DESIGN OF THE POWER FEEDING SYSTEM FOR ELECTRIFIED RAILWAYS
CASE STUDY: PANADURA- VEYANGODA RAILWAY SECTOR

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Degree of Master of Science in Electrical Engineering

Department of Electrical Engineering

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Dissertation submitted in partial fulfilment of the requirements
for the degree Master of Science in Electrical Engineering

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Dr. Tilak Siyambalapitiya

Signature of the supervisor: Date:

Prof. J.R. Lucas

ABSTRACT

In railway systems, electrical traction is more efficient, comfortable and more economical than diesel traction. Since the railway transportation is a major public transportation means in Sri Lanka, having an efficient and reliable electrified railway transportation system will increase the capacity of railway transportation and attract more passengers daily receiving the service.

This research is based on the proposed Panadura – Veyangoda railway electrification project. It is of vital importance to identify the required maximum power of the predicted system at the peak hours prior to designing the traction system. MATLAB Simulink software has been applied for the modelling the speed, power and distance of the train movement between stations with respect to time. Using the simulation results obtained from MATLAB Simulink model, a load flow study for the total train movements between Panadura station to Veyangoda station at peak hour is carried out in DIgSILENT Power Factory software to obtain the maximum power required for each traction substation.

Finally, the traction substation components are sized and layout of the system and earth grid arrangement is presented for Ratmalana traction substation as a case in point.

This software models can be applied for any other railway electrification systems to be predicted by modifying and changing their parameters accordingly.

Key words: Railway electrification, traction power, load flow, Scott-T transformer, MATLAB, DIgSILENT Power Factory

DEDICATION

I dedicate my M.Sc. research dissertation to my beloved parents for their guidance given throughout my life.

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LIST OF ABBREVIATIONS

AC- Alternative Current systems

CMR- Colombo Metropolitan Region

CEB-Ceylon Electricity Board

CoMTrans- Urban Transport System Development Project for Colombo Metropolitan Region and Suburb

DC -Direct Current

EMU -Electrical Multiple Unit

ETAP-Electrical Transient Analyzer Program

IGBT- Insulated Gate Bipolar Transistor

MFT -Medium Frequency Transformer

PCC - Point of Common Coupling

PEBB- Power Electronic Building Blocks

PPTA- Project Preparatory Technical Assistance

STRADA -System for Traffic Demand Analysis

SLR - Sri Lanka Railway

CHAPTER 1

INTRODUCTION

1.1 Railway Transportation in Sri Lanka

In 1864, railway transportation was introduced for the first time in Sri Lanka to transport coffee from plantations in the hill country to the Colombo Port for export purposes. The first train between Ambepussa and Colombo (54 km) made its historic journey on 27th December 1864 and had a coal fired boiler. During the inception stage, railway transportation was mainly focused on freight transportation like transportation of coffee, tea and coconut. The first passenger trip by rail took place from Colombo to Peradeniya on 5th April 1867. Today railway transportation is a major transportation means in Sri Lanka for passengers than freight, where the Sri Lanka Railway (SLR) acts as the only organization providing the railway services.

Diesel traction is the basic railway transportation technology in Sri Lanka at present. In diesel traction, every train has its own diesel engine and a generator to generate electrical power for motor driving or diesel engine with gear box to provide motive power for wheel driving. Diesel multiple units and diesel locomotives are the main railway vehicle types utilized in the service. There are about 1561km of rail track available for the railway transportation and 72 locomotives and 78 diesel multiple units are currently available for service. Railway network of Sri Lanka consists of number of railway tracks namely, Main line, Matale line, Puttalam line, Northern line, Batticoloa line, coastal line and KV (Kelani Valley) line.

The railway transportation is mainly utilized by daily commuters who are travelling to their work place in the morning and back home in the evening. Hence railway peak traffic occurs during 7.00 am to 9 am in the morning and 4.30 pm to 6.30 pm in the evening. There are over three-and-half million passengers daily travelling through the railway.

1.2 Electrification of the Sri Lanka Railway System

The first suggestion for railway electrification came in the year 1918 from the distinguished engineer in engineering history of Sri Lanka Eng. D J Wimalasurendra in his technical paper titled, 'Economics of Power Utilization in Ceylon' [1]. In his paper he has presented the importance and the advantages of railway electrification. Since 1924, there have been several proposals coming up for railway electrification in Sri Lanka. However, there was no steady action to plan to implement the project to get the benefits we could receive from railway electrification.

When comparing electric traction over diesel traction, there are many major advantages including less energy cost, less pollution and less noise than diesel traction. Passenger comfort is also garneted by the smooth operation, possibility of having faster speed levels and quieter train movements. Normally, electric trains are lighter in weight than diesel trains due to un-necessity of on board diesel engine and generator equipment. Hence, traction power required for propulsion of electric train is less than diesel trains.

With the drastic increase in crude oil prices, electrification will provide an economically and technically effective solution to decrease the energy cost annually spent on diesel for railway transportation. Also, it is much effective to control the environmental pollution occurring in a coal power plant than environmental pollution occurring by a few moving trains. Although initial cost for implementing electrification will be much higher, financial saving which can be generated through low energy cost and low maintenance cost in electric trains due to the fewer number of moving parts and modular units used is inevitable.

Other than the economic and technical benefits, railway electrification will enhance the social standard and social comfort. This can attract more commuters to railway transport and can minimize the present road traffic in suburban areas. By providing effective and efficient transport facility to the society through railway electrification, public transport sector can be improved and public society can be influenced to utilize public transport rather than their private vehicles which is the main cause for huge road traffic in suburban areas.

1.3 Research Motivation

Railway electrification in Sri Lanka is a major topic which has been discussed and argued for decades in past history without a proper plan for implementation. Vision of electrifying the railway system of Sri Lanka is going to be realized in recent future. Asian Development Bank has raised funds for the Colombo Suburban Railway Project, and the first stage of project has commenced with preparatory technical assistance reports for small-scale technical assistance that identifies, formulate, and prepare development projects. This improvement of suburban railway system in the Colombo Metropolitan Region (CMR) includes electrification of the 64 km long Veyangoda–Colombo Fort–Panadura section railway track.

Since this will be the first Sri Lankan railway electrification project, at present experience and resources related to railway electrification are considerably low in Sri Lanka. Hence, it is a great challenge to design the most technically sound and economically viable optimum electrified railway system to cater the forecasted railway traffic, which can occur approximately 20 years later.

1.4 Project Objectives

The main objective of this research is to design the proposed railway electric power feeding system of Sri Lanka. This study was done for the forecasted railway traffic in year 2035. Hence, it is importance to identify the train timetable to cater the maximum traffic, which predicted to occur in year 2035.

Specific objectives:

- To model and simulate train power variation based on the MATLAB Simulink software
- To model and simulate proposed railway electric power feeding system in DIgSILENT Power factory software
- To perform load flow calculations
- To size the power substation components and cables
- To arrange traction substation layout
- To design earth grid for the traction substation

1.5 Project Overview

The basic background information for the study is collected through interviewing technical personal in Sri Lanka Railway, expertise from preparatory technical assistance project team and contacting international railway electrification expertise in the world. Power Utility Supplier for the project, Ceylon Electricity Board (CEB) was interviewed as well and obtained the data related to the utility grid.

MATLAB Simulink software is used to generate the power variation of Electrical Multiple Units (EMUs) with time according to forecasted train traffic timetable. Load flow calculation for the movement of electric trains at different track sections is performed in 15.1 version of DIgSILENT Power Factory software. Maximum power capacity required for each track section is decided by utilizing the load flow data for each section.

Traction substation is designed and layout plan is delineated considering the international standard for substation designing and insulation coordination. Earth resistivity test is performed at the site for the proposed traction substation in Ratmalana. Earth grid for the proposed traction substation is prepared incorporating the data collected for earth resistivity test and based on the guide for measuring earth resistivity, ground impedance, and earth surface potentials of a grounding system.

CHAPTER 2

LITERATURE REVIEW

2.1 Train Time Table Optimization

A study has been carried out to obtain maximum regenerative power effectively through time table optimization. It is elaborated that the energy consumption is mainly influenced by headway and reserve times of trains and proposes an optimized reserve time for the system [1].

The train time table optimization is discussed in order to harness more regenerative braking energy from the system taking two working scenarios for peak hours and off peak hours. In the study headway time, departure time, arrival time and dwelling time are taken as decision variables. Few assumptions have been considered in the study including, up line and down line of the railway system operates independently where regenerative energy in up-line cannot be consumed by the trains in down- line. For an example, energy generated by braking in train 2 in up- line cannot be consumed by the train 4 in down -line as shown in the Figure 2.1 [3].

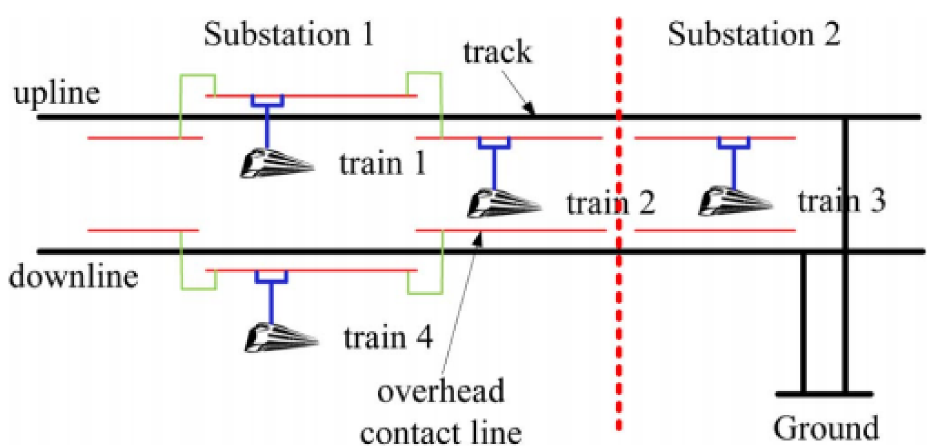


Figure 2.1 Structure of the power supply system [3]

Integer programming model for headway time and dwell time control and Genetic algorithm with binary encoding to optimize the solution are comprehensively presented in their research study. Finally it is discussed and numerically proved using practical values from the field that new train time table optimization method is working successfully [4].

2.2 Train Power Modelling

Train traction is mainly categorized as diesel traction and electrical traction. In diesel traction systems, locomotives operates by electricity generated from alternator, which is driven via diesel engines or locomotives operated by diesel engine combined with gear set. Depending on train movement variation as acceleration, constant speed and deceleration, the energy consumption of the train gets to fluctuate. Energy consumption of the train rise with acceleration and energy generation occurs in braking stage. The representation of energy profile of electric vehicles has done through different approaches as discussed below.

Most of the studies have covered the modelling and analysing of the train energy consuming behaviour depending on the train operation. Model is formulated to analyse the train in accelerating mode, which consumes the energy generated by braking of another train in the same power supply network. As per the study, if there is no another train to consume the energy generated by braking of the train in the power supply network, over voltage protection system will automatically trigger energy consumption through the braking resistance [5].

The study has presented a practical application of the system operation using sensors located in the electric trains. As per the study, information similar to train position and speed are obtained by the sensors located in electric train and those data is forwarded to zone controller and operation control centre through the vehicle on-board controller. After analysing the data, operation control centre provides effective coordination with the available trains in the same power feeding system for their acceleration and braking operations considering harvesting of maximum regenerative braking energy in the system [5].

As per a study, electric traction power has been divided into acceleration power, cruising power and braking power. Calculations have been done to obtain power required by train for different operation mechanisms incorporating train time table data, train parameters and field factors [6].

It is comprehensively discussed dynamic load estimation for the traction power systems using by Lomonossoff's Equation given in (1) [7].

$$(M+DM)\frac{dv}{dt} = T.E. - \left(a+bv+cv^2\right) - Mg\left(\alpha+\alpha'\right) \quad (1)$$

- M- Mass of transient
- DM- Dynamic Mass of Transient
- v- Speed
- T.E.- Traction effort or braking effort output
- a,b,c – Running resistance
- g- Gravity
- α – Slop at current position
- α' – Curvature at current position converted to equivalent slope according to (2).

$$\alpha' = \frac{\mu(G+L)}{2*R} * 10^6 \quad (2)$$

In which,

- μ - wheel-rail adhesion coefficient (Normal range: 0.1 ~0.3);
- G- track gauge(m);
- L- axial length(m);
- R- radius of curvature (m)

2.3 Simulation Tools Applied in Electrified Railway System Studies

In an electrified railway system both train power capacity and power loading point in the system frequently vary with time. While some electric trains are accelerating in the system, few trains may be in constant speed or descending stage in the system. Depending on the type of train operating stage in a moment, train can absorb power from the system or feed the power in to the system. Hence, it is immense important to evaluate the load flow for different scenarios in such system to get a thorough deliberation on total power requirement of the system.

There are few studies carried out by different parties related to electrified railway systems. Different software packages have been utilized to perform load flow calculations, short circuit calculations, harmonic analysis and voltage unbalance in electrified railway systems.

A study has been carried out to analyse the relationship between urban power distribution and urban rail transit traction power supply system in China using the PSCAD software. Simulation of the railway power system is represented by modelling of external power supply system, main step down substation, ring network cable, traction substation, traction load, catenaries, return line and filter. In this simulation study traction loads are characterized by a current source model. The current source has the capability to reflect the characteristics of the motor operation. The calculation of traction line inductance incorporating internal inductance, external inductance and total inductance is presented in the study [8].

The comprehensive study on Black water heavy haul rail network in Central Queensland provides the details related to multiple software products, which have been incorporated, interfaced the outputs and the inputs of these products accordingly in order to obtain realistic train performance and electrical behaviour of the system [9]. Incorporating the route characteristics and capabilities of the traction units, individual train movement has been modelled using Railplan software developed by Funkwerk-IT. SimPower Systems /Simulink tools have been applied to determine the total harmonic distortion, efficiency and load flow of the system. To simulate unbalanced load flow model and high voltage transmission system, DIgSILENT Power Factory software has utilized [9].

Since the load and loading point both vary with time, load flow need to be carried out for each snap shots of the trains' movement for a specified time period. The load flow of Tabriz urban railway is analysed using the Power World Simulator software and results are presented as designed system is able to feed all the traction substations without any issue like overloading. It is discussed in the study that effect on overloading is not influenced by regenerative braking or heavy traffic schedules but by feeder disconnection [10].

The Electrical Transient Analyser Program (ETAP) software is capable of performing load flow calculations in power systems. ETAP software is applied in Shanghai-Nanjing intercity high speed railway system to analyse the load flow, unbalance operation and harmonic injection considering the comparison between simulation data and measured data in the system. This study is adopted to evaluate the effects at point of common coupling (PCC) and the penetration in the power system [11].

The simulation of railway system in eastern Denmark is performed using DigSILENT Power Factory software to evaluate the voltage unbalance and voltage fluctuation of the system [6]. This study has focused on the sudden voltage fluctuations occurred in power grid due to shifting of traction load between two sections connected to two different substations.

The over designed issues occurred during the planning stages of the railway power system has been addressed by performing load flow calculations in DIgSILENT Power Factory software [7]. The study has elaborated the evaluation of power consumption of train loads during different stages of the train operation. Newton – Raphson current iteration method is applied for the load flow calculation in DigSILENT Power Factory software.

It is comprehensively discussed about simulation of motor characteristics based on four motor characteristics namely traction effort vs. train speed in motoring mode, power demand vs. train speed in motoring mode, braking effort vs. train speed in regenerative braking mode and power feedbacks vs. train speed in regenerative braking mode. The motor characteristic data tabulated in tables are accessed by multi-train simulator and the actual electric model was established by the linear interpolation [14].

2.4 Traction Feeding System

A research has carried out on specially connected transformers which are utilized in railway electrification traction feeding systems. Five traction transformers such as single phase transformers, V/V, Wye-Delta, Scott-T and Le-Blanc transformers are operated to convert three phase high voltage into one or two single phase supplies [15].

It is really important to examine on different types of traction transformers applied in railway systems using MATLAB Simulink software. This study provides information related to modelling of Scott-T, YNyd, Leblanc and impedance matching transformer. A dual converter with a compensator is introduced to reduce the harmonics, voltage unbalance, negative sequence currents and reactive power problems. Thyristor based traction load is considered for the simulation and it was discussed to apply compensation method in the utility or operating GTO converters or IGBT converters instead of thyristor converters [16].

The power quality issues are discussed related to events which can be occurred in an electrified railway systems and power improvement strategies to rectify them. For railway traction feeding systems, AC single phase high voltage feeder is obtained from step downing two phases of high voltage three phase systems. It leads to power quality issues, voltage unbalances, harmonic etc. This study has elaborated the outcomes of phase shifting method adopted by three adjacent traction substations. Compensation of fundamental neutral sequence current is achieved by connecting adjacent three traction substations between two different phases as shown in Figure 2.2[17].

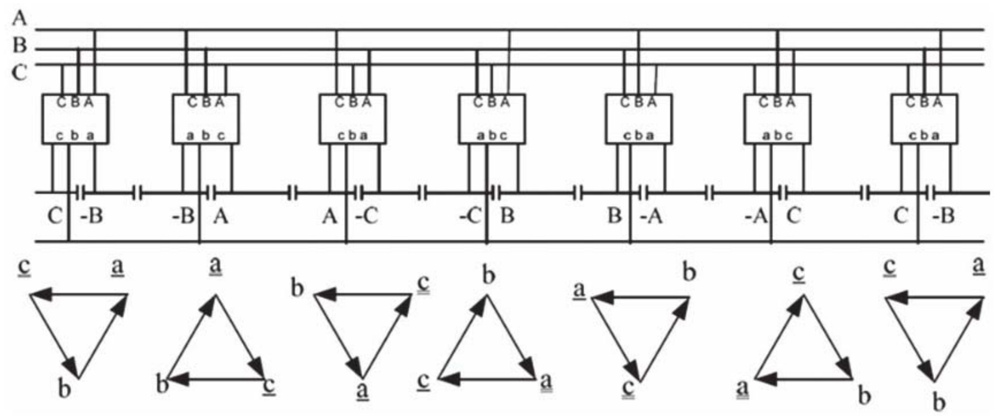


Figure 2.2-Transformer Interconnection with Utility Supply [17]

Power electronic traction transformer for 15kV at 16.7 Hz railway grid is developed and discussed in IEEE transaction paper. Insulated gate bipolar transistor (IGBT) based power electronic building blocks (PEBB) are utilized in both high voltage and low voltage side. This has been indicated in Figure 2.3. High voltage side is a combination of frond end device and dc- dc converter and galvanic isolation between medium voltage and low voltage side is obtained through medium frequency transformer (MFT)[18].

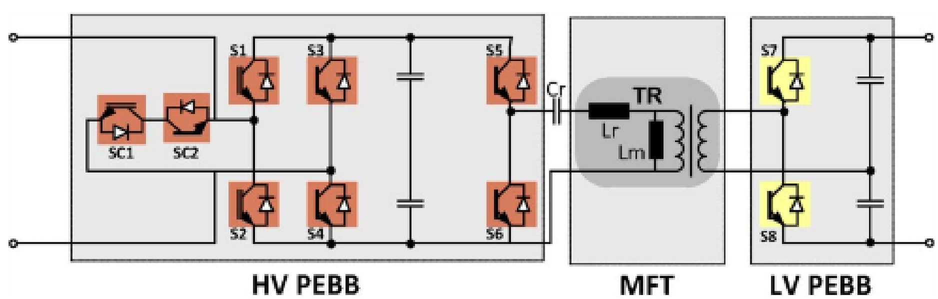


Figure 2.3 - Representation of HV PEBB, LV PEBB and MFT[18]

It is discussed that most of the locomotives employ ac-dc phase-controlled thyristor converters to feed dc motor drives and thyristor based locomotives grab electricity power at low displaced power factor and with high harmonics content. This direct to voltage drop in contact line due to reactive power compensation in the locomotives and contact voltage of the contact line drastically deviate from the permissible voltage. A hybrid compensation system consisted with active power filter and a passive RCL filter to eliminate the harmonic current in the system is proposed which is shown in Figure 2.4 [19].

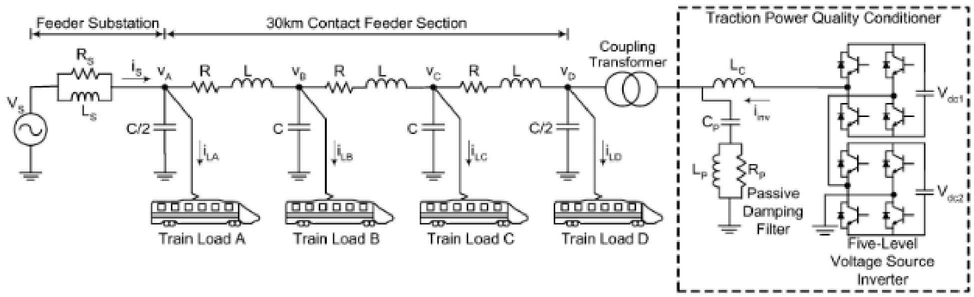


Figure 2.4 - Railway System with Active & Passive Harmonics Filters [19]

A study has discussed the operation of auto transformer sub stations in Tehran–Golshahr suburban electrical railway using the forward/backward sweep load flow method which is shown in Figure 2.5.

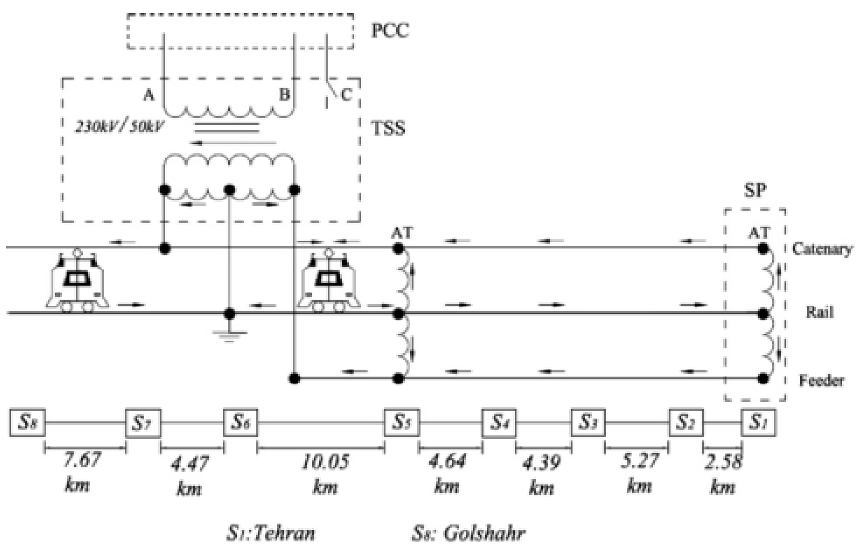


Figure 2.5- Auto Transformer Feeding System [20]

The analysis is done for simulation results gained from the modelling of asynchronous traction drives and the measurements obtained from the field data [20].

2.5 Earthing Grid Design for Traction Substation

Design of earthing system for new substation project in Myanmar is discussed about the safe earthing practices in AC substation design and to establish safe limits of potential differences under normal and fault conditions. MATLAB software has been utilized to design the earth grid and conductor flowing method for grid construction has been utilized for the design [21].

A study is done on the analysis for the modelling of the integrated power system and the grounding system of an electric traction system owned by Amtrak, North end Electrification Project. Grounding program is utilized to calculate the touch voltages and those have been compared with the allowable touch voltages per IEEE Standard 80. The simulation model consisted with both railway electrification system and earth grid is shown in Figure2.6 [22].

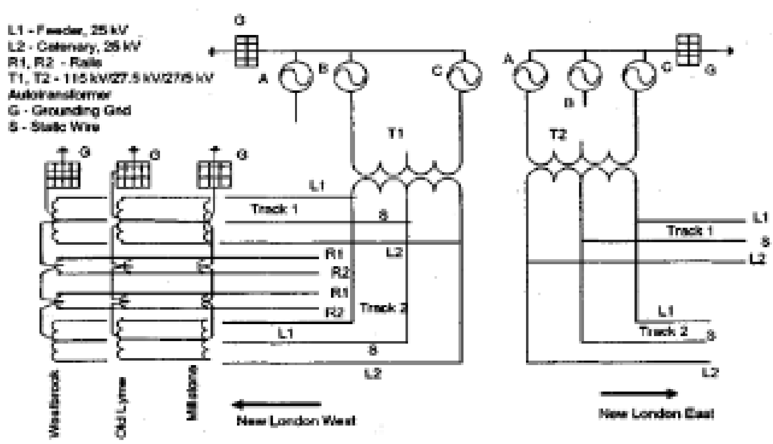


Figure 2.6 - Simulation Model of Railway System including Earth Grid [22]

CHAPTER 3

RAILWAY ELECTRIFICATION

3.1 Electrification Techniques

As per the historical records the electrification of railway was first begun in year 1883 with Magnus Volk's first electrified railway system. In between today and the past several railway electrification methods have been practiced for powering the trains directly by electricity. Electrification systems can be mainly categorized based on the current type, permissible voltage level and applied frequency of the system and electricity feeding method.

Both direct current (DC) systems and alternative current systems (AC) are available for electrification of railway, but DC systems are more complex than AC systems due to their power conversion equipment AC/DC rectifiers, DC breakers etc. Table 3.1 indicates the available DC and AC voltage levels with relevant frequencies available in the railway electrification systems.

Table 3.1- DC and AC Electrified Railway Systems

Nominal Voltage	Frequency	Applications /Applied Countries
600,750 V	DC	Many urban transport with a third rail for power supply/Germany, UK, Switzerland
1.5 kV	DC	Many urban transport with an overhead catenary/France, Spain, Netherlands, Australia
3 kV	DC	Intercity rail/Russia, Poland, Italy, Spain, South Africa
15 kV	16.7 Hz	Intercity rail/ Germany, Switzerland
20 kV	50 Hz	Intercity rail/Japan
20 kV	60 Hz	Intercity rail/Japan
25 kV	50 Hz	Intercity rail/Russia, France, Romania
25kV	60 Hz	Intercity rail/ Japan

The type of the technique utilized for the electrification depends and influenced by technical consideration mentioned as follows,

- Operational requirements (for urban metro, high-speed passenger or heavy haul freight)
- Physical route characteristics (such as gradients, and bridge and tunnel clearances)
- Proximity of generating plant and utility or railway-owned power networks
- Available traction technology(converters, traction motors and regenerative capability)

3.1.1 AC feeding system

Single phase 15kV voltage at 16.7Hz, 20kV voltage at 50Hz or 60Hz and 25kV voltage at 50Hz or 60Hz AC systems are the available AC railway electrification systems in the world and 25kV voltage at50Hz or 60Hz AC systems are most popular due to their reliability, effectiveness, and feasibility in application.

15kV voltage at 16.7Hz was first introduced to overcome commutator flash over problems and eddy current losses occurred in large series wound traction motors due to the high frequency of electricity power. 50Hz electricity supplies were tend to create high and frequency proportional interferences as well in cables which are running parallel to the traction feeding system. One third of the 50 Hz is exactly the 16.7 Hz which can be generated using rotary converters from the grid frequency or utilizing separate generators with same shaft speed as a standard 50 Hz generator and reducing the pole number by factor of three.

The main drawbacks of 16.7 Hz systems was the requirement of large transformers to convert feeding voltage into voltage required for the operation of motors and the other equipment in the locomotive. Substantial magnetic cores and larger windings were required in step down transformer for the same level of power conversion in low frequency. Hence heavier locomotive inbuilt transformer creates huge weight on axel loads and finally causing wear of tracks and frequent maintenance requirements in the railway track.

To establish a reliable and effective feeding system, 25kV voltage at 50 Hz or 60 Hz is been practiced as a railway electrification standard voltage level and frequency in most of the countries in the world. 25kV at 50 Hz system is mainly adapted by high speed and heavy haul railway systems and since new locomotives are built with asynchronous motors, there is no more issue with the range of input frequencies.

When comparing AC over DC systems, the high catenary AC voltage implies low currents and negligible power losses and hence fewer number of AC traction sub stations are required compared to lower voltage DC traction substations for a railway electrification track system.

3.1.2 DC feeding system

There are several DC systems voltages which are currently applied in railway systems in the world. 600V and 750V DC systems are mostly applied for tramways, 3000V DC system in interurban-urban railway systems and 1500V DC systems are utilized in metro systems. In DC power feeding systems DC power is derived by track side rectifier traction substations fed by AC utility supply or dedicated supply available for railway. Rectifier substations are occupied with 6 pulse rectifiers or 12 pulse rectifiers for conversion between three phase supply AC voltages into desired DC voltage. Since the currents available in these systems are much higher than high voltage AC systems, the contact cable sizes utilized in DC systems are considerably large. For the recovery of regenerative braking energy in the system, inverter system should be set up to convert generated DC voltage into AC three phase voltages. Hence in DC sub stations inverter systems are installed in parallel with rectifier systems.

3.2 Power Contact Systems

Depending on the mechanism utilized by electric rail vehicle to obtain electricity power for the motor operation, lighting, air conditioning etc., power feeding systems have been categorized as overhead contact system, third rail system and fourth rail system.

3.2.1 Overhead contact line system

Overhead contact system is consisted with few main parts to ensure capabilities mentioned below;

- The capability to carry required total current capacity for the electric rail vehicles in the system
- Guarantee the contact between catenary cable and the pantograph for smooth operation while meeting all the train speeds
- Provide ability to withstand tension during high speeds, strong winds, vibrations, corrosion, heat etc.

Overhead contact line system is consisted with overhead contact line, cantilevers, poles, foundation and return rail. Contact line is a combination of contact wire, catenary wire, droppers and tensioning devices. In overhead contact system, catenary cable is driven throughout the railway track to provide electricity power required for the rail vehicle. Electricity power is transferred to the vehicle by contacting the pantograph which is positioned at the top of the rail vehicle with the contact cable hang over the track. While catenary cable operates as the power supplying point, one rail is utilized as the neutral to complete the circuit. It is economical to keep the cross sections of the contact cable and catenary cable in minimal size.

3.2.2 Third rail system

Conducting current through a rail is the most ancient method of current carrying method utilized in railway electrification and it is mostly used in urban and underground railway systems. In third rail systems, conducting steel rail will be laid next to the running rails to provide electricity supply for the operation of electric rail vehicles. Mostly 600V and 750V DC systems utilize third rail system as the power transmitting mechanism. The conducting rail is shielded by protecting plates for the protection of humans and living beings. When mounting the conducting rail along the railway track, insulators are installed at 2.5m ~ 5m span and a flat shoe fixed in the electric vehicle directly collect the power from the top of the conducting rail. In order to protect live contact with the conducting rail, conducting rail is provided with insulation cover boards.

3.2.3 Overhead contact rail system

The conductor rail which is mounted above the vehicle gauge is called overhead contact rail system. It is mostly utilized in tunnel areas due to limited spacing. In this system required vertical clearance height for system installation is less with compared to overhead catenary system. Overhead contact rail is more reliable than overhead contact cable to operate in tunnels since less tensile forces, few components and inherent fire resistance capabilities.

3.3 Traction Transformers

Traction transformer is the main and most important component in a traction substation. The process of a traction transformer is to convert high voltage three phase powers into one or two single phase traction feeding power. This conversion disposes to create voltage unbalances and feed negative sequence components into the utility.

3.3.1 Single phase transformer

In single phase traction transformer, the primary side is connected to two phases of the high voltage utility supply and obtain single phase secondary side output for the feeding of catenary system in railway electrification. These types of transformer connection create high load unbalances in the high voltage side of the utility power supply systems since power is drawn only from two phases in the system.

3.3.2 Auto transformer

Auto transformer systems are mostly applied for long distance high speed electrified railway systems where it is essential to retain permissible voltage level in the overhead contact system between two adjacent auto transformer feeding substations. Typical spacing for two auto transformer fed substations is 50-60km.

Since the traction feeding system is single phase, the secondary side of the traction transformer is single phase while primary side is connected only to two phases in the high voltage three phase utility power supply. This tends to create load unbalances in the utility supply. To overcome this issue, it is recommended to connect adjacent auto transformers with alternated primary winding connection with the utility supply.

Available auto transformers in the railway traction fields operate at 2 x 12.5 kV and 2 x 25kV ac electrification voltages and 2 x 25kV ac electrification voltage is being the world standard. The special configuration in the transformer is built up by connecting the middle tapping point of the secondary winding with ground and connecting it into the return rail in the system. Hence in order to have 25kV single phase voltage in the feeding point, secondary winding of the auto transformer is consisted with 50kV potential without required clearances essential for a system with 50kV potential. In Figure 3.1 indicates the auto transformer connection arrangement.

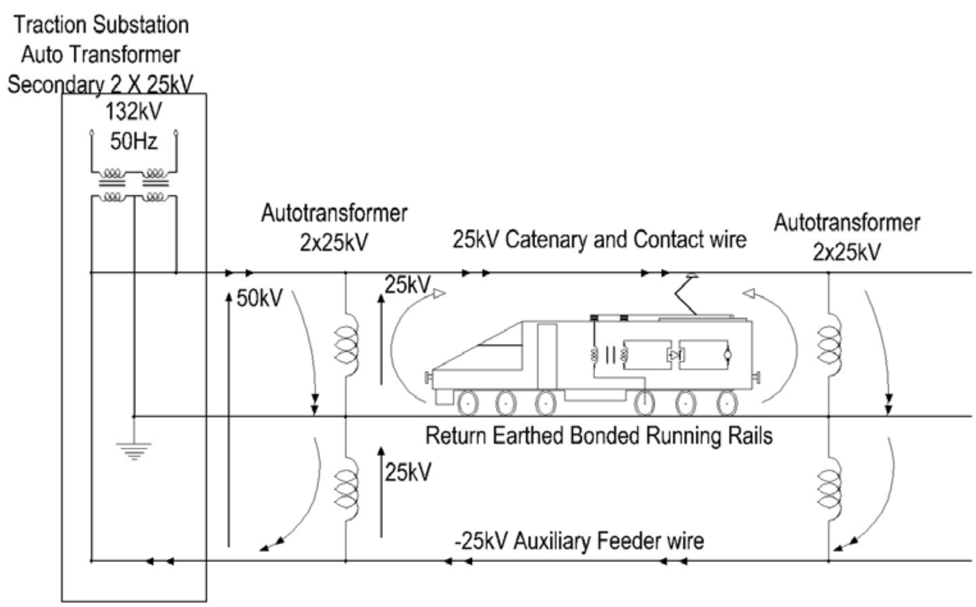


Figure 3.1- Auto Transformer Connection

3.3.3 Booster transformer

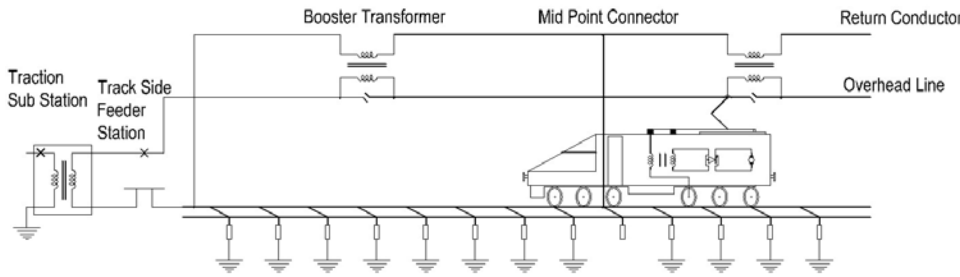


Figure 3.2 Booster Transformer

Booster transformers are mainly applied in railway electrification to mitigate the electromagnetic interferences occurred in telecommunication lines including other electronic devices and inrush current induced in pipe lines and other metallic parts located near to the railway electrification system. Generally booster transformers are utilized in the far end of the line to raise the voltage fed by other main transformers in lengthy railway catenary systems. Booster transformers in railway applications operate to collect return current from earth and rail to the return conductor which is indicated in Figure 3.2.

3.3.4 Scott –T transformer

Scott- T transformer is a special configured transformer for railway electrification purposes to obtain single phase power feeding capability through balanced three phase primary connection.

In this configuration two single phase transformers are associated in a special way where primary winding of one single phase transformer is connected between one phase and neutral of the utility supply and primary winding of the other transformer is connected between other two phases in the utility supply.

The phase to neutral connection and the phase to phase connection in primary sides of two single phase transformer is 90^0 out of phase and secondary windings of the two transformers are connected to provide two single phase power outputs in the transformer. The internal wiring arrangement is indicated in Figure 3.3.

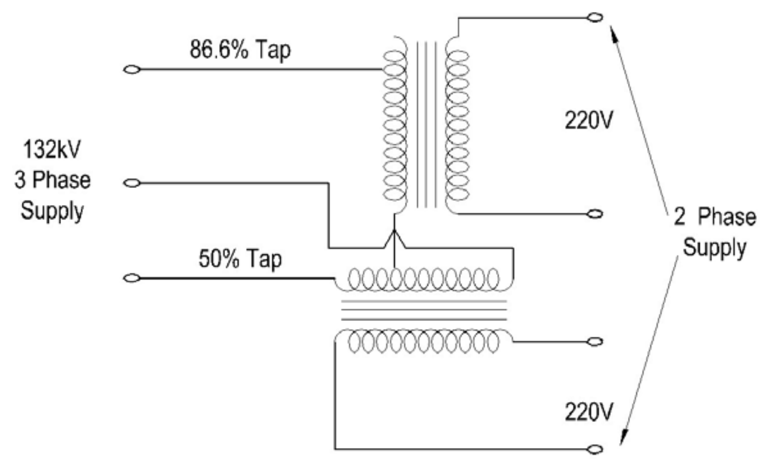


Figure 3.3- Scott-T Transformer Internal Circuit

3.3.5 V/V transformer

This also a specially constructed transformer type for railway electrification purposes considering two single phase transformers. As per the configuration, primary sides of the two single phase transformers are connected to two phases in the high voltage side in the utility supply such as AB and BC. This ensures to distribute the single phase train power loading evenly throughout the three phase system in the utility supply.

3.3.6 Wye – delta transformer

Wye – Delta transformer can be constructed by connecting three single phase transformers as delta connection from secondary side and primary side connecting as Wye connection. The whole purpose of this connection in the transformer is to obtain three phase balance connection in the utility supply side while loading the train loads in the electrified railway system.

3.4 Electrical Sectioning

It is required to have isolations between contact lines by subdividing it into different circuits. Sectioning has immense important when considering fault conditions, repair and maintenance of the contact line. Sectioning insulators and sectioning devices are applied to obtain the purpose. In order to facilitate switching of overhead contact system, each switching station is equipped with indoor or outdoor medium voltage switchgear.

3.5 Phase Breaks

Since the primary winding of the transformers are connected only to the two phases of three phase high voltage systems of the utility, there are voltage unbalance situations occurred in the utility system. In order to overcome the issue of voltage unbalance caused by above connection, adjacent transformers are connected in a rotating order to the two phases in three phase system. Hence voltage output in two adjacent transformer sections will be out of phase to each other. Electrical isolation has been introduced in such occasions by fixing phase breaks in the overhead contact systems at the grid substations and at switching stations.

3.6 Railway Block Signal Systems

In railway systems trains move forward in a fixed rail and railway traffic needs to be cleared without any collision between trains moving in the same direction. Due to the huge weight and inertia of the train, it is very difficult to suddenly stop a train at an obstacle. To avoid this issue and have a proper train operation in the system, train block signalling system has been introduced.

Since one track is always dedicated for trains moving in one direction, it is essential to ensure that trains moving in the track has sufficient gap between two trains to avoid any clash. Optimum headway and safety of the system has to be thoroughly considered when dividing the track into block sections.

3.7 Fixed block system

Block signal system is performed by dividing the rail track into sections in which only one train is permitted to travel at a time. In fixed block system, the track sections in the block system are marked between two fixed points. Red, amber and green colour lights are established at the starting point of each track section to indicate the permission for train entering to the track section. If red colour is indicated in the signal light, track section has occupied by a train and if the signal light is amber, it indicates that a train is moving in the track section immediately next to this. Train can move forward if the signal light appeared in green colour which give the idea that adjacent two track sections are free from train movement. Block signal system is presented in Figure 3.4.

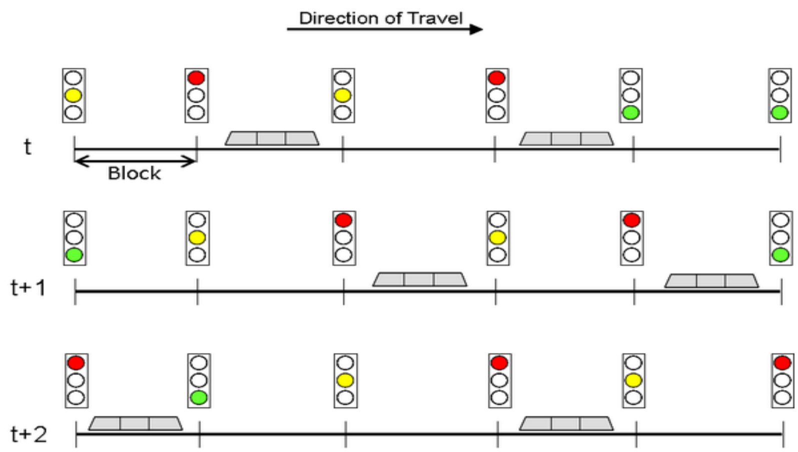


Figure 3.4 - Block Signal System

3.7.1 Automatic moving block system

In automatic block system, block sections are not fixed and block sections are defined in real time depending on the real time calculation of train travelling speed. If the train is travelling in high speed, the safety distance is long and the safety distance is low when the train speed is low. This allows reduction in the train headway and maximizing track capacity of the system. Since the safety distance is moving with block, it is called as 'Moving g block system'. Since the safety separation kept in minimum value, there is no wasted space between trains in operation.

3.8 Sector to be Electrified

The proposed railway line for electrification is the existing Panadura to Veyangoda 64 km long railway line with few upgrades in the tracks. There are 34 railway stations located between Panadura to Veyangoda railway station which is presented in Annexure- 1.

As per the recommendations of the preparatory technical assistance team, there will be few new tracks added to the system to cope with the increasing number of passengers by year 2035. Currently there are three tracks from Maradana to Ragama, two tracks from Ragama to Veyangoda and from Panadura to Maradana. With the purpose of increasing the number of trains passing through the system, there will be four tracks at Maradana to Ragama, three tracks from Ragama to Veyangoda and three tracks from Panadura to Maradana by year 2035.

Panadura to Veyangoda line is mainly utilized by working force daily travelling to Colombo from Panadura area and Veyangoda area. Hence railway traffic peak occurred during 7.00 am to 9.00 am in the morning and 4.30 pm to 6.30 pm in the evening.

When considering the geological background of the railway line, Panadura to Maradana line is located in coastal area and Maradana to Veyangoda line is located inside the country. Hence soil conditions are very different and track improvements of the existing tracks needs to be considered. Maximum track speed has to be fixed as 120km/h and track improvements needs to be done in order to accomplish above mentioned speed limit.

Land acquisition for another track in Panadura to Maradana railway line sector is much difficult due to unauthorized residential areas in coastal area and marine drive between Wellawaththa to Kollupitiya. Most of the lands between railway lines at Maradana to Ragama are dominated by unauthorized habitants.

3.9 Standards to be followed

Railway electrification itself has considerable number of international standards to be followed in order to obtain most effective and technically viable electrified railway system. Depending on the voltage and frequency levels applied in the system, the standard which needs to be followed can be varying.

In substation designing several international standards are referred and insulation coordination among the substation equipment is arranged referring to the respective international standards. Relevant international standards are followed in earth resistivity testing and designing of earth grid for the traction substation as well. Following standards are followed in the design presented in this research.

- BS EN 50163:2004-Railway applications — Supply voltages of traction systems
- TB 10009-2005 Design code of railway electric traction feeding
- IEC 60038-2002 Standard Voltages
- IEEE 80 - Guide for Safety in AC Substation
- IEEE 81 - Guide for Measuring Earth resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System
- IEC 60071-2 Insulation co-ordination – Part 2: Application guide
- EN 50163: Railway applications – Supply voltages of traction systems

Other than the above mentioned standards, there are many other standards followed in electrified railway systems and related services and equipment.

- EN 50388: Railway applications – Power supply and rolling stock – Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability
- EN 50329: Railway applications – Fixed installations – Traction transformers
- EN 50119: Railway applications – Fixed installations – Electrical traction overhead contact lines
- EN 50121: Railway applications – Electromagnetic compatibility
- EN 50122: Railway applications – Fixed installations – Electrical safety, earthing and the return circuit
- EN 50124: Railway applications – Insulation coordination – Over voltages and related protection
- EN 50149: Railway applications – Fixed installations – Electric traction – Copper and copper alloy grooved contact wires

- EN 50152: Railway applications – Fixed installations – Particular requirements for AC switchgear – Single-phase disconnectors, earthing switches and switches with Un above 1 kV
- EN 50155 - Railway applications - Electronic equipment used on rolling stock
- IEC 61000 series - Electromagnetic compatibility (EMC)
- IEEE 998-2012 - Guide for Direct Lightning Stroke Shielding of Substations.
- IS 2309-2005 - Protection of Buildings and Allied Structures against Lightning

3.10 Proposed Electrification System

The most applicable railway electrification system for Sri Lanka is 25 kV, 50 Hz AC overhead catenary power feeding system with Scott-T transformer configured traction substations. Even though the currently proposed electrification section is 64 km in length, electrification will be extended beyond Panadura and Veyangoda in future. Hence it is technically and economically feasible to integrate Scott-T transformers as traction transformers in the proposed system, since their capability to feed power large number of accelerating trains without exceeding the permissible voltage drop and minimum voltage unbalance at primary side of the transformer.

Fort and Maradana stations will be main transaction base point in the railway network, which allows getting together of all the railway lines spread inside the country.

3.11 Utility Grid in Sri Lanka

The main power utility supplier in Sri Lanka is Ceylon Electricity Board (CEB) and license for electricity transmission in Sri Lanka is owned only by the CEB. The currently available transmission grid consisted with high voltages of 132kV and 220kV.

The power supply connection for the proposed railway electrification project can be obtained from the utility grid and feeding points for the traction substations mainly depends on the available high voltage utility grid along the proposed railway track. Following Figure 3.5 indicates the distribution of high voltage transmission lines and high voltage substations at the proposed area in Sri Lanka. There are few possible points to obtain high voltage power for the railway electrification along Panadura to Veyangoda. From them most feasible locations has to be identified to build up the traction substations for the proposed system considering following main concerns as well.

1. The location of substations shall meet long term requirement
2. The location shall be a place with capacity of bearing 100 years once flood
3. The locations of substation shall be closed to load centre
4. The requirement for the minimum voltage level of overhead contact line shall be met
5. Feeding to adjacent line or branch line shall be convenient

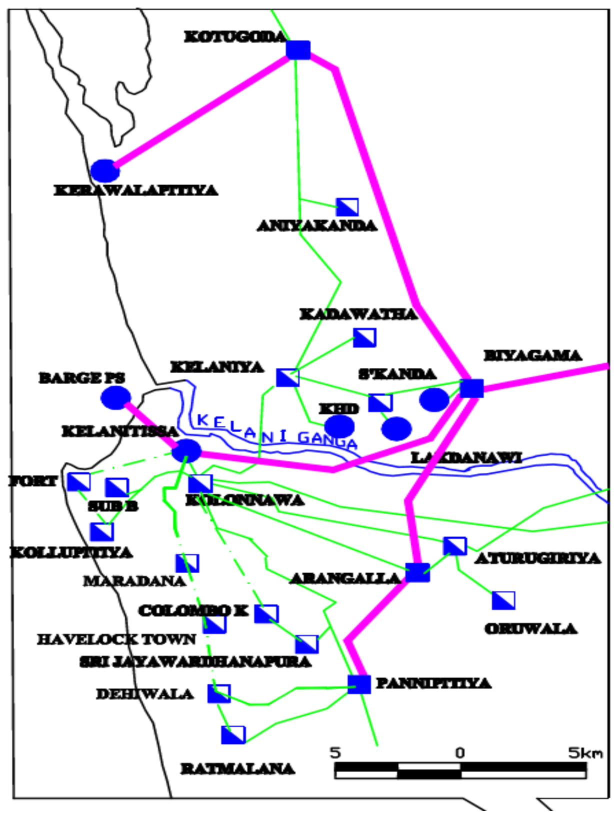


Figure 3.5 - Transmission Grid in the Proposed Area [29]

From the existing high voltage substations in the transmission system of CEB which are located close proximity to proposed railway corridors, Ratmalana, Dehiwala and Kollupitiya substation are proficient to feed power for Maradana to Panadura railway section. Ragama and Kelaniya grid substation are capable of feeding power to

Maradana to Veyangoda railway section. Table 3.2 presents the short circuit values of each substation at the feeding point to realize the strength of each substation in the utility network. The reliability of the power supply for a traction substation can be achieved by providing 132kV multiple connections from different grid substations in the utility system.

It is of immense importance to evaluate on the land availability and accessibility of the location for the proposed traction substations in the system. After analysing the power capacity and reliability of the utility substation and land availability for the proposed traction substation, Ratmalana is the most applicable location to establish traction substation for the Panadura to Maradana railway sector.

Table 3.2 - Fault Level at Grid Substations

Grid Substation	**Incoming 132kV transmission line from**	**Fault Level**	**Distance to the railway track**
Ratmalana GS	1. Pannipitiya GS 2. Dehiwala GS (Future upgrade)	14.3 kA	2.5 km
Dehiwala GS	1. Pannipitiya GS 2. Havelock GS	16.7 kA	2 km
Kollupitiya GS	1. Kolonnawa GS 2. Fort GS	17.7 kA	3 km
Fort GS	1. Kollupitiya GS 2. Kelanittissa GS	19.6 kA	2.5 km
Maradana GS	1. Kolonnawa GS 2. Havelock GS	18.8 kA	2.5 km
Kelaniya GS	1. Kottugoda GS 2. Kolonnawa GS	13.7 kA	2 km
Ragama	1. Kottugoda to Kelanitissa transmission line	17.9 kA	2 km

Considering all possible options, most suitable two locations are selected for the power feeding of Maradana-Veyangoda railway sector. Although it is difficult to select a location due to high urbanization, since the location is in the middle of the Maradana – Veyangoda railway sector, Ragama is the best option to establish the traction substation. Also, Kelaniya utility substation can be considered to tap the required high voltage power for railway electrification of Maradana to Veyangoda sector, and the traction substation can be established close to Wanawasala station.

Compared to Ragama, there is plenty of land that can be used to establish a traction substation at Wanawasala. Hence, in this study, both Wanawasala and Ragama are analysed as option-1 and option-2 respectively to feed the Maradana-Veyangoda railway sector.

3.12 System Voltage Conversion

Traction substation is consisted with traction transformer to convert 132kV, 50 Hz power into 25 kV, 50 Hz single phase power. Depending on the traction substation type utilized in the system, the connection between the three phase high voltage utility supply and the primary side of the traction substation differs and influence created on the utility grid varies. Typically traction substations are rated for the secondary output of 27.5 kV voltages since it is the maximum permissible voltage in an electrified railway system. Following Table 3.3 indicates the allowable system parameters which comply with EN 50163 standard for 25kV, 50 Hz railway electrification system.

Table 3.3 - Permissible System Parameters

Parameters for 25 kV AC, 50 Hz (EN 50163)	Value
Nominal Design System voltage (kV)	25
Maximum permanent voltage (kV)	27.5
Minimum permanent voltage (kV)	19
Maximum non-permanent voltage (kV)	29
Minimum non-permanent voltage (kV)	17.5
Frequency (Hz)	50

CHAPTER 4

METHODOLOGY

Designing the power feeding system for electrified railways is approached through several steps, which are discussed here in this chapter. Traction transformer capacity mainly depends on the maximum train load connected to the electrified railway system at the peak hours. The maximum train load is obtained from the power variation of trains with respect to time based on the forecasted time table for year 2035 in the proposed railway line. Figure 4.1 indicates the different stages in the process of approaching the ultimate design of the electrified railway power feeding system.

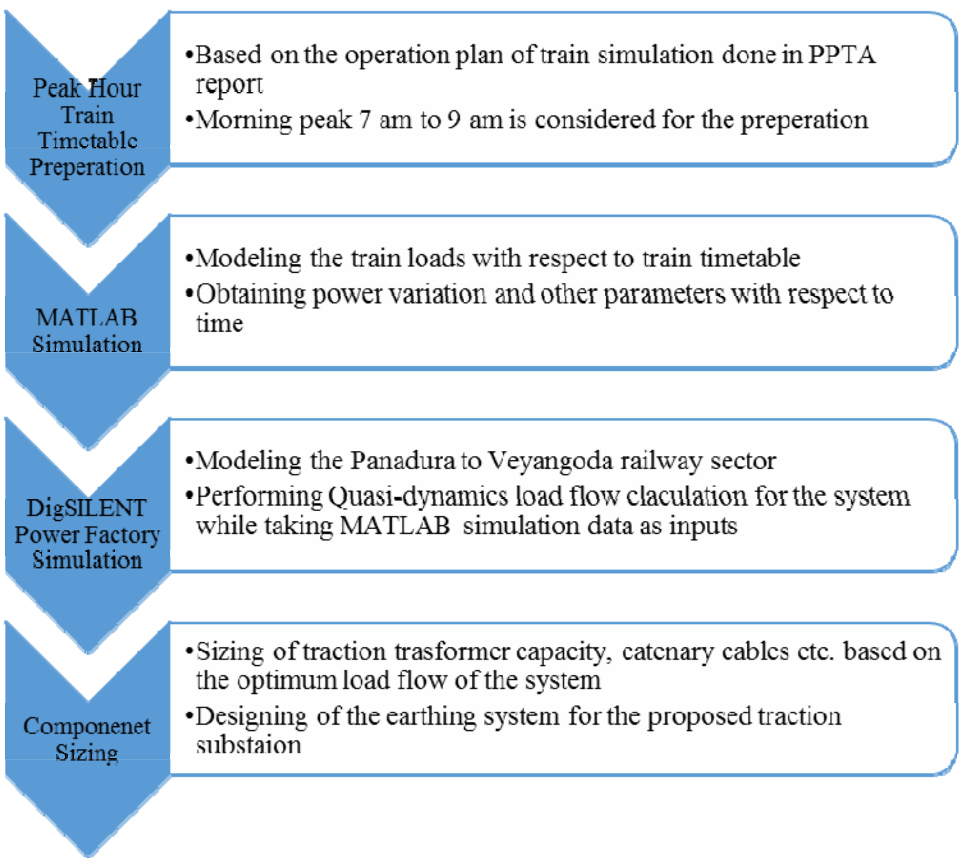


Figure 4.1 – Design Approach

Basically, two software applications are incorporated for the simulation purposes. MATLAB Simulink 2016 version software is applied to generate power variation of the trains connected to the system with time and speed based on the optimum train timetable. Using DIgSILENT Power Factory 15.1 version, dynamic load flow calculation is performed for several train operation scenarios to obtain the optimum power requirement for the traction transformers while MATLAB Simulink simulation results are given as the input data. After analysing the dynamic load flow results, optimum sizes for the traction transformers and feeder contact lines are defined considering available railway electrification products in the industry. Summarized simulation process is indicated in Figure 4.2.

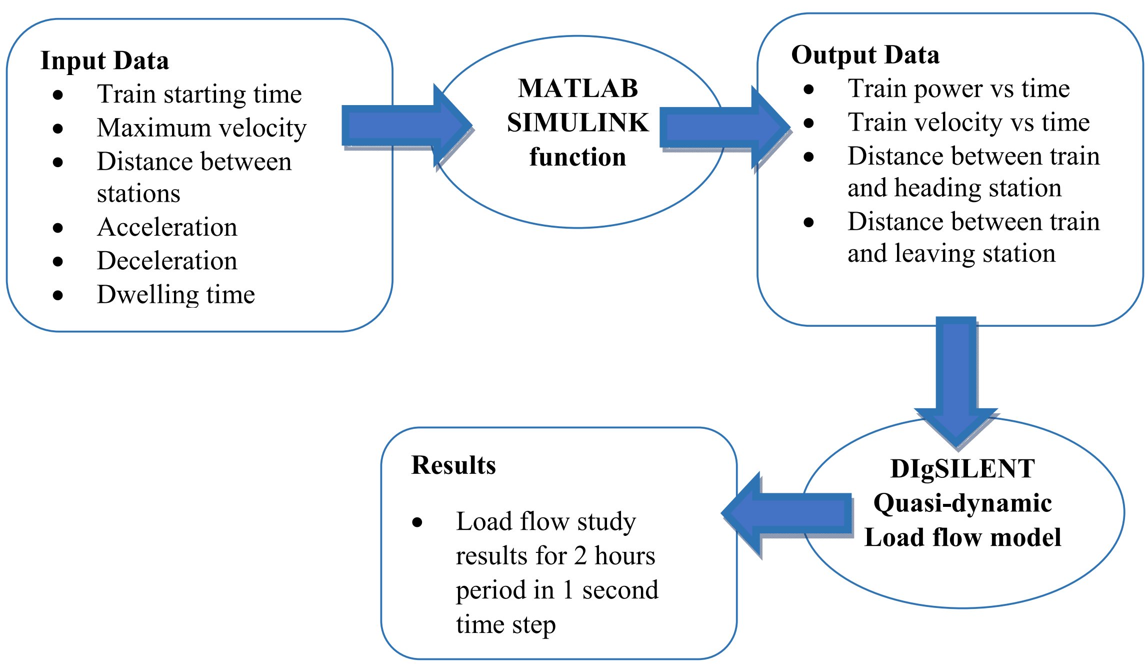


Figure 4.2– Simulation Process

4.1 Forecasted Timetable

Railway train timetable is an important and critical element in the railway system operation. In electrified railway system, train timetable has an additional importance as effective energy utilization with regenerative braking in the system which mainly depends on optimized railway time table. Hence, it is important to generate an optimized railway time table for the proposed electrified railway system in Sri Lanka as well.

According to the Project Preparatory Technical Assistance (PPTA) Report of Colombo Suburban Railway Project [30], in forecasting the traffic for the modernized priority corridors between Panadura to Veyangoda in year 2035, the following factors are considered:

i. currently available data
ii. additional data collected from the demand analysis
iii. existing traffic on the corridors
iv. the traffic forecasted for the year 2035 using the Urban Transport System Development Project for Colombo Metropolitan Region and Suburb (CoMTrans) System for Traffic Demand Analysis model (STRADA model), updated by the Mega Polis Project.
v. SLR record on boarding and alighting, boarding and alighting counts in Colombo Fort and Maradana stations and stated preference survey among rail and bus users inside the Panadura-Veyangoda corridor to analyse the existing demand in the proposed corridor in the PPTA report.

In the PPTA report, traffic forecasting is done for the demand projected to be in year 2035 considering the two main peak traffic hours occurred during in 7 am to 9 am in the morning and 4.30 pm to 6.30 pm in the evening. For the traffic forecasting, the Mega polis transport model takes key inputs such as socio-economic data (population, employment, income level) as well as information on the public transport network provision and coverage are used to produce forecasts for CMR as a whole. The spreadsheet based corridor model then takes as a key input to the future situations modelled with Mega polis model and allows running different tests to evaluate the impact on rail traffic of different projects and improvements of the characteristics of the rail service.

Forecasted railway traffic on Main Line and Coastal Line corridor predicted to be occurred in year 2035 is presented after a reference simulation and a sensitivity test to traffic. It was modelled including both commercial services and technical movements for injection of sufficient number of trains in the peak direction. Operation plan of train simulation done for 2035 is presented in ANNEXURE-D and it is referred for the simulation of trains operation in the proposed system in this research.

The train time table is generated considering the train dwell time at a main station as 180 s and train dwell time at intermediary stations as 60 s. From the total 34 number of railway stations located between Panadura to Veyangoda, Moratuwa, Fort, Maradana, Ragama and Veyangoda have been introduced as main railway stations. Train trips are commenced from Panadura station to Maradana station, Veyangoda station to Maradana station and vice versa.

Expected train timetable in year 2035 for the simulation of this research is presented in Table 4.1,   which prepared referring to the train operation plan (ANNEXURE-D) in the PPTA report. This train starting time data is applied in the simulation of MATLAB Simulink models, which is discussed in coming sections.

Table 4.1 - Train Starting Time at Morning Peak Hours

Train Starting Time at Morning Peak Hours						
Maradana Pandura-Track 1	**Panadura Mardana-Track 2**	**Panadura Mardana-Track 3**	**Veyangoda Maradana Track 1**	**Veyangoda Maradana Track 2**	**Veyangoda Mardana Track 3**	**Ragama Mardana-Track 4**
7:01:15	7:01:15	7:05:00	7:03:45	7:08:45	7:08:45	7:03:00
7:07:30	7:08:45	7:12:30	7:13:45	7:18:45	7:28:45	7:08:00
7:13:45	7:16:15	7:20:00	7:23:45	7:28:45	7:48:45	7:13:00
7:20:00	7:23:45	7:27:30	7:33:45	7:38:45	8:08:45	7:18:00
7:26:15	7:31:15	7:35:00	7:43:45	7:48:45	8:28:45	7:23:00
7:32:30	7:38:45	7:42:30	7:53:45	7:58:45	8:48:45	7:28:00
7:38:45	7:46:15	7:50:00	8:03:45	8:08:45		7:33:00
7:45:00	7:53:45	7:57:30	8:13:45	8:18:45		7:38:00
7:51:15	8:01:15	8:05:00	8:23:45	8:28:45		7:43:00
7:57:30	8:08:45	8:12:30	8:33:45	8:38:45		7:48:00
8:03:45	8:16:15	8:20:00	8:43:45	8:48:45		7:53:00
8:10:00	8:23:45	8:27:30	8:53:45	8:58:45		7:58:00
8:16:15	8:31:15	8:35:00				8:03:00
8:22:30	8:38:45	8:42:30				8:08:00
8:28:45	8:46:15	8:50:00				8:13:00
8:35:00	8:53:45	8:57:30				8:18:00
8:41:15						8:23:00
8:47:30						8:28:00
8:53:45						8:33:00
9:00:00						8:38:00
						8:43:00
						8:48:00
						8:53:00
						8:58:00

4.2 Modelling of Train Power Variation with Speed

4.2.1 Introduction to proposed EMU

In an electrified railway system, train operates in electric traction, which grants more efficient, reliable and productive energy consumption. In this study one typical train model is selected for the calculations and its behaviour is discussed. Selection of electric train for the proposed project has to be done by considering factors like, the short distance between two railway stations and high dense of traffic in the railway corridors in the proposed area. Generally electric multiple units (EMU) are more popular than electrical locomotives since they are consisted with multiple self-motored carriages.

Proposed EMU for the system is consisted with two sets of train sets, each containing six cars. Two train sets are coupled together to give more flexible operation by providing capability to adjust train capacity depending on the existing demand and easy replacement at failure of one train set. Since there are two driving and controlling cabins at two ends of the train set, EMUs can be operated bi-directionally.

One train set can accommodate around 2,000 numbers of passengers in its carriages which allowed accommodating 4,000 numbers of passengers at a time in two train sets. Single deck EMU is more applicable for easy accessibility and short dwell time for short running time and short distance between two consecutive railway stations. This EMUs shall operate in rapid acceleration with short dwell time at stations to limit the total travel time of a trip. Maximum permissible speed for the section is 100 km/hr and acceleration and deceleration of the EMU for the calculation purposes supposed to be 0.87 ms^{-2} and -0.8 ms^{-2} respectively. EMU parameters are presented in Table 4.2.

Table 4.2 - Proposed EMU Parameters

EMU Parameter	Unit	Value
Empty mass	ton	191.75
Passenger capacity	nos	4,000
Number of car	nos	12
Maximum electrical power	MW	5.2
Power factor	Cos θ	0.9
Maximum Speed	km/hr	100
Acceleration	ms^{-2}	0.87
Deceleration	ms^{-2}	0.8

4.2.2 Train modelling

There are few approaches to model electric traction of a train to demonstrate its dynamic behaviour with energy consumption. Train traction can be represented by the electrical analogy by discussing motor energy consumption for different stages in the train moment or by mechanical analogy through the relationship between the forces applied on train and velocity of the moving train.

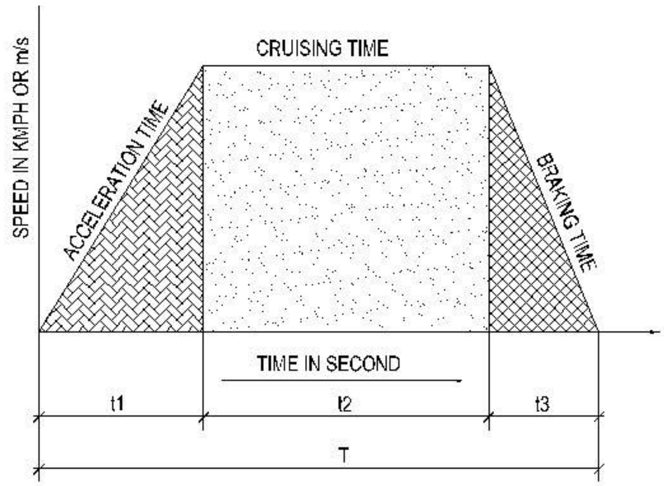


Figure 4.3 - Speed Variation of a Train with Time

In this study, train traction is widely discussed in aspect of mechanical analogy. The propulsion of a train can be mainly sub divided into three stages as acceleration, cruising and braking as indicated in Figure 4.3. The total power requirement of a train for travelling between two stations can be taken as the summation of acceleration power, cruising power and braking power. Power can be defined by the multiplication between the total force applied on the train and the velocity.

There are three different forces namely, force required for giving linear acceleration, force required to overcome the effect of gravity and force required to overcome the resistance of the train, which mainly affect different train movement stages. In the "acceleration mode" of the train, all the above mentioned three forces will be applied at the same time on the train consuming high energy with increasing speed. At "constant speed stage" of a train, force required for giving linear acceleration is not applicable and power is only required to overcome the effect of gravity and resistance of the train.

4.2.2.1 Introduction

Force required for linear acceleration:

According to the laws of dynamics force, the force required for the acceleration mainly depends on the mass of the propelling object and its acceleration. The linear acceleration of the train, wheels and motors of the train accelerate in angular direction. Hence traction effort required for the propulsion is the summation of power required for linear acceleration and angular acceleration of rotating parts. The angular acceleration force depends on the individual weight, radius of gyration of the rotating parts. To calculate total accelerating power, effective mass of the train is considered, which is greater than 10 ~12 % dead weight of the train.

Force required for overcoming effect of gravity:

When a train is moving on a slope, it is involved to have extra force addition to the force required for linear acceleration to overcome the gravitational effect. In railway works, gradient is denoted as percentage gradient (G%), which is expressed as rise in meters in a track distance of 100 m. The gravitation force is applied in positive direction when a train in moving upwards in the slope and force is applied in negative direction when it is moving downwards.

Force required overcoming resistance of train:

Train resistance is consisted with all the forces resisting the motion of train when it is running at uniform speed on a straight and level track. Train resistance can be categorized in to following points.

- Friction at the various parts of rolling components
- Friction at the railway track
- Air resistance

Therefore, the first two points depends on the mechanical resistance within the train. The train resistance depends on various factors like train shape, size and condition of the track and those are represented as "Newtons per tone" of the dead weight of the train. Train resistance is represented by Equation (3).

$$\textit{Train resistance } r = k_1 + k_2 V + k_3 V^2 \qquad (3)$$

Where, k_1, $k2$ and k_3 factors depends on the train and the track. k_1 and $k2$ represent the mechanical resistance and $k_3$represents the air resistance. V is the speed in kmh^{-1}.

4.2.2.2 Modelling the train movement

Forces applied for linear acceleration, forces to overcome resistance of train and forces to overcome effect of gravity are presented by Equations (4), (5) and (6) respectively.

- Force for linear acceleration

$$Fa = Me \times a \qquad (4)$$

- Force to overcome resistance of train

$$Fr = M \times r \qquad (5)$$

- Force to overcome effect of gravity

$$Fg = M \times g \times \sin\theta = M \times g \times (G/1000) \qquad (6)$$

M_e – Effective Mass (kg)

M – Total train mass (kg)

r- Specific resistance of train (Nton^{-1})

a - Linear acceleration (ms^{-2})

G- Gradient of slope in 1000

θ- Angle of the gradient

Using the mechanical analogy, the power of a moving mass can be obtained as a product of force and velocity applied on the moving mass. Equation (7) is indicating the equation for a power of moving mass. The formulae for force at acceleration, cruising and deceleration of moving mass are specified by Equation (8), (9) and (10).

- Power in Mechanical equivalence

  $$\textbf{\textit{Power = force x velocity}} = F_t \times V \quad (7)$$

- For Acceleration

  $$F_t = F_a + F_g + F_r \quad (8)$$

- For Cruising

  $$F_t = F_r + F_g \quad (9)$$

- For Deceleration

  $$F_t = F_a - F_g + F_r \quad (10)$$

4.2.2.3 Sample Calculation

Sample calculation for the proposed EMU performance at maximum speed in the system is presented in Table 4.3. Total acceleration power of the proposed EMU is 5.2 MW at maximum speed of the EMU.

Table 4.3- Sample Calculation for the EMU at maximum Speed

Parameters	Symbol	Value	Unit
Max Speed	V_m	27.78	ms^{-1}
Train Mass	M	191.75	ton
Acceleration	a	0.87	ms^{-2}
Gradient in 1000	G	0	
Train dynamic Mass	M_e	210.93	ton
Retardation	b	-0.8	ms^{-2}
Efficiency	n	0.8	
Train resistance	r	20	$Nton^{-1}$
Acceleration time	t_1	31.93	s
Retardation time	t_3	34.7	s
Tractive effort	F_t	187.19	kN at V_m
Acceleration Power	P_{acc}	5200	kW at V_m

4.3 Modelling of Power Output Variation with Time

It is essential to obtain the power consumption of each train in the electrified railway system at a moment to determine the load flow calculation of the system. Depending on their stage of operation and the speed, the power consumption of the train fluctuates. MATLAB Simulink software is exercised to generate the power consumption, velocity and location of each and every train in the system at a given time based on the operation plan of trains forecasted for year 2035.

4.3.1 MATLAB Simulink model

MATLAB Simulink model is developed to present the train movement between two adjacent railway stations considering allowable maximum speed limit in the section, distance between railway station, acceleration and deceleration of the system. One EMU started from specific station arrived at the next station after certain time, which is calculated within the algorithm written in the simulation model depending on the acceleration and deceleration and waiting time at the next station for a predefined time period. This simulation model generates the velocity, distance and power consumption of each train with respect to time based on the operation plan of trains.

Train movement is modelled by MATLAB Simulink models, which are given in Figure 4.4 and Figure 4.5. It is required to create a MATLAB code for the operation of the functions in the train model and it is required to generate three separate functions for the train models depending on the position of train and depending on whether the train is reaching or not its maximum speed. MATLAB code in ANNEXURE-E is for the train at starting station. For example a train starting from Panadura station towards Maradana or train starting from Veyangoda station towards Maradana can be taken. Since the starting of the train depends on this station, the code includes a separate algorithm to allow the train starts after the time as per the train operation plan.

MATLAB code in ANNEXURE-F is written for the trains running in between middle station to ending stations and trains reaching to their maximum speed during the travelling. Separate code in ANNEXURE-G is written for the trains moving between stations without reaching their maximum speed due to the short distance between the stations. For example, trains running between Secretariat Halt station and Fort station are not reaching the maximum speed due to the short distance.

MATLAB Simulink models for each track are developed separately for the proposed Panadura - Veyangoda railway section. Since there are three tracks between Panadura to Maradana, three tracks between Maradana to Veyangoda and one track between Maradana to Ragama, entirely seven MATLAB Simulink models are created to simulate the train operation in peak hours between Panadura station to Veyangoda station. Part of the MATLAB Model is indicated in ANNEXURE-H.

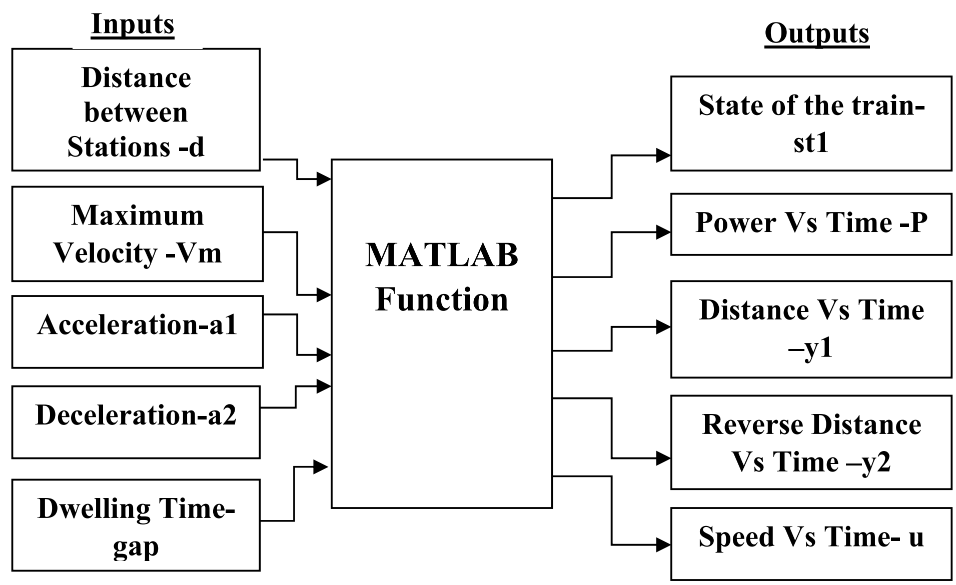


Figure 4.4- MATLAB Function for Train Running Between Two Stations

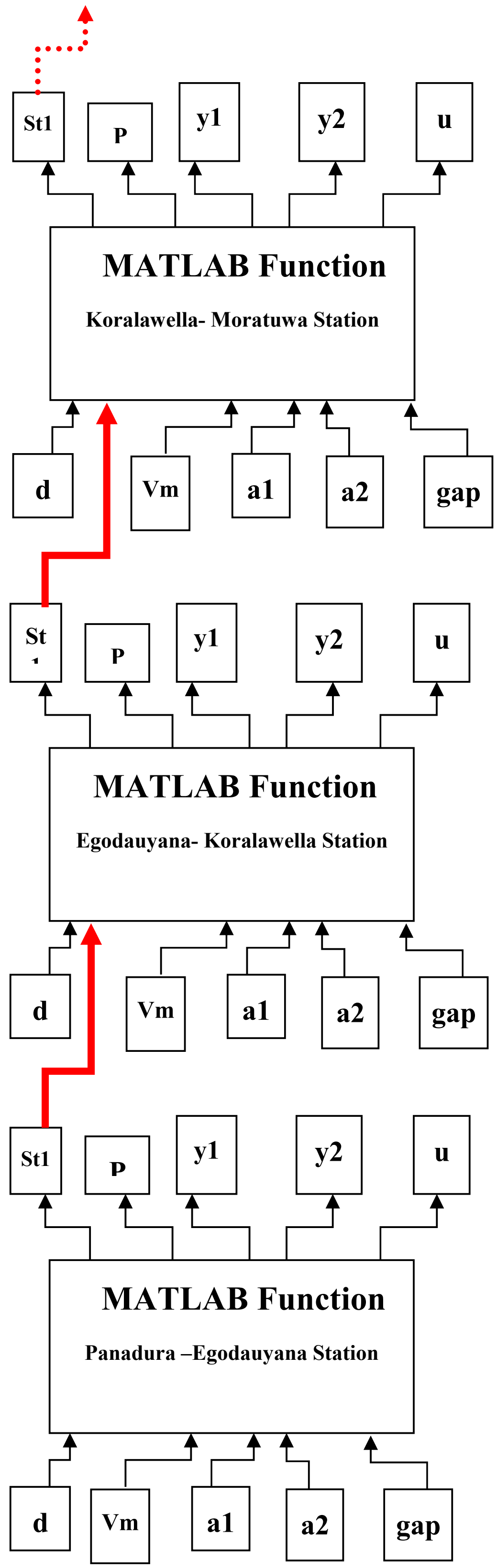


Figure 4.5- Part of MATLAB Functions for Panadura to Maradana Track

4.3.2 Simulation results

The simulation results gained from the MATLAB models are tabulated into excel files individually for each track section in the proposed system. Simulation results are collaborated for the load flow calculations in DIgSILENT Power Factory software. Table 4.4 indicates sample simulation results obtained from MATLAB modelling.

Table 4.4- Train Data Table Generated from MATLAB

Time	power_Ragama-Horape	distance_Ragama-Horape	Bdistance_Ragama-Horape	power_Horape-Enderamulla	distance_Horape-Enderamulla	Bdistance_Horape-Enderamulla
7:03:05	0	0	0	0	0	0
7:03:06	0.017929	0.005264	1499.995	0	0	0
7:03:07	0.180918	0.535964	1499.464	0	0	0
7:03:08	0.343908	1.936664	1498.063	0	0	0
7:03:09	0.506897	4.207364	1495.793	0	0	0
7:03:10	0.669886	7.348064	1492.652	0	0	0
7:03:11	0.832876	11.35876	1488.641	0	0	0
7:03:12	0.995865	16.23946	1483.761	0	0	0
7:03:13	1.158854	21.99016	1478.01	0	0	0
7:03:14	1.321844	28.61086	1471.389	0	0	0
7:03:15	1.484833	36.10156	1463.898	0	0	0
7:03:16	1.647823	44.46226	1455.538	0	0	0
7:03:17	1.810812	53.69296	1446.307	0	0	0
7:03:18	1.973801	63.79366	1436.206	0	0	0
7:03:19	2.136791	74.76436	1425.236	0	0	0
7:03:20	2.29978	86.60506	1413.395	0	0	0
7:03:21	2.462769	99.31576	1400.684	0	0	0
7:03:22	2.625759	112.8965	1387.104	0	0	0
7:03:23	2.788748	127.3472	1372.653	0	0	0
7:03:24	2.951737	142.6679	1357.332	0	0	0
7:03:25	3.114727	158.8586	1341.141	0	0	0
7:03:26	3.277716	175.9193	1324.081	0	0	0
7:03:27	3.440706	193.85	1306.15	0	0	0
7:03:28	3.603695	212.6507	1287.349	0	0	0
7:03:29	3.766684	232.3214	1267.679	0	0	0
7:03:30	3.929674	252.8621	1247.138	0	0	0

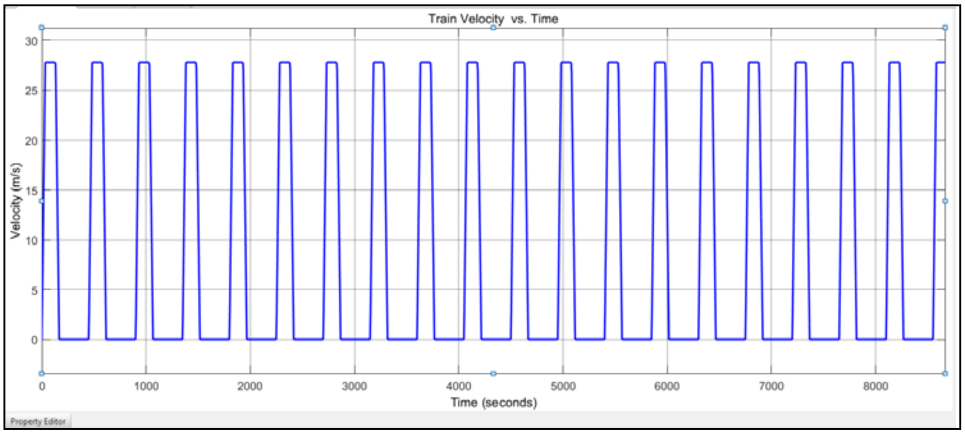


Figure 4.6-Train Velocity Vs. Time of EMU between Panadura and Egodauyana

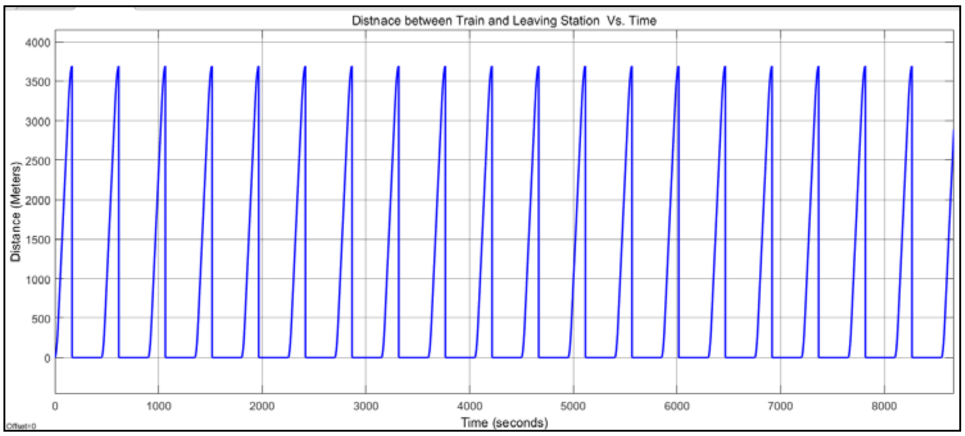


Figure 4.7-Distance between Train & Leaving Station Vs. Time

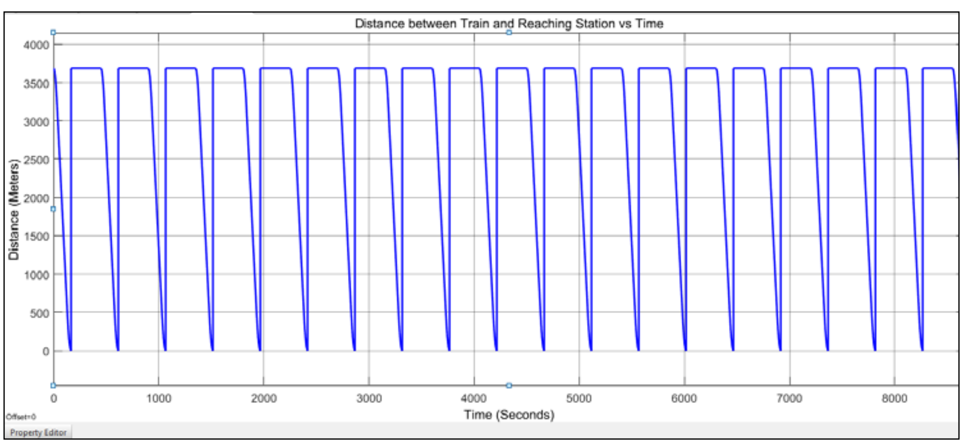


Figure 4.8-Diatance between Train & Reaching Station

After performing the simulation in MATLAB, Figures 4.6, 4.7 and 4.8 are generated for the train model moving between Panadura station and Egodauyana Station. Figure 4.6 indicates the velocity of the train running between Panadura and Egodauyana stations with respect to time during peak period. Train velocity starts from zero and reaches to its maximum value of 27.78 ms^{-1} and run at constant speed for a while and decreases the velocity to obtain zero velocity at the next station. Depending on the distance between consecutive two stations, constant speed travelling time of train between respective stations varies.

Distance between train and the leaving and reaching stations are presented in Figure 4.7 and 4.8 respectively. It is clearly indicated that distance between train and leaving station increases with time in Figure 4.7 and distance between train and reaching station decreases with time in Figure 4.8.

4.4 Traction Power Modelling

4.4.1 Load flow calculation

Load flow calculation is generally executed to get information regarding load profile, voltage profile and losses in the power system. Load flow studies are very important in planning the future expansion of the power systems as well as for the best operation of the existing system. In traction substation designing, load flow calculation is used to identify the expected power capacity from the power supply system for the movement of EMUs in forecasted train time table, which to be occurred in year 2035.

Basically, load flow calculation is done for power flow of a power system at steady state condition. Since the electrical train traction loading and loading point in the system is varying with the time, it is necessary to perform load flow calculation for each snapshot of the system for a given time period and obtain average loading. In this research, power loading, velocity and distance data with compared to time generated from MATLAB Simulink train load modelling are applied to the simulation model in DIgSILENT software to simulate load flow calculations. There are several techniques exercised for the load flow calculation including Gause-Seidel method, Newton-Raphson algorithm and simplified Newton- Raphson method etc.

4.4.2 DIgSILENT power factory software

DIgSILENT Power Factory software is leading software in power system analysing including analysing of generation, transmission and distribution of power systems. It is consisted with very sophisticated and advanced tools to achieve the best results for the power system simulations.

Load flow analysis using DIgSILENT Power Factory software assures an effective and reliable solution for the power flow analysis in the power systems. There are several power flow analysis techniques incorporated in the DIgSILENT software including AC Newton- Raphson technique for balanced and unbalanced loads and linear DC method. It assures to deliver algorithms with excellent stability and convergence.

Power loading profile, voltage profile and losses of the system can be easily obtained using this software and it is done through solving set of nonlinear equations by iteration method. In this study, DIgSILENT Power Factory software is applied to perform load flow calculations for the electrified railway system consisted with train loads in different PCCs.

4.4.3 Railway power feeding system model in DIgSILENT

Railway power feeding system comprising the train loads in the system is modelled in DIgSILENT software to perform load flow calculations. The train loads are represented by the load model offered by the software and similarly contacts cables, traction transformer and circuit breakers are indicated by relative models included in the software.

Figure 4.9 illustrates the adjustment in the distance between train and two stations with the train movement. The distance between two adjacent stations is d and at time t_1 if the train travelled x distance, distance between the train and the reaching station will be $d- x$.

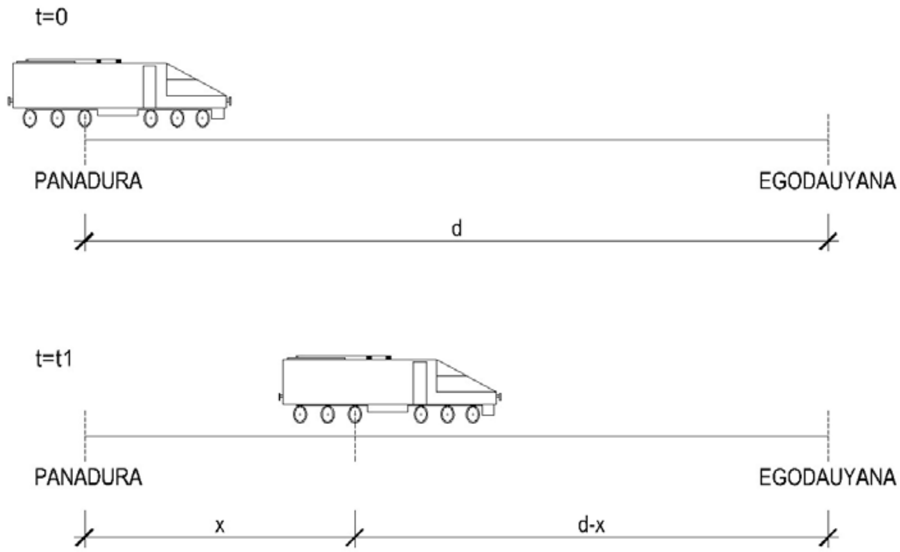


Figure 4.9- Train Travelling from Panadura to Egodauyana

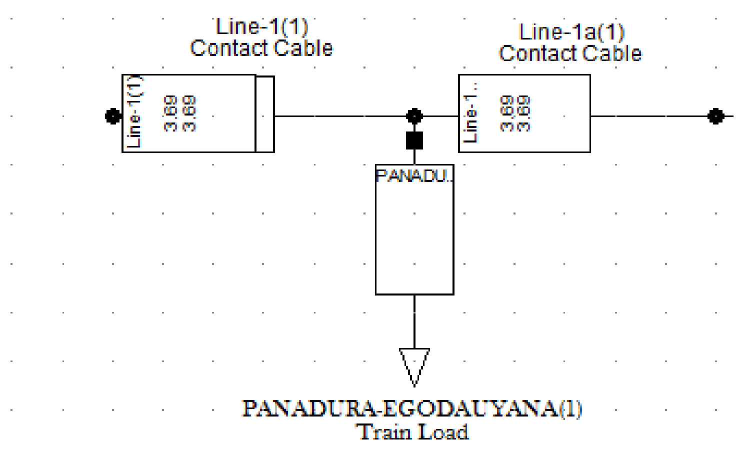


Figure 4.10 - Train Movement between Panadura and Egodauyana Station

As an example Figure 4.10 disclose the train movement between Panadura and Egodauyana railway station in the software model. Total distance between Panadura to Egodauyana railway stations is 3.69 km and two lines connected between the train-load represent the contact cables.

Initially train is at Panadura station and hence the length of the cable 1 between Panadura station and the train load is represented in zero length and the length of cable 2 between train load and Egodauyana station is 3.69 km. When the train travels from Panadura to Egodauyana, the length of the cable 1 gets increased while length of cable 2 decreases. Figure 4.11 and Figure 4.12 demonstrate the simulation results of travelling train-load between Panadura and Egodauyana station.

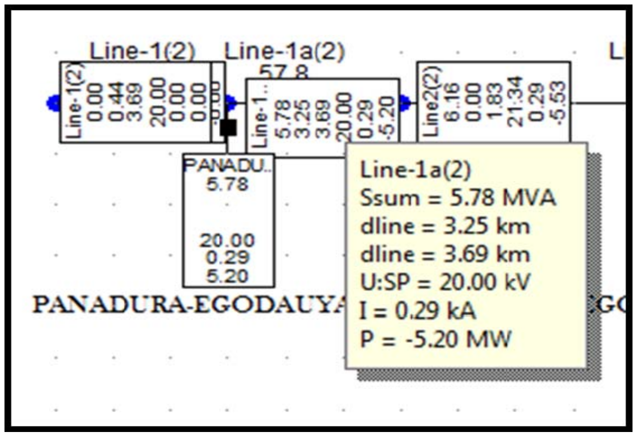


Figure 4.11 - Simulation Results 1 of Travelling Trainload

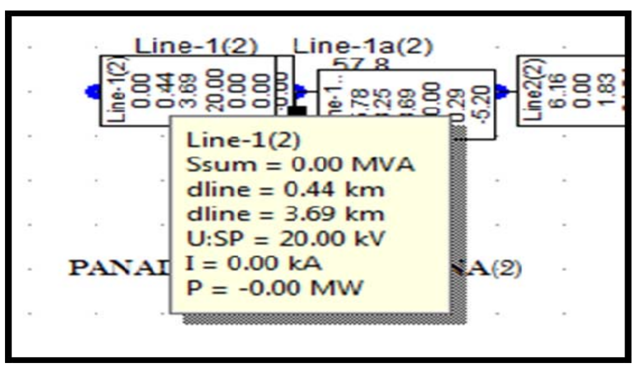


Figure 4.12 -Simulation Results 2 of Travelling Trainload

In option -1, Wanawasala is considered as the place of traction substation in Maradana to Veyangoda railway sector. The system consists of three railway tracks in between Panadura to Maradana and Ragama to Veyangoda and four tracks between Maradana to Ragama. Figure 4.13 specifies the DIgSILENT Power Factory software model for option-1. In options-1 traction substations are at Ratmalana, Wanawasala and sub sectioning posts at Moratuwa, Wellawaththa, Ganemulla and Gampaha and sectioning post at Maradana are considered. Schematic diagram for the option1 is given in Figure 4.14. In option- 2, same system is considered except that the feeding point at Wanawasala is shifted to Ragama feeding point and it is represented in Figure 4.15. Schematic diagram for the option2 is given in Figure 4.16.

The load flow calculation is performed for the railway system model in DIgSILENT Power Factory software by applying the train power loading data obtained from MATLAB software simulation as input data. Load flow simulation results gained for traction substations for a one snapshot of the system are shown in Figure 4.17, Figure 4.18 and Figure 4.19. Since this a dynamic modelling, Quasi-dynamic simulation is performed to obtain load flow calculations for morning peak period in the day.

4.4.4 Quasi- dynamic simulation

Generally load flow calculation is done for power systems at steady state conditions. Since the railway electrification system performs dynamic load profile, it is required to execute dynamic load flow calculation to get proper awareness about the maximum train load which can be connected to the system. DIgSILENT Power Factory software offers quasi-dynamic simulation for the execution of medium to long term simulations. It is possible to carry out multiple load flow calculations with user defined time steps for a power system through quasi-dynamic simulation.

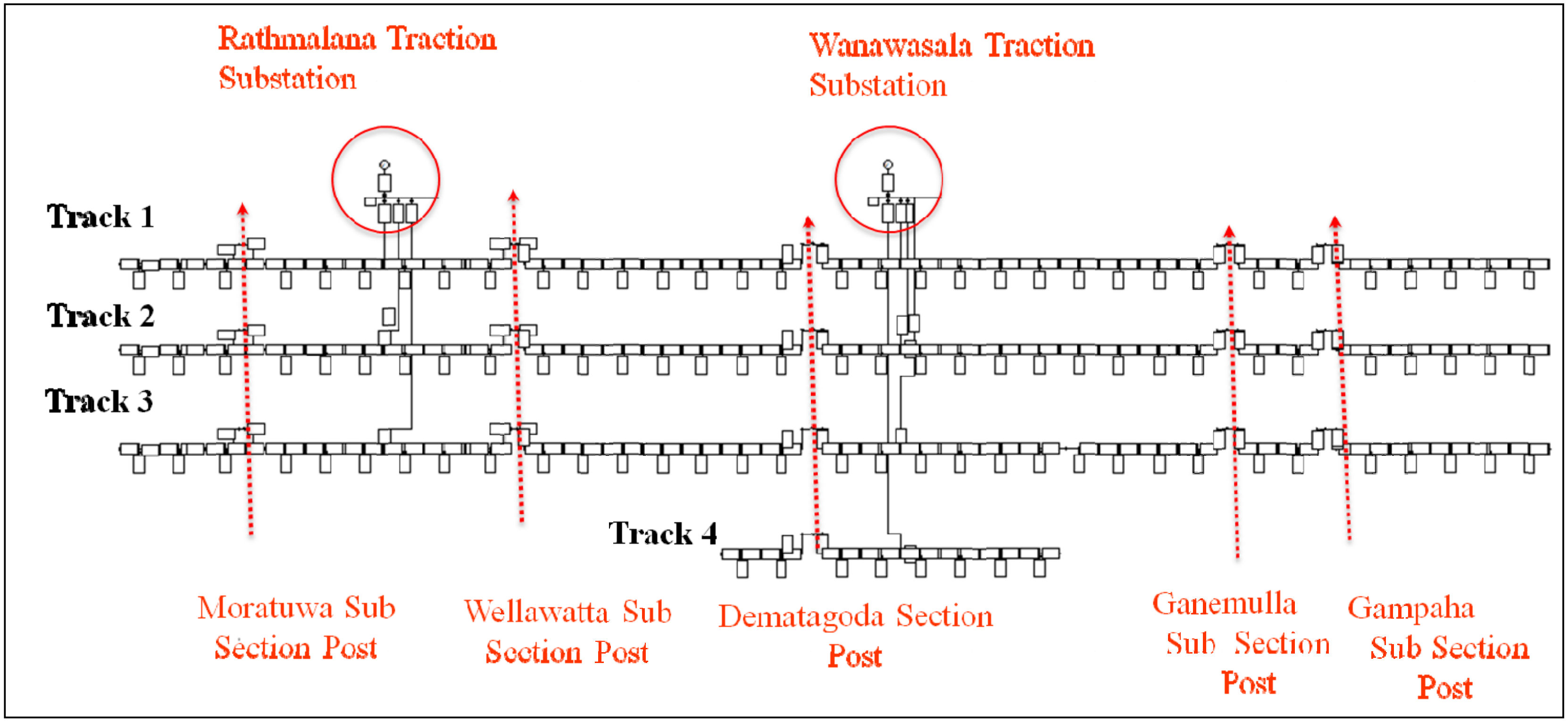


Figure 4.13 –Proposed Railway Electrification System for Option 1

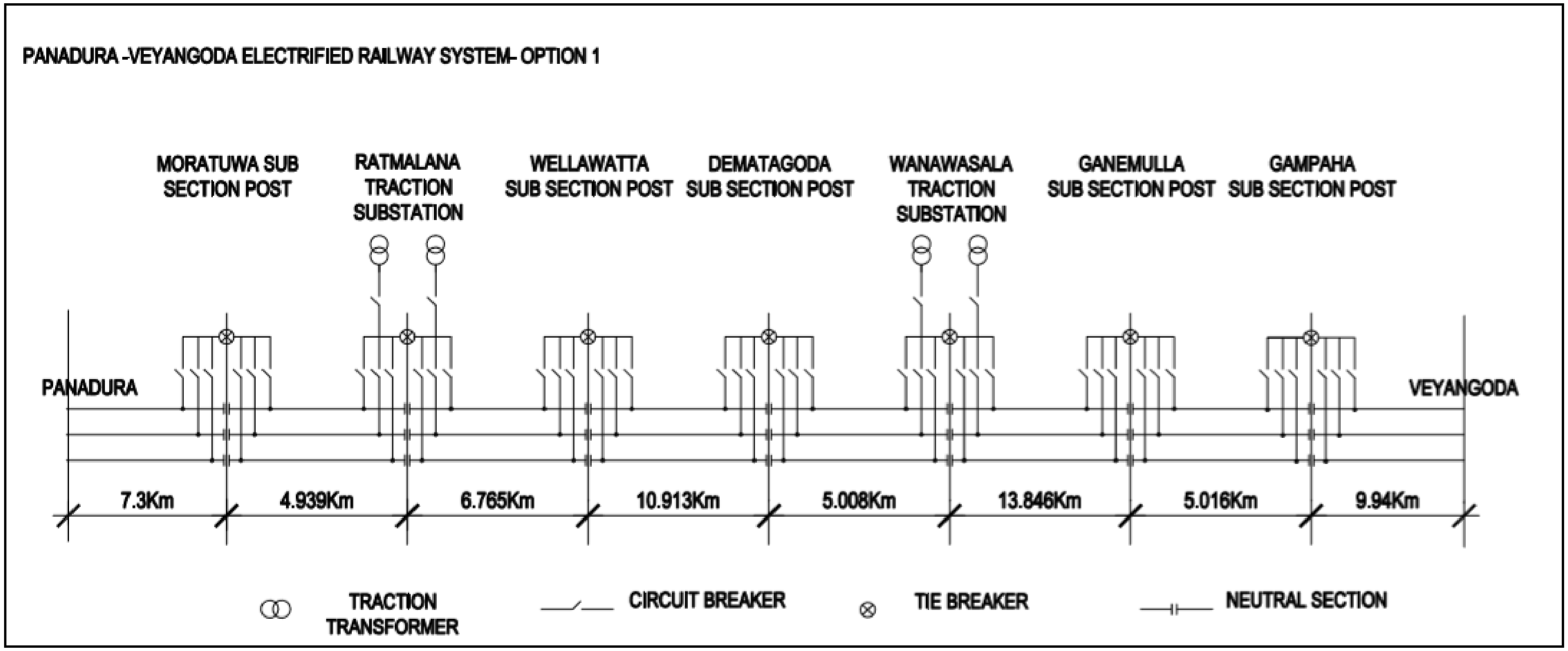


Figure 4.14 –Schematic Diagram for Option 1

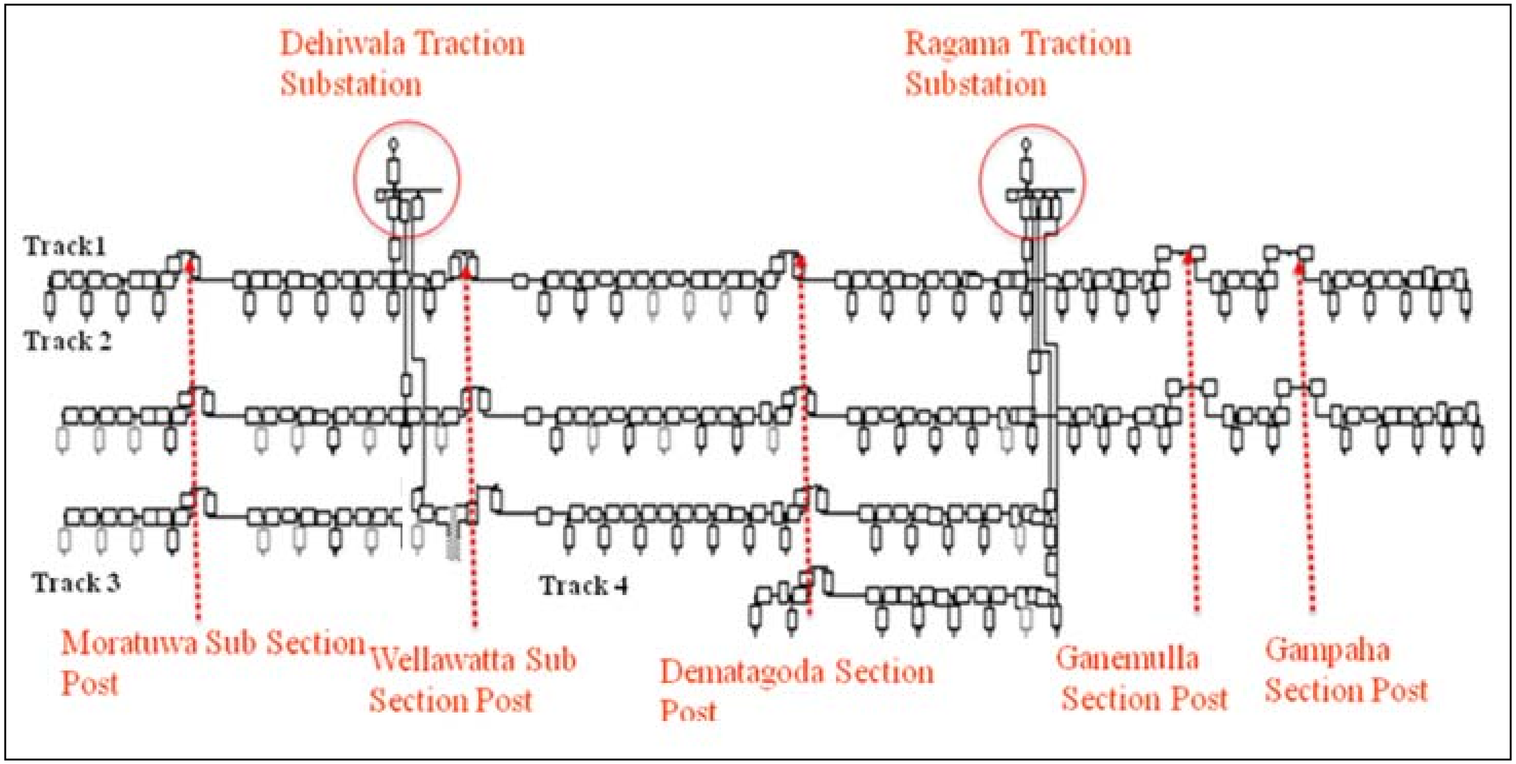


Figure 4.15 – Proposed Railway Electrification System for Option 2

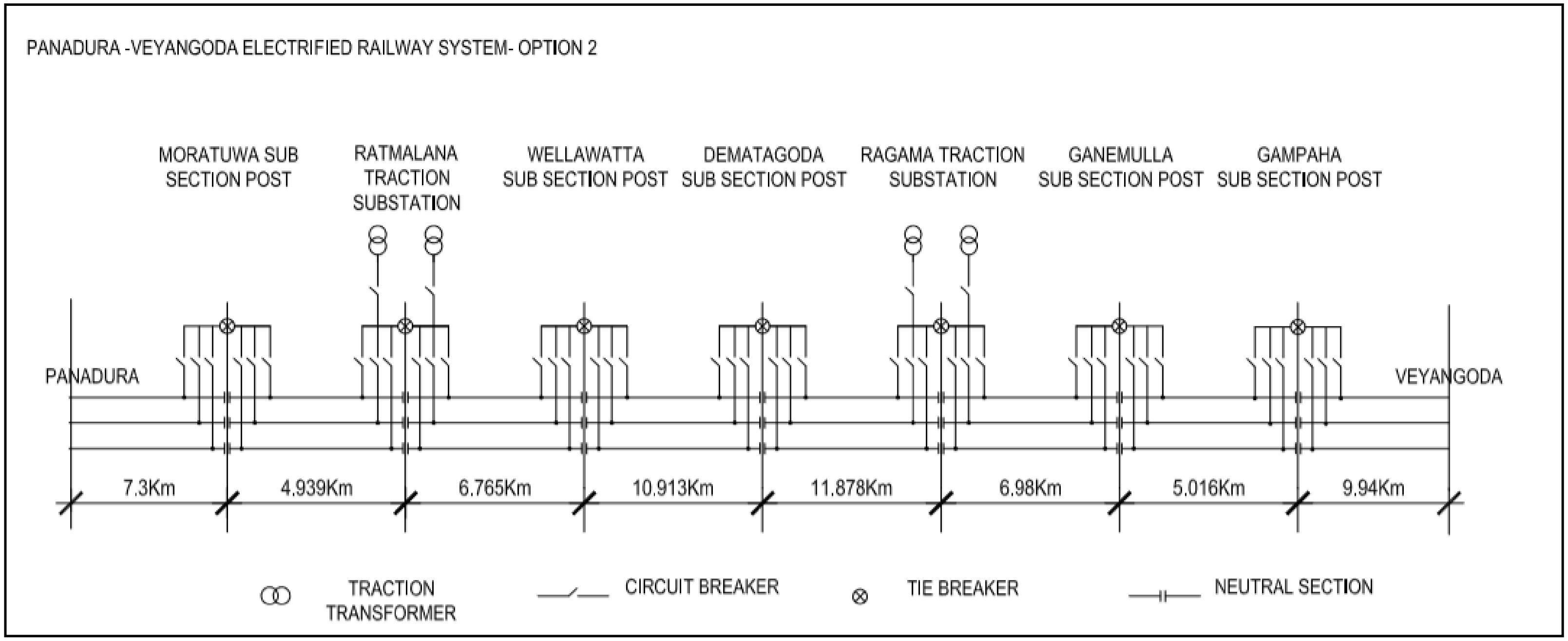


Figure 4.16 – Schematic Diagram for Option 2

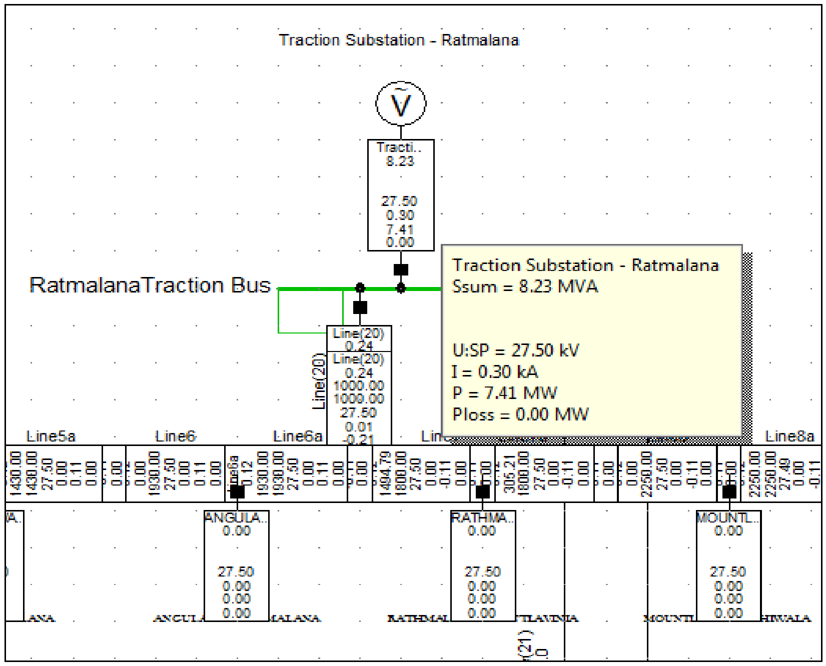


Figure 4.17 - Load Flow Results at Ratmalana Traction Substation

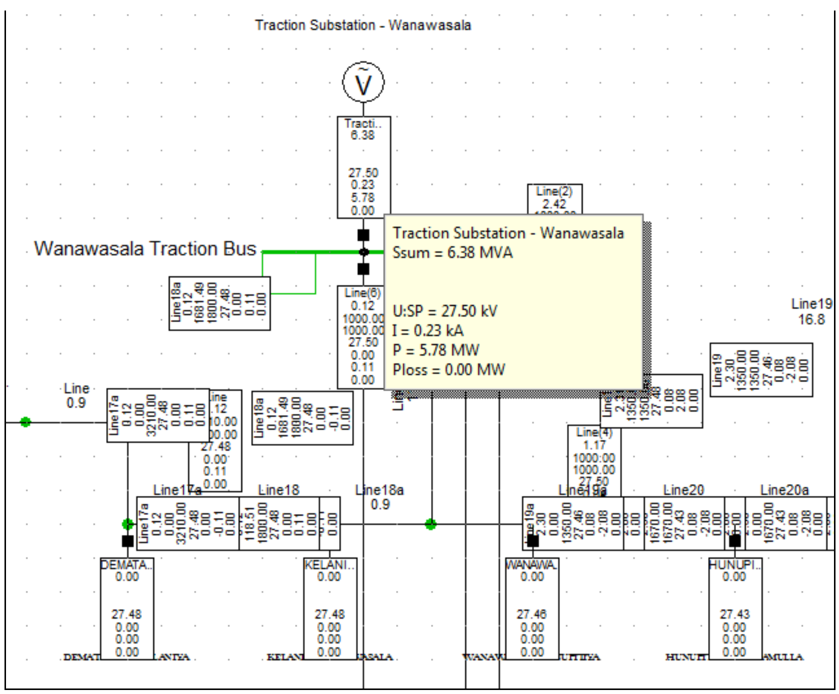


Figure 4.18 -Load Flow Results at Wanawasala Traction Substation

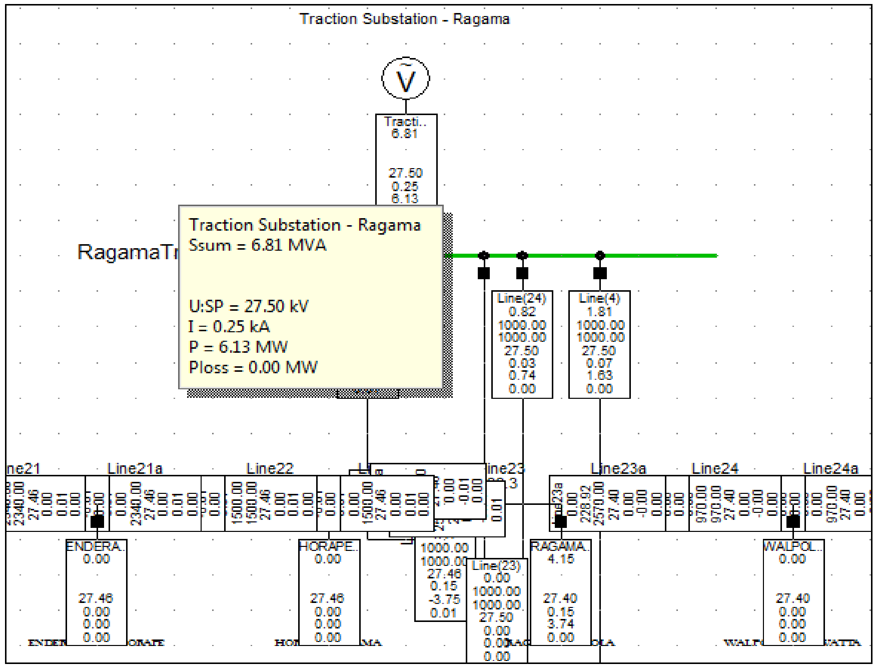


Figure 4.19 - Load Flow Results at Ragama Traction Substation

CHAPTER 5

RESULTS

Based on the simulation results and load flow calculation results, the sizing of the traction substations are discussed in the following sections. Two load flow calculation studies are executed for Maradana -Veyangoda sector considering Wanawasala and Ragama as feeding point in two options proposed for the sector.

5.1 Maximum Capacity of the Traction Load

As per the simulation results obtained from the load flow calculation, it is observed that power loading occurred in the traction substations drastically vary with the time. Table 5.1, Table 5.2 and Table 5.3 represent sample results obtained from the load flow calculations for traction substation at Ratmalana, Wanawasala and Ragama during 10 minutes time period. Figure 5.1, Figure 5.2 and Figure 5.3 are presented to illustrate the power variation at the traction substations for one peak hour.

Table 5.1 –Load Flow Calculation Results for Ratmalana Substation

Time	Active Power (MW)	Reactive Power (Mvar)	Apparent Power (KVA)	Active Power for 1 Min Average (MW)	Reactive Power for 1 Min Average (Mvar)	Apparent Power for 1 Min Average (MVA)
7:00:00	12.737	6.132	14.136	9.54	4.6	10.591
7:00:10	12.542	6.059	13.929			
7:00:20	6.173	2.983	6.856			
7:00:30	8.796	4.244	9.766			
7:00:40	6.935	3.343	7.699			
7:00:50	10.057	4.837	11.159			

7:01:00	6.586	3.166	7.308	11.423	5.487	12.672
7:01:10	6.517	3.138	7.233			
7:01:20	9.995	4.822	11.097			
7:01:30	17.017	8.188	18.884			
7:01:40	18.508	8.857	20.518			
7:01:50	9.915	4.75	10.994			
7:02:00	5.37	2.572	5.954	6.016	2.897	6.677
7:02:10	4.863	2.334	5.394			
7:02:20	4.045	1.949	4.49			
7:02:30	6.301	3.046	6.999			
7:02:40	8.174	3.945	9.077			
7:02:50	7.34	3.538	8.148			
7:03:00	4.796	2.314	5.325	8.026	3.87	8.911
7:03:10	7.324	3.522	8.127			
7:03:20	9.515	4.578	10.559			
7:03:30	6.401	3.089	7.107			
7:03:40	8.563	4.137	9.51			
7:03:50	11.558	5.583	12.836			
7:04:00	11.508	5.549	12.776	9.867	4.742	10.947
7:04:10	11.785	5.679	13.082			
7:04:20	14.359	6.878	15.922			
7:04:30	10.878	5.226	12.069			
7:04:40	8.651	4.144	9.592			
7:04:50	2.019	0.977	2.244			
7:05:00	7.773	3.757	8.633	13.203	6.34	14.646
7:05:10	17.74	8.553	19.694			
7:05:20	23.645	11.357	26.231			
7:05:30	16.078	7.674	17.816			
7:05:40	11.868	5.676	13.155			
7:05:50	2.114	1.023	2.348			

7:06:00	6.564	3.169	7.288	8.534	4.116	9.475
7:06:10	13.97	6.734	15.508			
7:06:20	14.347	6.918	15.928			
7:06:30	7.047	3.4	7.825			
7:06:40	2.643	1.276	2.934			
7:06:50	6.636	3.201	7.368			
7:07:00	12.332	5.935	13.686	8.584	4.134	9.528
7:07:10	8.867	4.271	9.842			
7:07:20	5.442	2.617	6.038			
7:07:30	5.057	2.44	5.614			
7:07:40	9.552	4.608	10.605			
7:07:50	10.258	4.932	11.382			
7:08:00	9.303	4.481	10.326	6.899	3.321	7.657
7:08:10	5.963	2.871	6.618			
7:08:20	7.648	3.67	8.483			
7:08:30	5.554	2.661	6.159			
7:08:40	3.172	1.534	3.523			
7:08:50	9.753	4.71	10.831			
7:09:00	16.697	8.05	18.536	10.552	5.075	11.709
7:09:10	18.695	8.971	20.736			
7:09:20	9.25	4.429	10.256			
7:09:30	4.481	2.148	4.97			
7:09:40	4.712	2.275	5.232			
7:09:50	9.475	4.575	10.522			

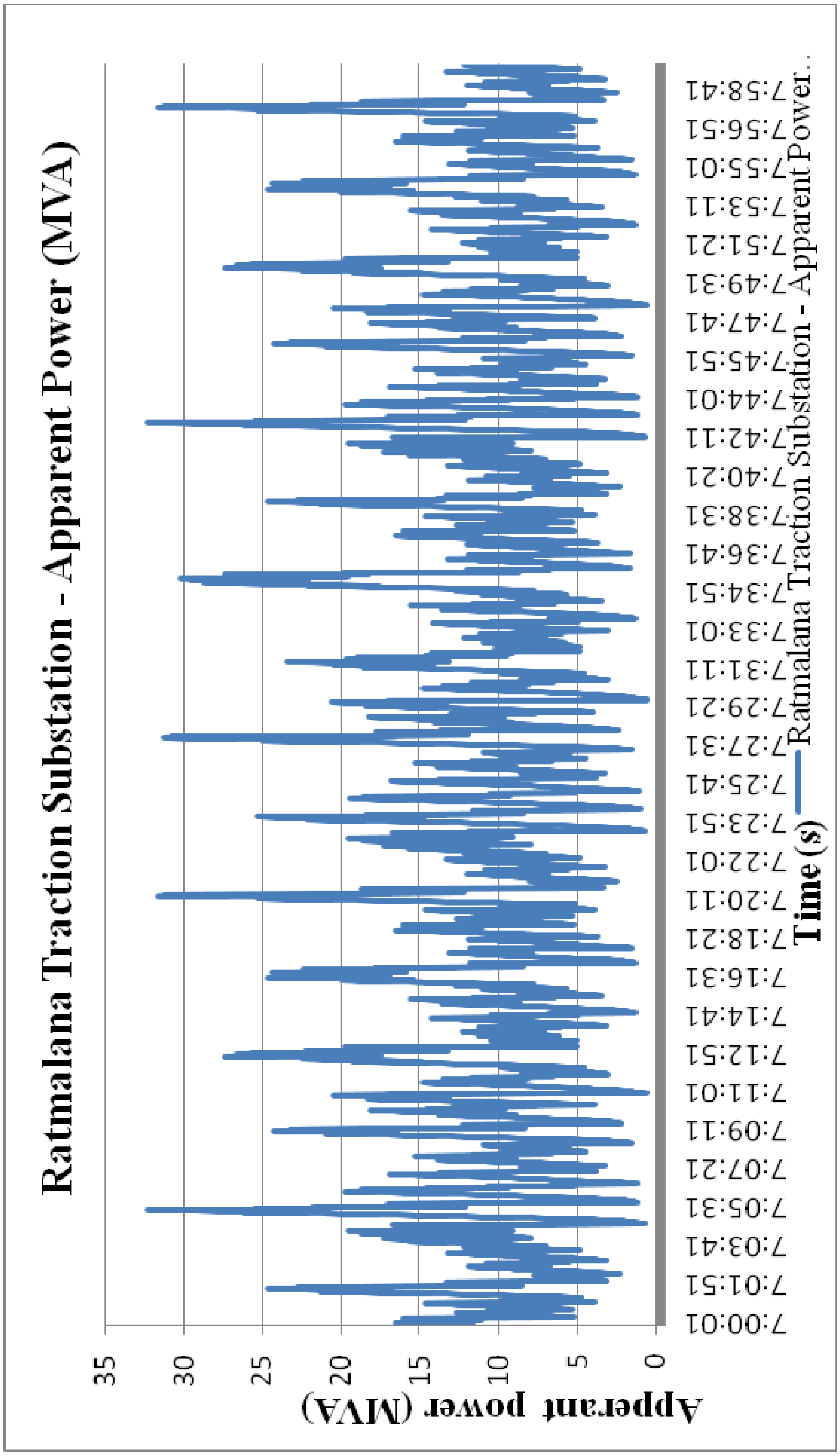


Figure 5.1 – Ratmalana Traction Substation - Apparent Power (MVA)

Table 5.2 –Load Flow Calculation Results for Wanawasala Substation

Time	Active Power (MW)	Reactive Power (Mvar)	Apparent Power (KVA)	Active Power for 1 Min Average (MW)	Reactive Power for 1 Min Average (Mvar)	Apparent Power for 1 Min Average (MVA)
7:00:00	15.503	4.822	16.247	5.503	2.043	5.890
7:00:10	5.320	1.762	5.633			
7:00:20	0.640	0.207	0.672			
7:00:30	0.714	0.274	0.765			
7:00:40	3.176	1.490	3.508			
7:00:50	7.668	3.702	8.515			
7:01:00	13.031	6.333	14.488	13.243	5.622	14.416
7:01:10	11.984	5.756	13.294			
7:01:20	15.587	7.392	17.251			
7:01:30	16.246	7.015	17.700			
7:01:40	11.502	3.894	12.143			
7:01:50	11.111	3.339	11.620			
7:02:00	3.565	0.174	3.570	7.158	2.182	7.553
7:02:10	5.809	0.488	5.839			
7:02:20	6.345	1.736	6.579			
7:02:30	12.069	3.724	12.631			
7:02:40	9.580	4.308	10.516			
7:02:50	5.578	2.664	6.182			
7:03:00	3.125	1.474	3.455	8.527	4.088	9.457
7:03:10	4.739	2.276	5.257			
7:03:20	7.866	3.801	8.736			
7:03:30	10.613	5.166	11.803			
7:03:40	11.467	5.599	12.761			
7:03:50	13.354	6.212	14.729			
7:04:00	8.148	2.910	8.666	9.819	3.536	10.455
7:04:10	10.827	3.448	11.363			
7:04:20	13.700	5.684	14.859			
7:04:30	7.756	3.379	8.463			
7:04:40	7.271	2.348	7.646			
7:04:50	11.213	3.449	11.731			

7:05:00	9.583	3.817	10.337	4.795	2.142	5.258
7:05:10	3.633	1.698	4.010			
7:05:20	4.113	1.941	4.548			
7:05:30	0.617	0.247	0.665			
7:05:40	3.211	1.501	3.544			
7:05:50	7.612	3.650	8.442			
7:06:00	12.832	6.208	14.255	13.231	5.614	14.407
7:06:10	12.784	6.262	14.235			
7:06:20	15.879	7.576	17.594			
7:06:30	16.115	6.930	17.546			
7:06:40	11.097	3.637	11.678			
7:06:50	10.680	3.073	11.132			
7:07:00	4.074	0.470	4.103	8.004	3.295	8.710
7:07:10	7.568	1.914	7.830			
7:07:20	6.527	3.103	7.227			
7:07:30	9.770	4.668	10.828			
7:07:40	7.453	3.550	8.255			
7:07:50	12.634	6.067	14.015			
7:08:00	6.469	3.128	7.185	9.989	4.649	11.021
7:08:10	5.081	2.472	5.651			
7:08:20	8.291	4.028	9.217			
7:08:30	10.460	5.048	11.614			
7:08:40	11.576	5.496	12.815			
7:08:50	18.058	7.720	19.641			
7:09:00	18.223	6.265	19.278	12.408	4.255	13.143
7:09:10	21.118	6.865	22.206			
7:09:20	13.679	5.561	14.798			
7:09:30	7.701	3.302	8.384			
7:09:40	5.778	1.600	6.007			
7:09:50	7.951	1.933	8.182			

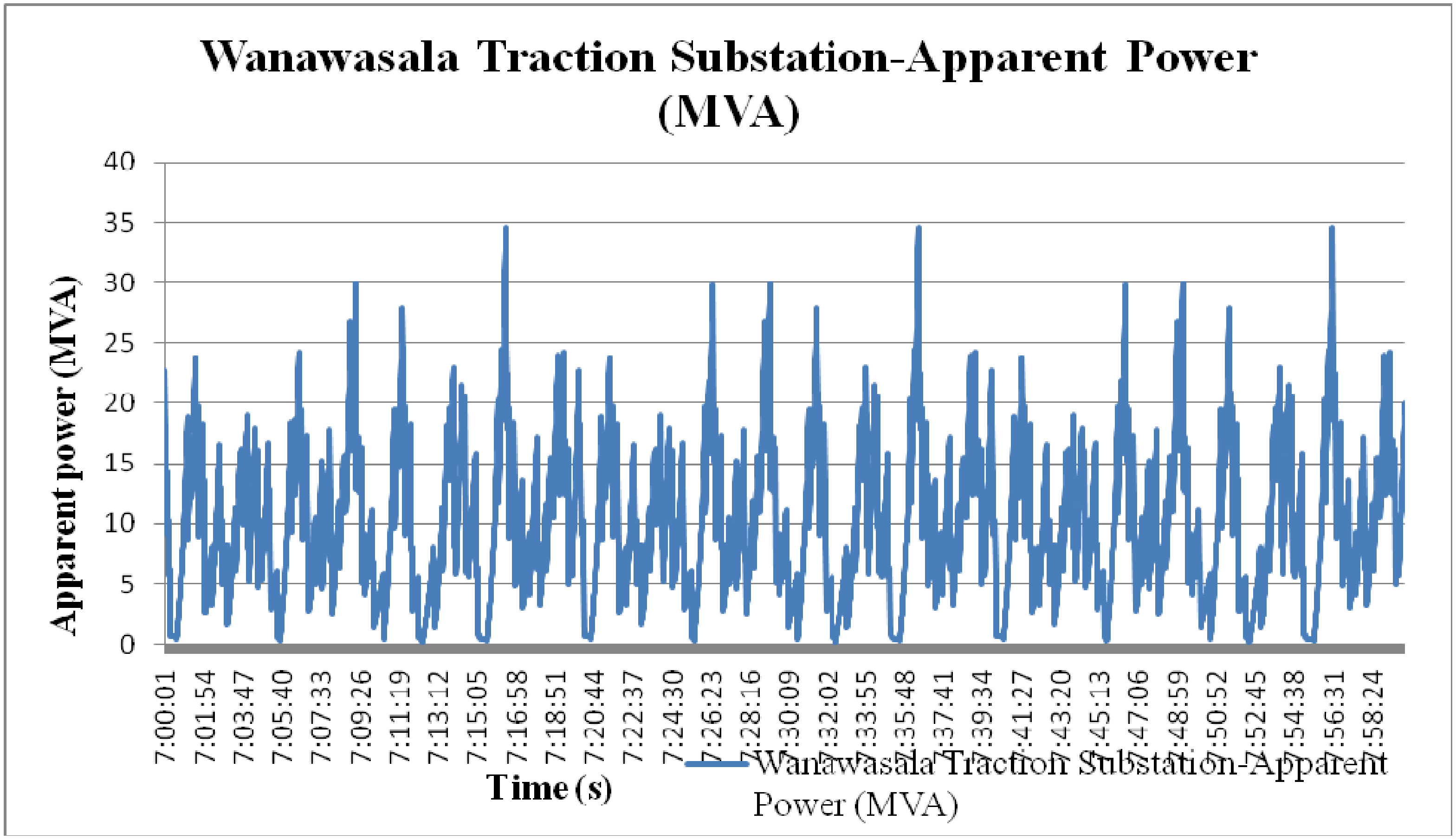


Figure 5.2 - Wanawasala Traction Substation-Apparent Power (MVA)

Table 5.3 Load Flow Calculation Results for Ragama Substation

Time	Active Power (MW)	Reactive Power (Mvar)	Apparent Power (KVA)	Active Power for 1 Min Average (MW)	Reactive Power for 1 Min Average (Mvar)	Apparent Power for 1 Min Average (MVA)
7:00:00	15.394	4.762	16.126	5.461	2.020	5.843
7:00:10	5.320	1.762	5.633			
7:00:20	0.639	0.207	0.672			
7:00:30	0.713	0.273	0.765			
7:00:40	3.151	1.476	3.479			
7:00:50	7.549	3.638	8.380			
7:01:00	12.666	6.145	14.078	13.078	5.542	14.233
7:01:10	11.826	5.710	13.133			
7:01:20	15.362	7.285	17.002			
7:01:30	16.138	6.958	17.578			
7:01:40	11.497	3.890	12.138			
7:01:50	10.978	3.266	11.473			
7:02:00	3.548	0.172	3.552	6.534	2.094	6.934
7:02:10	5.779	0.484	5.809			
7:02:20	12.059	3.718	12.619			
7:02:30	9.496	4.261	10.420			
7:02:40	5.299	2.509	5.863			
7:02:50	3.024	1.420	3.341			
7:03:00	4.716	2.272	5.234	9.196	4.237	10.135
7:03:10	7.796	3.775	8.662			
7:03:20	10.383	5.038	11.541			
7:03:30	11.024	5.352	12.255			
7:03:40	13.193	6.123	14.545			
7:03:50	8.064	2.863	8.571			
7:04:00	10.679	3.362	11.196	10.046	3.681	10.720
7:04:10	13.750	5.702	14.914			
7:04:20	7.828	3.416	8.544			
7:04:30	7.262	2.346	7.637			
7:04:40	11.185	3.445	11.704			
7:04:50	9.570	3.815	10.324			

7:05:00	3.633	1.698	4.010	5.287	2.519	5.857
7:05:10	4.113	1.941	4.548			
7:05:20	0.617	0.247	0.665			
7:05:30	3.206	1.500	3.540			
7:05:40	7.573	3.637	8.401			
7:05:50	12.580	6.089	13.976			
7:06:00	12.076	5.873	13.428	11.570	4.550	12.488
7:06:10	15.563	7.415	17.240			
7:06:20	16.053	6.902	17.478			
7:06:30	11.116	3.644	11.698			
7:06:40	10.651	3.058	11.100			
7:06:50	3.959	0.406	3.981			
7:07:00	7.335	1.782	7.574	8.424	3.750	9.249
7:07:10	6.548	3.105	7.248			
7:07:20	9.819	4.680	10.878			
7:07:30	7.527	3.597	8.343			
7:07:40	12.845	6.200	14.264			
7:07:50	6.468	3.132	7.186			
7:08:00	4.963	2.407	5.516	11.879	5.144	12.962
7:08:10	8.107	3.929	9.009			
7:08:20	10.422	5.043	11.578			
7:08:30	11.507	5.487	12.749			
7:08:40	18.030	7.716	19.613			
7:08:50	18.246	6.283	19.305			
7:09:00	21.202	6.918	22.302	10.385	3.567	11.011
7:09:10	13.837	5.642	14.975			
7:09:20	7.751	3.325	8.438			
7:09:30	5.716	1.566	5.938			
7:09:40	7.756	1.825	7.968			
7:09:50	6.048	2.129	6.442			

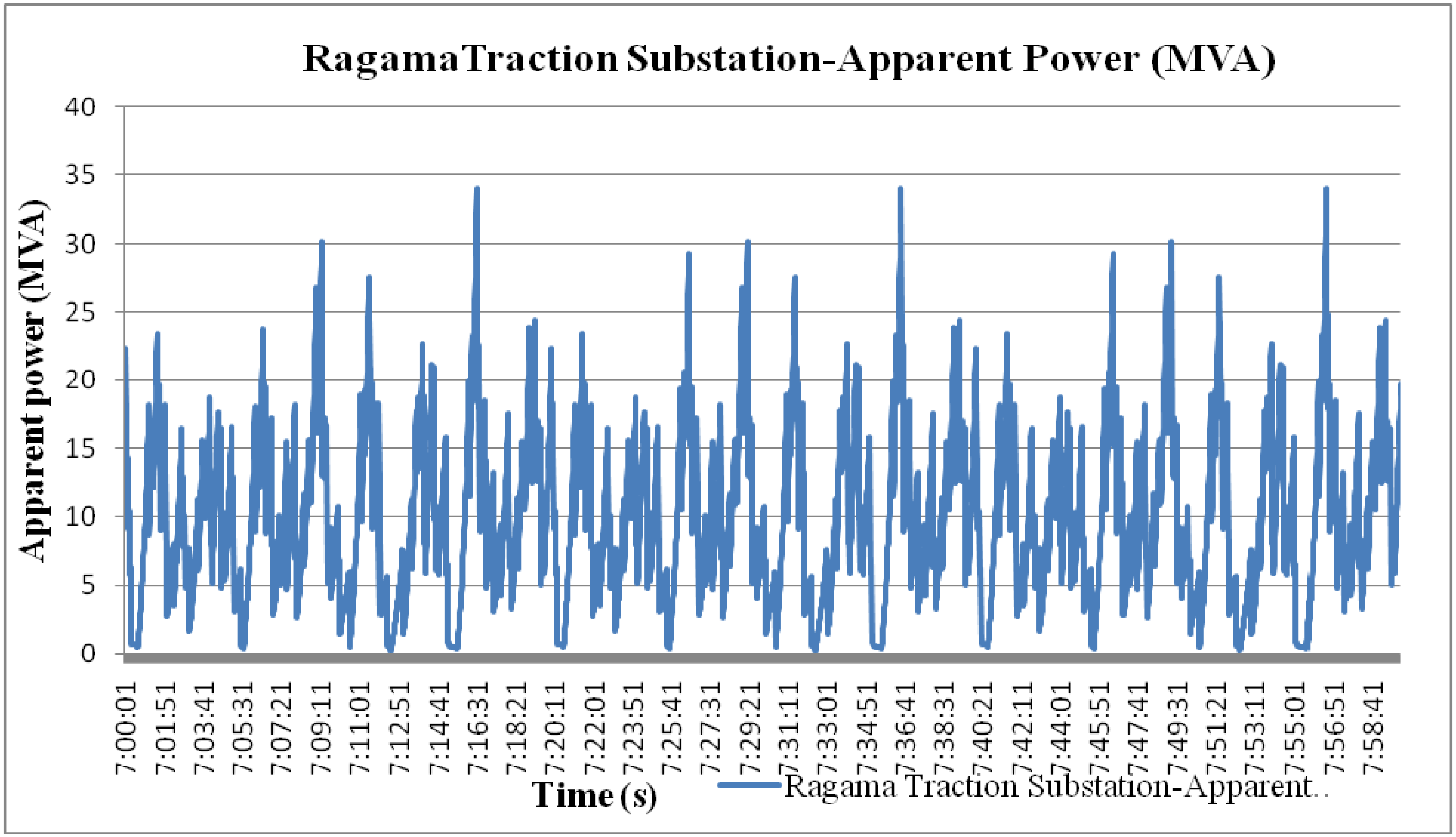


Figure 5.3 - Ragama Traction Substation-Apparent Power (MVA)

Maximum power variations of proposed traction substations based on time averages are represented in the Table 5.4. Since it is necessary keep a reserved margin for future expansions, Table 5.5 presents the expected traction substation capacities for the proposed two traction substations at Ratmalana, Wanawasala as option 1 and Ragama as option 2.

Table 5.4 - Maximum Power Variation in Traction Substations

Time	Ratmalana Substation			Wanawasala Substation – Option 1			Ragama Substation – Option 2		
	Active power (MW)	Reactive power (MVar)	Apparent power (MVA)	Active power (MW)	Reactive power (MVar)	Apparent power (MVA)	Active power (MW)	Reactive power (MVar)	Apparent power (MVA)
1 min average	17.775	8.529	19.715	16.174	6.917	17.639	15.961	6.801	17.397
10 min average	9.658	4.646	10.717	9.393	3.803	10.170	9.318	3.765	10.086
1h average	9.387	4.517	10.417	9.357	3.726	10.112	9.281	3.687	10.028

Table 5.5 - Proposed Capacities for the Traction Transformers

Traction Substation	Apparent Power (MVA)	Apparent Power with 10 % Margin (MVA)	Proposed Traction Transformer Capacity (MVA)
Ratmalana Substation	10.417	11.46	20
Wanawasala Substation – Option1	10.112	11.12	20
Ragama Substation– Option2	10.028	11.03	20

From the results obtained and analysing the calculated traction transformer capacities, it is observed that proposed power capacity of the traction transformer at each traction substation is 20MVA. Traction transformers at Wanawasala and Ragama in option 1 and option 2 respectively calculated to be with capacity of 20 MVA which conclude that traction capacity of transformer is not affected by the location of the feeding point.

5.2 Catenary Cable Sizing

According to the load calculation results, the traction demand is highly fluctuating and current loading in the each catenary system is correspondingly fluctuating. The catenary cable selection for the proposed system is discussed for two options. In option 1, Maradana to Veyangoda sector is fed by traction substation at Wanawasala and in option 2 it is fed by the traction substation at Ragama. Panadura to Maradana sector is to be fed by Ratmalana traction substation in both options. The maximum loading of each catenary cable and selected catenary cable types are presented in Table 5.6 and Table 5.7 for option 1 and option 2 respectively. Catenary cables are selected with refereeing to catenary cable catalogue in ANNEXURE -J .

Table 5.6 – Catenary Cable Selection for each Track Segment in Option-1

Option -1								
Description	Panadura-Ratmalana		Ratmalana-Maradana		Maradana-Wanawasala		Wanawasala-Veyangoda	
	Current (A)	Cable Size (mm^2/ Type)	Current (A)	Cable Size (mm^2/ Type)	Current (A)	Cable Size (mm^2/ Type)	Current (A)	Cable Size (mm^2/ Type)
Track - 1	381.4	100/ Cu-ETP	392.3	100/ Cu-ETP	285.5	80/ Cu-ETP	378.8	100/ Cu-ETP
Track-2	362.3	80/ Cu-ETP	394.8	100/ Cu-ETP	233.9	80/ Cu-ETP	378.8	100/ Cu-ETP
Track - 3	354.8	80/ Cu-ETP	389.2	100/ Cu-ETP	229.4	80/ Cu-ETP	588.7	80/ CuAg
Track-4	N/A				273.0	80/ Cu-ETP	272.6	80/ Cu-ETP

Table 5.7 – Catenary Cable Selection for each Track Segment in Option-2

Option -2								
Description	Panadura-Ratmalana		Ratmalana-Maradana		Maradana-Ragama		Ragama-Veyangoda	
	Current (A)	Cable Size (mm²/ Type)	Current (A)	Cable Size (mm²/ Type)	Current (A)	Cable Size (mm²/ Type)	Current (A)	Cable Size (mm²/ Type)
Track - 1	381.4	100/ Cu-ETP	392.3	100/ Cu-ETP	473.7	150/ Cu-ETP	373.1	100/ Cu-ETP
Track-2	362.3	80/ Cu-ETP	394.8	100/ Cu-ETP	354.5	100/ Cu-ETP	373.1	100/ Cu-ETP
Track - 3	354.8	80/ Cu-ETP	389.2	100/ Cu-ETP	232.0	80/ Cu-ETP	398.6	100/ Cu-ETP
Track-4	N/A				473.7	120/ Cu-ETP	N/A	

Catenary cable selected for each track section in Panadura to Maradana railway sector in both option 1 and option 2 is similar since there is no any difference in the Panadura to Maradana railway sector in both options. But the catenary cable sizes in Maradana to Veyangoda sector is to be differed in both options since there is a significant current variation between both option due to change in the feeding location.

5.3 Traction Substation Designing

Traction substation is the most important part in the electrified railway system which is consisted with many components to provide reliable and effective power supply to the EMUs in railway electrification system. The traction substation receives the high voltage power from the utility supplier and ensures to provide permissible voltage to railway system while evade the voltage unbalance, voltage flickers and harmonics caused by the single phase, non-sinusoidal train loads.

Results obtained from performing the load flow calculation of the system, ensure the capacity requirement of the system components and their applicable ranges to comply with the system parameters.

5.4 Main Apparatus

5.4.1 High voltage supply line termination

132 kV high voltage power line from utility supplier shall be terminated at the primary side of the traction transformer at the traction substation. High voltage power line can be reached the traction substation through underground or as an overhead line.

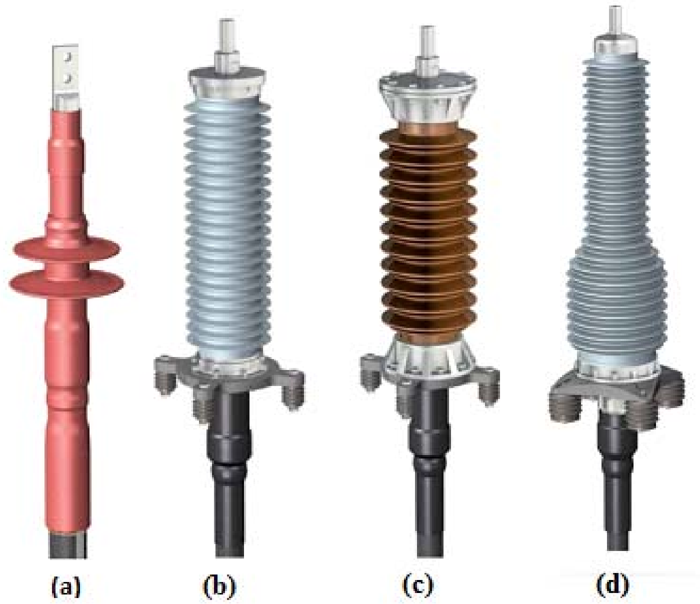
When considering the 132kV high voltage feeding from Ratmalana and Kelaniya grid substations up to proposed traction substation locations, the feeder cables have to be drawn through underground to avoid disturbances in high urbanized areas.

Minimum clearances required with respect to the international standards are represented in Table 5.8.

Table 5.8 - Minimum Clearance Levels

Minimum Spacing between conductors	**Minimum Clearance**
Horizontal	3.9 m
Vertical	6.8 m
Between the nearest live conductor and the Earth	6.1 m
Open route	6.1 m
Between the nearest live conductor and any tree or hedge in the vicinity.	4.6 m

There are few types of high voltage supply line terminations available for outdoor line terminations which are shown in Figure 5.4. Heat-Shrinkable Terminations, Outdoor Terminations Composite, Outdoor Terminations Porcelain and Outdoor Terminations Dry-type are mainly used for high voltage terminations at outdoor type substations.



(a) Heat-Shrinkable Terminations

(b) Outdoor Terminations Composite

(c) Outdoor Terminations Porcelain

(d) Outdoor Terminations Dry-type

Figure 5.4 - High Voltage Termination

5.4.2 High voltage circuit breakers

High voltage circuit breakers shall be installed on high voltage side prior to the traction transformer in the traction substation in order to have disconnection of traction transformer at normal conditions and at over load fault conditions.

High voltage circuit breaker shall be complied with following standards to provide better operation of the equipment.

1. IS: 13118/ - Specification for high-voltage alternating current circuit
IEC56 breakers
2. IEC: 62271 - High voltage alternating current circuit breakers
3. IEEE: 37010 - IEEE Application Guide for AC high voltage circuit breakers

4. IEEE 37013 - AC high voltage generator circuit breaker rated on symmetrical current basis

When categorizing the available high voltage circuit breakers in the industry, following types can be identified as main commonly used types.

5.4.2.1 Sf-6 – Sulphur hexa flouride breakers

Sulphur Hexa Fluoride (SF6) gas is inert in the breaker to provide good arc quenching and insulating properties inside the breaker since it is designed for breaking in on load states. It is essential to track the pressure of SF6 gas since with low pressure the dielectric strength of the SF6 gas get reduced.

5.4.2.2 Vacuum circuit breakers

Vacuum circuit breakers are designed by enclosing contacts inside a vacuumed cylinder to provide proper insulation level and dielectric strength of the vacuumed media is much higher than the dielectric strength obtained with conventional circuit breakers.

Table 5.9 indicates the general description of high voltage circuit breakers required for the system and in Figure 5.5 indicates a circuit breaker used in high voltage applications.

Table 5.9 - High Voltage Circuit Parameters

Description	**Rating**
Nominal system voltage	132 kV
Rated voltage of circuit breaker	145 kV
Number of poles	3
Class	Out door
Rated frequency	50 Hz

Figure 5.5- High Voltage Circuit Breaker

5.4.3 High voltage isolators

It is essential to install isolators after the high voltage circuit breaker at the traction substation to ensure the isolation of the traction transformer from the high voltage feeder line prior for any service or maintenance requirements of the downstream of the system. Isolators are deployed merely for the no-load breaking of the circuits where it can be switched on only if the adjacent circuit breaker is closed or isolator can be switched off when the circuit breaker is open. Hence there shall be effective interlock between the operation of circuit breaker and the isolator of the system. The main advantage of incorporating isolator in the system is that it provides clear visible confirmation of isolation of circuit prior to engage in any maintenance operation in the system. In Figure 5.6 indicates an isolator used in the grid substation.

Figure 5.6 - High Voltage Isolator

5.4.4 Traction transformer

Traction transformer is the most vital and critical component in the traction substation. It is very important to pay attention on many factors when selecting the most applicable traction transformer type from the existing special type traction transformers in the field. As illustrate in Chapter 3, most appropriate traction transformers have been presented as the Scott-T transformer since it is capable of providing better solution for the load unbalance which deficiently affect the high voltage side of the utility power system. The traction transformer step down the 132 kV, 50 Hz power three phases in to two 25kV, 50 Hz single phase supply feeders for the electrified railway system. Generally each substation is equipped with two equally sized transformers to increase the redundancy of the system. Each transformer shall be capable of bearing total substation load and one transformer will be a spare for the system.

Figure 5.7- Scott -T Transformer

Specification sheet in ANNEXURE-I provide the specification details on traction transformers which can be deployed in the proposed project for the proper operation and execution of the system and in Figure 5.7 represent a Scott-T traction transformer.

There are clearance requirement for the better performance and hazard free safety operation of the transformer.

5.4.5 Medium voltage circuit breakers and disconnect switches

Medium voltage circuit breakers are required to install in order to isolate traction transformer from feeders dedicated for distribution of power to the railway catenary system. It is recommended to apply medium voltage circuit breakers for main incoming circuit breakers at secondary side of the traction transformer, bus couplers, catenary power supply disconnecting circuit breaker. The circuits breakers deploy for overhead power distribution system shall be protected the overhead system against short circuits and enable outages for service and maintenance purposes.

Figure 5.8 - Medium Voltage Circuit Breakers

Addition to the power distributing feeders, circuit breakers are applied when connecting phase balancing equipment, harmonic filters, static var compensators and power factor correction equipment. Figure 5.8 indicates a medium voltage circuit breaker.

5.4.6 Bus bars and bus bar connectors

The power which is step downed to 25 kV, 50 Hz power is directed to bus bar system established at the traction substation, prior to the power distribution to the overhead catenary system. It is necessary to select the bus bar system with optimized current capacity and short circuit level of the proposed system.

5.5 Layout of Traction Substation

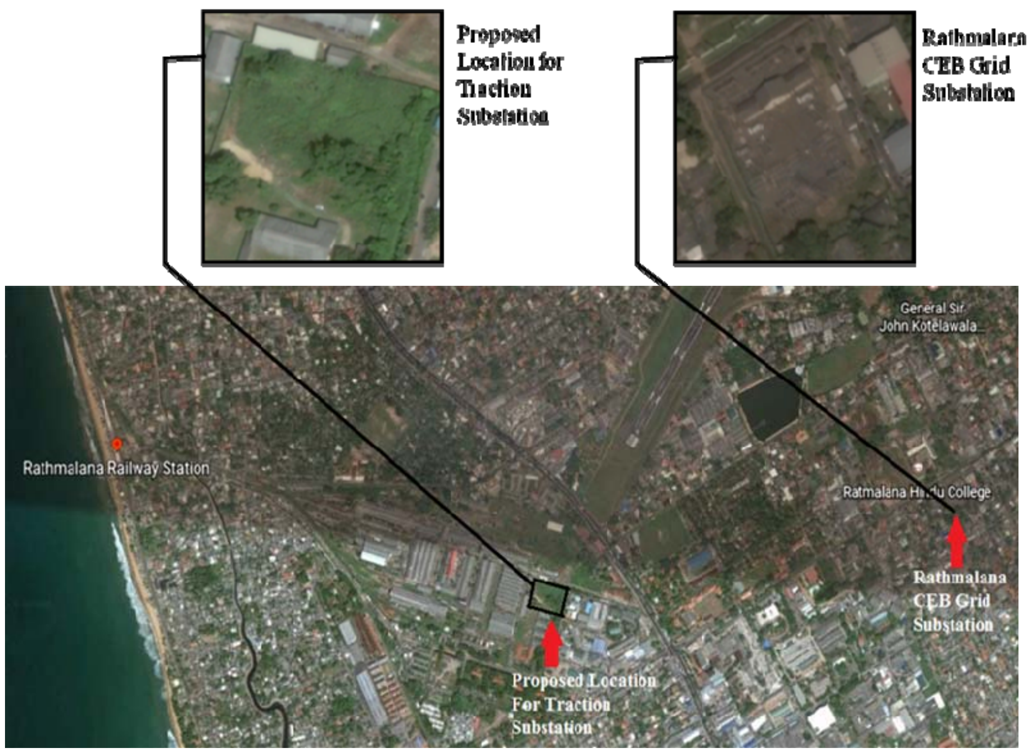


Figure 5.9- Proposed Location for the Traction Substation at Ratmalana

As per the discussion in Chapter 3 Ratmalana for Panadura to Maradana railway sector and both Wanawasala and Ragama for Maradana to Veyangoda railway sector are the most applicable locations for traction substation establishment. The proposed location for the Ratmalana traction substation is presented in Figure 5.9.

Single line diagram for Ratmalana traction substation is provided in ANNEXURE – K. It is very important to deem on the minimum clearances which need to be satisfy when positioning the each and every component in the traction substation. Table 5.10 indicates the minimum clearances required in 132kV and 27.5 kV side of the traction substation. Figure 5.10 signifies the layout of the proposed traction substation for the railway electrification system and the complete drawing is provided in ANNEXURE – L.

. Table 5.10 – Minimum Clearances Required

Description	132 kV Side	27.5 kV Side
Phase to phase clearance	1350 mm	325 mm
Phase to earth clearance	1350 mm	325 mm
Safety working clearance	3650 mm	2625 mm
Vertical distance between lowest part of the insulator and plinth level	2300 mm	2300 mm

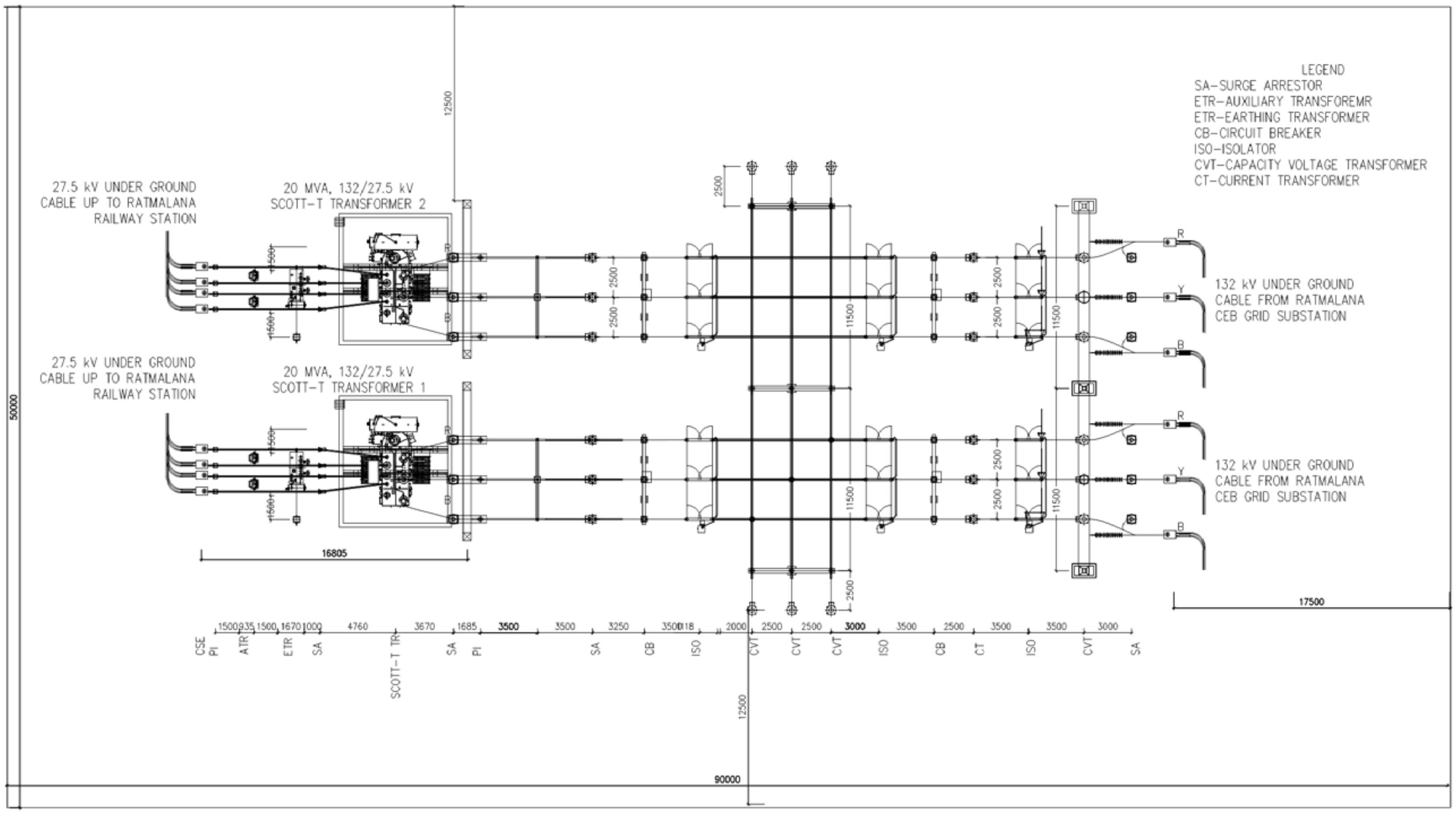


Figure 5.10- Traction Substation Layout

5.6 Earth Grid Designing

The purpose of establishing an earth grid for the outdoor substation is to ensure the carrying of electric current into the earth under normal and fault conditions without exceeding any operating and equipment limits. It is necessary to guaranty that a person in the vicinity of the substation is not exposed to danger of critical electric shock as well. The designing of the earth grid for proposed AC outdoor traction substation at Ratmalana is discussed in this section. IEEE Std 80-2000 standard is followed for the design and field data is measured at the proposed location for earth resistivity measurements. The proposed location which is indicated in Figure 5.11 is situated at coordinates 6.8108700N, 79.879359^0 E.

Figure 5.11- Proposed Location for Ratmalana Grid Substation

5.6.1 Importance of the grounding system

Having a proper grounding system for the grid substation is very important to have hazard free environment in the premises at normal operation and fault condition. It is essential to bond all the metal equipment including transformer enclosure, metal structures, pipes etc. with the ground properly.

During a fault condition, the fault current conducts through the earth electrodes to the ground and creates a potential gradient in the premises. Having a properly designed earth grid at the substation promises the potential gradient to be at permissible level and touch and step voltages at the location to be tolerable by human body.

5.6.2 Facts required for the designing of earth grid

For a designing of the earth grid for a grid substation, several data need to be obtained.

- Substation grid area
- Soil resistivity at the site
- Fault clearing time
- Maximum grid current
- Resistivity of soil at surface

The designing of earth grid mainly depends on the electrodes and conductor material used for the earth grid and its properties, size of the conductor used and step and touch potential limitations in the system.

5.6.3 Accidental ground circuit

The internal resistance of the human body is approximated to be 300Ω and resistance of the human body including skin ranges from 500Ω to 3000Ω [28]. The resistance of the human body is considered as 1000Ω from hand to feet, hand -to -hand and from another foot to other foot which is defined in Equation (11).

$$R_B = 1000\Omega \qquad (11)$$

Tolerable body current limit for a body is defined as the magnitude and duration of the current conducted through a human body at 50Hz which shall be less than the value that can cause ventricular fibrillation of the heart.

$$I_B = 0.116/\sqrt{t_s} \quad \text{for 50 kg body weight} \qquad (12)$$

Equation (12) results in values of 116 mA for t_s = 1 s and 367 mA for t_s = 0.1 s.

$$I_B = 0.157/\sqrt{t_s} \quad \text{for 70 kg body weight} \qquad (13)$$

5.6.3.1 Touch & step voltage

As per the standard, the body current I_b occurring at a situation when a human body touches with the conductive parts in the substation at fault condition is given in Equation (14).

$$I_b = V_{Th} / (Z_{Th} + R_B) \qquad (14)$$

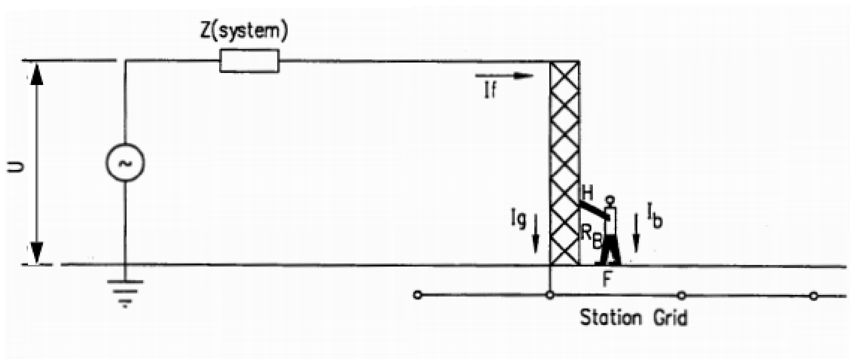


Figure 5.12 - Exposure to Touch Voltage [28]

As shown in the Figure 5.12, the Thevenin voltage V_{Th} is the voltage between terminals H and F when the person is not present and the Thevenin impedance Z_{Th} is the impedance of the system as shown between the H and F with voltage sources of the system short circuited.

Z_{Th} for the touch voltage accidental circuit is given in Equation (15).

$$Z_{Th} = R_f / 2 \qquad (15)$$

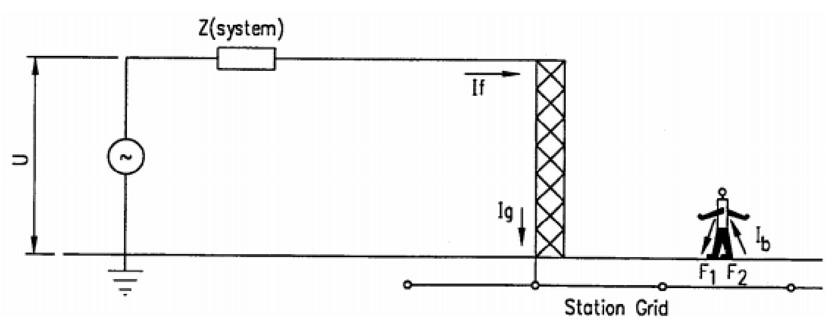


Figure 5.13- Exposure to Step Voltage [28]

The step voltage is calculated when the fault current I_f is discharged to the ground by grounding system of the substation and the current I_b is passing from one foot through the body of the person to the other foot. Figure 5.13 is given to indicate the exposure the step voltage.

Z_{Th} for the step voltage accidental circuit is given in Equation (16).

$$Z_{Th} = 2\, R_f \qquad (16)$$

R_f is the ground resistance of one foot in Ω.

R_f is defined as a conducting metallic disc and contact resistance of shoes, socks etc. is neglected and it is illustrated by a metallic disc of radius b (m) on the surface of a homogeneous earth of resistivity ρ (Ωm) as shown in Equation (17).

$$R_f = \rho / 4b \qquad (17)$$

Generally the radius of the metallic foot is taken as 0.08m and hence the Z_{Th} for touch voltage accidental circuit and step voltage accidental circuit can be given as in Equation (18) and Equation (19).

For the touch voltage accidental circuit

$$Z_{Th} = 1.5\,\rho \qquad (18)$$

For the step voltage accidental circuit

$$Z_{Th} = 6.0\,\rho \qquad (19)$$

By substituting Equation (18) and (19) in Equation (3), the tolerable touch voltage and the tolerable step voltage can be defined as in Equation (20) and Equation (21).

$$E_{touch} = I_B\,(R_B + 1.5\,\rho) \qquad (20)$$

$$E_{step} = I_B\,(R_B + 6.0\,\rho) \qquad (21)$$

5.6.4 Step and touch voltage criteria

With the purpose of having shock energy free environment in the substation before the fault clearance or the system is de energized, following limits needs to be achieved by the earth grid system.

Earth step voltage limits is given in Equation (22) and step voltage defined for the body mass of 50kg and 70 kg is presented in Equation (23) and Equation (24).

$$E_{step} = I_B (R_B + 2 R_f) \qquad (22)$$

For the body weight of 50 kg

$$E_{step50} = (1000 + 6.0 C_s x \rho_s) \; 0.116/\sqrt{t_s} \qquad (23)$$

For the body weight of 70 kg

$$E_{step70} = (1000 + 6.0 C_s x \rho_s) \; 0.157/\sqrt{t_s} \qquad (24)$$

Similarly, Earth touch voltage limits is given in Equation (25) and step voltage defined for the body mass of 50kg and 70 kg is presented in Equation (26) and Equation (27).

$$E_{touch} = I_B (R_B + R_f/2) \qquad (25)$$

For the body weight of 50 kg

$$E_{touch50} = (1000 + 1.5 C_s x \rho_s) \; 0.116/\sqrt{t_s} \qquad (26)$$

For the body weight of 70 kg

$$E_{touch70} = (1000 + 1.5 C_s x \rho_s) \; 0.157/\sqrt{t_s} \qquad (27)$$

C_s – The surface derating factor

ρ_s - The resistivity of surface material in Ωm.

t_s - Duration of shock current in seconds

Deriving the metal to metal touch voltage limits are done by substituting $\rho_s = 0$ in the Equation (26) and Equation (27). Metal to metal touch voltage limit for the body weight of 50 kg in Equation (28) and for the body weight of 70 kg in Equation (29) are stated below.

For the body weight of 50 kg

$$E_{mm-touch50} = \frac{0.116}{\sqrt{t_s}} \qquad (28)$$

For the body weight of 70 kg

$$E_{mm-touch70} = \frac{0.157}{\sqrt{t_s}} \quad (29)$$

When designing the earth grid for the substation, it is necessary to keep the actual step voltage, touch voltage and metal –metal touch voltage less than the allowable maximum voltage limits mentioned above to ensure the safety.

5.6.5 Conductor sizing

Conductor sizing for the system can be given as a function of conductor current which is stated in Equation (30).

$$Amm2 = If \frac{1}{\sqrt{\left(\frac{(TCAP \times 10^{-4})}{(t_c \times \alpha_c \times \alpha_r \times \rho_r)} \times \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)\right)}} \quad (30)$$

***I_f* - rms current in kA**

***A_{mm}^2* – Conductor cross section in mm^2**

***T_m* - Maximum allowable temperature in ^{0}C**

***T_a* –Ambient temperature in ^{0}C**

***T_r* – The reference temperature for material constant in ^{0}C**

***α_r* –Thermal coefficient of resistivity at reference temperature *T_r* in 1/^{0}C**

***α_0* – The thermal coefficient of resistivity at 0 ^{0}C in 1/^{0}C**

***ρ_r* – The resistivity of the ground conductor at reference temperature *T_r* in µΩ-cm**

***K_0*- 1/ α_0 or (1/ α_r) - T_r in ^{0}C**

***t_c* - Duration of current in s**

TCAP – The thermal capacity of unit volume

5.6.6 Earth resistivity measurements

Earth resistivity testing is performed at the proposed site using Megger earth resistivity tester. As per the IEEE std 81 -1983 standard, different earth resistivity measuring methods are discussed. Commonly Wenner four-pin method is popular for the measurement of resistivity in the soil. Four probes are driven into the earth for b depth at equal distance of a, along a straight line in the proposed area. As shown in the Figure 5.14 the middle two probes are potential probes and other two probes measure the current through the earth. The measurement of R in Ω is given by dividing the voltage at potential probe from current between two outer probes.

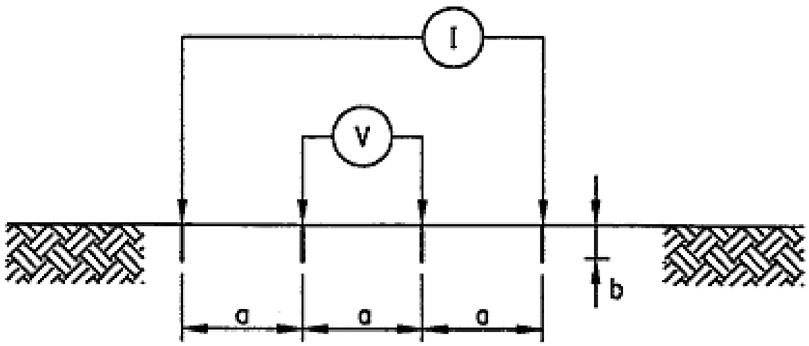


Figure 5.14- Wenner Four Pin Method [28]

Figure 5.15 -Resistivity Reading at the Site

Figure 5.16 -Measuring of Resistivity at Site

Figure 5.15 and Figure 5.16 indicates the measurements obtained at the site and the location of the proposed Ratmalana traction substation. For the better estimation of the earth resistivity at the site, measurements are taken at different directions at the site covering the proposed location. Since there are several soil layers each having different soil resistivity, it is important to take the measurements for gradually increasing probe distances. When the probe distances are increased, the test source current penetrates more and more distance areas, in both vertical and horizontal direction.

The apparent resistivity of the soil can be obtained by Equation (31) using the measured resistance values from earth resistivity tester.

$$\rho a = \frac{4\,\Pi\,aR}{1 + \frac{2a}{\sqrt{a2+4b2}} - \frac{a}{(\sqrt{a2+b2})}} \qquad (31)$$

Where

ρ_a - Apparent resistivity of soil in Ωm

R – Measured resistance in Ω

a- Distance between adjacent electrodes in m

b- Depth of electrodes in m

In Table 5.11 presents the earth resistivity measurements obtained at the site.

Table 5.11- Earth Resistivity Measurements at the Site

Probe Spacing (m)	Measurement (Ω)	Resistivity (Ωm)	Location
1	0.52	3.27	**27.5 kV Yard**
2	1.17	14.70	
3	2.1	39.58	
4	2.7	67.86	
5	2.4	75.40	
1	0.78	4.90	**132 kV Yard**
2	1.12	14.07	
3	1.34	25.26	
4	1.76	44.23	
5	1.98	62.20	
10	2.21	138.86	
15	2.2	207.34	
20	1.67	209.86	
25	1.38	216.77	

In the Figure 5.17 and Figure 5.18 to presents the graphs obtained for apparent resistivity with respect to probe distance for the 25kV side and 132 kV side of the proposed location.

5.6.7 Interpretation of soil resistance measurements

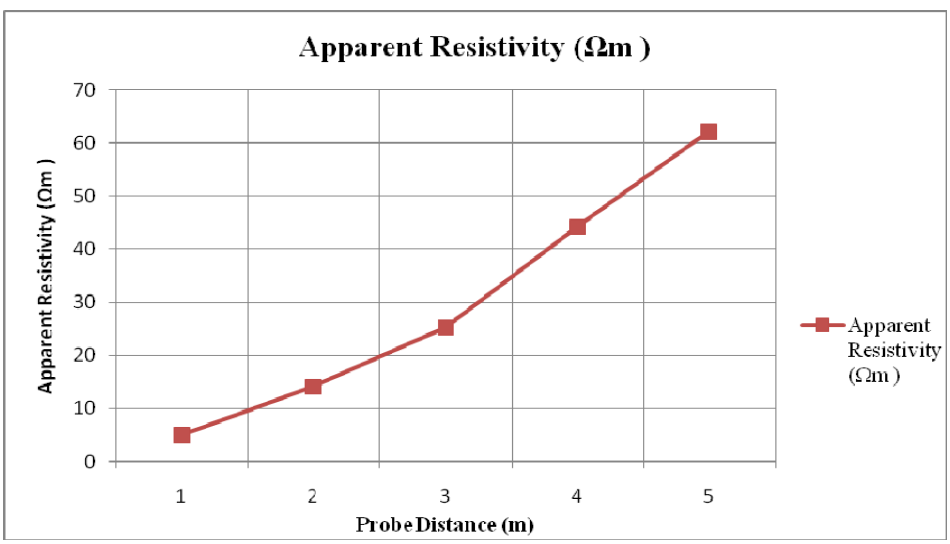


Figure 5.17- Probe Distance Vs Apparent Resistivity of the Soil for 25kV Grid Side

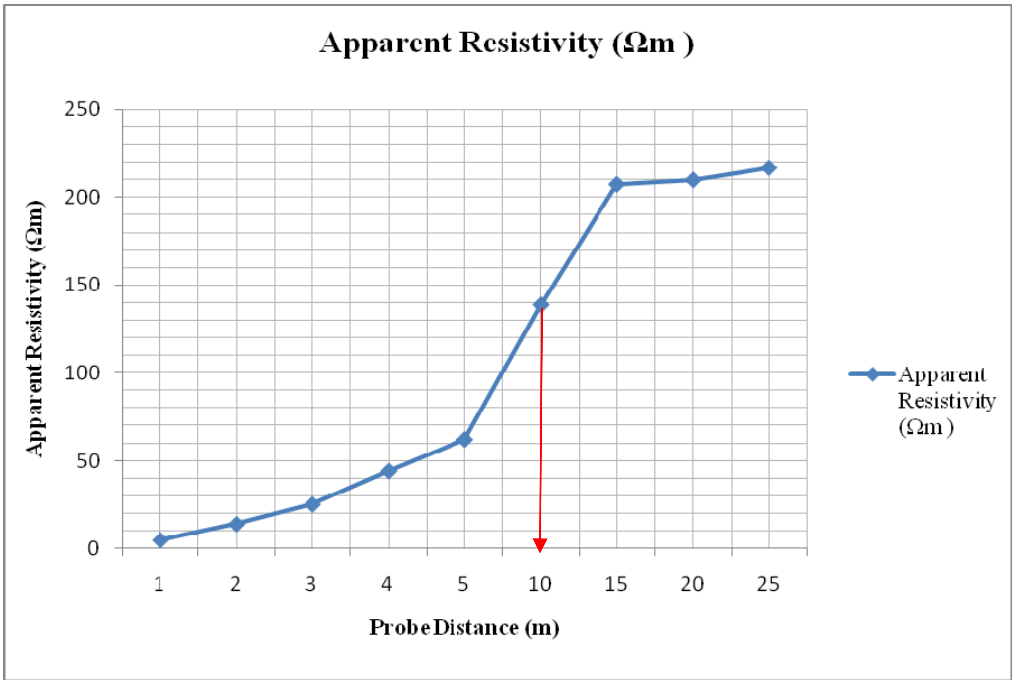


Figure 5.18- Probe Distance Vs Apparent Resistivity of the Soil for 132kV Grid Side

5.6.8 Two layer soil model by graphical method

Upper layer soil resistivity ($\rho 1$) = 70 Ωm

Lower layer soil resistivity ($\rho 2$) = 210 Ωm

Depth of the upper layer determined by Sunde's graphical method

$\rho 2/ \rho 1$ = 3

$\rho a/ \rho 1$ = 2

a/h1 = 2.7 (Read from Sunde's graphical method in ANNEXURE - M)

$\rho a = 2 \rho 1 = 2 \times 70 = 140$ Ωm

a = 10 m (Read from the Figure 5.14)

h = a/ (a/h) = 10/(2.7) = 3.703 m

5.6.9 Calculations

Table 5.12 provides the parameter values required for the calculation of applicable earth conductor cross section for the proposed grid system based on the maximum fault current.

Table 5.12 Parameter required for Earth Conductor Sizing

Description	Symbol	Unit	Value
Fault Current for conductor sizing	I_f	kA	25
Fault Current for maximum grid current calculation	I_f	kA	15
Fault Duration	t_c	s	1
Maximum allowable temperature	T_m	ºC	350
Ambient temperature	T_a	ºC	35
Material constant for copper	K_0		234
Thermal capacity factor for copper	TCAP	J/cm^3 ºC	3.422
Thermal coefficient of resistivity for copper	α_r	$ºC^{-1}$	0.0038
Specific resistivity for copper	rr	Ωm	1.78
Soil resistivity	r	Ωm	210
Resistivity of surface layer	rs	Ωm	3000
Thickness of surface layer	h_s	m	0.1
Surface layer de-rating factor	C_s		0.732
X/R Ratio			10
Decrement factor	D_f		1.013
Symmetrical grid current	I_g	A	1429.759
Maximum grid current	I_G	A	1448.346
Current division factor	S_f		0.5395

By applying the Equation (30) for the system,

$A_{mm}{}^2 = I_f\ (1/\ (\sqrt{(TCAP.\ 10^{-4}\ /\ (t_c\ \alpha_r\ \rho_r))}\ *(\ln((\ K_0 + T_m)/\ (\ K_0 + T_a))))$

$A_{mm}{}^2 = 15\ (1/\ (\sqrt{(3.422 \times 10^{-4}\ /\ (1 \times 0.0038 \times 1.78))}\ *(\ln((\ 234 + 350)/\ (\ 234 + 35))))$

$= 53.686\ mm^2$

Cross section of selected conductor – 75 mm^2 Cu flat (25 mm × 3 mm), approved conductor is appropriate.

By applying the Equation (12) and (13) for the system,

Tolerable Body Current for 50kg body weight (Rb) =0.116/ √1

Tolerable Body Current for 70kg body weight (Rb) =0.157/ √1

By applying Equation (23) and (24)

For the body weight of 50 kg

$E_{step50} = (1000 + 6.0\, C_s \times \rho_s)\ 0.116/\sqrt{t_s} = 0.116 \times (1000 + 6 \times 0.732 \times 3000)$

= 1644.56V

For the body weight of 70 kg

$E_{step70} = (1000 + 6.0\, C_s \times \rho_s)\ 0.157/\sqrt{t_s} = 0.157 \times (1000 + 6 \times 0.732 \times 3000)$

=2225. 827 V

By applying Equation (26) and (27)

For the body weight of 50 kg

$E_{touch50} = (1000 + 1.5\, C_s \times \rho_s)\ 0.116/\sqrt{t_s} = 0.116 \times (1000 + 1.5 \times 0.732 \times 3000)$

=498.14 V

For the body weight of 70 kg

$E_{touch70} = (1000 + 1.5\, C_s \times \rho_s)\ 0.157/\sqrt{t_s} == 0.157 \times (1000 + 1.5 \times 0.732 \times 3000)$

=674.21 V

5.6.10 Proposed earth grid parameters

Table 5.13 presents the parameters of the proposed earth grid for the traction substation at Ratmalana.

Table 5.13 - Parameter for the Proposed Earth Grid

No	Description	Value
1	Length of the ground grid	90 m
2	Width of the ground grid	50 m
3	Distance between conductors laid in X direction	9 m
4	Distance between conductors laid in Y direction	10 m
5	Number of conductors in X direction	11
6	Number of conductors in Y direction	6
7	Cross section area of the grid conductor	75 mm^2
8	Diameter of the grid conductor	0.011 m
9	Area of the Grid (A)	4500m^2
10	Peripheral Length of the Ground Grid (Lp)	280 m
11	Total length of buried conductors (Lc)	950 m
12	Grid Burial Depth (h)	0.6 m
13	Top Layer Soil Resistivity (ρ1)	70 Ωm
14	Derating factor (Df)	1.022
15	Fault current deviation factors (Sf)	0.5395

5.6.11 Validation of proposed grid parameters for safety

Ground Grid Resistance without Ground Rods

$R_g = \rho[1/L_T + 1/\sqrt{20A}\ (1+1/(1+h\sqrt{(20/A)}))] = 0.385\ \Omega$

Maximum Grid Current

$I_G = D_f \times S_f \times I_f = 8270.535$ A

Ground Potential Rise

$GPR = I_G \times R_g = 3184.155$ V

As Etouch50 < GPR < 5000 V the requirement for GPR is satisfied.

Calculated Mesh Voltage for the Design (Em) = 479.4 V

Calculated Step Voltage for the Design (Es) = 288.9 V

The earth grid designed for the proposed traction substation at Ratmalana is presented in Figure 5.19 and complete drawings is presented in ANNEXURE-N.

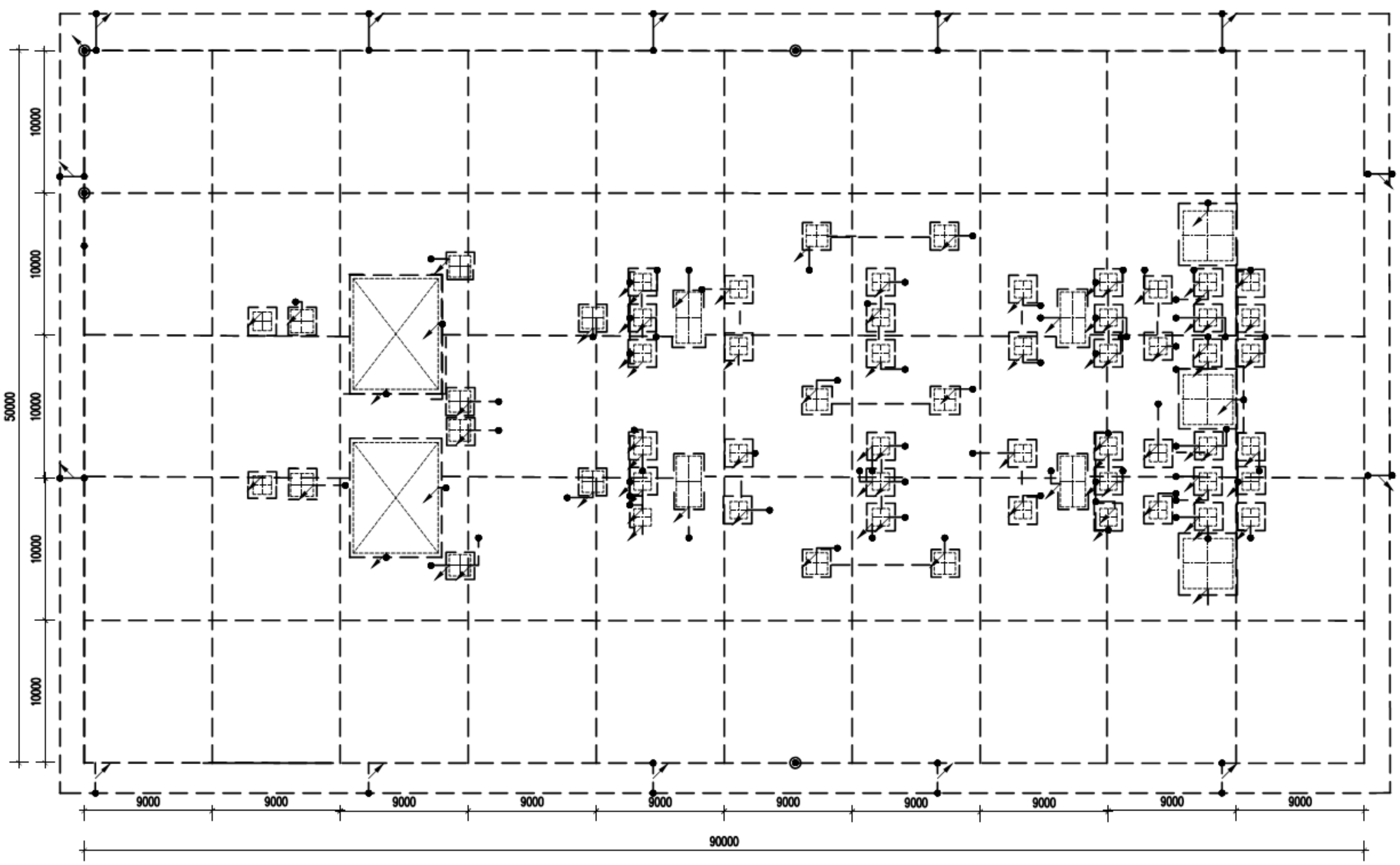


Figure 5.19- Proposed Earth Grid for the Ratmalana Traction Substation

CHAPTER 6

CONCLUSIONS

This research study is based on the electrification of Panadura to Veyangoda railway sector. Using MATLAB Simulink software velocity, power and distance of EMUs with respect to the time is modelled based on the forecasted train timetable for year 2035. The resulting train power data is applied to the load model in DIgSILENT Power Factory software in order to simulate the load flow calculation for the system at peak hours considering two options. Panadura to Maradana railway section is proposed to be fed by traction substation at Ratmalana and two power feeding options available for Maradana to Veyangoda sector are discussed and analysed. It is observed that both Wanawasala and Ragama locations are technically viable for traction substation and only few replacements in the cable sizes of overhead catenary system in Maradana to Veyangoda sector need to be done. The maximum power required for traction transformers in each traction substation is obtained as 20 MVA. The catenary contact cables are sized for each track section based on the maximum power requirements of the predicted train operation. Finally layout of the traction substation and earth grid arrangement is presented for Ratmalana traction substation as an example.

6.1 Model Limitations

The simulation model is designed and analysed considering the train movement between Panadura and Veyangoda railway sector only. For the application of this model for another railway sector, the model need to be modified and variable parameters need to be applied accordingly.

In this study, constant values are taken for train acceleration and deceleration considering the collision free train running in each signal block system. Depending on the train timetable, the movements of the trains in the system gets varied. Hence it is required to consider on an optimized train time table.

6.2 Future Research and Applications

In this research, designing of traction substation is mainly considered and this can be further developed for the area of designing the overhead catenary feeding system and signalling system for the proposed railway electrification project. Since the proposed railway sector is planned to apply for both diesel and electric railway traction, the operation and signal compatibility of the system need to be addressed.

It is important to optimize the train time table as well. Train timetable can be optimized in order to consume the regenerative braking energy by other trains accelerating in the same system. It is important to mention that railway electrification area has more research gaps which need to be addressed.

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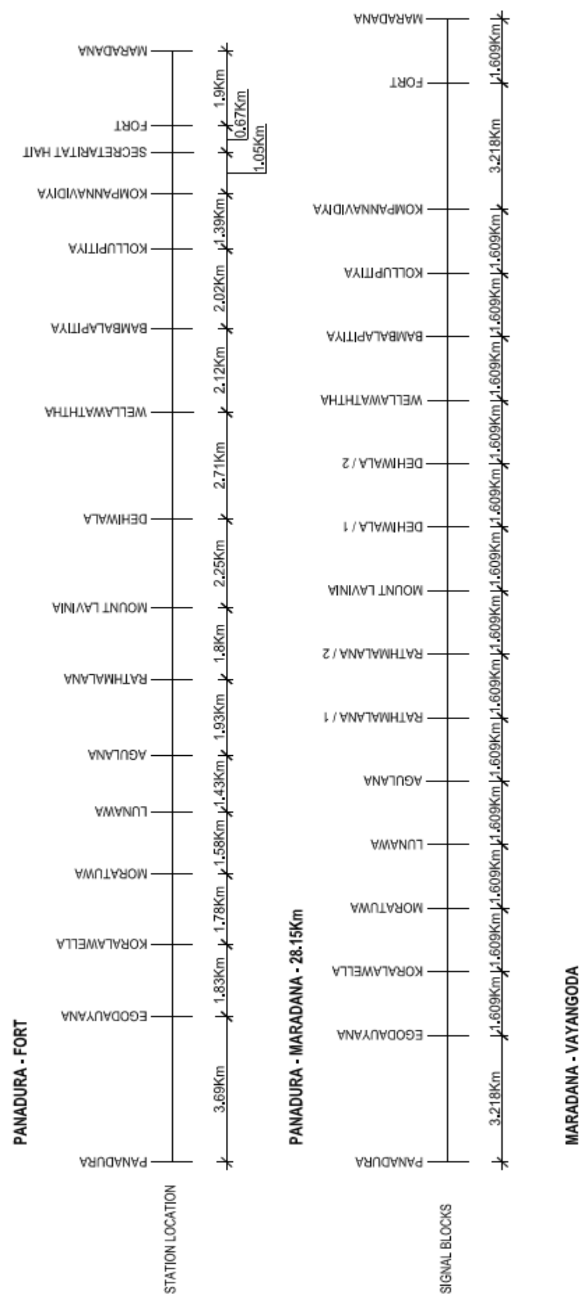
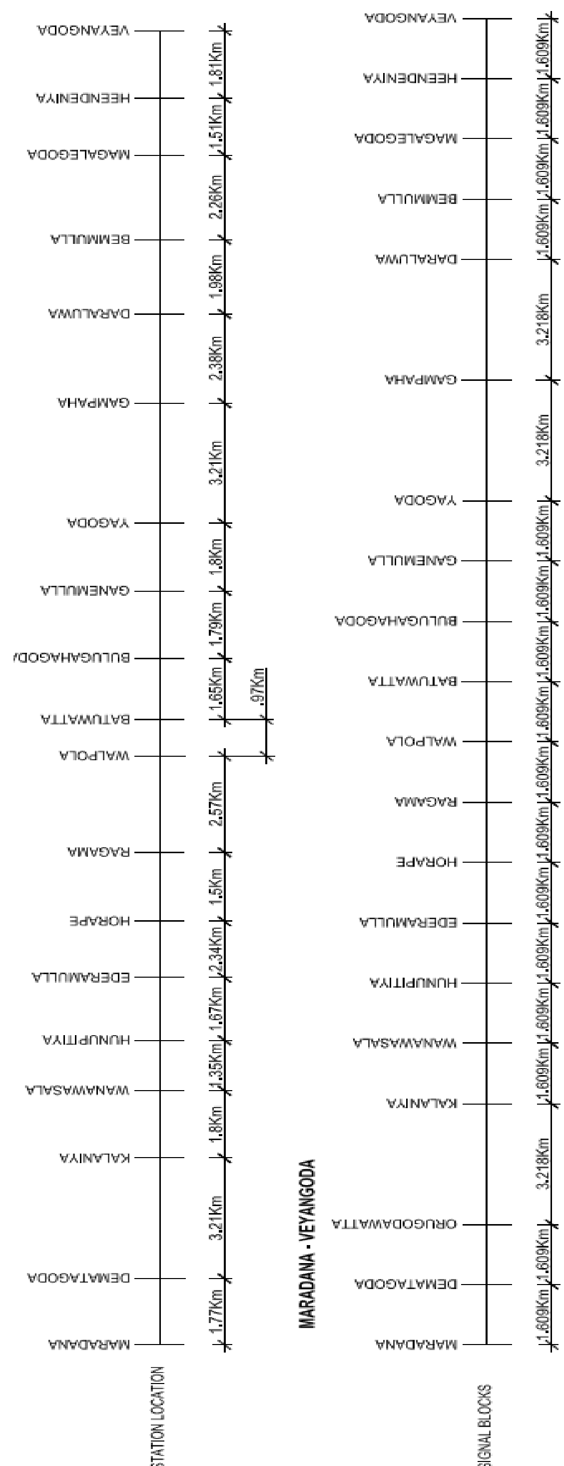
ANNEXURE A - Railway stations located between Panadura to Veyangoda

No	Distance between two stations		Distance (km)
1	Panadura	Egodauyana	3.69
2	Egodauyana	Koralawella	1.83
3	Koralawella	Moratuwa	1.78
4	Moratuwa	Lunawa	1.58
5	Lunawa	Angulana	1.43
6	Angulana	Ratmalana	1.93
7	Ratmalana	Mount Lavinia	1.80
8	Mount Laviniya	Dehiwala	2.25
9	Dehiwala	wellawatte	2.71
10	wellawatte	Bambalapitiya	2.12
11	Bambalapitiya	Kollupitiya	2.02
12	Kollupitiya	Kompnnavidiya	1.39
13	Kompnnavidiya	Secretariat Halt	1.05
14	Secretariat Halt	Fort	0.67
15	Fort	Maradana	1.90
16	Maradana	Dematagoda	1.77
17	Dematagoda	Kelaniya	3.21
18	Kelaniya	Wanawasala	1.80
19	Wanawasala	Hunupitiya	1.35
20	Hunupitiya	Enderamulla	1.67
21	Enderamulla	Horape	2.34
22	Horape	Ragama	1.50
23	Ragama	Walpola	2.57
24	Walpola	Batuwatte	0.97
25	Batuwatte	Bulugahagoda	1.65
26	Bulugahagoda	Ganemulla	1.79
27	Ganemulla	Yagoda	1.80
28	Yagoda	Gampaha	3.21
29	Gampaha	Daraluwa	2.38
30	Daraluwa	Bemmulla	1.98
31	Bemmulla	Magelegoda	2.26
32	Magelegoda	Heendeniya	1.51
33	Heendeniya	Veyangoda	1.81
	Panadura	**Veyangoda**	**63.727**

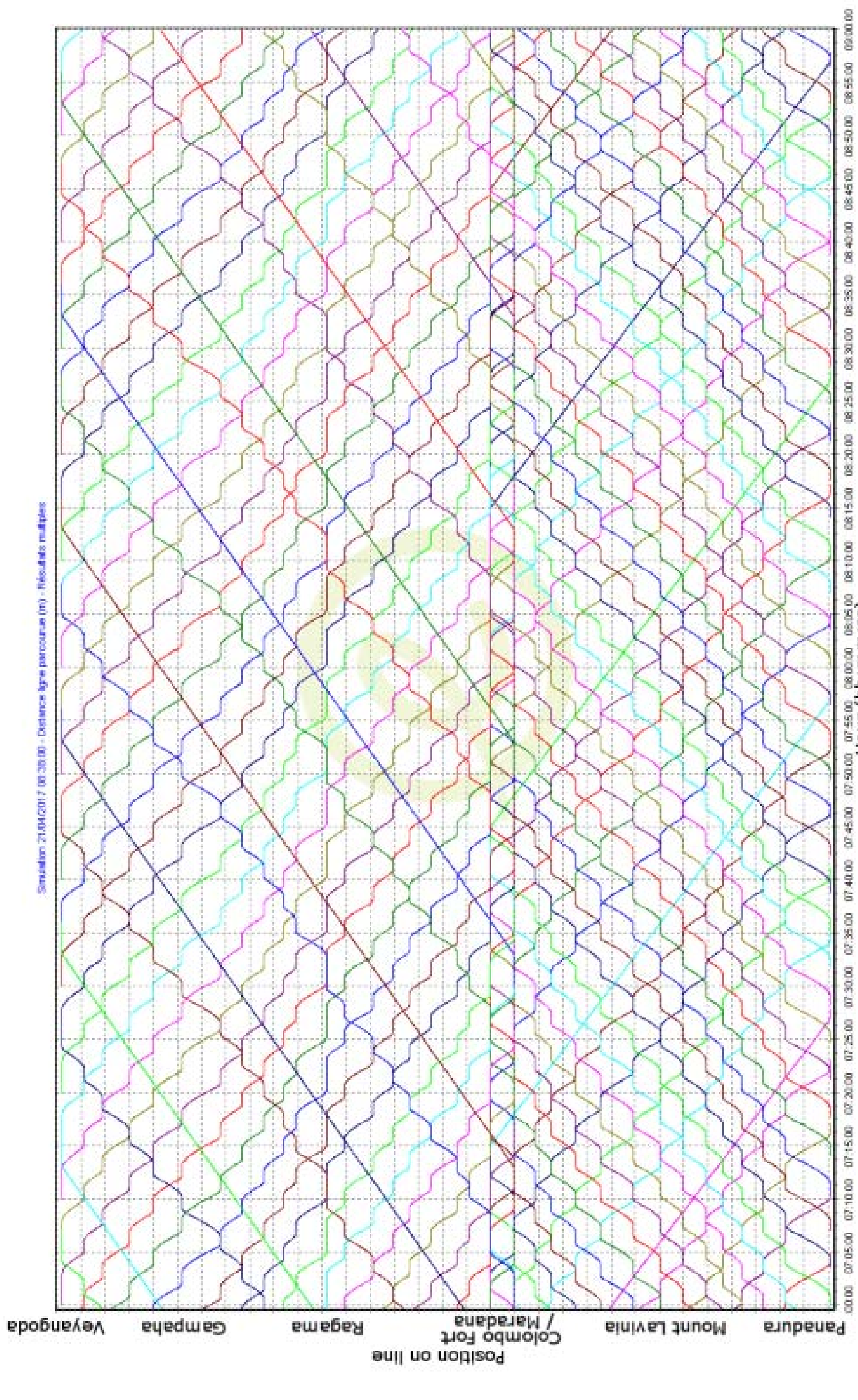
ANNEXURE B - Signal Block System between Panadura and Maradana Railway Stations



ANNEXURE C - Signal Block System between Maradana and Veyangoda Railway Stations



ANNEXURE D - Operation Plan of Train Time Table Simulation forecasted for Year 2035 [30]



ANNEXURE E - MATLAB Code for the Train Model at Staring Station

```
function [u,y1,y2,sta1,p,t0]= fcn(t,a1,a2,Vm,d,gap)
a=0;
temp = 0;
dis1=0;
dis2=0;
n=0;
R=0;
k=0;
f=0;
 n =  fix(t/gap); % return the integer valve
if( n*gap<=t && t< 2*n*gap)
        a = n*gap;
end
if(t<(a+Vm/a1) && k>=0)
        k= a1*(t-a);
        dis1=0.5*a1*(t-a)*(t-a);
        f=(210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(t-a)*(t-a));

elseif(((a+Vm/a1)<=t)&&(t<(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)))&& k>=0)
         k= Vm;
         dis1=0.5*a1*(Vm/a1)*(Vm/a1) + Vm*(t-a-Vm/a1);
         f=(191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(Vm/a1)*(Vm/a1) + Vm*(t-a-Vm/a1));

elseif(((a+(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))<=t)&&
(t<(a+(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm)))&& k>=0)
          k= Vm - (a2*(t-(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm))));
          dis1=0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)))-0.5*a2*(((t-(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm))))^2);
         f=(-210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(Vm/a1)*(Vm/a1)+Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)))-0.5*a2*(((t-(a+(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm))))^2));
end;
if dis1>=(d-0.0001)
         sta1=1;
else
         sta1=0;
end
%  a=a+300;
t0=(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm);
p=f;
y1=dis1;
y2=dis2;
u=k;

end
```

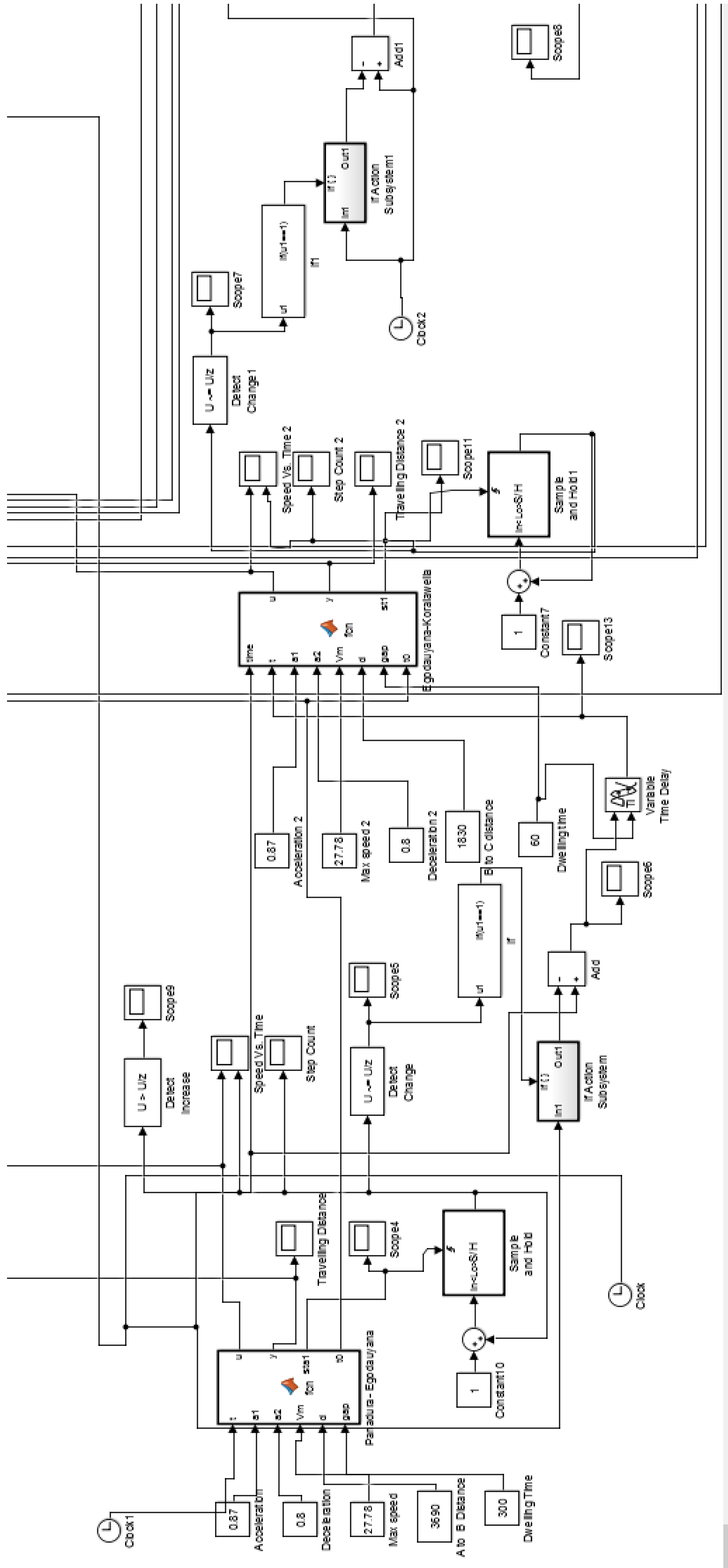
ANNEXURE F - MATLAB Code for the Train Model at Intermediate Station

```
function [u,y1,y2,p, st1,t1]= fcn(time,t,a1,a2,Vm,d,gap,t0)
k=0;
dis1=0;
dis2=0;
f=0;
if(time>(t0+gap))
% n =  fix((t-(t0+gap))/gap); % return the integer valve

%  if( n*gap<=(t-(t0+gap)) && (t-(t0+gap))< 2*n*gap)
  %%  end

if((t)<(Vm/a1) && k>=0)
        k= a1*((t));
        dis1=0.5*a1*((t))*((t));
     f=(210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*((t))*((t)));
elseif(((Vm/a1)<=t)&&((t))<((Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm))&& k>=0)
         k= Vm;
         dis1=0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((t)-Vm/a1);
   f=(191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((t)-Vm/a1));
elseif(((Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm)<=t)&&
((t)<(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))&& k>=0)
          k= Vm - (a2*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)));
          dis1=0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))-
0.5*a2*((t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))^2);
       f=(-210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))-
0.5*a2*((t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))^2));
end;
if dis1>=(d-0.0001)
         sta1=1;
else
         sta1=0;
end
%  a=a+300;
else
      sta1=0;
end
t1=t0+gap+(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm);
u=k;
p=f;
y1=dis1;
y2=dis2;

st1=sta1;

end
```

ANNEXURE G- MATLAB Code for the Train Model which does not reach the maximum speed

```
function [u,y1,y2,p,st1,t1]= fcn(time,t,a1,a2,Vm,d,gap,t0)
k=0;
dis1=0;
dis2=0;
f=0;
if(time>(t0+gap))

% n =  fix((t-(t0+gap))/gap); % return the integer valve

%  if( n*gap<=(t-(t0+gap)) && (t-(t0+gap))< 2*n*gap)
  %%  end

if((t)<(Vm/a1) && k>=0)
        k= a1*((t));
        dis1=0.5*a1*((t))*((t));
      f=(210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*((t))*((t)));

elseif(((Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm)<=t)&&
((t)<(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))&& k>=0)
          k= Vm - (a2*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)));
          dis1=0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))-
0.5*a2*((t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))^2);
       f=(-210.93*a1*1000+191.75*20)*k/1000000;
        dis2=d-(0.5*a1*(Vm/a1)*(Vm/a1) + Vm*((d -0.5*Vm*Vm/a2-
0.5*Vm*Vm/a1)/Vm)+Vm*(t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))-
0.5*a2*((t-(Vm/a1+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm))^2));
end;

if dis1>=(d-0.0001)
         sta1=1;
else
         sta1=0;
end

%  a=a+300;
else
      sta1=0;
end

t1=t0+gap+(Vm/a1+Vm/a2+(d -0.5*Vm*Vm/a2-0.5*Vm*Vm/a1)/Vm);
u=k;
p=f;
y1=dis1;
y2=dis2;
st1=sta1;

end
```

ANNEXURE H – MATLAB Model for Train Movement



ANNEXURE I – Specification for Scott-T Transformer

ANNEXURE-3

SCHEDULE OF GUARANTEED PERFORMANCE, TECHNICAL AND OTHER PARTICULARS
(GUARANTEED PARTICULARS ARE TO BE ESTABLISHED BY ACTUAL TESTS/TEST REPORTS)

SR NO	DESCRIPTION	UNIT OF MEASUREMENT	VALUE/INFORMATION
1	2	3	4
A	*RATINGS/ PARTICULARS*		
1	Name of the Manufacturer		ABB India ltd
2	Country of Manufacturer		INDIA
3	Reference to specification based on which performance data is prescribed		ETI/PSI/118(10/93) with A&C Slip no. 1 to 10
4	Rated Power	MVA	21.6 / 30.24
5	Primary current at:		ONAN / ONAF
i)	Rated load	A	163.63 / 229.1
ii)	150% rated load for 15 min.	A	245.45 / 343.65
iii)	200% rated load for 5 min.	A	327.27 / ---
6	Secondary current at:		
i)	Rated load	A	800 / 1120
ii)	150% rated load for 15 min.	A	1200 / 1680
iii)	200% rated load for 5 min.	A	1600 / --
7	Rated Voltage:		
i)	Primary	kV	132
ii)	Secondary (at no-load)	kV	27
8	Rated frequency	Hz	50 ± 3%
9	Temperature rise above ambient temp. of 50 Deg.C		
1	Oil:		
i)	At rated load	Deg C	40 max.
ii)	At 150% rated load load for 15 min.	Deg C	40 max.
iii)	At 200% rated load for 5 min.	Deg C	40 max.
2	Winding:		
i)	At rated load	Deg C	50 (Max.)
ii)	At 150% rated load load for 15 min.	Deg C	60 (Max.)
iii)	At 200% rated load for 5 min.	Deg C	60 (Max.)
10	Hot-Spot temperature of winding over ambient temperature of 50 Deg.C		
i)	At rated load	Deg C	65(Max.)
ii)	At 150% rated load load for 15 min.	Deg C	65(Max.)
iii)	At 200% rated load for 5 min.	Deg C	65(Max.)

APPROVED IN PRINCIPLE
For Director General/T.I./R.D.S.O./LKO 25/01/17

ABB INDIA LIMITED VADODARA

ANNEXURE-3

SCHEDULE OF GUARANTEED PERFORMANCE, TECHNICAL AND OTHER PARTICULARS
(GUARANTEED PARTICULARS ARE TO BE ESTABLISHED BY ACTUAL TESTS/TEST REPORTS)

SR NO	DESCRIPTION	UNIT OF MEASUREMENT	VALUE/INFORMATION
	Note : Overloading Condition **ONAN Rating - 150% of rated load for 15 Min. & 200% of rated load for 5 Min.** **ONAF Rating - 150% of rated load for 15 Min.**		
11	Interval of time between two successive overloads after continuous working at full load at maximum ambient temperature of 50 Deg.C		
i)	Between two consecutive overloads of 50% for 15 min.		3 HOURS(APPROX.)
ii)	Between two consecutive overloads of which one is of 50% for 15 min. and the other of 100% for 5 min.		3 HOURS(APPROX.)
12	No-load current referred to primary side at rated frequency and at:		
i)	90% rated voltage	A	0.2(APPROX.)
ii)	Rated Voltage:	A	0.3(APPROX.)
iii)	110% rated voltage	A	0.45(APPROX.)
iv)	Appropriate Voltage at 15% tap	A	0.4(APPROX.)
v)	Appropriate Voltage at +10% tap	A	1.2(APPROX.)
13	Power Factor of no-load current at rated voltage and rated frequency		0.3(APPROX.)
14	Value of the inrush current at rated voltage on primary side, the secondary side being open circuited	A	1050 Approx.
15	Losses:		
i)	No-load loss at rated frequency and at:		
1)	90% rated voltage at the principal tapping	kW	7.5(APPROX.)
2)	rated voltage at the principal tapping	kW	9 (MAX)
3)	110% rated voltage at the principal tapping	kW	11.8 (APPROX.)
4)	Appropriate voltage at the -15% tap	kW	7.0 (APPROX.)
5)	Appropriate voltage at the +10% tap	kW	11.8 (APPROX.)
ii)	Load loss (at 75 Deg.C) with rated current and frequency @ 21.6 MVA		
1)	Principal tapping	kW	80 (MAX)
2)	-15% tapping	kW	107 (APPROX.)
3)	+10% tapping	kW	74 (APPROX.)
iii)	Total losses at rated current and frequency:		
1)	Principal tapping	kW	89 (MAX.)
2	-15% tapping	kW	114 (APPROX.)
3	+10% tapping	kW	85.8 (APPROX.)
16	Resistance voltage (at 75 Deg.C) at rated current at principal tapping:		
i)	Primary	%	0.163(APPROX.)
ii)	Secondary	%	0.153(APPROX.)

APPROVED IN PRINCIPLE

For Director General/T.I./R.D.S.O./LKO.

ABB INDIA LIMITED VADODARA

ANNEXURE-3

SCHEDULE OF GUARANTEED PERFORMANCE, TECHNICAL AND OTHER PARTICULARS
(GUARANTEED PARTICULARS ARE TO BE ESTABLISHED BY ACTUAL TESTS/TEST REPORTS)

SR NO	DESCRIPTION	UNIT OF MEASUREMENT	VALUE/INFORMATION
17	Reactance voltage at 75 Deg.C at rated current and frequency at principal tapping:	%	11.99(APPROX.)
18	Impedance voltages (at 75 Deg.C) at rated current and frequency at 21.6MVA :		
i)	Principal tapping	%	12(+/- 0.5% TOL)
ii)	-15% tapping	%	12.0 Approx.
iii)	+10% tapping	%	12.0 Approx.
19	Resistance at (75 Deg.C) of primary winding	Ohm	1.40(APPROX.)
20	Resistance (at 75 Deg.C) of secondary winding at:		
i)	Principal tapping	Ohm	0.058(APPROX.)
ii)	+10% tapping	Ohm	0.050(APPROX.)
iii)	-15% tapping	Ohm	0.075(APPROX.)
21	Reactance of winding:		
i)	Primary	H	1.538(APPROX.)
ii)	Secondary at:		
1)	Principal tapping	H	0.055(APPROX.)
2)	+10% tapping	H	0.0307(APPROX.)
3)	-15% tapping	H	0.070(APPROX.)
22	Regulation (at 75 Deg.C) with rated current and at power factor of:		
i)	Unity	%	1.09
ii)	0.8 lagging	%	7.93
23	Efficiencies:		
i)	Efficiency (at 75 Deg.C) at unity power factor at:		
1)	100% load	%	99.59
2)	75% load	%	99.67
3)	50% load	%	99.73
4)	25% load	%	99.74
ii)	Efficiency (at 75 Deg.C) at .8 power factor lagging at:		
1)	100% load	%	99.49
2)	75% load	%	99.59
3)	50% load	%	99.67
4)	25% load	%	99.68
iii)	Percentage of rated load at % which maximum efficiency occurs.	%	33.541

APPROVED IN PRINCIPLE

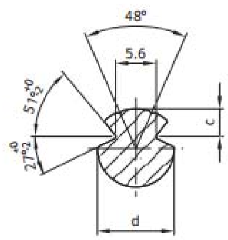
For Director General/T.I./R.D.S.O./LKO.

ABB INDIA LIMITED VADODARA

ANNEXURE J - Catenary Cable Guide

Grooved contact wire AC, CuAg0.1

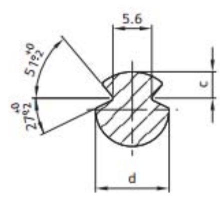
acc. to EN 50149



Order no.	8WL7000-1	8WL7001-1	8WL7002-1	8WL7003-1
Designation	Contact wire AC-80	Contact wire AC-100	Contact wire AC-120	Contact wire AC-150
Material	CuAg0.1	CuAg0.1	CuAg0.1	CuAg0.1
Weight	0.71 kg/m	0.89 kg/m	1.07 kg/m	1.33 kg/m
Nominal cross-section	80 mm²	100 mm²	120 mm²	150 mm²
Min. tensile strength	365 N/mm²	360 N/mm²	350 N/mm²	350 N/mm²
Min. breaking load	28.3 kN	34.9 kN	40.7 kN	50.9 kN
Perm. permanent current	620 A	705 A	750 A	875 A
Resistance at 20 °C	0.22 Ω/km	0.18 Ω/km	0.15 Ω/km	0.12 Ω/km
Conductivity at DC (20 °C)	56 m/Ω mm²	56 m/Ω mm²	56 m/Ω mm²	56 m/Ω mm²
c	3.8 mm	4.0 mm	4.0 mm	4.0 mm
d	10.6 mm	12.0 mm	13.2 mm	14.8 mm

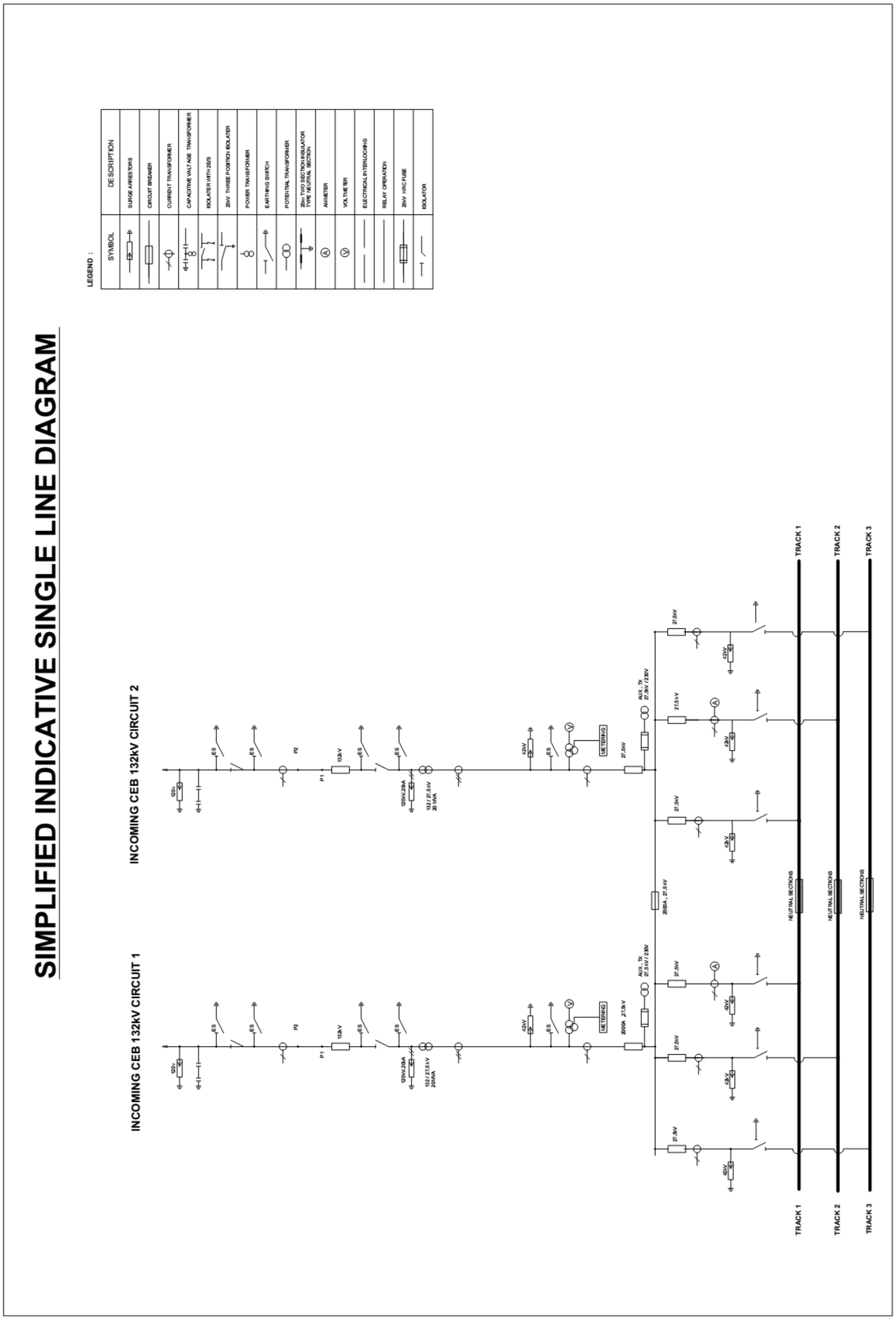
Grooved contact wire AC, Cu-ETP

acc. to EN 50149

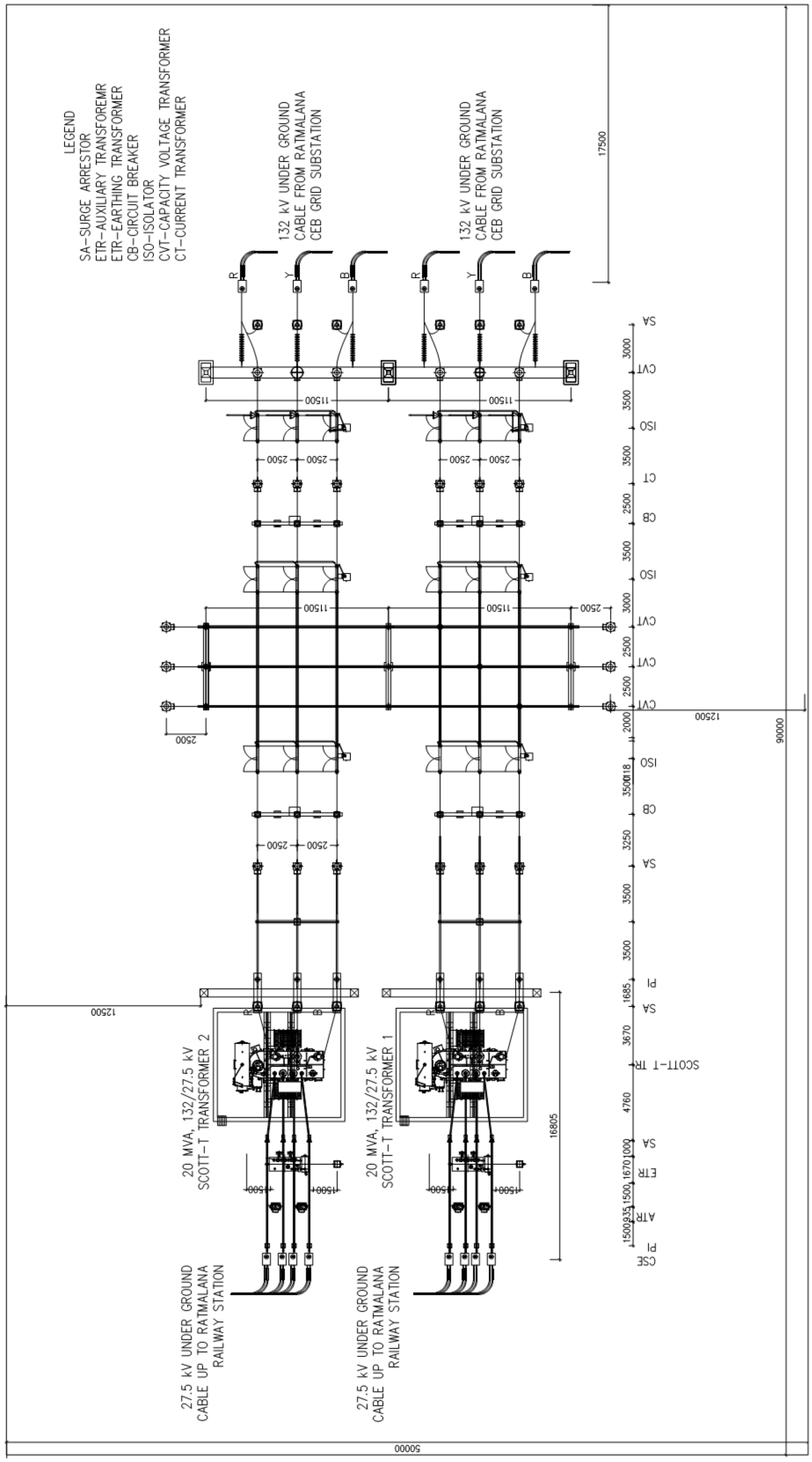


Order no.	8WL7000-0	8WL7001-0	8WL7004-0	8WL7002-0	8WL7003-0
Designation	Contact wire AC-80	Contact wire AC-100	Contact wire AC-107	Contact wire AC-120	Contact wire AC-150
Material	Cu-ETP	Cu-ETP	Cu-ETP	Cu-ETP	Cu-ETP
Weight	0.71 kg/m	0.89 kg/m	0.95 kg/m	1.07 kg/m	1.33 kg/m
Nominal cross-section	80 mm²	100 mm²	107 mm²	120 mm²	150 mm²
Min. tensile strength	355 N/mm²	355 N/mm²	350 N/mm²	330 N/mm²	310 N/mm²
Min. breaking load	27.5 kN	34.5 kN	36.3 kN	38.4 kN	45.1 kN
Perm. permanent current	370 A	455 A	468 A	490 A	540 A
Resistance at 20 °C	0.22 Ω/km	0.18 Ω/km	0.17 Ω/km	0.15 Ω/km	0.12 Ω/km
Conductivity at DC (20 °C)	57 m/Ω mm²	57 m/Ω mm²	57 m/Ω mm²	57 m/Ω mm²	57 m/Ω mm²
c	3.8 mm	4.0 mm	4.0 mm	4.0 mm	4.0 mm
d	10.6 mm	12.0 mm	12.3 mm	13.2 mm	14.8 mm

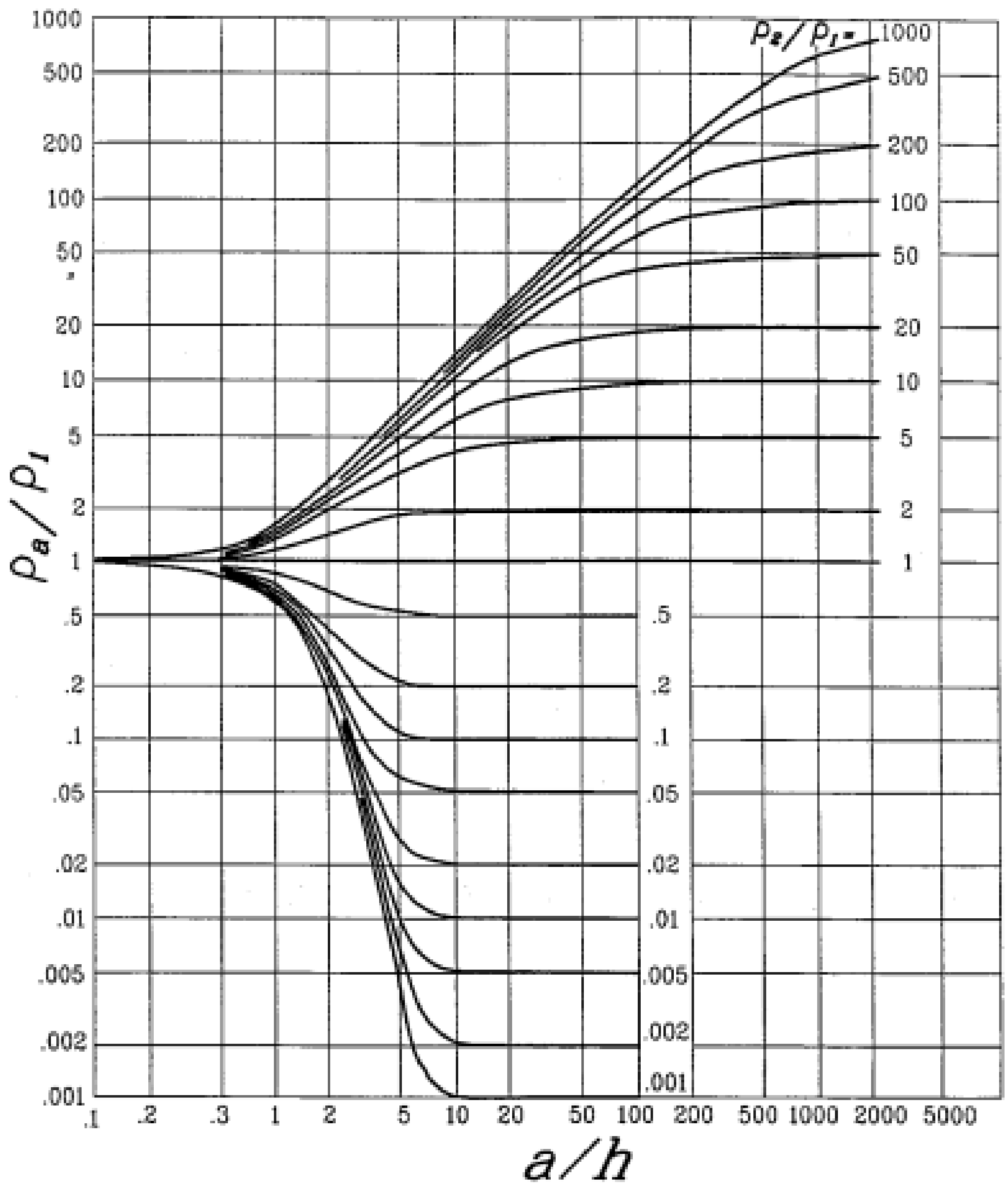
ANNEXURE K – Single Line Diagram for Traction Substation at Ratmalana



ANNEXURE L – Substation Layout for Proposed Traction Substation at Ratmalana



ANNEXURE M - Sunde's Graphical Method



ANNEXURE N – Earth Grid Arrangement for Proposed Traction Substation at Ratmalana