is flat unless there is sufficient information available to make an assessment for the case being considered.

It can be shown (using parabolic equations) that the average conductor sag is 2/3 of overall sag when measured from the points of attachment. Alternatively, the average conductor height is equal to ground clearance at the low point of the parabola, plus 1/3 sag. Conductor electrical loading (calculated or assumed) causes a conductor temperature rise above ambient but the temperature will normally remain below that corresponding to maximum design load (minimum (design) ground clearance is based on this maximum load).

Average height above ground = (minimum ground clearance at max design temperature) + (additional height due to assumed operating temperature below max design temperature) + (1/3 sag at that assumed operating temperature).

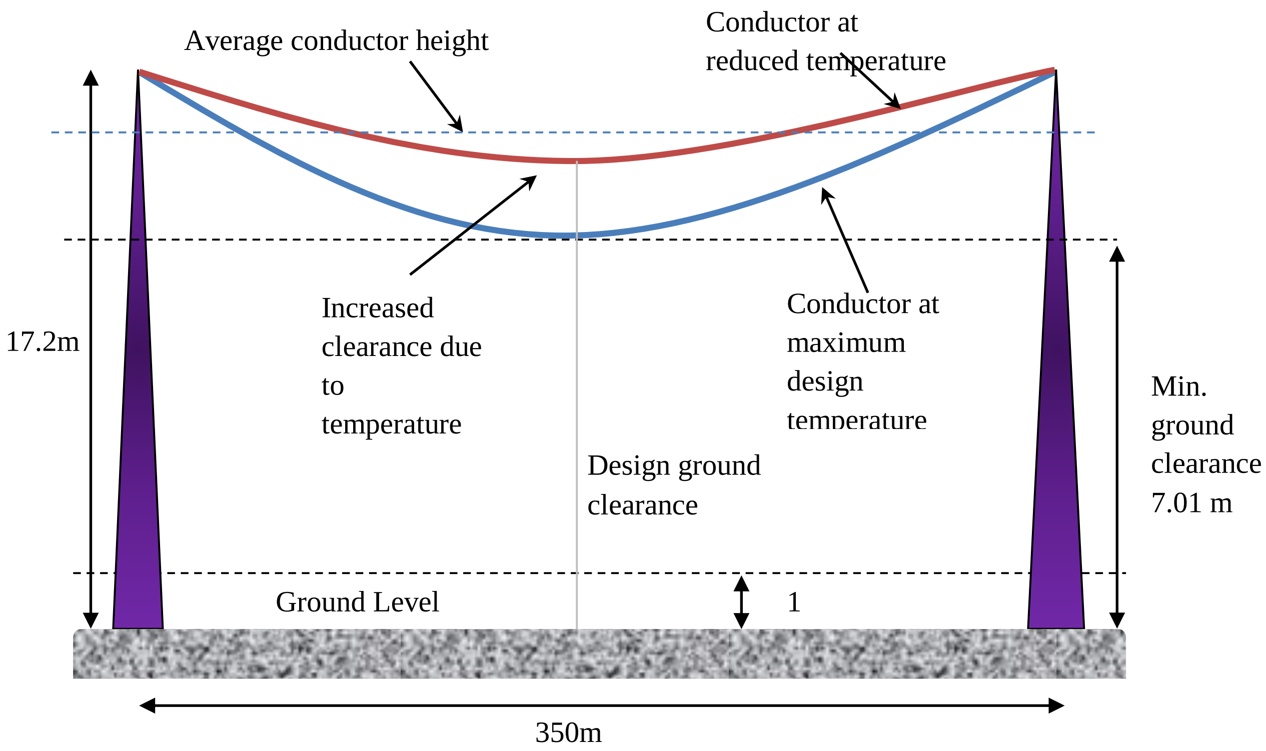


Figure 3.2 The average height above ground calculation for 220kV lines

Table 3.6 : Calculation of average ground clearance

Voltage (kV)	Basic Span (m)	Ground Clearance (m)	Buffer (m)	Sag @ EDS (Everage Daily Stress)(m)	Sag @ Maximum Temperature (75oC)(m)	Average Ground Clearance (m)
220	350	7	0.3	8.637	10.316	11.558
132	300	6.7	0.3	6.214	7.793	10.350
33	300	5.5	0.3	5.255	6.812	8.808

3.2 Magnetic field around Transmission line

Assumptions;

1. The current carrying conductors are infinitely long and straight.
2. The permeability of air is independent of the weather and equal to the permeability of free space.
3. The effect from structures at ground potential are ignored.

According to the Biot-Savart's law it is derived that the magnetic field '**B**' at a point 'P' distant 'r' from an infinitely long Straight line conductor carrying a current 'I' is given by,

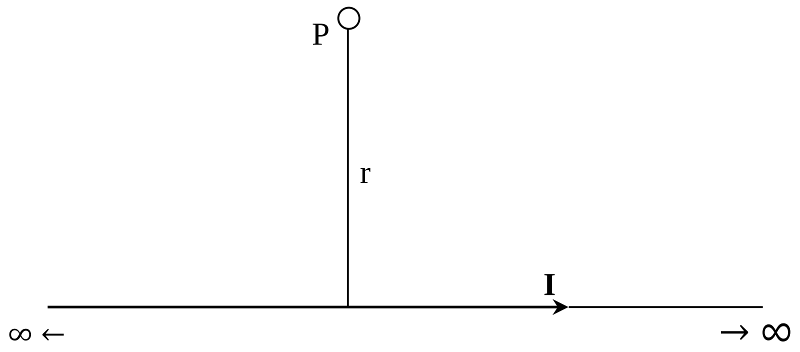


Figure 3.3 An infinitely long conductor carrying current I

The direction of B is circumferential.

$$\boldsymbol{B\ x\ (2\pi r) = \mu_0 I}$$

i.e. the vector **B** multiplied by the length of the contour, is propotional to the current in the wire.

By Ampere's law it is defined that the vector **H**-magnetic field intensity,

$$\mathbf{H} = \frac{\boldsymbol{B}}{\mu} \qquad (\mu = \mu_0 \text{ in free space})$$

Hence in general, $\mathbf{H} = \dfrac{\mathbf{I}}{2\pi \mathrm{r}}$

For 'n' number of conductors

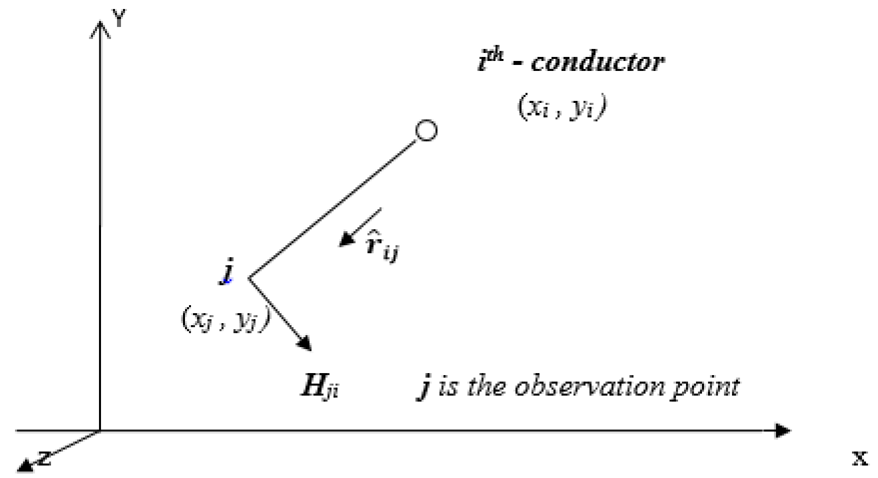


Figure 3.4 Coordinate system for magnetic field calculations

Considering only one conductor,

$$\vec{\mathrm{H}}_{ji} = \frac{\vec{\mathbf{I}}_{\mathrm{i}} \times \hat{\mathbf{r}}_{ji}}{2\pi\, \mathbf{r}_{ij}} = \frac{\mathbf{I}_{\mathrm{i}}}{2\pi\, \mathrm{r}_{ij}} \ \widehat{\emptyset}_{ij}$$

$\emptyset_{ij}$ is the unit vector in the direction of the product of the vector current and the vector segment r_{ij} .The unit vector is equal to;

$$\widehat{\emptyset}_{ij} = -\frac{\mathrm{Y}_i - \mathrm{Y}_j}{\mathrm{r}_{ij}} \ \vec{\mathbf{u}}_{x} + \frac{\mathrm{X}_i - \mathrm{X}_j}{\mathrm{r}_{ij}} \ \vec{\mathbf{u}}_{y}$$

$\vec{\mathbf{u}}_{x}$, $\vec{\mathbf{u}}_{y}$ are the unit vectors in x, y directions.

Magnetic field intensity

$$\vec{\mathrm{H}}_{j} = \sum_{i=1}^{n} \frac{\mathrm{I}_{\mathrm{i}}}{2\pi\, \mathrm{r}_{ij}} \ \widehat{\emptyset}_{ij}$$

$$\mathbf{B}_{j} = \mu_{air} \ \mathbf{H}_{j}$$

Where

$$r_{ij} = \sqrt{(\mathrm{x_i} - \mathrm{x_j})^2 + (\mathrm{y_i} - \mathrm{y_j})^2}$$

The effects of earth's return currents ;

The magnetic field produced by each conductor and its earth return is expressed by;

$$\mathrm{H}_{ij_{earth}} = \sum_{i=1}^{n} \frac{\mathrm{I_i}}{2\pi\, \boldsymbol{r}'_{ij}} \left(1 + \frac{1}{3}\left(\frac{\mathrm{I_i}}{\gamma_{ij}}\right)^{4}\right) \widehat{\emptyset}'_{ij}$$

$$\gamma = \sqrt{j\,\omega\,\mu\,(\sigma + j\,\omega\,\epsilon)}$$

ω – angular frequency μ – *permeability of earth*

σ – *Earth's Conductivity* 0.001 – 0.002 $^{S}/_{m}$

$\epsilon - earth's\ permitivity$

$$\boldsymbol{r}'_{ij} = \sqrt{\left(\mathrm{x_i} - \mathrm{x_j}\right)^2 + \left(\mathrm{y_i} - \mathrm{y_j} + \frac{2}{\gamma}\right)^2}$$

$$\widehat{\emptyset}'_{ij} = -\left[\frac{\mathrm{y_i} - \mathrm{y_j} + \frac{2}{\gamma}}{\mathrm{r}_{ij}}\right] \hat{\boldsymbol{u}}_x + \left(\frac{\mathrm{x_i} - \mathrm{x_j}}{\mathrm{r}_{ij}}\right) \hat{\boldsymbol{u}}_y$$

Total effect of magnetic field intensity;

$$\mathbf{H}_j = \sum_{i=1}^{n} \frac{\mathbf{I_i}}{2\pi\,\mathrm{r}_{ij}} \widehat{\emptyset}_{ij} - \sum_{i=1}^{n} \frac{\mathbf{I_i}}{2\pi\, r'_{ij}} \left(1 + 3\left(\frac{2}{\gamma\, r'_{ij}}\right)^{4}\right) \widehat{\emptyset}'_{ij}$$

$$\mathbf{H}_{\boldsymbol{j}} = \mathrm{H}_{xj}\ \hat{\boldsymbol{u}}_x + \mathrm{H}_{yj}\ \hat{\boldsymbol{u}}_y$$

$$\mathrm{H}_{xj} = \mathrm{H}_{x,r} + \mathrm{j}\,\mathrm{H}_{x,im}$$

$$\mathrm{H}_{yj} = \mathrm{H}_{y,r} + \mathrm{j}\,\mathrm{H}_{y,im}$$

$$\vec{H}_r = H_{x,r}\ \hat{u}_x + H_{y,r}\ \hat{u}_y \qquad (H_r = \sqrt{H^2_{x,r} + H^2_{y,r}})$$

$$\vec{H}_i = H_{x,im}\ \hat{u}_x + H_{y,im}\ \hat{u}_y \qquad (H_{im} = \sqrt{H^2_{x,im} + H^2_{y,im}})$$

$$\text{Absolute value } \mathbf{H}_T = \sqrt{H^2_{x,r} + H^2_{x,im} + H^2_{y,r} + H^2_{y,im}}$$

3.2.1 Simulation of magnetic field profiles using MATLAB

Considering the effect of transmission line and the earth image, MATLAB models have been introduced by several researches. Using those models it is simulated magnetic field under several voltages and transmission lines structures. From the model of Fernando [], following simulations were taken.

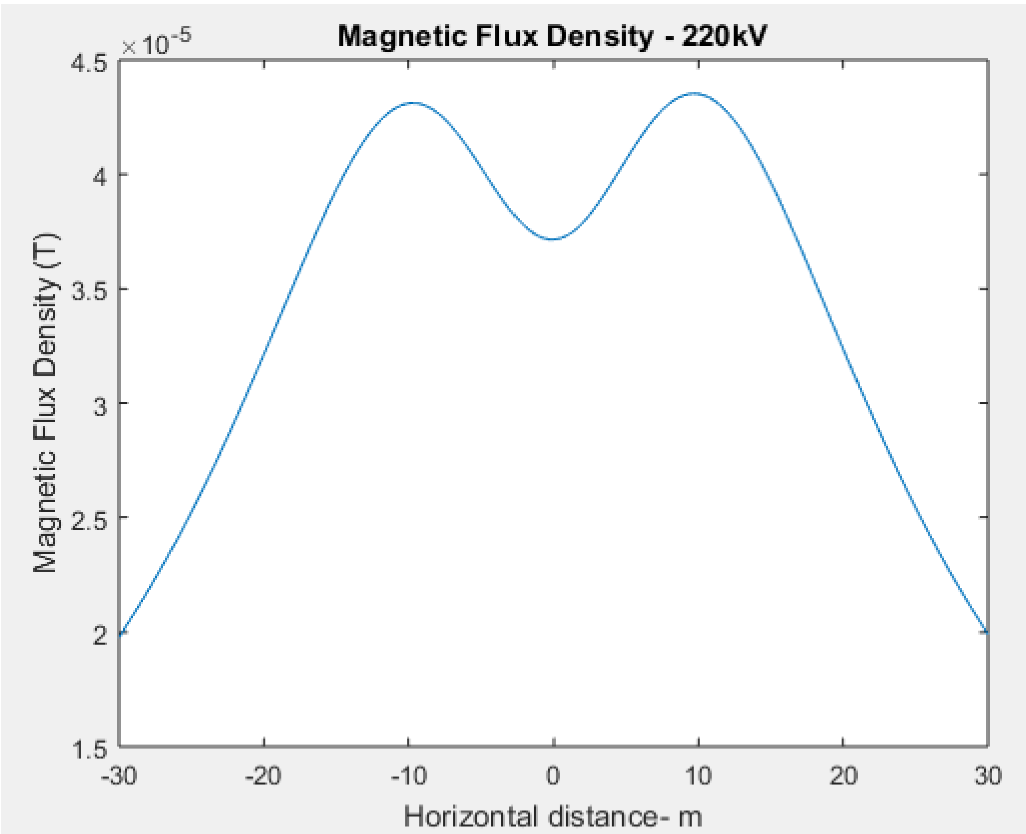


Figure 3.5: Magnetic flux variation under 220 kV

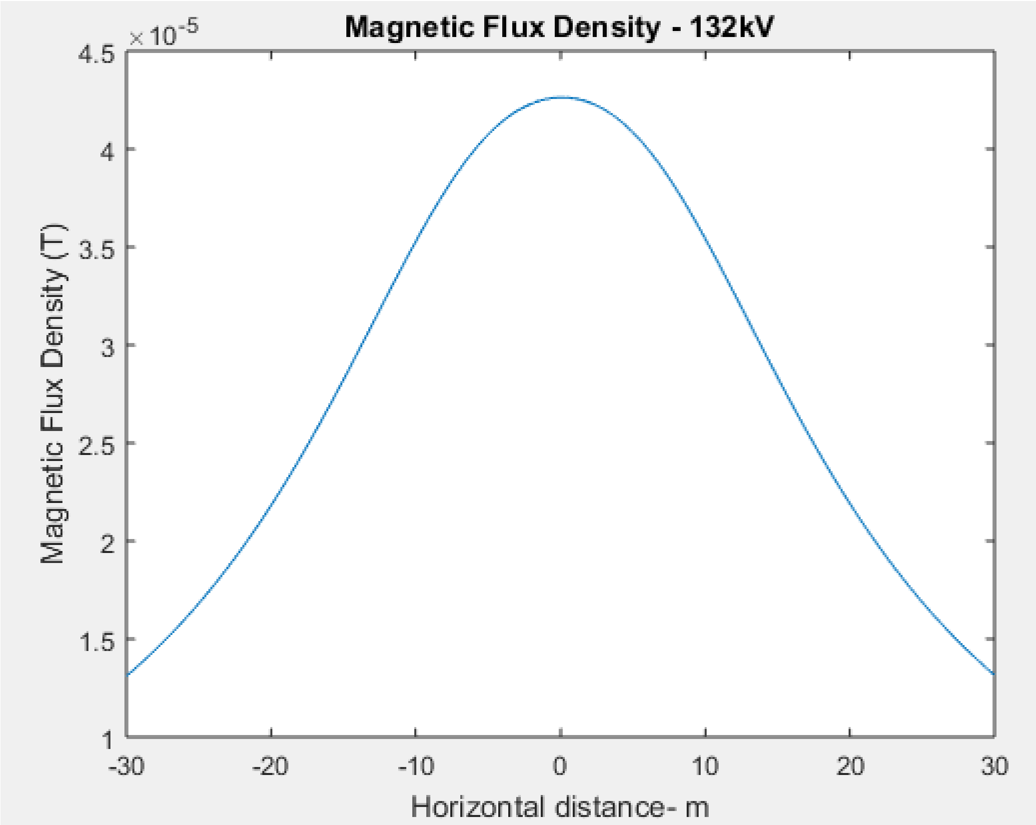


Figure 3.6: Magnetic flux variation for 132 kV

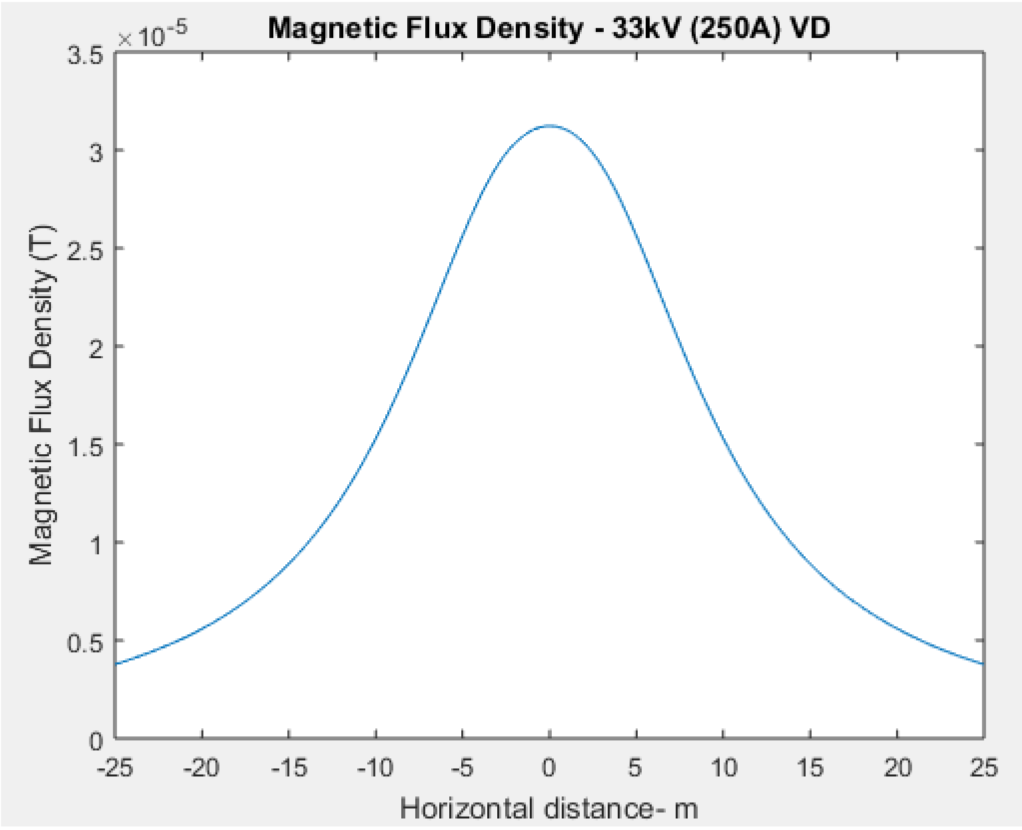


Figure 3.7: Magnetic flux variation 33 kV Vertical direction

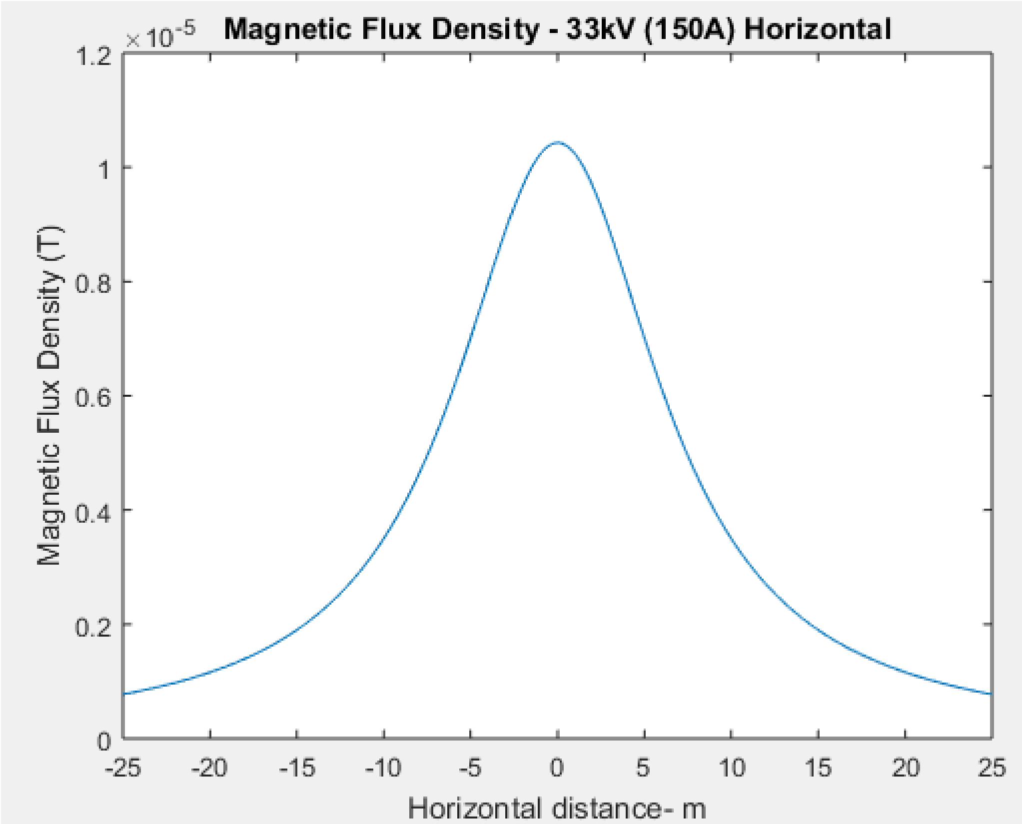


Figure 3.8: Magnetic flux variation 33 kV horizontal direction

Chapter 4

Measuring the field values physically under the transmission lines and comparison with MATLAB model

4.1 Measuring the magnetic field under the transmission lines

The selected model for magnetic field is verified with the measured magnetic field values under the transmission lines. An abonded paddy field was selected as location for measuring magnetic field to avoid the outside effect from the machines, structures and vehicles. The clear terrain was about 100m wide and measurements were taken for every 0.5m up to 30meters. For measuring the magnetic fields, Tri-axial ELF Magnetic Field Meter of Model SK-8301 manufactured by Kaise Corporation, Japan and the meter measures AC electric field in the vertical direction were used. The accuracy of the instrument at 50/60Hz is +/-2% and the resolution is $.01\mu T$. While taking measurements, the meter was kept as distant as possible from the body in order for measuring the unperturbed magnetic field. The magnetic field measurement values for New Chillaw 220 kV transmission lines with 610A and 620A as follows.

Table 4.1: Magnetic field measurements for New Chillaw 220kV line.

220kV, Double Circuit twin zebra, 610A, 620A								
Distance from Center (m)	**Magnetic Field (uT)**		**Distance from Center (m)**	**Magnetic Field (uT)**		**Distance from Center (m)**	**Magnetic Field (uT)**	
	Left	**Right**		**Left**	**Right**		**Left**	**Right**
0	37.2	37.2	8.5	42.88	42.9	17	36.63	37.48
0.5	37.2	37.2	9	43.12	43.2	17.5	35.91	36.65
1	37.32	37.38	9.5	43.13	43.2	18	35.1	36.1
1.5	37.41	37.5	10	43.11	43.18	18.5	34.22	35.47
2	37.68	37.7	10.5	43.07	43	19	33.58	34.9

2.5	38	38.3	11	42.9	43	19.5	32.8	34.29
3	38.5	38.3	11.5	42.52	42.9	20	32.11	33.54
3.5	38.92	39	12	42.29	42.5	20.5	31.45	32.1
4	39.4	39.52	12.5	41.92	42.13	21	30.67	31.5
4.5	39.8	39.86	13	41.53	41.8	21.5	29.95	31.28
5	40.28	40.3	13.5	40.07	41.4	22	29.2	29.7
5.5	40.8	40.76	14	40.53	40.9	22.5	28.51	29.37
6	41.31	41.3	14.5	40.1	40.52	23	27.9	28.79
6.5	41.74	41.75	15	39.35	40.18	23.5	27.23	28.2
7	42.1	42.3	15.5	38.7	39.76	24	26.5	27.56
7.5	42.4	42.5	16	38	39.4	24.5	25.75	27
8	42.7	42.72	16.5	37.34	38.94	25	25.43	26.28

Table 4.2: Magnetic field measurements for 33kV line.

33kV, Double Circuit, 180A & 165A								
Distance from Center	**Magnetic Field**		**Distance from Center**	**Magnetic Field**		**Distance from Center**	**Magnetic Field**	
	Left	**Right**		**Left**	**Right**		**Left**	**Right**
0	5.4	5.4	8.5	3.44	3.8	17	1.35	1.40
0.5	5.48	5.55	9	3.2	3.67	17.5	1.32	1.36
1	5.5	5.62	9.5	3.07	3.5	18	1.26	1.33
1.5	5.47	5.5	10	2.93	3.33	18.5	1.24	1.29
2	5.45	5.48	10.5	2.8	3.1	19	1.24	1.28
2.5	5.42	5.44	11	2.66	2.98	19.5	1.23	1.25
3	5.38	5.46	11.5	2.3	2.57	20	1.2	1.23
3.5	5.35	5.3	12	2.15	2.4	20.5	1.18	1.23
4	5.3	5.37	12.5	2.06	2.25	21	1.15	1.20
4.5	5.12	5.2	13	1.9	2.11	21.5	1.15	1.16
5	5	5.13	13.5	1.83	2.04	22	1.15	1.17
5.5	4.78	5.04	14	1.69	1.88	22.5	1.14	1.15
6	4.5	4.8	14.5	1.7	1.73	23	1.13	1.13

6.5	4.15	4.62	15	1.65	1.68	23.5	1.12	1.13
7	4.02	4.51	15.5	1.59	1.6	24	1.1	1.12
7.5	3.8	4.3	16	1.48	1.53	24.5	1.1	1.1
8	3.52	4.09	16.5	1.4	1.51	25	1.0	1.1

4.2 Plotting the profiles of measured magnetic field values vs modeled values

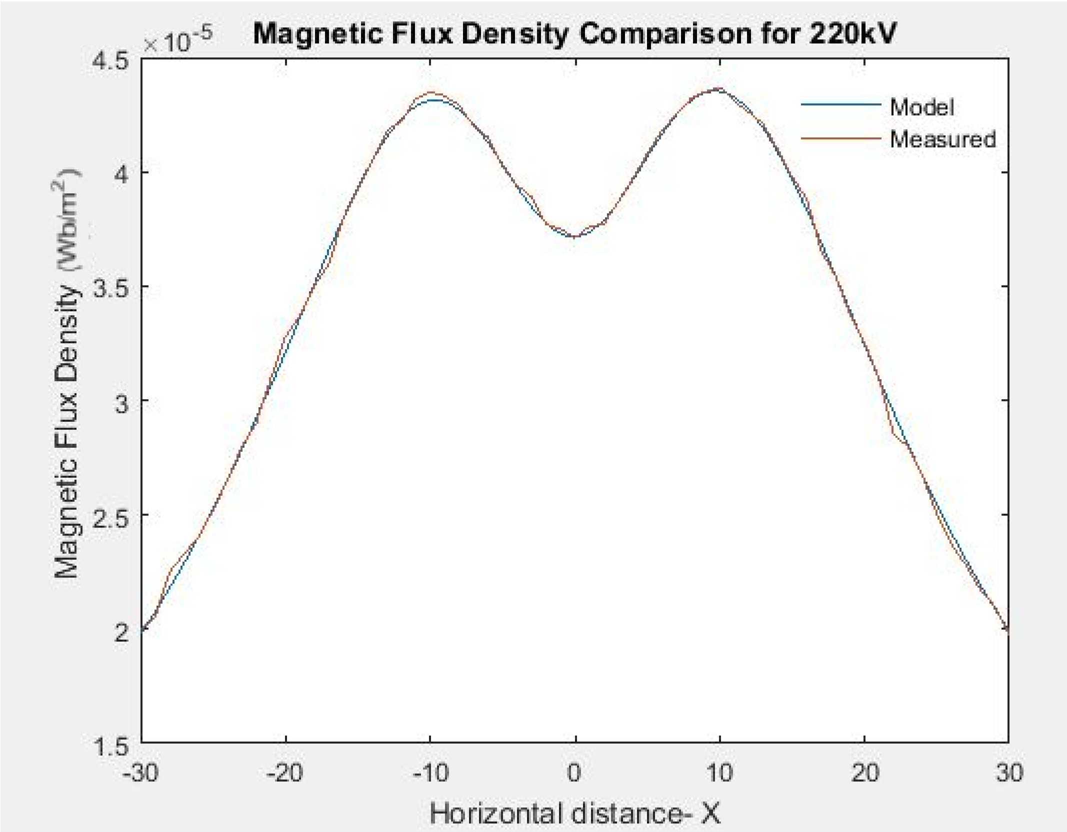


Figure 4.1: Magnetic field profiles comparing the modeled and measured values for 220kV double circuit configuration

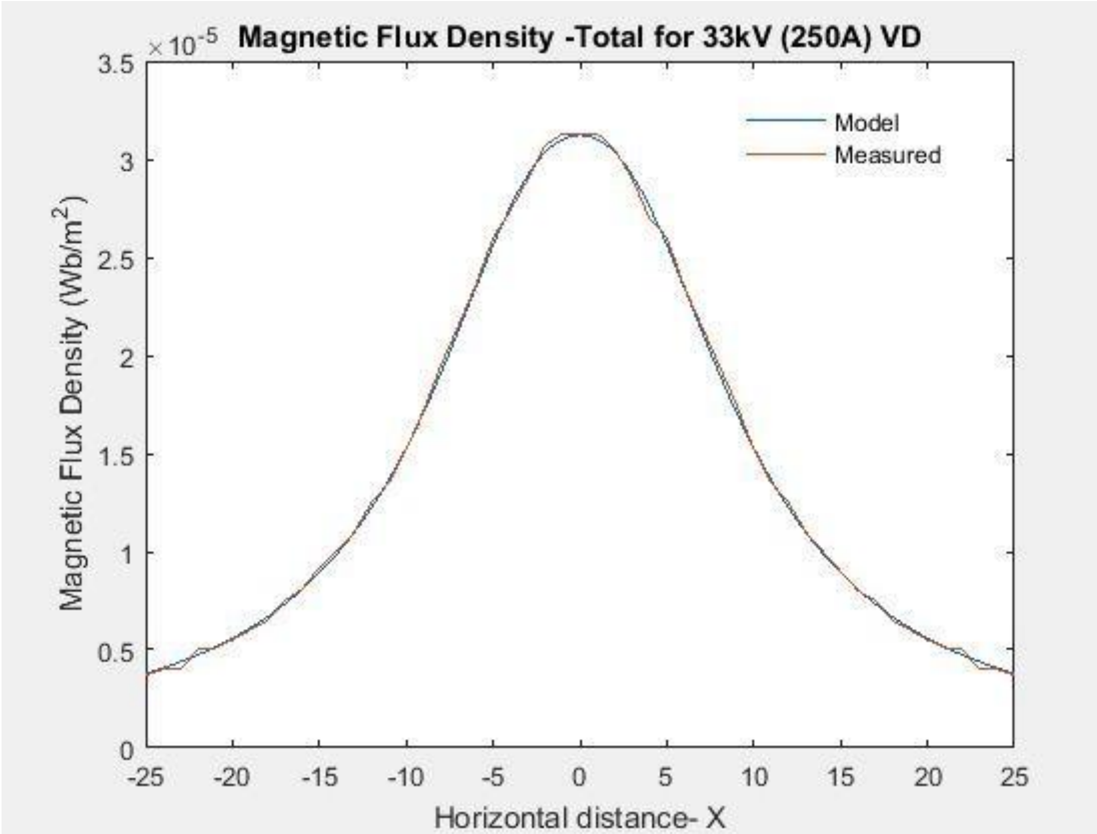


Figure 4.2: Magnetic field profiles comparing the modeled and measured values for 33kV double circuit configuration

4.3 Comparison of the measured values and the modeled values

Measured magnetic field values are compared with the MATLAB model of Fernando [3]. The deviations between measured and modeled values are due to

- Variation of the currents during measuring period
- Average conductor height is taken
- Changes in the medium of air such as moisture, wind speed
- Human errors during measurement

As measured values are very close to the modeled values and the profile shapes are the same, the selected model is used to calculate magnetic field for different current and for different formations of transmission towers.

4.4 Magnetic Flux variation for different currents

Magnetic flux induced by current carrying conductor is mainly depends on the magnitude of current flow of conductor. With the selected magnetic flux model it was identified the magnetic flux variation with the rated, infrequent high load and for emergency short time high load currents. Infrequent high loads and emergency short time currents are not considered in this research as time duration of those are very short.

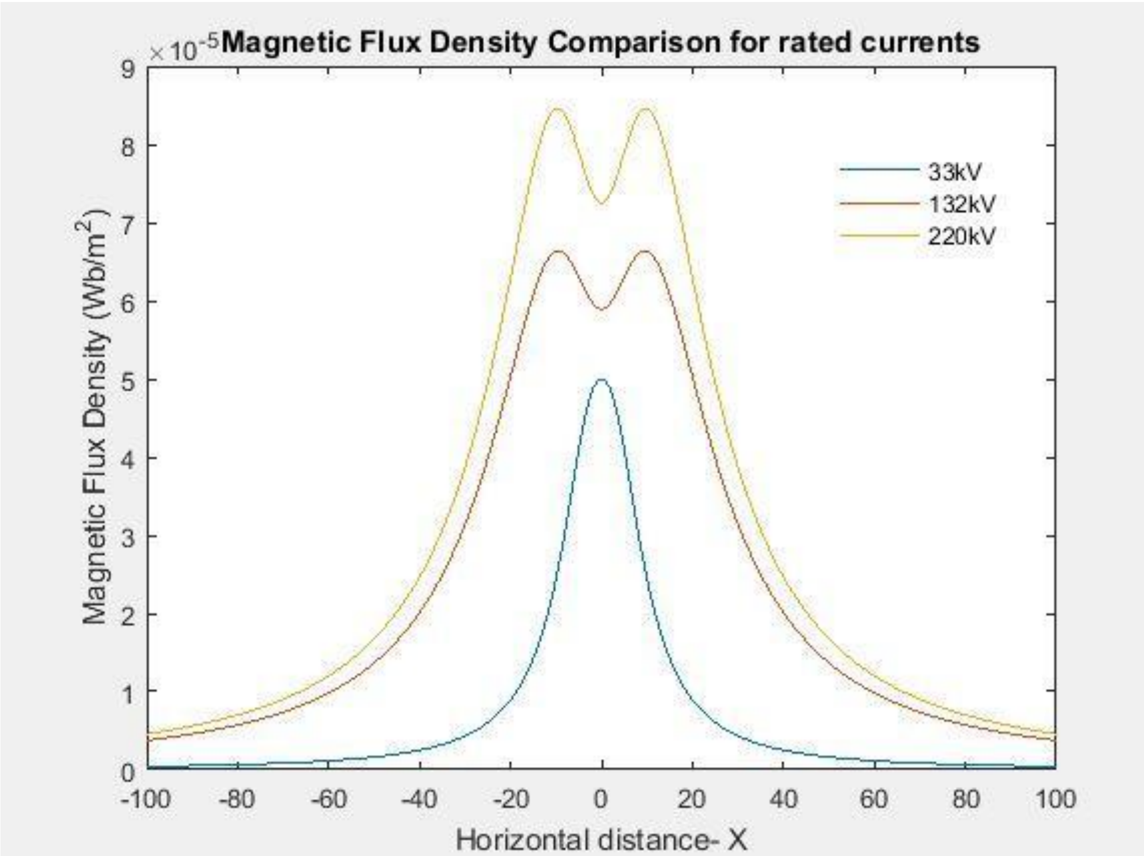


Figure 4.3: Flux density variation for rated currents – 220 kV,132 kV and 33 kV

Voltage of 25 kV is used in electrified system and 300A is the rated current of such systems.

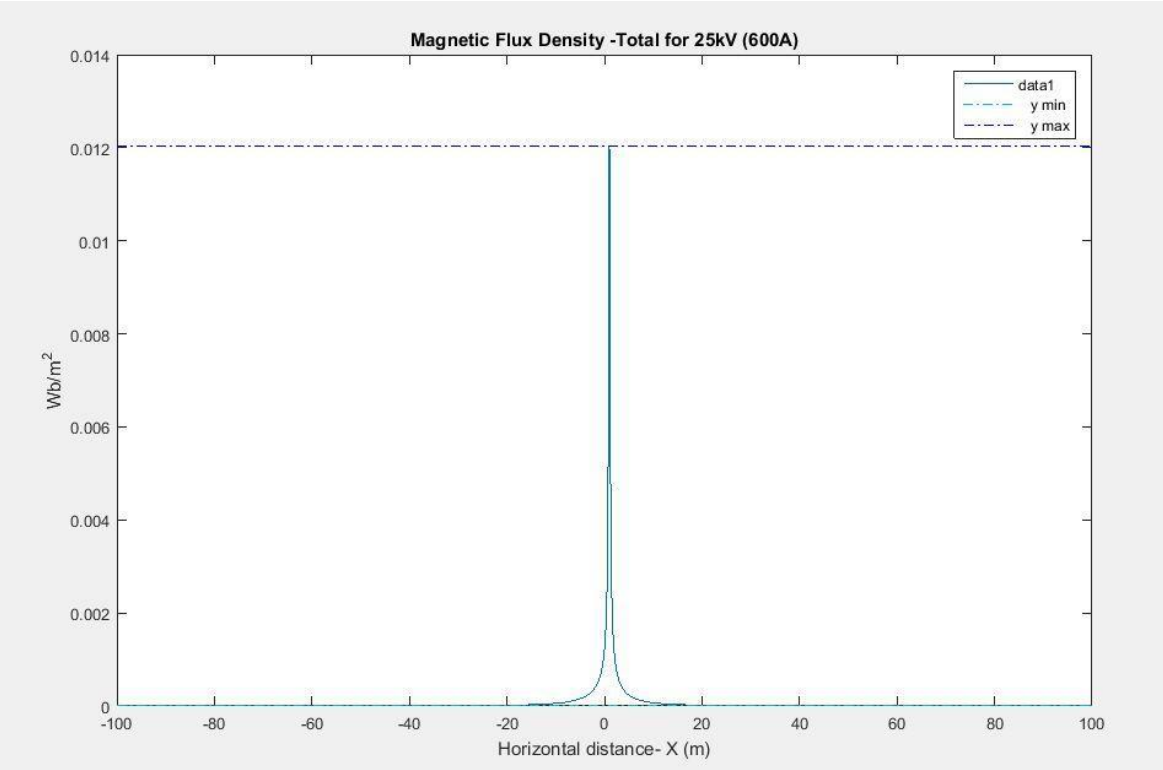


Figure 4.4 : Flux density variation for rated current – 25 kV

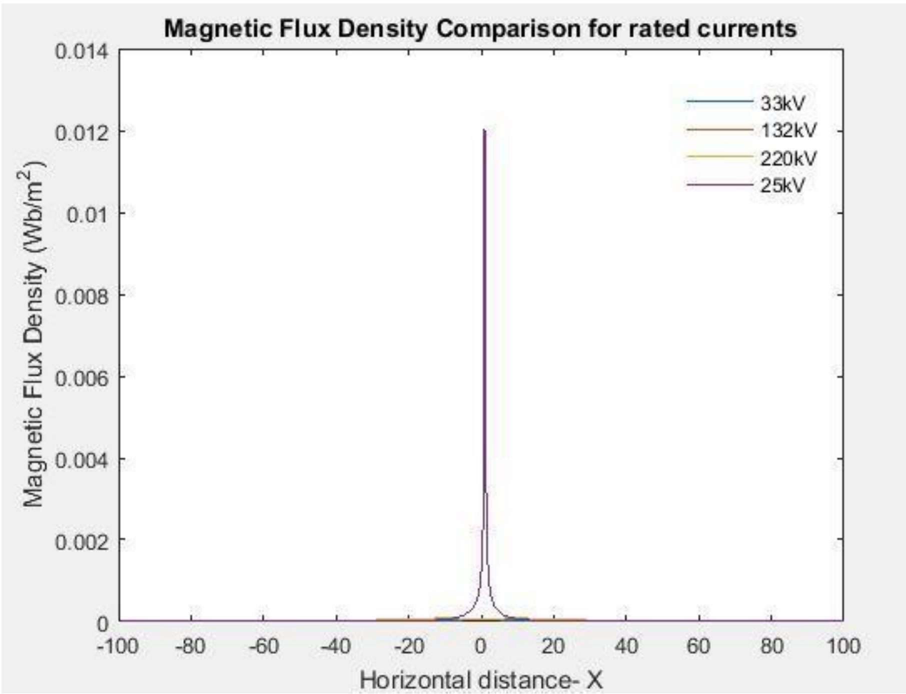


Figure 4.5: Flux density variation comparison for rated currents 220 kV, 132 kV, 33 kV and 25 kV

Chapter 5

Susceptibility of Track Circuits under Transmission lines

5.1 Relationship between induced emf (E) and magnetic flux (B)

According to the Faraday's law the induced emf (E) of a wire loop C (Figure 5.1), is derived as

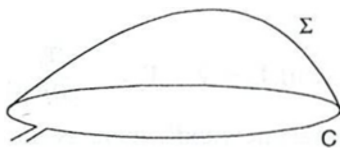


Figure 5.1: Induced emf in the wire loop.

$$\boldsymbol{E} = -\frac{\mathrm{d}\Phi}{\mathrm{dt}}$$

Where Φ is the surface integral of electromagnetic flux evaluated over any surface Σ with its edge on C. The emf of a battery is the energy supplied per unit charge delivered; and an electric force **E** is set up within a wire connecting the terminals, and hence (Figure 5.2):

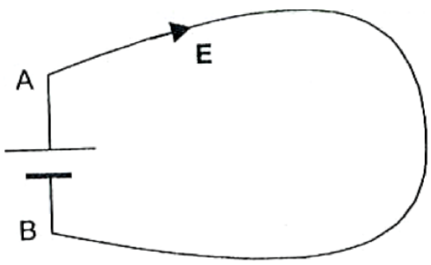


Figure 5.2: Battery loop.

The energy supplied per unit charge, $E = \int_A^B E_1 \; dl$

The line integral of $\boldsymbol{E}$ along the wire = $V_A - V_B$

∴ For any loop whether of wire or otherwise is

$$\oint E_1 \, dl = -\frac{d\Phi}{dt}$$

Considering an element δl contour δC, enclosing an area δA, then

$$\Phi = B \cdot \delta A$$

∴

$$\oint E_1 \, dl = -\delta A \cdot \frac{\partial B}{\partial t}$$

$$\boldsymbol{E} = -\delta A \cdot \frac{\partial B}{\partial t}$$

Where, E is the induced emf , δA is the loop area and $\frac{\partial B}{\partial t}$ is the rate of change of flux density with respect to time.

Considering a loop area of 1m^2 loop

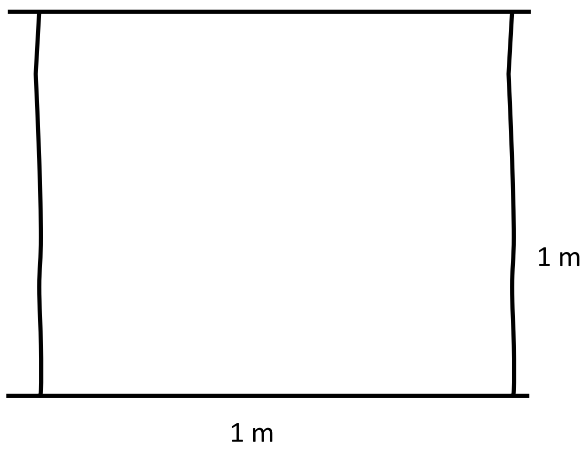


Figure 5.3: 1 m^2 track circuit loop

Induced emf; E $= \frac{-d\emptyset}{dt}$

$$= -\delta A \frac{dB}{dt}$$

$$= -A.\omega.B_{rms}$$

$$= -1.(2\pi f)B_{rms}$$

5.2 Track Circuit and track relay Parameters

Track Relay

Considering track relays, main parameters are pick up voltage, pick up current, and coil resistance. Even though different type of track relays are used in SLR, main different is manufacturer not the pickup voltages and currents.

Table 5.1 : Track relay parameters

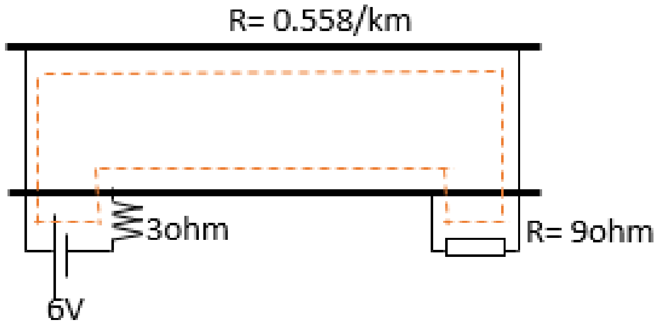
Type	QT2
Contacts	2F/1B
Pick up voltage	1.5 V
Pick up current	103mA
Coil resistance	9 ohms

5.2.1 Track Circuit Parameters

For highly maintained tracks, ballast leakage current does not come to calculations and cable end resistance and rail resistance are neglected. Therefore relay resistance, rail resistance, variable resistance and shunt resistance are only considered during calculations. Maximum rail length is 450 meters and the distance between two rails are assumed as 1 meter.

Without train on track the track relay should be in the pickup condition and when train occupy the track the relay should be dropped. If the track relay drops without a train, is not an acceptable condition but it is safe as it shows danger and if track relay pickup during train occupancy is very dangerous. Therefore induced emf should not pass the limit of both conditions.

5.2.2 Track without train



For safe operation,

$$6 - E \ > I \times (3 + 9)$$

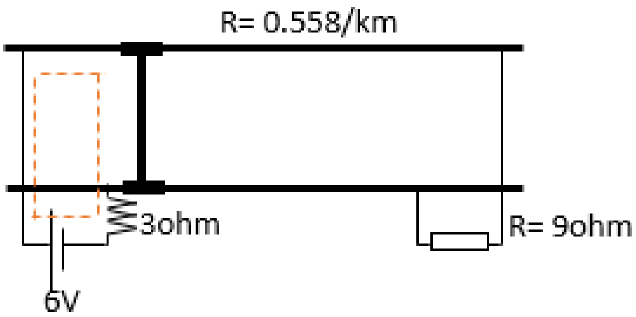
When I = Drop away current,

$$6 - E \ > 0.103 \times (3 + 9)$$

$$E \ < 4.764 \text{ V}$$

Track with train

Track is shunted by loco axel and due that current does not pass through the relay resulting relay to drop. If induced voltage at the terminals of relay is greater than the pickup voltage value, induced voltage is caused to pick up the relay.



$$E \ < 1.5 \, V$$

As $E \ < 1.5 \, V$ satisfies both conditions, for further calculations induced emf value of safe margin is considered as 1.5V.

$$E \quad = A.\, \omega.\, B_{rms}$$

$$1.5 \quad = 450 \times 1 \times 2\pi \times 50 \times \ B_{rms}$$

$$B_{rms} \ = 1.311 - \ e5$$

The magnetic flux variation of rated current of transmission voltages and for 25 kV electrified system with MATLAB model safe margin distance was obtained.

Case 1 : Power line parallel with rail line

From drawn graphs by the MATLAB model for different transmission voltages, the distance that shown minimum flux density is obtained.

5.3 Safety Margin

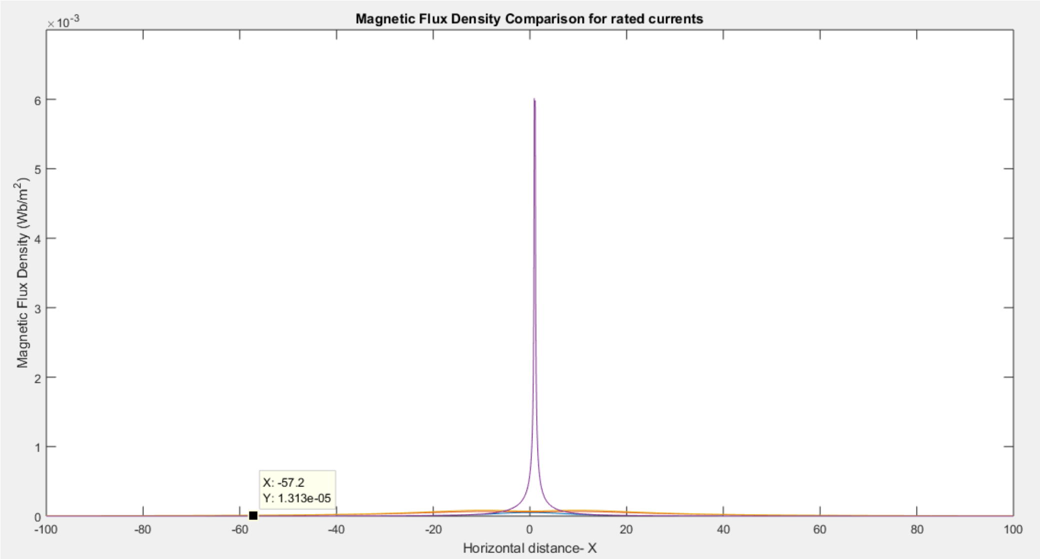


Figure 5.4: Safe margin to keep with track at rated current

Table 5.2 : Safe margin to keep with track at rated current

Transmission Voltage (kV)	Minimum Distance (m)
220	57.2
132	51.2
33	15.9
25	15.6

Case 2: Transmission line cross the rail line

Transmission lines cross the rail lines with different angles and with different distance to track circuits. Magnetic flux inside the track circuit vary with the crossing angle and distance. As flux linkage of left side and right side having opposite direction, summation of the flux need to be calculated. From the MATLAB model, area is calculated under the flux density curves.

When the transmission line cross the rail line at 90 degree and at the middle of the track circuit the effective flux becomes zero and maximum flux obtains when it is crossed at the beginning of the track circuit. Track circuit length is taken as maximum of 450m.

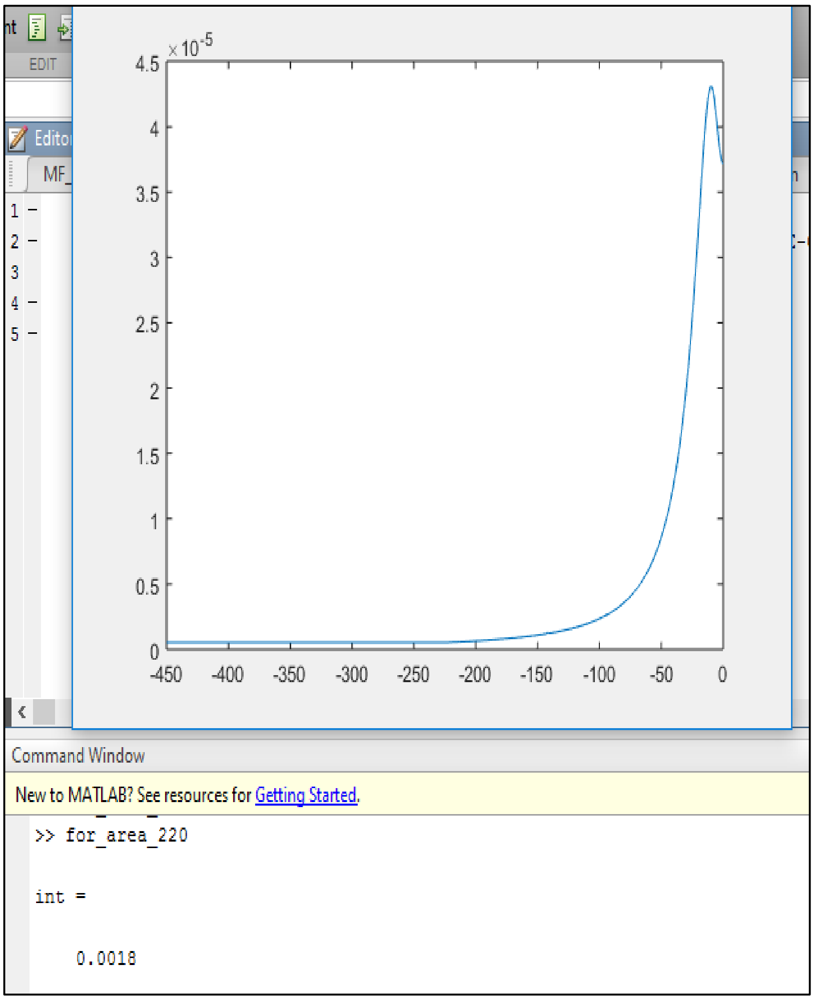


Figure 5.5: Area calculation for Flux density

Table 5.3 : Flux density variation for 220kV crossing lines

Angle (deg)	**Total Flux (Wb)**	**B (Wb/m^2)x10^(-6)**
90	0.0018	4
60	0.0020	4.44
30	0.0033	7.33
15	0.0056	13.2

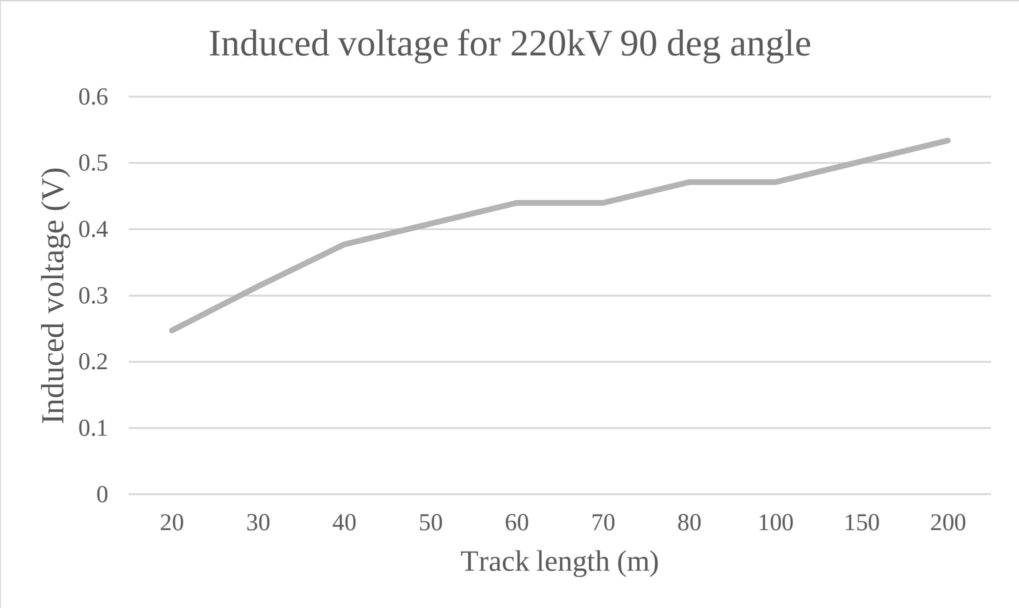


Figure 5.6: Voltage variation with track length for 90 deg crossing of 220 kV

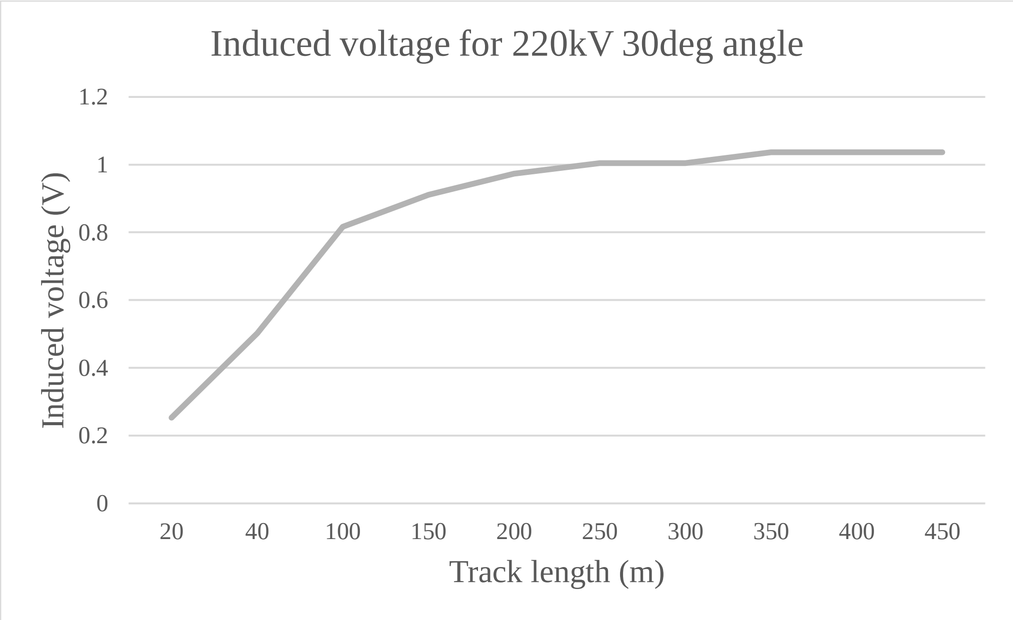


Figure 5.7: Voltage variation with track length for 30 deg crossing of 220 kV

According to the values received when 220 kV transmission lines cross the rail line below 15 degree the track circuits are affected.

5.4 Mitigation Methods

The induce voltage directly connect with the area involve with transmission line and also with the distance to transmission line. Therefore induce voltage can be reduce by reducing the area: track length. For different distances following is the maximum track length should involve with transmission line.

Table 5.4 : Maximum track length with the distance

Voltage (kV)	**Distance with transmission line (m)**	**Maximum track length (m)**
220	20	47
	30	76
	40	119
	50	176
132	20	58
	30	93
	40	146
	50	215
33	10	120
	15	208

Reducing track area is very cost effective as new relays, rail joints and wirings should be introduce along with the new tracks. Also finally all tracks should be connected in series to get the same previous track.

5.5 Discussion on results

Safe level distance for both parallel transmission lines and electrified traction are obtained. Also safe level crossing angle has been calculated for parallel transmission lines. Those values are very important during electrified train system implementations.

Safe level margins are obtained for rated current values of transmission lines but surge current and emergency currents are not considered since the time duration of those are less than the pickup time of track relays.

The minimum flux density has been calculated with the maximum track circuit length. Maximum flux linkage is obtained for the crossing of transmission line at the edge of track circuit.

It is assumed that rail track and transmission lines are straight and transmission line is infinitely long. Apart from that there is no emf effect on rail track due to external sources and current is uniform.

For the 220 kV, 132 kV, 33 kV and for 25 kV transmission lines, the distance to be maintained with the track is 57.2 m, 51.2 m, 15.9 m and 15.6 m respectively for rated currents. Even though the flux density is high in electrified system, emf value is drastically reduced within 7.5m. Beyond 7.5m emf value is lowered than the value of 220 kV flux value. It is proved that the angle between 220 kV transmission line and rail track should be more than 15 degree at rated current. Considering the transmission line profile through the rail track, it is observed that in several places the distance between the transmission line and rail track is not within the safe margin. This will not affected until transmission line carry normal load current. With the increasing of energy demand, current of the transmission lines may be increased. Hence it will be affected to the track circuits in near future. Therefore the magnetic field mitigation methods should be implemented with transmission lines and track circuits for a secured signaling system.

The values obtained from MATLAB magnetic model for safe emf, can be used as guide lines for transmission system of Ceylon Electricity Board and track circuit systems used by the SLR.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

6.1.1 As measured magnetic field values are closely matched with the values taken from the simulation model, that model can be used to model the induced voltages for rated currents.

6.1.2 Magnetic field density varies with the distance from the conductors of the transmission line. But behavior of the magnetic field under transmission line has different formation. Flux density inside the track circuit loop varies with the current of conductor, tower structure and crossing angle of conductors with track circuit.

6.1.3 No significant effect for the track relay with normal current of conductors as induced voltage does not exceed the operating values. But induced voltage at rated current may affect to track relay operation.

6.2 Recommendations

6.2.1 When the transmission line and rail line use the same parallel corridor, following safe margin distances are recommended for future constructions.

Table 6.1: Safe margin distances for rated currents

Transmission Voltage (kV)	Minimum Distance (m)
220	57.2
132	51.2
33	15.9
25	15.6

6.2.2 For the crossed transmission lines, the maximum flux density occurs when the cutting edge at the track initiation point. With rated current flow of 220 kV, up to 15 degree of crossing angel track circuits are in safe margin.

6.2.3 Mitigation methods should be used as shortened track circuit, for effected track circuits.

Table 6.2: Safe track lengths for different distances

Voltage (kV)	**Distance with transmission line (m)**	**Maximum track length (m)**
220	20	47
	30	76
	40	119
	50	176
132	20	58
	30	93
	40	146
	50	215
33	10	120
	15	208

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