DESIGNING OF RAILWAY ELECTRIFICATION NETWORK CONFIGURATION TO MINIMIZE POWER QUALITY ISSUES:
A CASE STUDY FOR PROPOSED SRI LANKAN RAILWAY ELECTRIFICATION

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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(Dr. Asanka Rodrigo)

ABSTRACT

Electrified railway system is a better solution for the rapidly increasing congestion of traffic in urban areas and railway transportation has many advantages compared with other modes of land/air transportation. In Electrified railway system ,energy delivered to the train when needed(running), unlike the other modes of transportation (land, air, sea).According to the present railway passenger flow, suburban railway stations Panadura – Veyangoda sector was selected as high passenger density area which served 44% of all railway passengers and government has decided to electrified that sector first. The total track length between Panadura and Veyangoda is 156km.

Due to the rapid acceleration and frequent starts of electric trains, there may large magnetic induction current in the power circuits and it may contribute to the grid voltage drop near urban areas. The energy flow back to the grid with regenerative braking and harmonics will added to the system. So, there are lot of power quality issues with electrified railway system and it is time to accept the challenge as Electrical Engineers.

This research titled as "DESIGNING OF RAILWAY ELECTRIFICATION NETWORK CONFIGURATION TO MINIMIZE POWER QUALITY ISSUES: A CASE STUDY FOR PROPOSED SRI LANKAN RAILWAY ELECTRIFICATION" was carried out to find out an optimum voltage configuration to feed the railway system with minimum disturbing to the available power system.

Electric train model was developed using Matlab Simulink to study the behavior of power distribution system while operating of the electric trains with current time schedule of the Sri Lankan Railways.

The results were obtained and analyzed under the critical times at proposed railway substations .According to the results, optimum voltage configuration was selected in order to minimize the power quality issues to the utility grid.

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ABBREVIATIONS

SLR	: Sri Lanka Railways
DC	: Direct Current
AC	: Alternating Current
CEB	: Ceylon Electricity Board
THD	: Total Harmonic Distortion
OCS	: Overhead Contact Systems
FOC	: Field Oriented Control
GS	: Grid Substation
FL	: Fault Level
MW	: Mega Watt
Mvar	: Mega vars

CHAPTER 1

INTRODUCTION

1.1 Background

The railway and locomotive technologies were continually developed, and the first electrified railway was introduced in the 1880s [1-3]. As a result of this revolution, the traction motor and the power supply system have become important parts of modern electrified railways.

In the past, DC power supplies (1.5 kV from the early 1900s and 3 kV from the 1930s) were mainly used because of ease of control. However, difficulties of DC motor commutation, limitations of feeding distance and expensive power supply equipment has been led to the restrictions on the use of DC mainline railways. Using a high-voltage AC power transmission system, long distance feeders have become possible. Until recently, AC/DC converter-fed DC motors were used, with the converters fed from the AC supply through a traction transformer. The advantage of DC motors is simple torque-speed control. There exist different operating frequencies that are used in electrified railways in various parts of the world. Low-frequency high-voltage transmission networks, 15 kV at 16 2/3 Hz and 12 kV at 25 Hz, are used to feed AC commutator motors in some central European countries (Norway, Sweden, Switzerland, Austria and Germany) and in New York, USA, respectively [4,5].

Around the 1950s, electrified railways at the industrial frequency, 50 Hz, were established. The Valenciennes-Thionville line in France was the first 50 Hz railway electrification [6]. Thus far, a single-phase feeding system with 25 kV at 50 Hz has become the world standard of mainline railway electrification while a 50 kV feeding system has been used for railways with heavily loaded locomotives.

1.1.1 Sri Lankan Context

Sri Lankan Government has been identified that electrified railway system is a better solution for the rapidly increasing congestion of traffic in urban areas. The railway transportation has many advantages compared to the other modes of land/air transportation. There are, better control on schedule and travel time, lower exposure to risk factors such as heavy traffic and road accidents, more comfortable seating and economy. Another advantage of electrified railway system is energy delivered to the train when needed(running), unlike the other modes of transportation (land, air, sea) where the source of energy must be carried by the vehicle for the duration of the journey.

According to the recent studies carried out, by considering present railway passenger flow, geographical data of railway tracks and other railway statistics and population of Sri Lanka, the network between suburban railway stations Panadura to Veyangoda sector was selected as high passenger density area which served 44% of all railway passengers as shown in table 1.

Table 1: Origin and destination analysis of SLR passengers

	Sector Starts	Sector Ends	Sector length (km)	% of all SLR passengers starting and ending journey within the electrified sector			Passengers starting and ending journey within sector per month per route km		
				Average	Maximum	Minimum	Average	Maximum	Minimum
1	Panadura	Veyangoda	63.4	43%	44%	42%	58,233	61,313	55,049
2	Kalutara S	Veyangoda	79	48%	50%	47%	52,430	55,359	49,251
3	Panadura	Ragama	41.7	21%	21%	20%	42,414	44,904	40,000
4	Fort	Ragama	15.5	8%	9%	8%	46,196	48,171	43,429
5	Fort	Gampaha	27.5	21%	22%	20%	65,342	68,233	62,768
6	Fort	Polgahawela	73.8	39%	40%	38%	45,462	47,532	43,323
7	Maradana	Panadura	28.1	11%	11%	11%	33,430	35,600	31,385
8	Maradana	Kalutara S	43.7	16%	16%	15%	31,457	33,674	29,029
9	Fort	Negombo	38.9	13%	14%	13%	28,869	29,881	28,090

Source: [7]

The total track length between Panadura and Veyangoda is 156km, and serves 44% of all railway passengers on a given day. Under the proposed system, an overhead catenary wire will be supplied 25kV power to a dedicated electric multiple unit (EMU) train, while the rails will function as a return wire. [7]

Further studies have been approved based on a Cabinet Paper submitted by the Ministry of Power and Energy and the Ministry of Internal Transport. The Asian Development Bank also has been expressed willingness to fund a detail feasibility study and a steering committee has been appointed, comprising of senior officials representing Ministries of Internal Transport, Power and Energy, Ceylon Electricity Board, Department of Sri Lanka Railways, the Institution of Engineers, the Department of National Planning, and the General Treasury to study in detail the feasibility of this proposal to electrify the railway segment between Panadura – Veyangoda and also to determine appropriate strategies and projects to electrify the railway system based on the findings of the feasibility reports.[8]

1.2 Problem Statement

The electric locomotive has been consisted of fast acceleration, high speed and their economic benefits, and it has become more popular as a transportation solution. Due to the rapid acceleration and frequent starts of electric trains, there may large magnetic induction current in the power circuits and it may contribute to the grid voltage drop near urban areas. The energy flow back to the grid with regenerative braking and large amount of harmonics will be added to the power system.

The railway power supply would have to be constructed and electric infrastructures such as grid substations and overhead lines would have to be laid while the existing system in operation. Several high voltage, medium voltage and low voltage lines cross the rail track and therefore require proper clearance and protection. [9]

The most affected systems among existing lines are the track circuits that use 50 Hz for train detection and wired signaling and telecommunications systems that are run in parallel to the railway line. In absence of protection for the electromagnetic induction hazards can cause to personnel, material deterioration and problems can occur in the proper functioning railway signaling installations. [10]

The infrastructure required for power transmission, electrical signals must be transmitted to convey information in real time about the position of the trains to avoid collisions and to control traffic light at rail crossings. To accomplish this task and to distinguish between sections of the rails, the rail sections must be isolated for signaling purposes but must be continuous for power purposes. Therefore, circuits for signals' transmission must be considered when designing the power circuits. [11]

With the introduction of PWM controllers on the trains, either simply as traction controllers or to provide reactive power compensation as well can create problem at frequencies other than the fundamental. These controllers behave as harmonic frequency current generators and can cause substantial harmonic currents to be injected into the system at the load point. Hence, the harmonics can be distributed to power feeding system and cause substantial problems to other consumers. [12]

1.3 Motivation

The latest effort is by the Institution of Engineers, Sri Lanka (IESL) in August 2008, as a responsible body of professionals has been presented a new proposal to electrify a segment of the railway network. The Institution of Engineers India is gracefully accepted the request from IESL and they have provided the honorary services of an experienced railway electrification engineer. Through a series of deliberations and field visits are facilitated by the Sri Lanka Railways (SLR), the study is concluded the most widely used sector of the existing railway network is from Veyangoda to Panadura, and should be the first to be electrified. In their conclusion state that the investment about 6 billion on electrification can be recovered fully with cost savings in energy and maintenance alone.

This situation is highly motivated me to initiate this research, “Designing of railway electrification network configuration to minimize power quality issues in proposed Sri Lankan railway electrification”.

1.4 Objective

The feeding voltage is directly affected the traction performance of electric locomotive and its onboard traction equipment, and also power quality, stability and security of the whole power feeding system. Computer-based simulation and the theoretical study of railway electrification has influenced the modern railway system in several aspects.

In this thesis, proposed Sri Lankan railway electrification with overhead AC catenary feeding systems has been considered. The aim of the research was to find out the optimum railway network configuration to minimize power quality issues in proposed Sri Lankan railway electrification system based on computer modelling and simulation.

1.5 Scope of Work

Scope of work is as follows.

- Studying the literatures on the same research area.
- Collecting electrified data of different voltage configurations.
- Collecting data of available electric locomotives.
- Collecting Utility transmission network parameters including grid locations.
- Collecting railway track data and their geographical location.
- Analyzing the train time table data separately and identify the critical time intervals in morning and evening peaks.
- Analyzing the distances to the nearest 132kV grid substation from the proposed railway substation along the railway track.
- Analyzing the above all data and prepare them for simulation.
- Modeling the Electric Locomotive in Mat lab Simulink.
- Modeling the transmission network and railway overhead feeding system in Mat lab Simulink.
- Combine all models in to one general model

- Validate the model with available practical data
- Simulate general model for critical times according to railway time table along the railway track for different voltage-frequency configurations.

- Taking following measurements with different configuration of 25kV-50Hz, 15kV-16.7Hz and 15kV-50Hz.
    - 132kV voltage drop at grid interconnection point.
    - Current drawn from the 132kV transmission network.
    - Current and voltage THD% at grid inter connection point.
    - Active and Reactive power requirement
- Identify the different power quality issues related to the different configurations by analyzing results.
- Select optimum configuration as shown below figure.

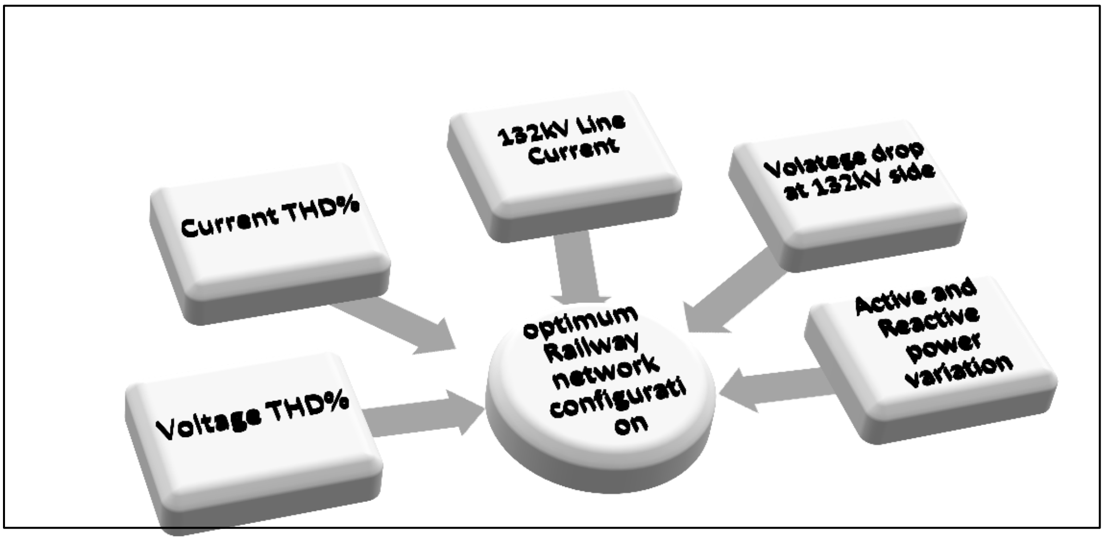


Figure 1: Methodology for optimum railway configuration

1.6 Structure of the dissertation

Chapter 1 is the introductory chapter and it discuss background of electrified railway systems and the potential of the proposed Sri Lankan railway electrification system. In addition it describe the problems related to the current electrified systems .Finally present the motivation and objective of the thesis.

Chapter 2 gives an analysis of the existing electrified railway system with different voltage configurations. This analysis is conducted to identify the main components of electrified railway system used in different countries. Then discuss on the proposed Sri Lankan railway electrification project.

Chapter 3 covers the data collection and data analysis which are used in Mat Lab simulation model.

In Chapter 4, it describe the developed Mat Lab model for proposed Sri Lankan railway electrification system.

Chapter 5 presents the model validation and obtained results with different voltage configurations for proposed two substations.

The final chapter provides the discussion and conclusions based on the results obtain in Chapter 5.

RAILWAY ELECTRIFICATION SYSTEMS

2.1 Overview

Today, new railway electrification systems need to serve a wide variety of railway applications. The light rail, commuter rail, rapid transit, heavy rail, intercity, high-speed passenger service, heavy-haul freight rail are having quite different requirements. These different requirements result in a variety of potential of AC and DC electric traction systems.

2.2 Different voltage configurations

2.2.1 DC System (600V-3kV)

The 600-1500V DC systems are adequate for rolling stocks with low power demand (Less than 5MW)Higher power requires catenary voltages to be increased up to 3kV, which can found in Italy, Belgium, Spain and Poland. But rule of thumb, 3kV catenaries are limited to train speeds lower than 250 km/h. [13]

2.2.2 AC System

For high speed railway electrification systems, 25kV/50Hz and 15kV/16.7 Hz catenary systems become a standard in world wide. [13]

- **15kV, 16.7 Hz system** :

This voltage configuration is mainly used in Germany, Austria, Switzerland, and Sweden as their national standard. [13]

- Austria- Austrian Federal Railways-national standard
- Germany - German National Railways-national standard
- Norway -Norwegian National Rail Administration-national standard

- **25 kV, 50Hz system :**
- This voltage configuration is used in European countries such like Portugal, Denmark, England and Finland.[14]
    - India-National standard
    - Italy-New High-speed lines only
    - Netherlands-Used on new High Speed Lines and Freight Lines
    - France (SNCF) -Used on new High Speed Lines (TGV)

In DC systems, high direct current is required for heavy conductors, require closely spaced substations, relatively high line resistance losses ,lower voltage DC systems is not as efficient as high voltage AC systems.[15]

The economic selection in terms of the cost of traction power for railway electrification will be lead to use one of the high voltage AC systems such as the 15 kV, 25kV or 25kV/25kV auto-transformer, or a 50kV system. Hence following voltage configurations are used for the future analysis in this thesis. [16]

- 25kV-50Hz configuration
- 15kV-16.7Hz configuration
- 15kV-50Hz configuration

However, every scenario will be required a detailed examination to determine the feasibility of electrifying and the type of traction power system that will best serve site-specific requirements.

There are four main parts in traction power system [17]

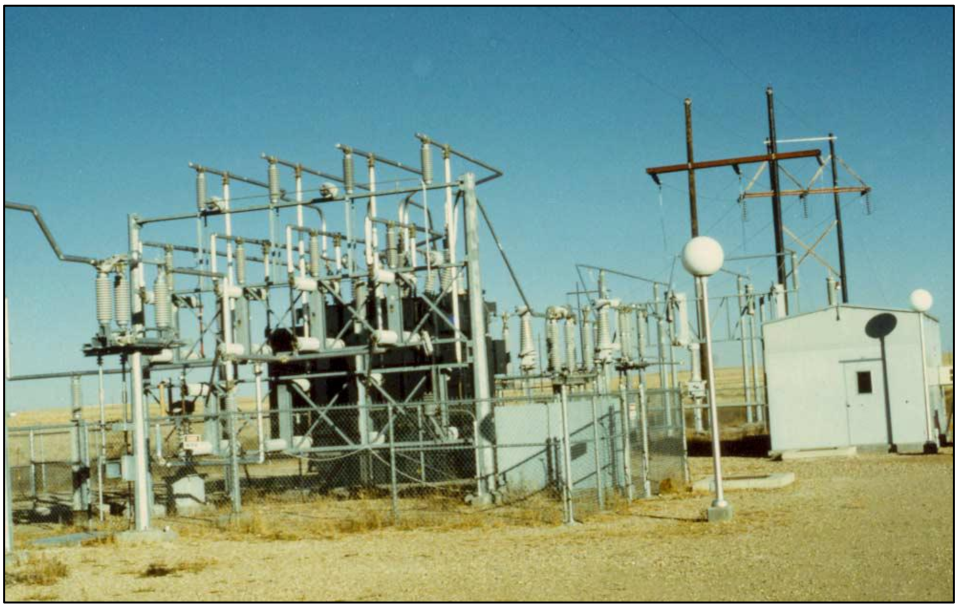
- Sources of primary power
- Railway substations
- power distribution system (overhead or third rail)
- Current collectors (on the locomotives)

2.2.3 Source of primary power

National grid is the common power supply to the traction power system in most of the countries and some different dedicated power networks for railway systems are also identified in some countries.

2.2.4 Substation

AC systems usually receive power at commercial frequency and it will be transformed it to the traction voltage. Those systems that use a frequency except commercial frequency will be converted the power using either motor generator sets or frequency converters, which may be located separately from the substation.



Source: [17] **Figure 2: Railway Substation**

2.2.5 Power Distribution Systems

Traction power distribution systems comprise three sub systems.

- Feeder cables
- Negative return cables
- Contact system

2.2.5.1 Feeder cables (from the substation to the bare conductors).

Source: [17] **Figure 3: Feeder Cables**

2.2.5.2 Negative return cables

The negative return cables are used to connecting to the rails or the return conductor back to the substation.

Source: [17] **Figure 4: Negative Return via the Running Rail**

2.2.5.3 Contact system

The contact system comprising bare conductors (overhead or third rail) located along the track-from which the trains draw power through some form of sliding contact. Contact system can differentiate to third rail system and overhead contact system.

2.2.5.4 Third rail system

Third rail system provides the positive supply in a DC powered traction system from a traction rail that parallels the track. The third rail is typically rests on insulators on the field side of either side of the track.

Source: [17] **Figure 5: Third Rail Contact System**

2.2.5.5 Overhead contact systems

Overhead contact systems are comprised a support system (poles, wall and soffit attachments, cantilevers, cross-spans, etc.), conductors and anchorages to tension the conductors.

2.2.5.6 Current Collectors

The current collectors that draw power from the third rail systems or from the OCS.In third rail, the contact shoe slides over the top of the conductor rail to supply the power requirement.

Source: [17] **Figure 6: Third Rail Contact Shoe**

In OCS , the pantograph that have a wide rubbing strip on the head and collect power through their carbon strips at any point.

Source: [17] **Figure 7: Pantograph System**

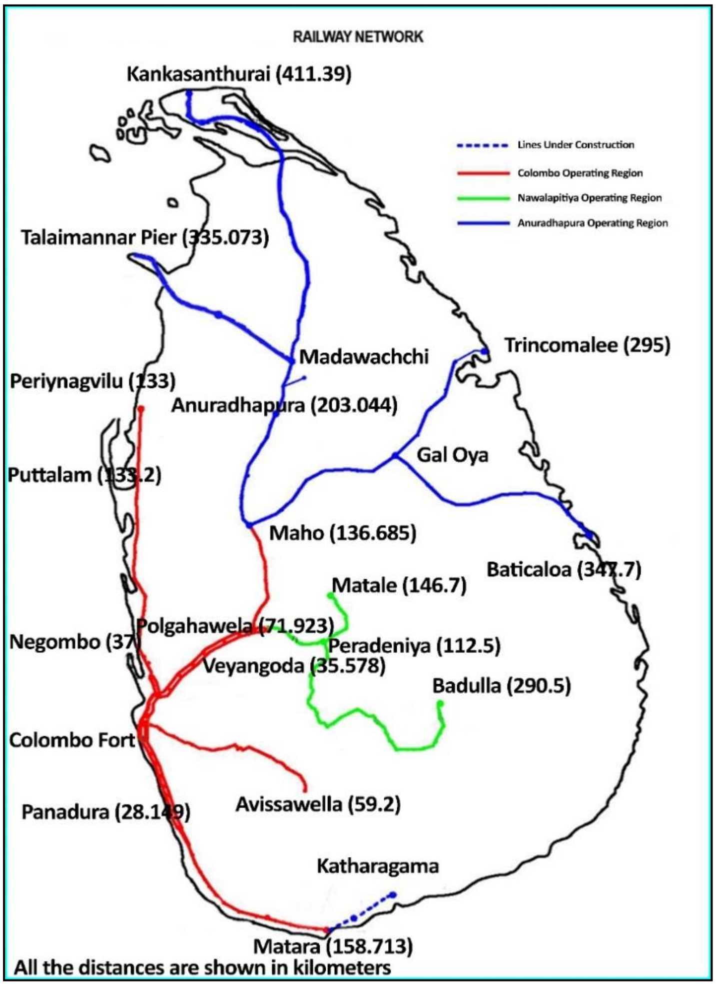
2.3 Railway Electrification of Sri Lanka

Electrification of railways of both Colombo suburban and long-distance has been proposed by many in the past. The Ministry of Transport has so far not taken any meaningful steps to launch a project. In 1918, Engineer DJ Wimalasurendra was provided the first inspiration, who on his paper titled ‘Economics of Power Utilization in Ceylon’ mentioned the importance and advantages of electrifying our railways. [7]

Forty four percent (44%) of the passengers are used the present rail network today get-in and get-off in the Panadura-Veyangoda sector. This sector is 64 km long, which is a manageable length (and a manageable investment) for the first step to establish and electrified rail network. There are other sectors such as Kalutara South-Polgahawela, which can be covered more than 50% of current passengers, but the length would be more, making the initial capital outlay higher. So, the sector to be selected to launch electrification depends on further study, to provide the optimum benefit to commuters for the given investment. Whichever sector is selected, it would only be the first step, and eventually the entire railway network should be electrified, based on an economic justification. [7]

2.3.1 The proposed electrification Project

Electric lines would be drawn above the railway lines and loops. The operating voltage will be 25 kV, which is now the standard in India and most other countries. Current will be come from the overhead wire and return along one of the rails. The rails will be at zero voltage; so crossing them or stepping on them will not be dangerous. However, extreme caution is required at level crossings, to ensure vehicles taller than the stipulated height do not cross. The high voltage lines cross our roads at thousands of locations, and this should not be a problem. Some existing station roofs and passenger bridges would have to be modified or re-built. The proposal of IESL, reviewed by the Indian Railways expert, was to begin with the Veyangoda-Panadura sector, with five electric multiple units. [12]



Source: http://www.railway.gov.lk

Figure 8: Existing Sri Lankan railway network

Source: [12]

Figure 9: Sector to be electrified and technical proposal for Power Supply

According to the proposal which is done by IESL in 2008, there are two proposed traction substations along the track from Veyangoda to Panadura sector.

One of them is in Dehiwala , which can connected to 132kV grid substation at Dehiwala and other one is located in Ragama, which can feed from Aniyakanda 132kV grid substation.[12]

DATA COLLECTION AND ANALYSIS

According to the methodology, model for the railway electrification is going to develop using Matlab simulation software. For this model, transmission network parameters, electric locomotive parameters, parameters of railway substations and their geographical locations are needed. In this chapter, collected data will be presented and analyzed in order to use in Matlab simulation model.

3.1 Data of Transmission network

Figure 10: The map of Grid substations along the proposed railway section

According to the Utility transmission line parameters, following data was collected as per the requirement for Matlab simulation model along railway track which is proposed to electrify as shown in Figure 9.

- Fault current at grid interconnection point
- Distance to the nearest railway feeding station
- Resistance(R), inductance(X) and impedance (Z) for the feeder.

Table 2 : Transmission network paramaetrs

Location	voltage level (kV)	R		X		Z		X/R		Fault Current(kA)		Fault Level(MVA)		Distance to GS
		50Hz	16.7Hz	50Hz	16.7Hz	50Hz	16.7Hz	50Hz	16.7Hz	50Hz	16.7Hz	50Hz	16.7Hz	(km)
Dehiwala	132	1.78	0.809	5.46	1.981	5.74	2.14	3.067	2.449	13.26	35.61	3031.6	8142	2
Aiyakanda	132	1.39	0.809	6.12	2.119	6.28	2.27	4.403	2.619	12.14	33.57	2775.6	7675.59	4.5
Maradana	132	1.53	0.604	4.71	1.699	4.96	1.804	3.078	2.813	15.36	42.25	3511.8	9658.54	1(I)
Pettah	132	1.68	0.799	4.81	1.73	5.1	1.905	2.863	2.165	14.93	40.01	3412.3	9146.46	1(F)
Ratmalana	132	2.12	1.24	6.14	2.166	6.5	2.49	2.896	1.746	11.72	30.61	2679.6	6997.59	3
Kelaniya	132	1.18	0.515	4.24	1.515	44	1.6	3.593	2.941	17.29	47.63	3953	10890	3.5
Kollupitiya	132	1.69	0.805	4.8	1.724	5.09	1.903	2.84	2.141	14.95	40.05	3418	9156.07	3(E)
Bambalapitiya	132	2.02	0.9	5.41	1.95	5.78	2.15	2.544	2.166	13.17	35.45	3011.1	8104.19	1.5(A)
Veyangoda	132	1.177	0.565	11.93	4.047	11.99	4.086	10.14	7.162	6.356	18.65	1453.2	4254.19	5
Panadura	132	2.36	1.43	7.13	2.49	7.51	2.872	3.021	1.741	10.09	26.54	2306.9	6066.85	4

Source: Transmission planning division of CEB

3.2 Proposed railway substation

When we consider the railway track along Panadura to Veyangoda, there are number of railway stations located. The distances to each railway stations along main line and coast line from the Colombo Fort are shown in below Table 03.

Table 3 : Locations of railway stations along the railway track from Panadurata-Veyangoda

Railway Station	Distance from Fort (km)
Main line	
Dematagoda	3.668
Kelaniya	6.873
Wanawasala	8.676
Hunupitiya	10.026
Enderamulla	11.699
Horape	14.043
Ragama	15.546
Walpola	18.116
Batuwatte	19.083
Bulugahagoda	20.731
Ganemulla	22.522
Yagoda	24.324
Gampaha	27.538
Daraluwa	29.921
Bemmulla	31.905
Magelegoda	34.164
Heendeniya	35.67
Veyangoda	37.478
Coast line	
Secretartat Halt	0.666
Kompnnavidiya	1.72
Kollupitiya	3.108
Bambalapitiya	5.125
Wellawatte	7.245
Dehiwala	9.957
Mount Laviniya	12.211
Rathmalana	14.01
Angulana	15.939
Lunawa	17.366
Moratuwa	18.949
Koralawella	20.731
Egodauyana	22.563
Panadura	26.249

Source: http://www.railway.gov.lk

The Dehiwala railway substation and Ragama railway substation are the proposed railway substations which are close to the 132kV grid substations along the proposed electrified railway track from Panadura to Veyangoda. The distance to the proposed railway substations from closer grid substations are as below.

Table 4 : Distance to grid from proposed railway substations

Railway substation	Grid Substation	Distance
Dehiwala	Dehiwala GS	2 km
Ragama	Aniyakanda GS	4.5 km

3.3 Data of electric locomotive

Three phase traction motor type 6 FRA 6068 is used on WAG9/ WAP7 class of locomotives. It is an asynchronous squirrel cage rotor motor which operates by a three phase supply fed by 3 phase converter. It is forced air cooled through a vent in the non-drive end housing. The traction motor blower supplies filtered air to cool the traction motor. The flexible bellows connect the traction motor vent and the air outlet of the blowers on the locomotive under frame. The rotational force from the traction motor is transmitted to the gear box by a pinion drive coupling. The opposite end of rotor shaft is enclosed by an end plate.

Table 5 : Electric locomotive paramaetrs

Equipment	**Details**
Traction motors	ABB's (850 kW, 2180V, 2 pole)
Suspension of motors	Axle hung Nose suspended
Transformer (Onboard)	ABB's LOT 6500, Class A Insulation, OFAF cooling, (25 kV, 6531 kVA)
PE converters	ABB Power converter.
Gear ratio	65:19 / 107:21/72:20

No of bogies	02
Traction motors	06 motors per train

3.4 Analysis of railway time table

When the railway time table is considered, there are two identified peak hours during morning and evening. Once we analyzing the train locations and their feeding stations within those peaking times, it was observed that there were some time intervals feeder has to feeding about more than six trains simultaneously.

The Daily up and down railway time table of Panadura to Maradana and Colombo Fort to veyangoda is presented in ANNEX 1 and ANNEX 2 respectively.

3.4.1 Critical situation in Panadura- Maradana section

The critical time is observed at 07:06 hrs with ten numbers of simultaneous operated trains, which were feeding from Dehiwala railway substation.

Table 6 : Critical situation in Panadura- Maradana section

Train No	Time	Location	Feeding station	Distance (km)	Status
8310	07:06	Moratuwa	Dehiwala	11km	Slowdown
8317	07:06	Bambalapitiya	Dehiwala	4.5km	Slowdown
8316	7:06	Mt-lavinia	Dehiwala	2.5km	Accelerating
8320	7:06	Angulana	Dehiwala	6km	Full speed
8063	7:06	Egodauyana	Dehiwala	13km	Full speed

8324	7:06	Panadura	Dehiwala	16.3km	Stop
8327	7:06	Panadura	Dehiwala	16.5km	Accelerating
8324	7:06	Moratuwa	Dehiwala	9km	Slowdown
8723	7:06	Seceratary office	Dehiwala	9.5km	Slowdown
8050	7:06	Bambalapitiya	Dehiwala	5km	Full speed

3.4.2 Critical situation in Veyangoda- Colombo Fort section

The critical time is observed at 18:19 hrs with 11 numbers simultaneous operated trains, which are feeding from Ragama railway substation.

Table 7 : Critical situation in Veyangoda- Colombo Fort section

Train No	Time	Location	Feeding station	Distance (km)	Status
1020	18:19	Ganemulla	Ragama	7 km	Full speed
1006	18:19	Bemmulla	Ragama	16.3 km	Full speed
1581	18:19	Dematagoda	Ragama	11.5 km	Slowdown
1577	18:19	Hunupitiya	Ragama	5.5 km	Accelerating
1569	18:19	Veyangoda	Ragama	21.7 km	Accelerating
1173	18:19	Veyangoda	Ragama	22 km	Slowdown
1039	18:19	Gampaha	Ragama	12 km	Slowdown

1578	18:19	Gampaha	Ragama	11.9 km	Slowdown
1176	18:19	Ragama	Ragama	0.5 km	Accelerating
1177	18:19	Maradana	Dehiwala	Different feeder	Slowdown
4078	18:19	Kelaniya	Ragama	8.67 km	Full speed

CHAPTER 4

MODELING OF RAILWAY NETWORK

MATLAB Simulink was selected for the modeling of the required components of the railway network, transmission network and electric locomotive with the different scenarios according to the railway time table with following configurations.

- 25kV-50Hz configuration
- 15kV-16.7Hz configuration
- 15kV-50Hz configuration

The two Railway substations are directly connect to the 132kV voltage transmission system of the Utility. The two railway substations were consistence of 132kV/25kV or 132kV/15kV substation transformers and overhead catenary contact wire system. Electric locomotive is basically consist of 3 phase induction motors and motor drives. Modelling of the Utility transmission systems was required the model of the 132kV transmission line and the utility grid. Modeling of railway substation was required 3 phase step down transformer. The electric locomotive model was required 3 phase induction motors and associate driver systems. The following models were created using MATLAB Simulink to simulate and analyze the characteristics under different scenarios.

a. Utility grid
b. 132kV transmission line
c. Railway substation
d. Overhead catenary contact wire system
e. Electric locomotive
f. Harmonic filter

4.1 Utility Grid

The utility grid was modeled using a block of 3 phase source implements a balanced three-phase voltage source with an internal R-L impedance. The three voltage sources are connected in Y with a neutral connection that can be internally grounded or made accessible. The internal resistance is specified the source inductive short-circuit level and X/R ratio. The main details of the utility grid modelling are shown in the Table 5.

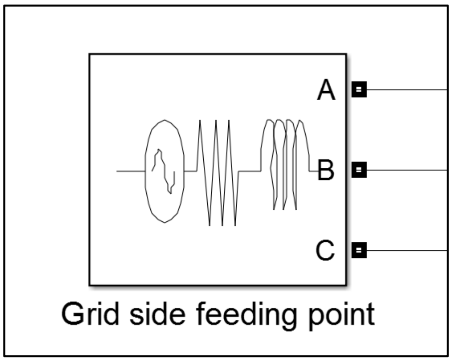


Figure 11: Utility Grid Model

Table 8 : Utility grid modelling details of Dehiwala Grid at 50 Hz

Component	Description
Generator Type	Swing
Base voltage	132kV
3-phase short-circuit level	1750.32MVA
X/R ratio	3.0674
Frequency	50

4.2 132kV Transmission Line Model

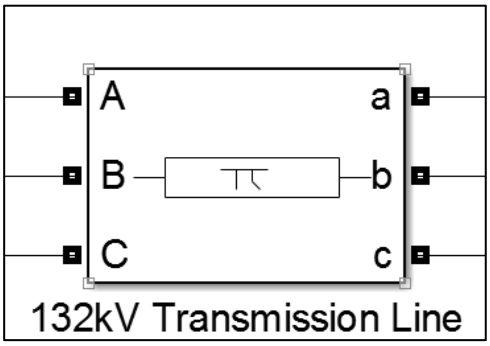


Figure 12: 132kV Transmission Line model

The high voltage transmission lines are used as overhead bare lines and underground cables. The most commonly available type is the overhead bare conductors. The model was developed for the overhead bare conductor using three- Phase PI Section Line in MATLAB Simulink blocks.

The Three-Phase PI Section Line blocks is implemented a balanced three-phase transmission line model with parameters lumped in a PI section. Contrary to the Distributed Parameter Line model where the resistance, inductance, and capacitance are uniformly distributed along the line, the three-Phase PI Section line block lumps the line parameters in a single PI section as shown in the figure below. The one set of RL series elements are connected between input and output terminals and two sets of shunt capacitances are lumped at both ends of the line.

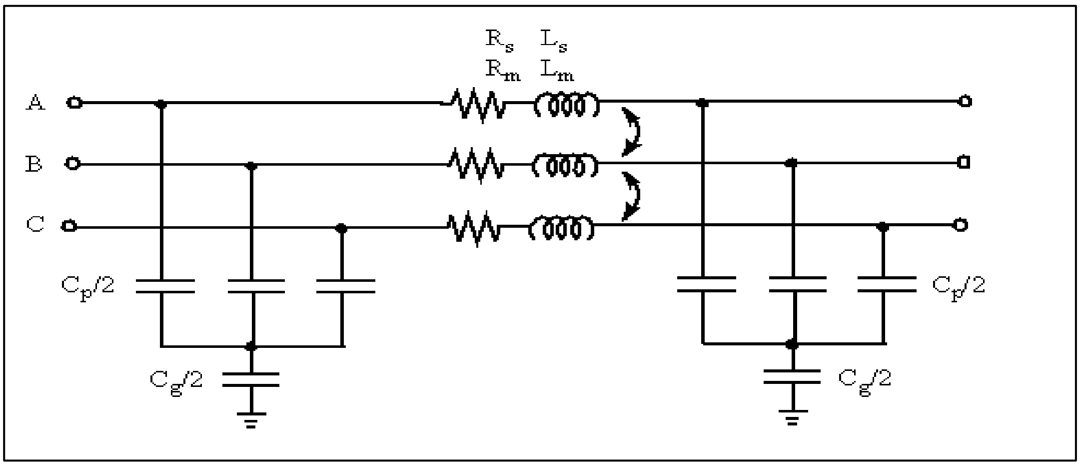


Figure 13: 132kV Transmission Line model

The parameters of a typical Zeebra conductor were used to model the overhead line. The resistance of the Zeebra conductor was set to 0.0677312 Ω/km at the temperature 30°C. The inductance of the conductor was considered 0.001157 H/km and the capacitance of the conductor was considered 12.74 nF/km.

4.3 Railway Substation model

Railway substation mainly consist of three-Phase step down transformer and transformer block was used to model 132kV/25kV and 132kV/15kV transformer as per required. The capacity was set to **31.5x2MVA** and the vector group was set to Dyn11.

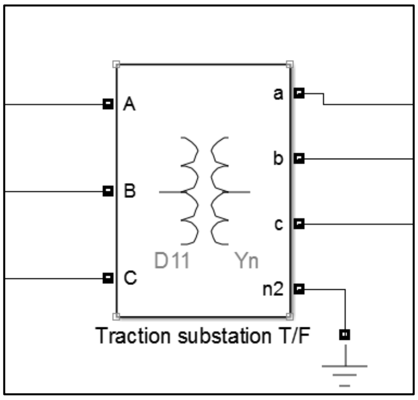


Figure 14: Distribution transformer model

4.4 Model of Overhead catenary contact wire system

The model was developed for the overhead bare conductor using MATLAB Simulink blocks. The parameters of a typical overhead cu/cd conductor were used to model the overhead line. The resistance of the overhead conductor was set as 0.185Ω/km. The inductance of the conductor is 0.161 H/km.

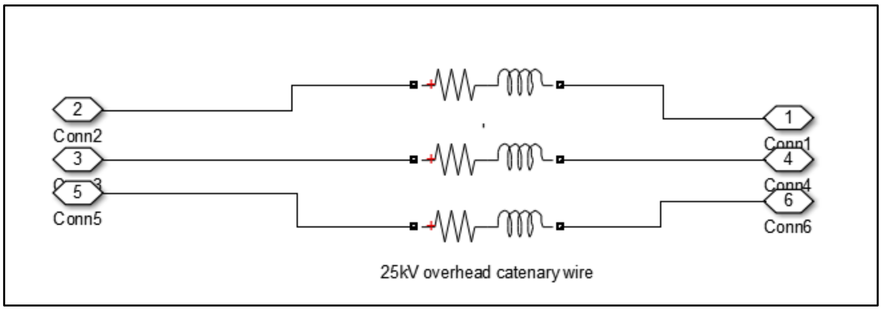


Figure 15: Model of overhead contact wire

4.5 Electric Locomotive model

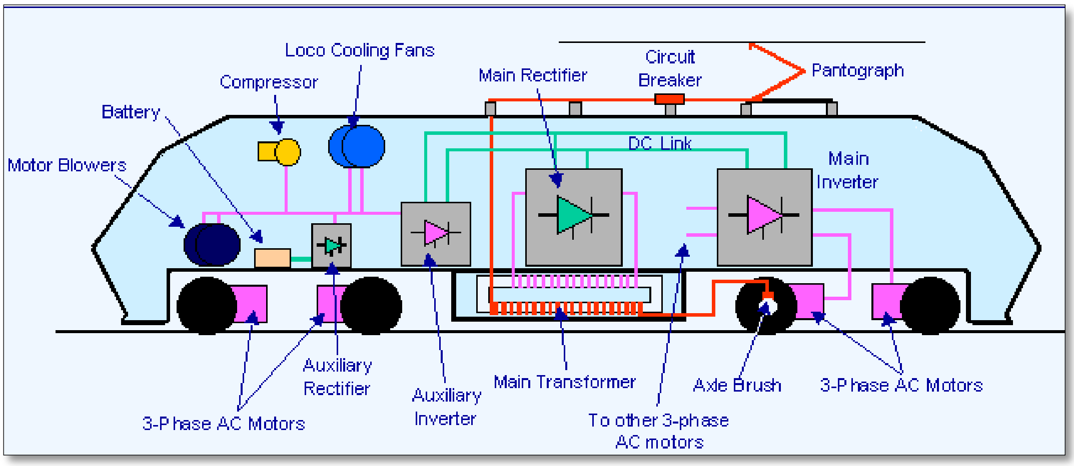


Figure 16: General AC Electric Locomotive model

Three-Phase induction motors are more efficient alternative to the DC motor because of simpler to construct, no mechanical contacts to work (such as brushes) and lighter than DC motors for equivalent power, modern electronics allow AC motors to be controlled effectively and they are more robust and easier to maintain than DC motors. The general AC electric locomotive model is shown in Figure 16. [8, 9, 10]

The economic selection in terms of the cost of traction power for railway electrification will lead to use one of the high voltage AC systems such as the 15 kV, 25kV or 25kV/25kV auto-transformer, or a 50kV system. In this thesis, Mat lab model is developed basis with following basic structure of the electric locomotive. In electric locomotive, loco engine cabin is consisted of two bogies and one induction motor driver per bogie. The single induction motor driver operates three induction motors simultaneously. The dry type 6.5MVA traction transformer is used to step down single phase voltage to 2180V.The Mat Lab model for the electric train is shown in Figure 17.

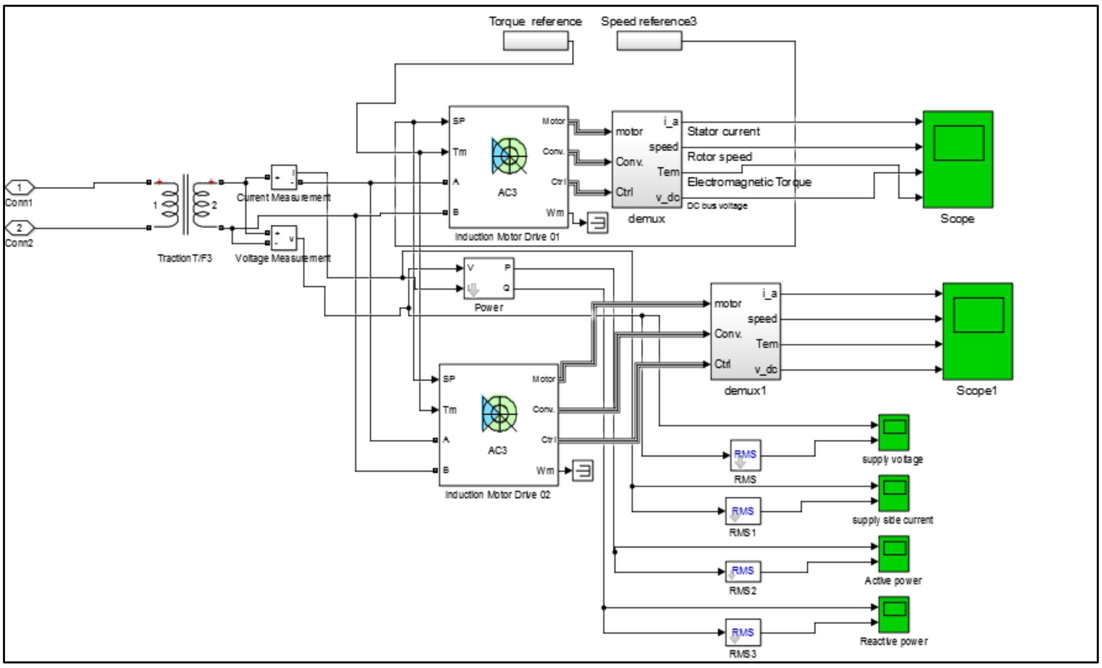


Figure 17: Model of Electric Locomotive

4.5.1 Selecting Torque reference (Tm) and Speed reference (Sp) for Mat Lab train model

Torque reference and speed reference were selected by analyzing the real time data of M9 train while in its test run operations from Dematagoda to Veyangoda. In these test runs, real time power demand was recorded with respect to the rpm of the motor. The recorded data at the starting of train No: 867 is shown in table 09.

Table 9 : The recorded data at the starting of train No: 867

rpm	Power Demand (kW)
450	109
575	290
692	505

779	700
845	900
900	1000
951	1100
1000	1500

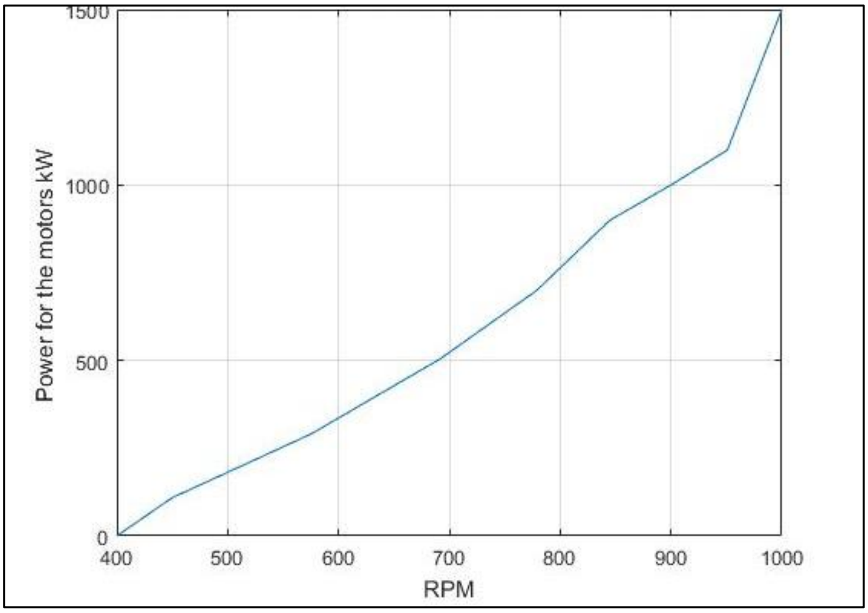


Figure 18: Power demand variation with the rpm in starting of a M9 train

According above characteristics, rpm and the torque variation in the staring was obtained and torque and speed references are selected in order achieve the above practical characteristics as shown in following figures 19 and 20.

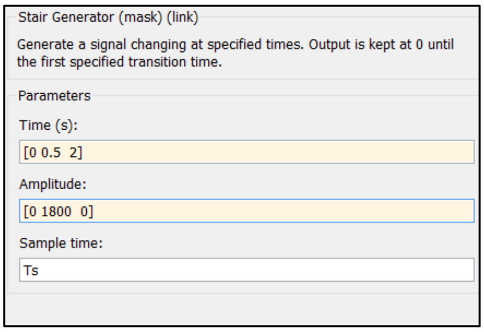


Figure 19: Speed reference (Sp)

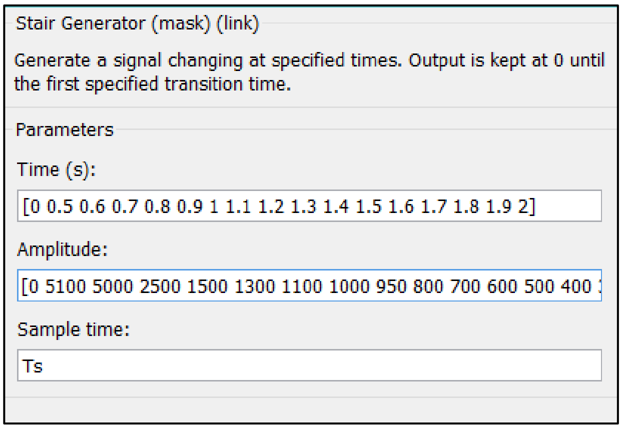


Figure 20: Torque reference (Tm)

4.5.2 Filed orient control (FOC)

The field oriented control (FOC) driver is used as the induction motor controller .The FOC is consists of main six blocks such as induction motor, the three-phase inverter, and the three-phase diode rectifier, speed controller, the braking chopper, and the FOC model as shown in Figure 21.

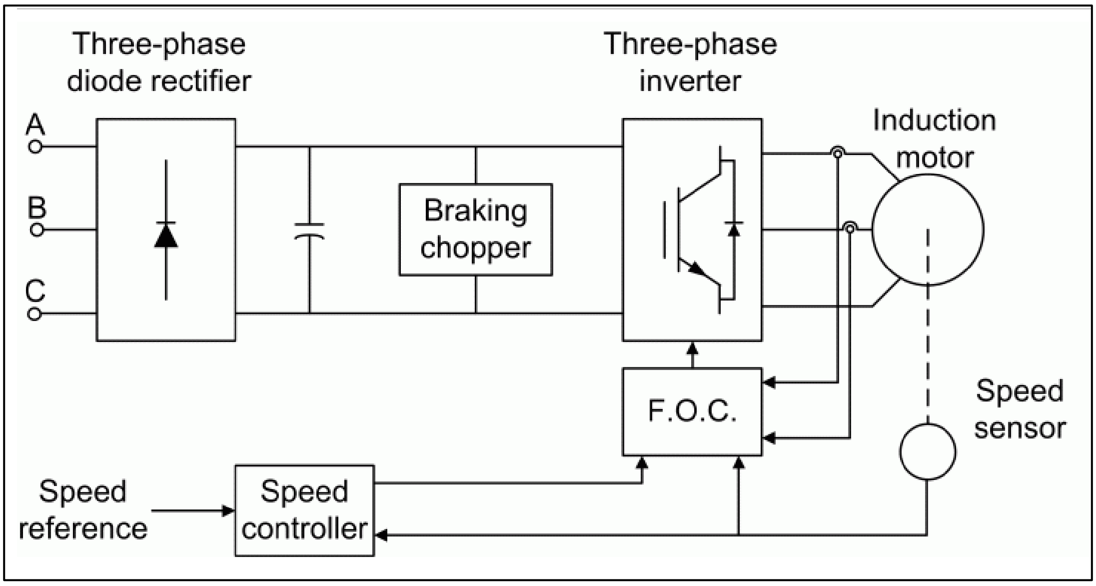


Figure 21: Schematic diagram of Field-Oriented Control Induction Motor Drive

The model of the field oriented controller, which used in electric locomotive in this developed Mat lab model is shown in Figure 22.

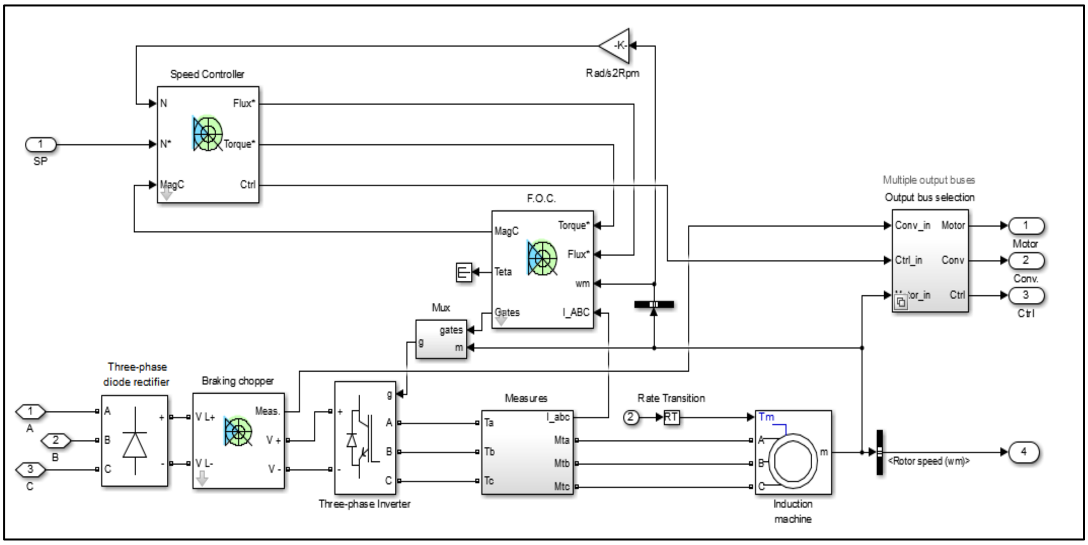


Figure 22: Field-Oriented Controller in Electric Locomotive

The main details of the parameters which used in FOC are shown by Figures 23, 24 and 25.

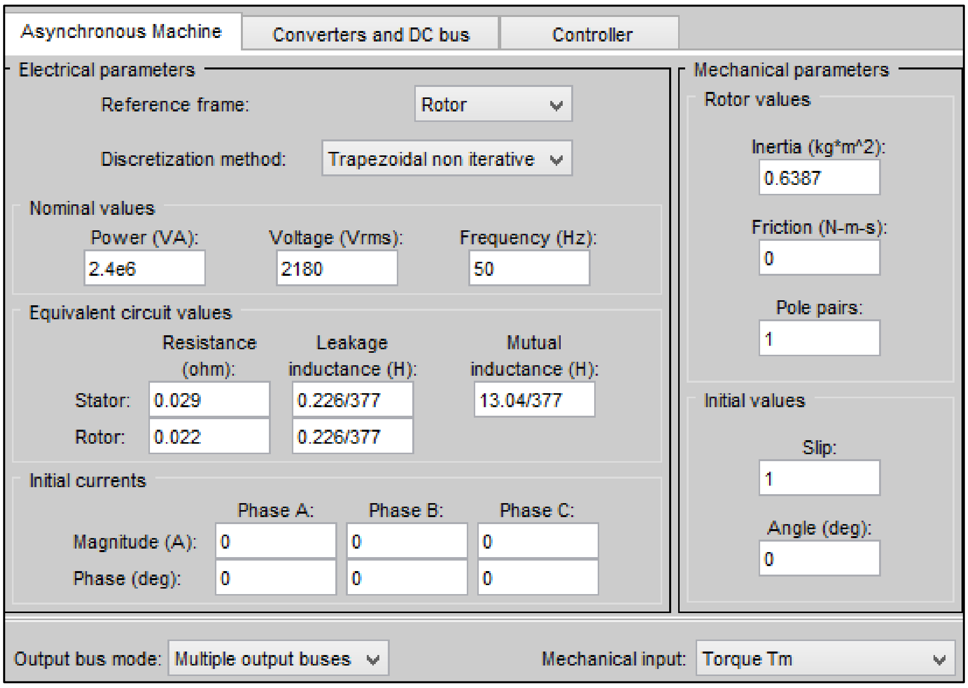


Figure 23: Set parameters of Field-Oriented Controller

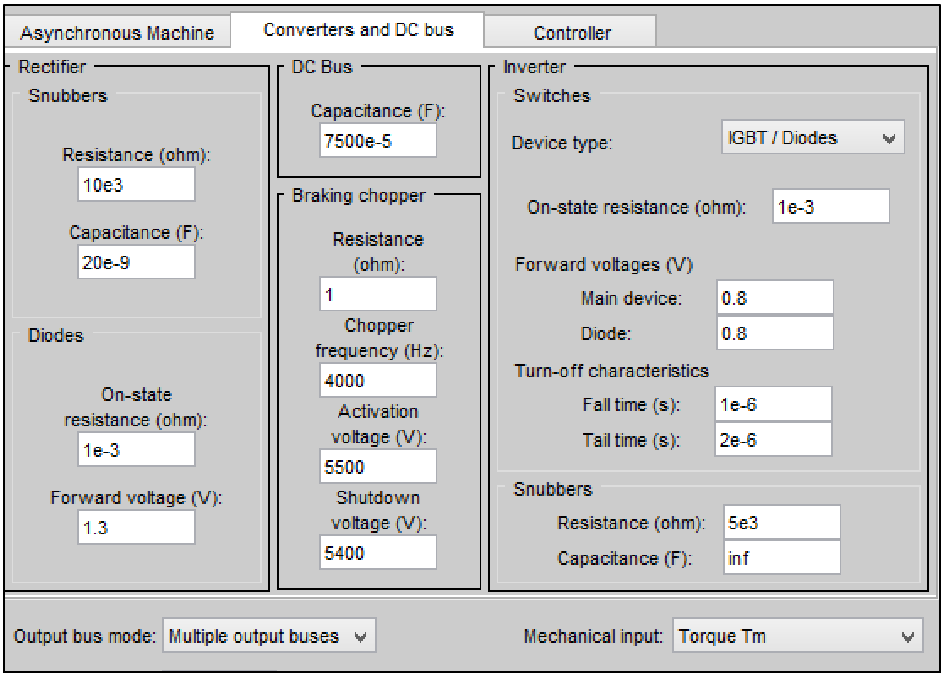


Figure 24: Set parameters of Field-Oriented Controller

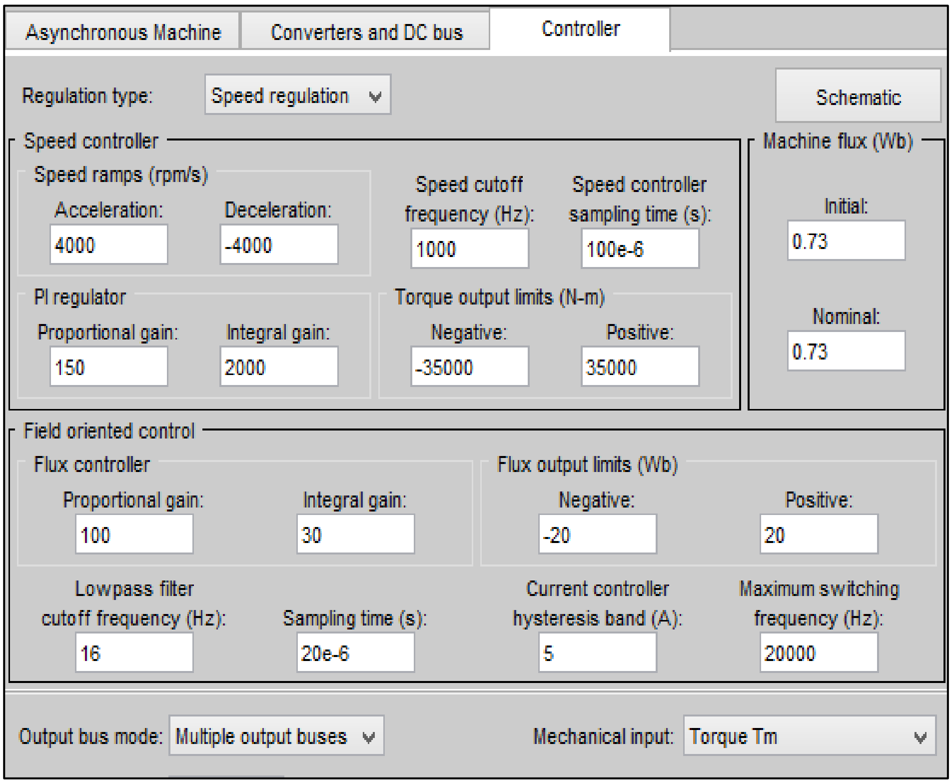


Figure 25: Set parameters of Field-Oriented Controller

The total Electric railway system is a combination of the models mentioned above as shown in Figure 20. This Simulink model of the overall railway system is shown in Figure 26.

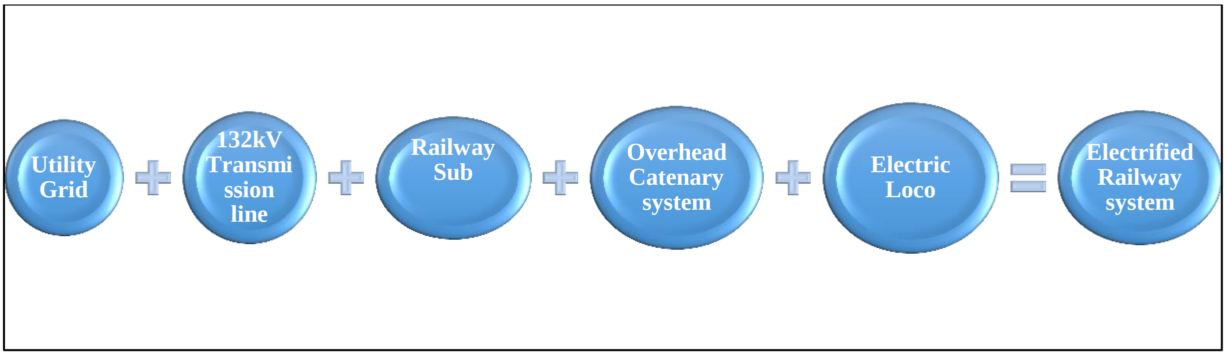


Figure 26: Total Electrified Railway System

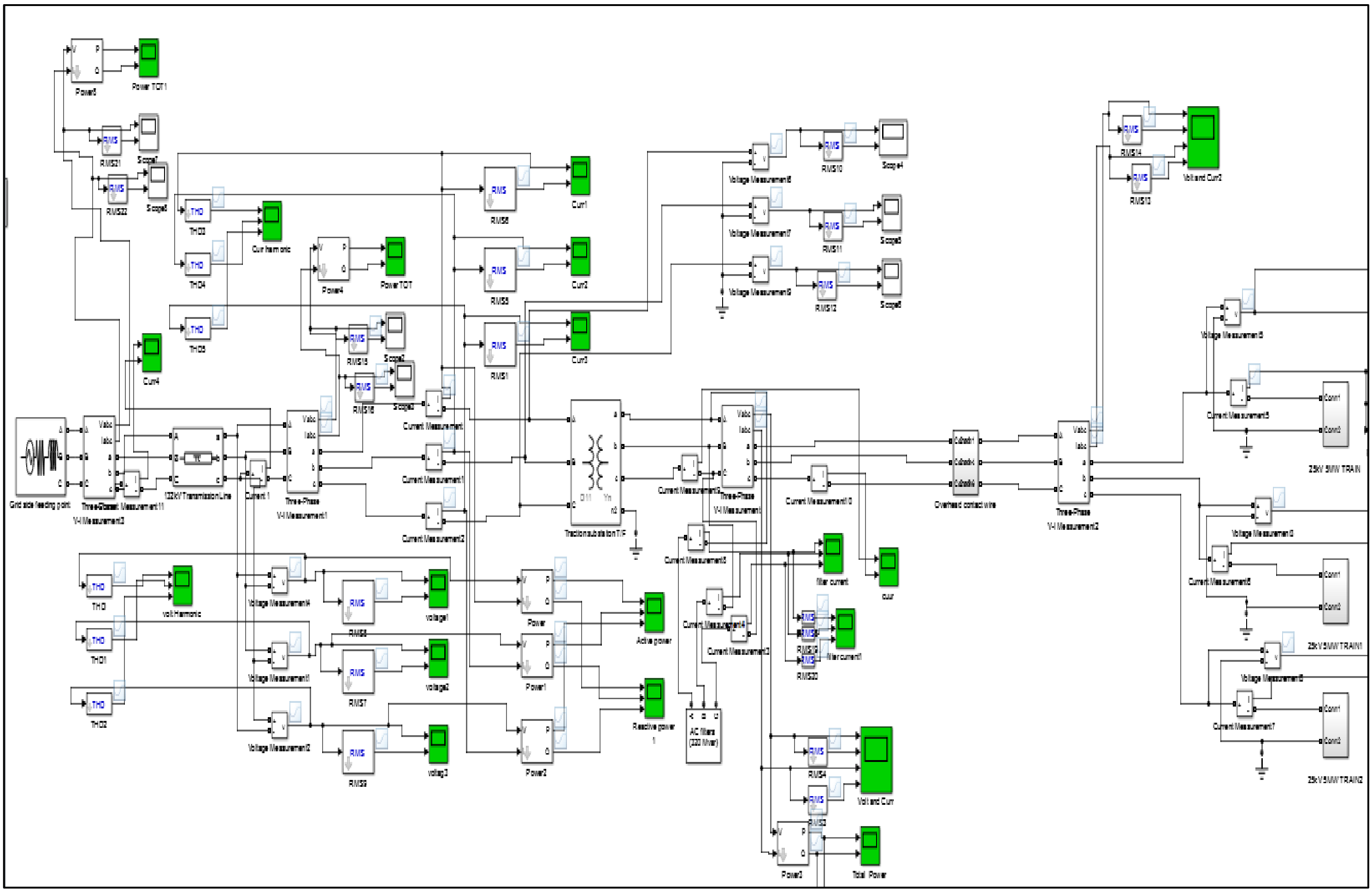


Figure 27: Mat Lab model of total Electrified Railway System

4.6 Harmonic Filter

A passive filter was modeled using MATLAB Simulink in order to mitigate the harmonics penetration to the utility grid.

The passive harmonic filter consists of inductors and capacitors which are passive elements. They can inject reactive power to help reactive power shortage situation and minimize harmonic interference in the system.

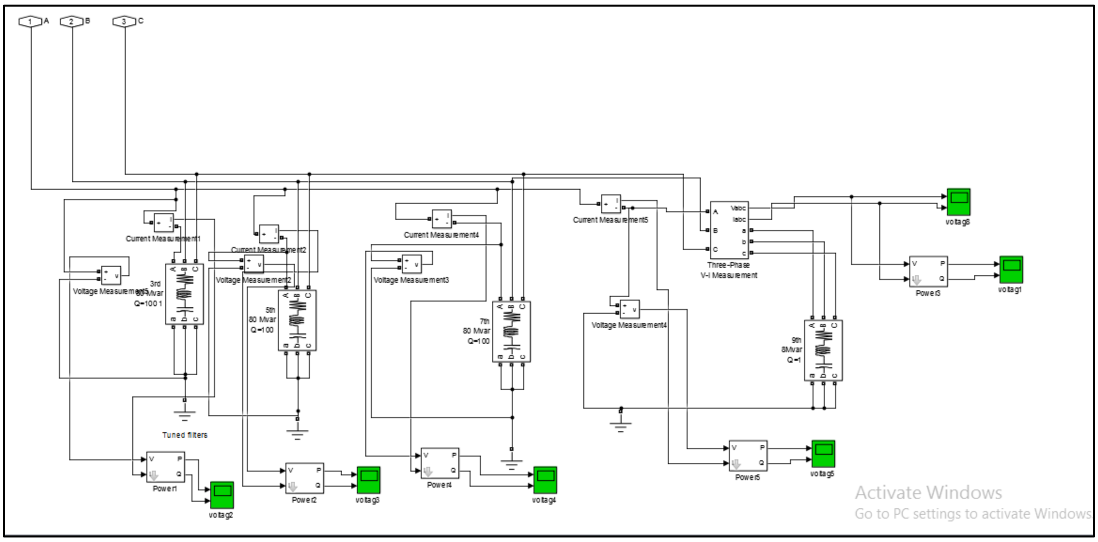


Figure 28: Harmonic Filter

RESULTS AND MODEL VALIDATION

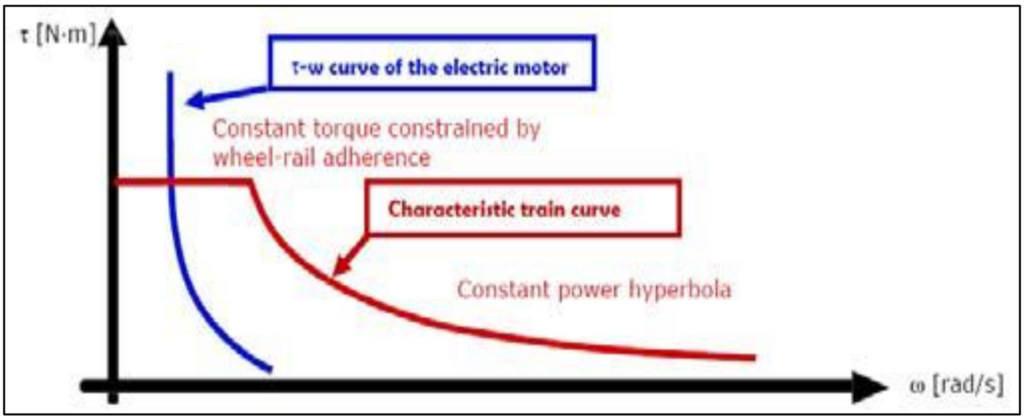
In this chapter Mat lab model is validated and results were obtained using following parameters of railway system to identify the power quality issues with respect to 25kV-50Hz, 15kV-16.7Hz, 15kV-50Hz voltage configurations.

- Active power requirement at grid interconnection point.
- Reactive power requirement at grid interconnection point.
- 132kV voltage drop at grid interconnection point.
- Current drawn from the 132kV transmission network.
- Current and voltage THD% at grid inter connection point.

5.1 Model Validation

5.1.1 Using characteristic curve of electric locomotives

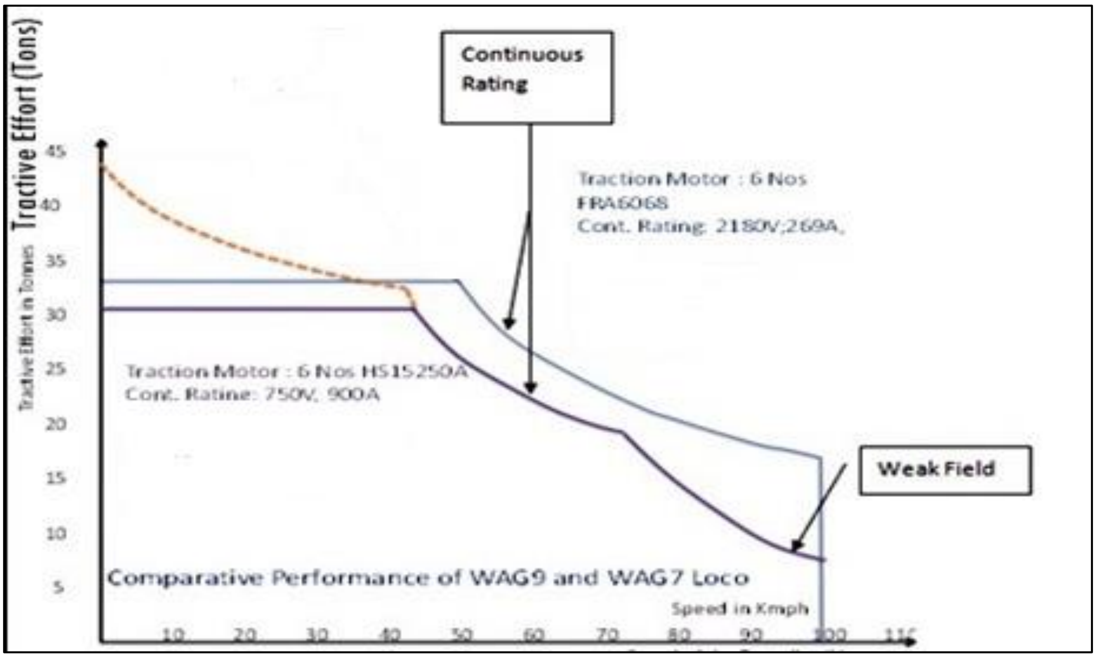
The ideal traction curve is a constant power hyperbole. It is said to be optimum for traction because if the motors had this operating curve their power could be put to full use, with large torques at low speeds and small torques at high speeds, as figure 29 shows.



Source [17], Figure 29: Ideal traction curve

Mat lab model for the electric loco motive was validated using the characteristic curve for the electric train using the test report data of Indian railway.

According to the literatures of Indian railway (WAG-9) performance analyzing reports, the characteristic curve for the WAG 7 and WAG-9 trains are shown in below Figure. [14, 15, 16]



Source [18] Figure 30: Traction curve of WAG7 and WAG 9

In order to obtain traction curve for the developed Mat lab train model, traction effort was change from 1000 N to 6000 N (maximum tractive force for 900kW motor) and recorded the maximum rpm that can reach by the motor. The results are shown in Table 10.

Table 10 : The obtain rpm for selected torque values

Torque (N)	rpm
1000	7100
1500	5425
1700	5187
2000	4664
2200	4538
2500	4200
3000	3812
4000	3340
5000	2740

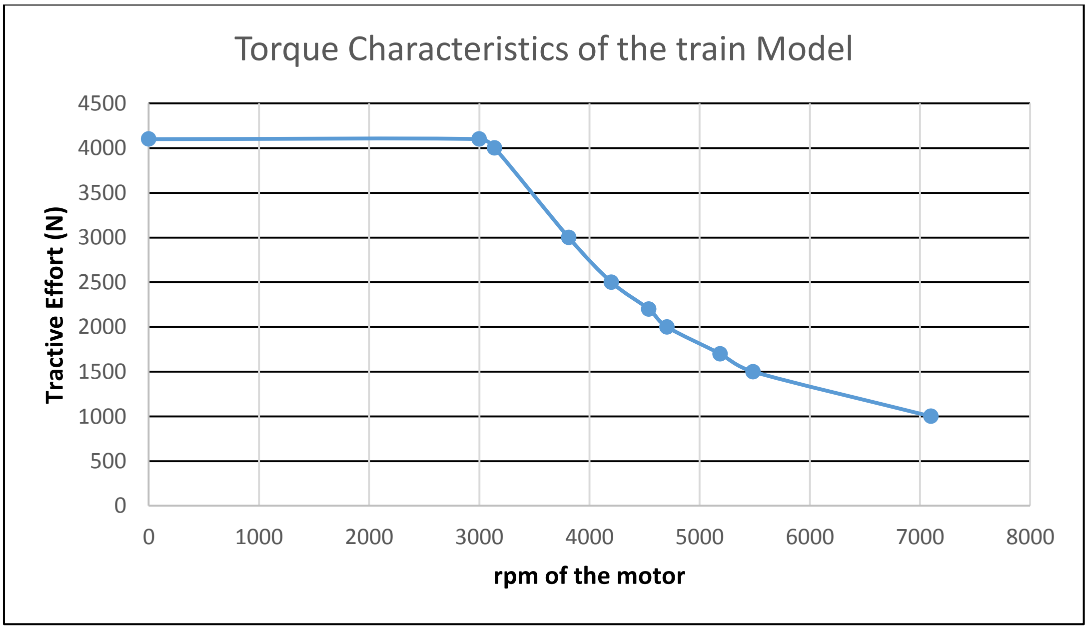


Figure 31: Torque characteristics of the train Model

According to the above Figure, the obtain torque characteristics curve is similar with the actual torque speed characteristic curve of Indian railway (WAG-9) performance analyzing reports in Figure 30.Therefore, the developed model will be valid as a AC electric train model for the further analysis.

5.1.2 Result verification for a single train

Simulate Mat lab model of a single train with different voltage configurations to identify the parameters will be within the acceptable regions for an electrified train before considering further analysis. For this analysis train No: 8310 was selected and feeding from Dehiwala substation and results were compared with the real time data of the Indian railway systems.

Table 11 : Data of train model verification

Train	Location	Feeding substation
No 8310	10 km away	Dehiwala

5.1.2.1 Motor parameter variation for one bogie of the train

The speed variation in the startup and the stop , total stator current variation for 03 800kW induction motors in a single bogie and dc bus voltage variation and electromagnetic torque variations are shown in following Figures.

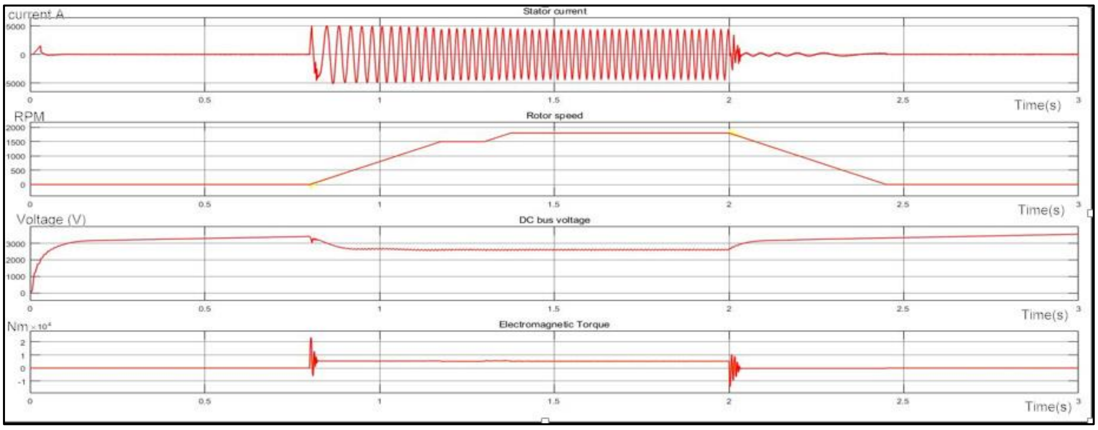


Figure 32: 25kV/50Hz system

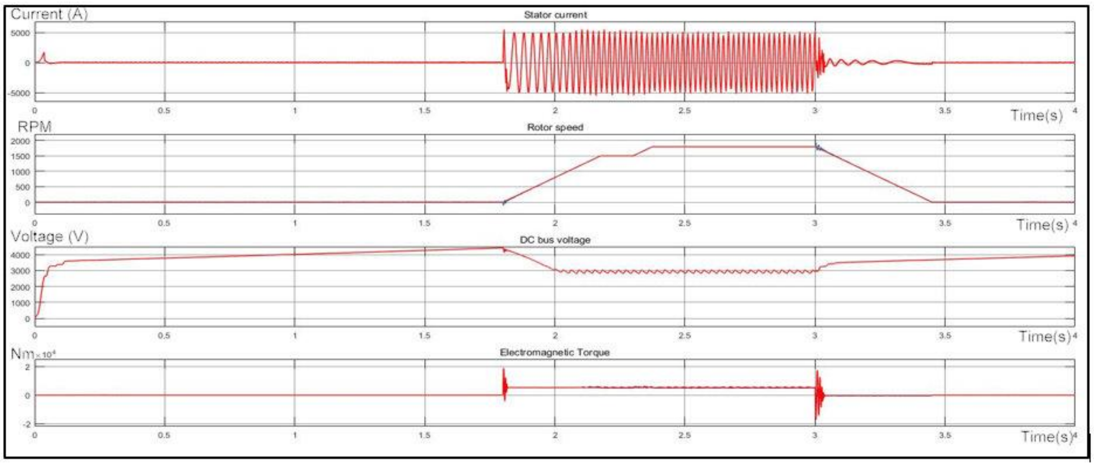


Figure 33: 15kV/16.7Hz system

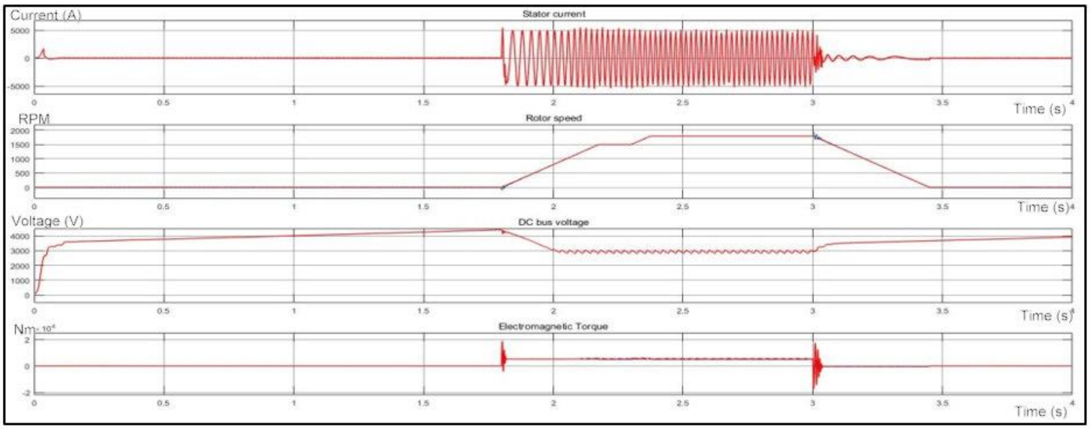


Figure 34: 15kV/50Hz system

5.1.2.2 Active and reactive power variation

The active power requirement of electric locomotive of same ratings is around 5-6 MW in full load operation and the simulation results of active power variation around within 5.5-6 MW range and reactive power requirement is within 1 -1.5 Mvar range for all configurations as shown in following Figures.[14,15,16]

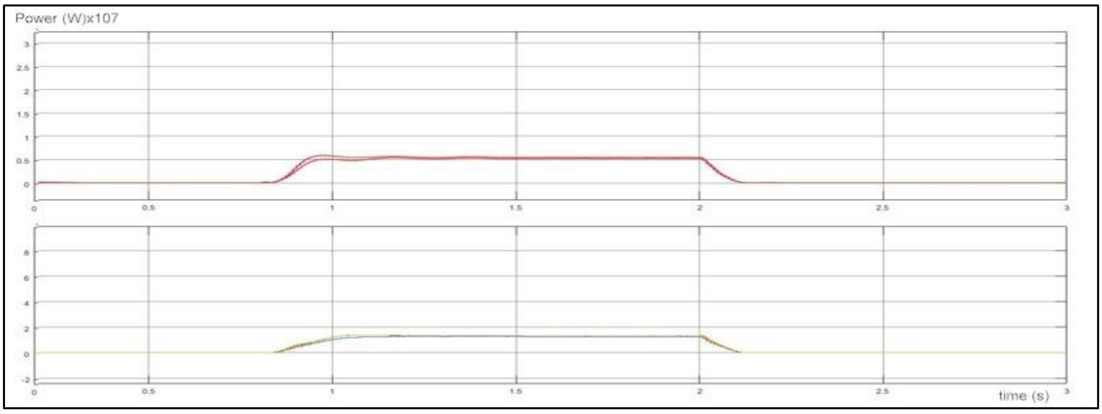


Figure 35: 25kV/50Hz system

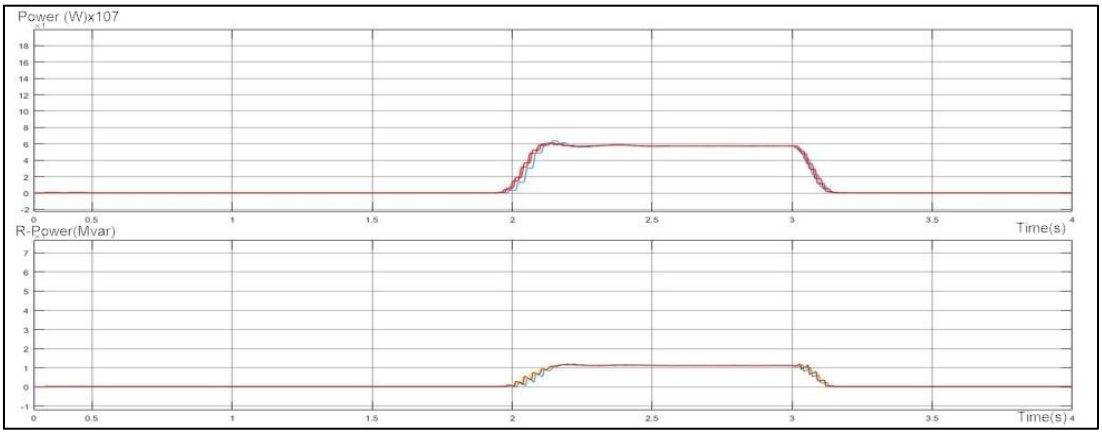


Figure 36: 15kV/16.7Hz system

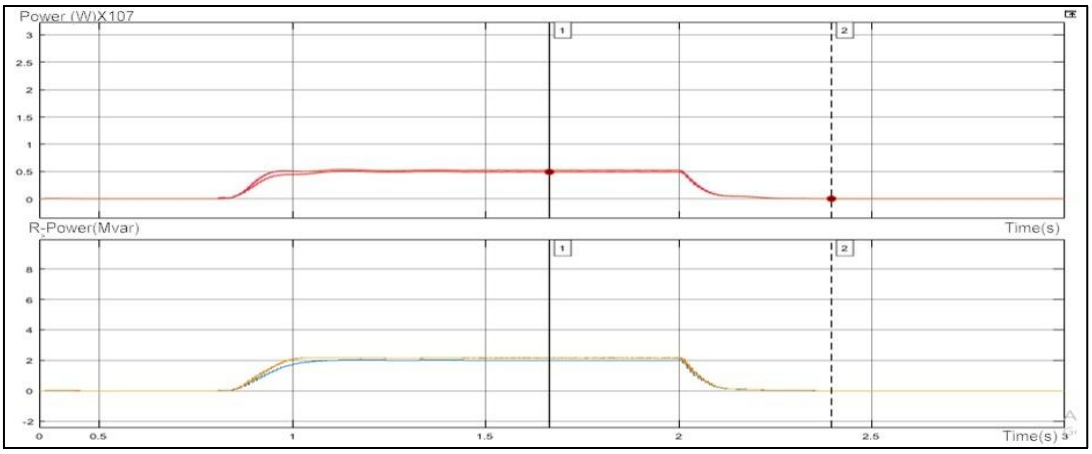


Figure 37: 15kV/50Hz system

5.1.2.3 132 kV voltage variation

The voltage drops in 132kV transmission network for operating a single train are 435V, 320V and 798V respectively as shown in following Figures.

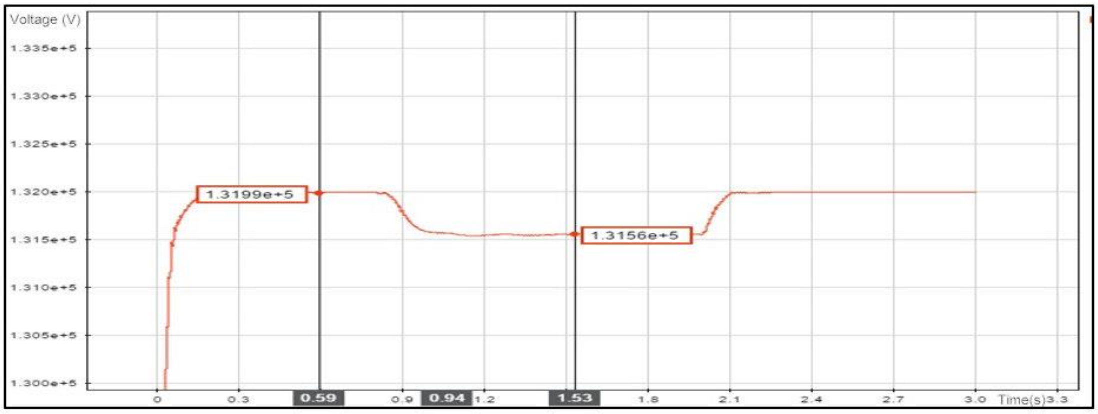


Figure 38: 25kV/50Hz system

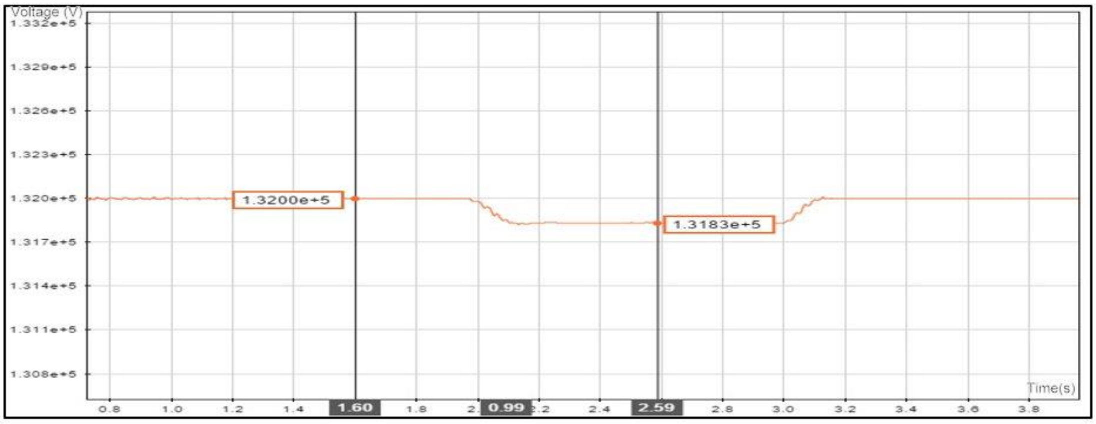


Figure 39: 15kV/16.7Hz system

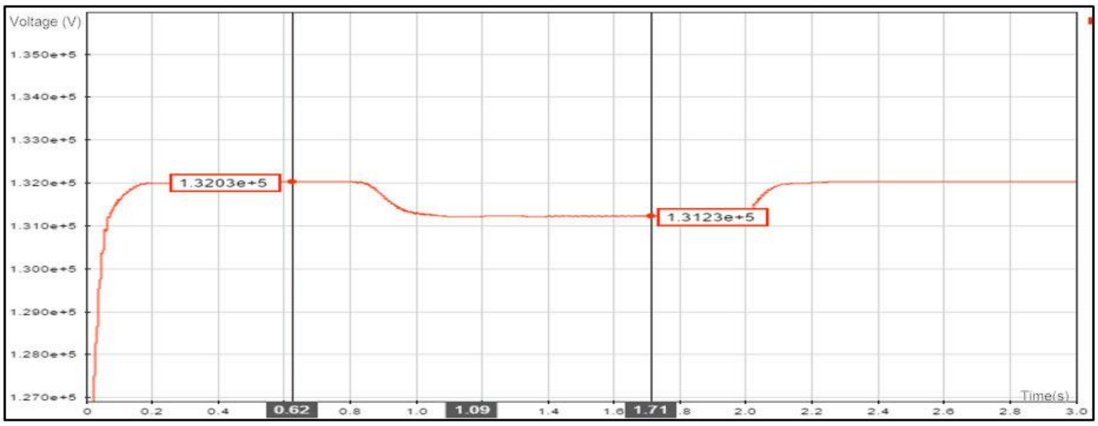


Figure 40: 15kV/50Hz system

5.1.2.4 132kV line current variation

The Current in 132kV transmission network for operation of single train are 53A, 48.03A and 50.7A respectively as shown in following Figures.

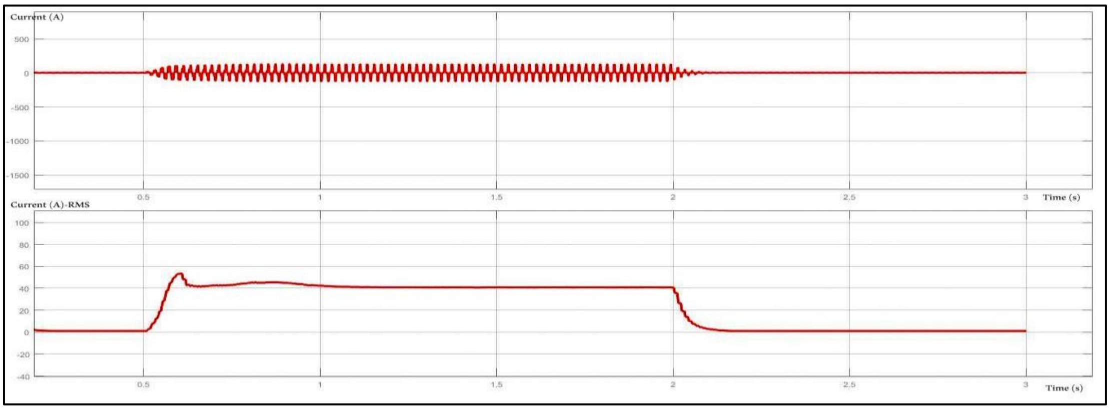


Figure 41: 25kV/50Hz system

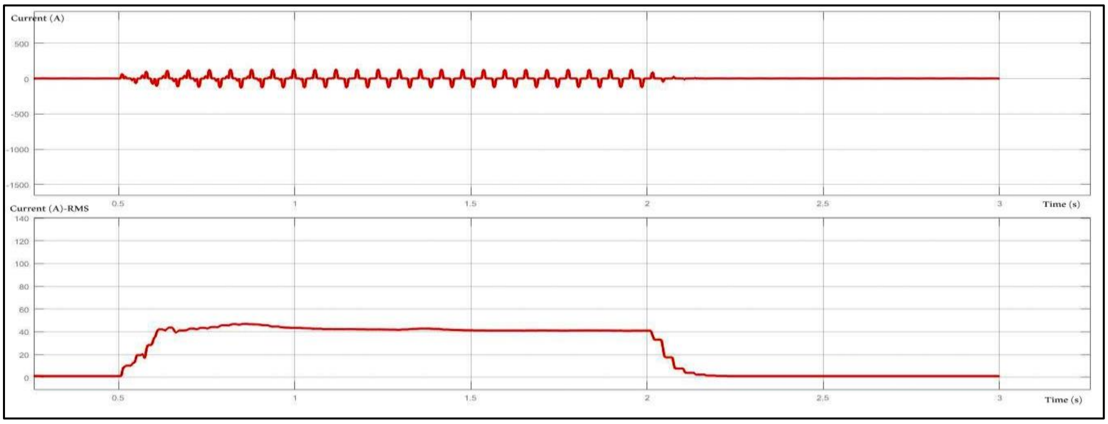


Figure 42: 15kV/16.7Hz system

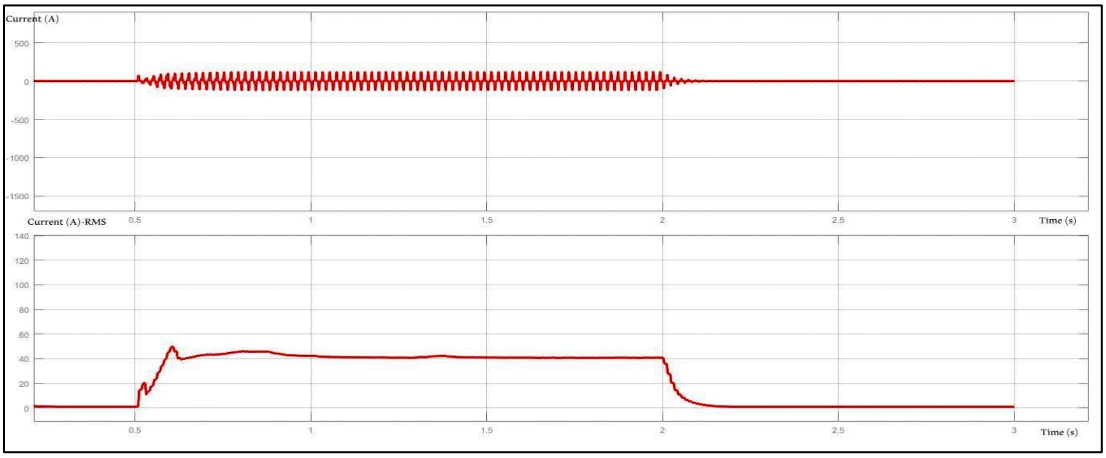


Figure 43: 15kV/50Hz system

5.1.2.5 Total harmonic distortion of current in transmission side

The total harmonic distortion of current in 132kV transmission network for single train is shown in following Figures. According to the results, the THD% is less than 10% at both accelerating and de-accelerating of the train which is in acceptable region for a power system.

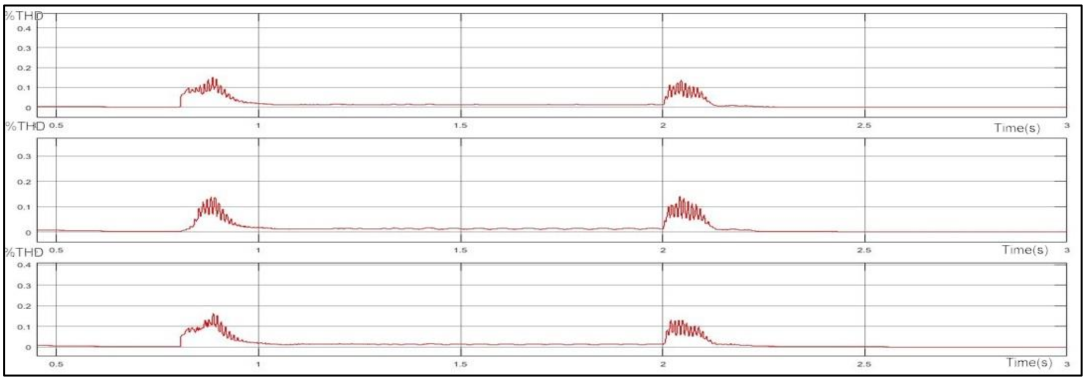


Figure 44: 25kV/50Hz system

Table 12 : THD in current at 132kV transmission line for 25kV/50Hz system

Harmonic order	Accelerating t=0.9s	Constant speed t= 1.5s	De-accelerating t=2.05s
THD%	5.01%	1.22%	5.4%
3rd %	3.74%	0.27%	1.93%
5th	1.98%	0.8%	2.71%
7th	0.54%	0.09%	0.5%
9th	0.27%	0.03%	0.32%
11th	0.19%	0.35%	0.66%

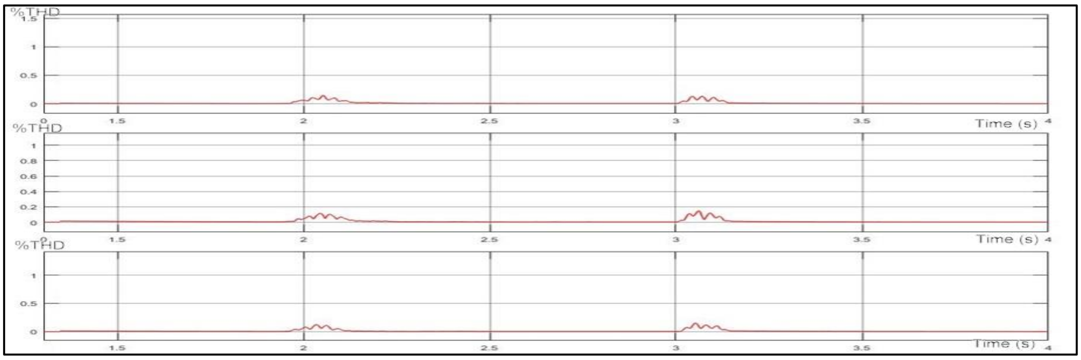


Figure 45: 15kV/16.7Hz system

Table 13: THD in current at 132kV transmission line for 15kV/16.7Hz system

Harmonic order	Accelerating t=2s	Constant speed t= 2.5s	De-accelerating t=3s
THD%	9.86%	0.35%	7.76%
3rd	4.57%	0.05%	2.14%
5th	0.89%	0.21%	1.19%
7th	1.11%	0.01%	0.80%
9th	0.97%	0.01%	0.54%
11th	0.68%	0.13%	0.42%

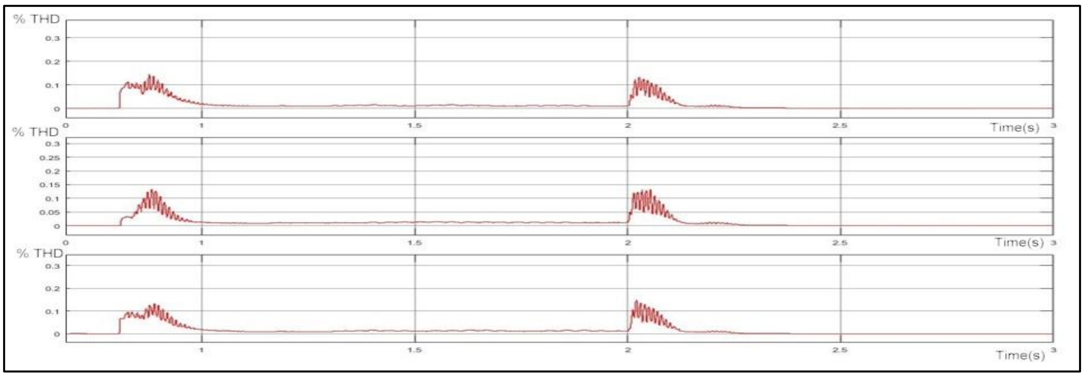


Figure 46: 15kV/50Hz system

Table 14: THD in current at 132kV transmission line for 15kV/50Hz system

Harmonic order	Accelerating t=0.9s	Constant speed t= 1.5s	De-accelerating t=2.05s
THD%	5.98%	1.15 %	4.94%
3^{rd}	4.96%	0.22%	1.51%
5^{th}	1.31%	0.56%	0.81%
7^{th}	0.68%	0.10%	0.77%
9^{th}	0.42%	0.09%	0.45%
11^{th}	0.66%	0.42%	0.78%

5.1.2.6 Total harmonic distortion of voltage in transmission side

The total harmonic distortion of voltage in 132kV transmission network for single train is shown in following figures. According to the results, the THD% is less than 10% at both accelerating and de-accelerating of the train which is in acceptable region for a power system.

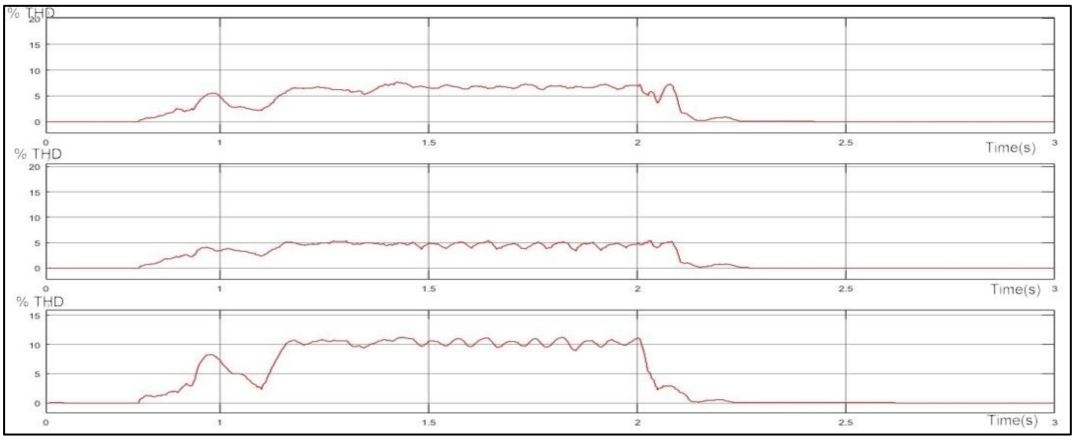


Figure 47: 25kV/50Hz system

Table 15 : THD in voltage at 132kV transmission line for 25kV/50Hz system

Harmonic order	Accelerating t=0.9s	Constant speed t= 1.5s	De-accelerating t=2.05s
THD %	0.22%	0.65%	0.70%
3rd	0.04%	0	0.01%
5th	0.03%	0.02%	0.03%
7th	0.01%	0.01%	0.01%
9th	0.01%	0	0
11th	0.01%	0.02%	0.02%

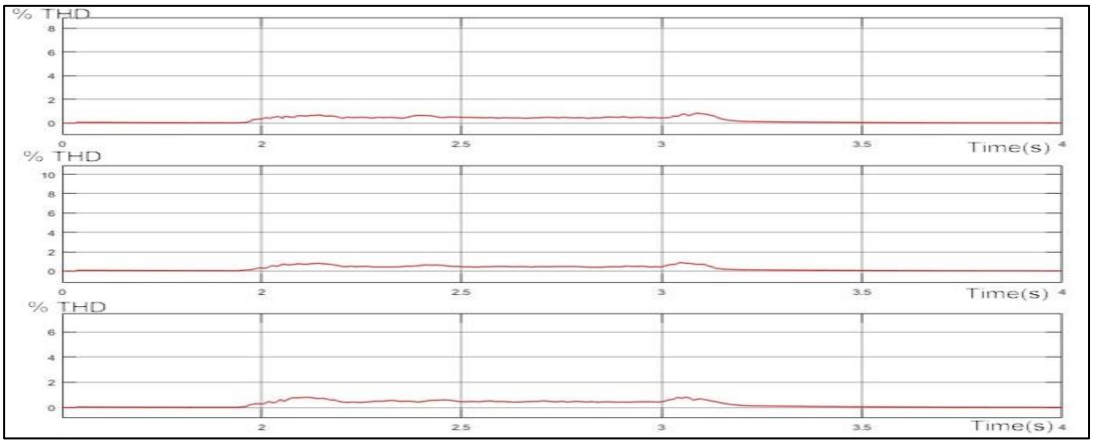


Figure 48: 15kV/16.7Hz system

Table 16: THD in voltage at 132kV transmission line for 15kV/16.7Hz system

Harmonic order	Accelerating t=2s	Constant speed t= 2.5s	De-accelerating t=3s
THD%	0.06%	0.05%	0.07%
3rd	0.03%	0	0.02%

5^{th}	**0.02%**	**0**	**0.01%**
7^{th}	**0.01%**	**0**	**0**
9^{th}	**0.01%**	**0**	**0**
11^{th}	**0.01%**	**0**	**0.01**

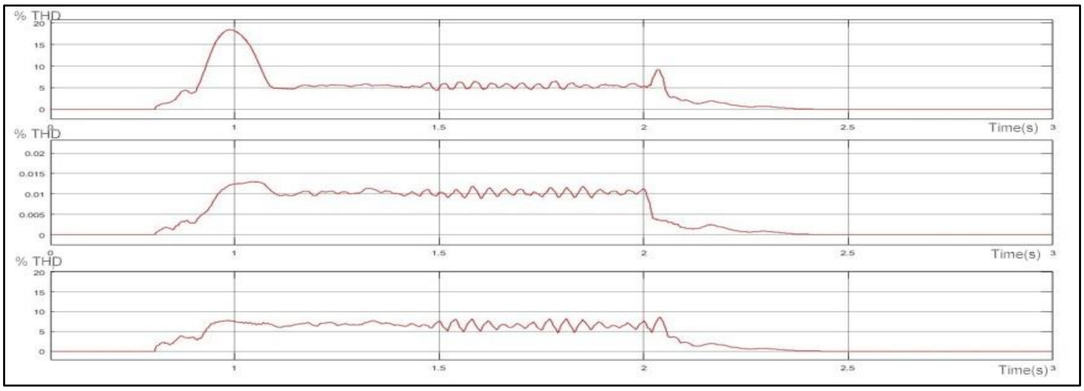


Figure 49: 15kV/50Hz system

Table 17: THD in voltage at 132kV transmission line for 15kV/50Hz system

Harmonic order	**Accelerating t=0.9s**	**Constant speed t= 1.5s**	**De-accelerating t=2.05s**
THD%	**0.72%**	**0.56%**	**0.28%**
3^{rd}	**0.06%**	**0.01%**	**0.01%**
5^{th}	**0.01%**	**0.02%**	**0.01%**
7^{th}	**0.01%**	**0.01%**	**0.01%**
9^{th}	**0.01%**	**0.0%**	**0%**
11^{th}	**0.02%**	**0.04%**	**0.02%**

5.2 Results

Simulate Mat lab model for critical times according to railway time table as shown in table 18 and 25 for different voltage-frequency configurations of 25kV-50Hz ,15kV-16.7Hz and 15kV-50Hz .The obtain parameters were analyzed to identify the different power quality issues related to the different configurations . The following criteria was used to obtain and analyzing the results.

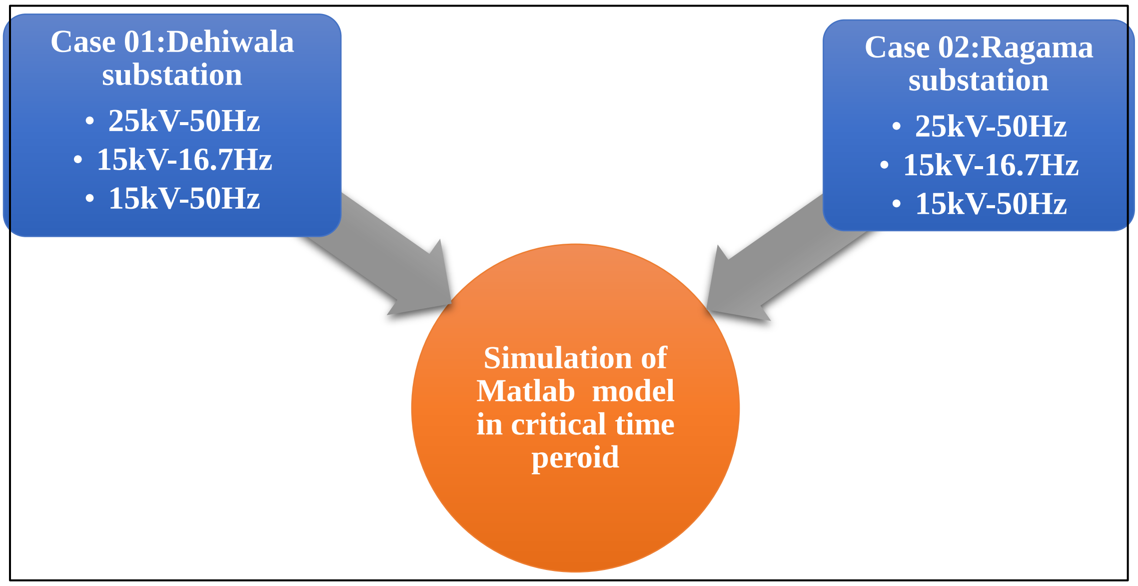


Figure 50: Simulate Mat Lab model with different configurations.

5.2.1 Case 01 : Dehiwala Railway Substation

The Mat lab model was simulated with the identified critical situation within the time table of Panadura to Maradana sector as shown in following Table.

Table 18: Train status in critical time in dehiwala substation

Train No	Time	Location	Feeding station	Distance (km)	Status
8310	07:06	Moratuwa	Dehiwala	11km	Slowdown
8317	07:06	Bambalapitiya	Dehiwala	4.5km	Slowdown

8316	7:06	Mt-lavinia	Dehiwala	2.5km	Accelerating
8320	7:06	Angulana	Dehiwala	6km	Full speed
8063	7:06	Egodauyana	Dehiwala	13km	Full speed
8324	7:06	Panadura	Dehiwala	16.3km	Stop
8327	7:06	Panadura	Dehiwala	16.5km	Accelerating
8324	7:06	Moratuwa	Dehiwala	9km	Slowdown
8723	7:06	Seceratary office	Dehiwala	9.5km	Slowdown
8050	7:06	Bambalapitiya	Dehiwala	5km	Full speed

In this simulation, critical time period 07:06 hrs is represent at 2s point of the time axis for 50Hz and 3s for 16.7Hz .Therefore the variations of the selected parameters before and after the 2s is consider for 50Hz systems and the variations of the selected parameters before and after the 3s is consider for 16.7Hz systems in this study.

5.2.1.1 Active and reactive power variation

The active power and reactive power variation for 25kV/50Hz voltage configuration around 07:06 hrs are shown in following Figures 51 and 52.

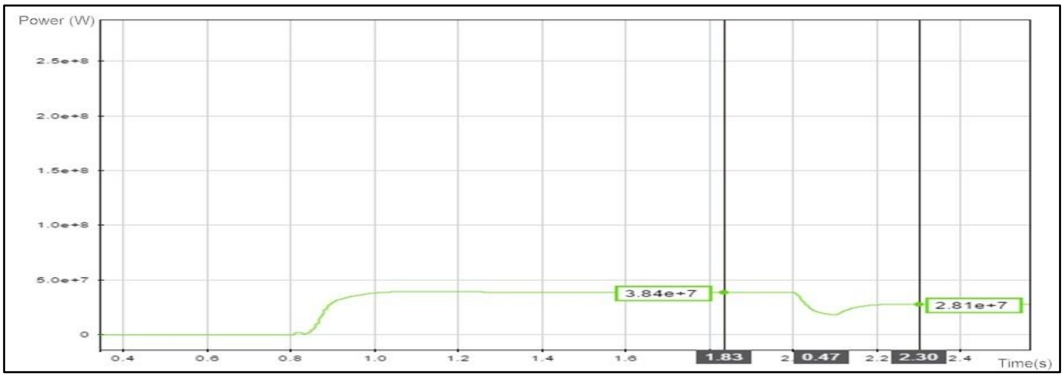


Figure 51: Active power variation -25kV/50Hz system

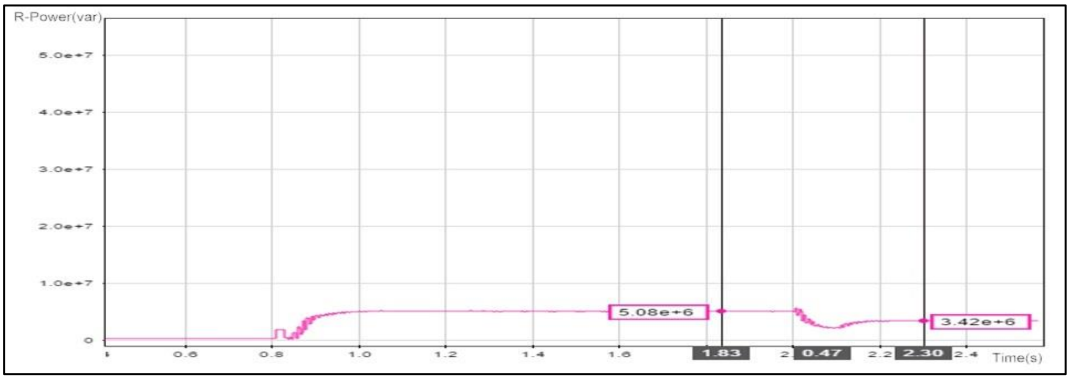


Figure 52: Reactive power variation -25kV/50Hz system

The active power variation at 2s is 38.443MW to 27.986MW and reactive power variation at 2s is 5.057Mvar to 3.374Mvar.The maximum active power requirement is 38.43MW and maximum reactive power requirement is 5.05 Mvar.

The active power and reactive power variation for 15kV/16.7Hz voltage configuration around 07:06 hrs are shown in following Figures 53 and 54.

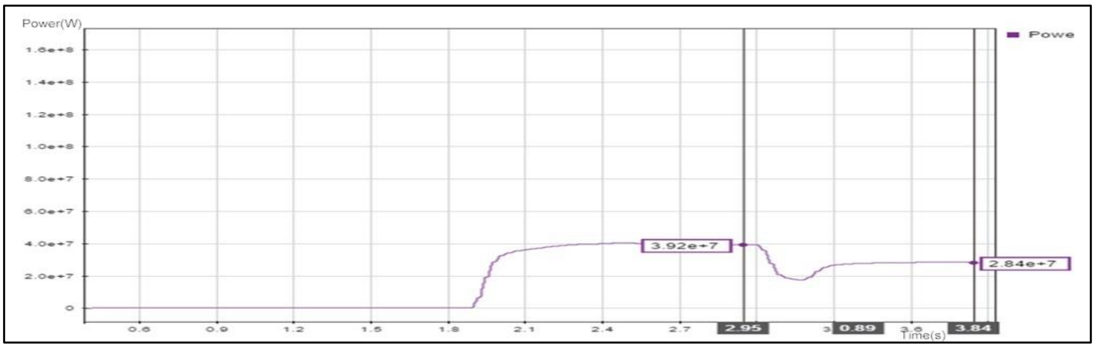


Figure 53: Active power variation 15kV/16.7Hz system

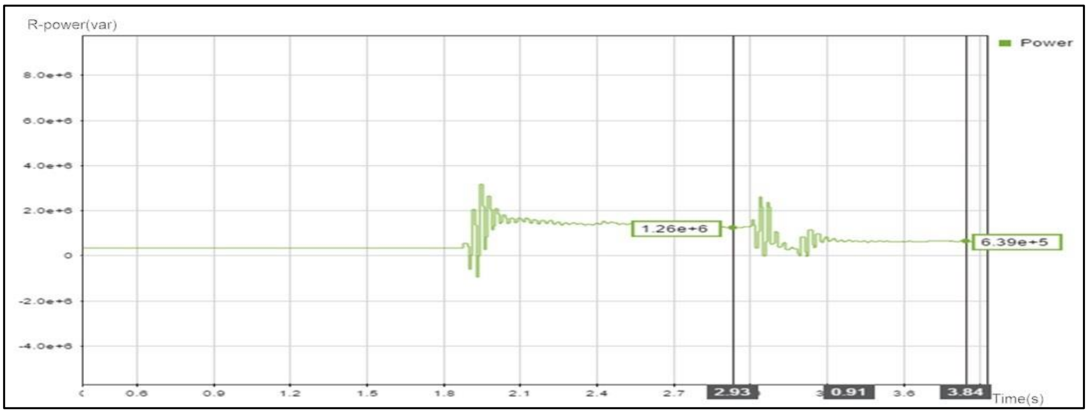


Figure 54: Reactive power variation 15kV/16.7Hz system

The active power variation at 3s is 39.173MW to 28.43MW and reactive power variation at 3s is 1.25Mvar to 0.64Mvar. .The maximum active power requirement is 39.17MW and maximum reactive power requirement is 1.25 Mvar.

The active power and reactive power variation for 15kV/50Hz voltage configuration around 07:06 hrs are shown in following Figures 55 and 56.

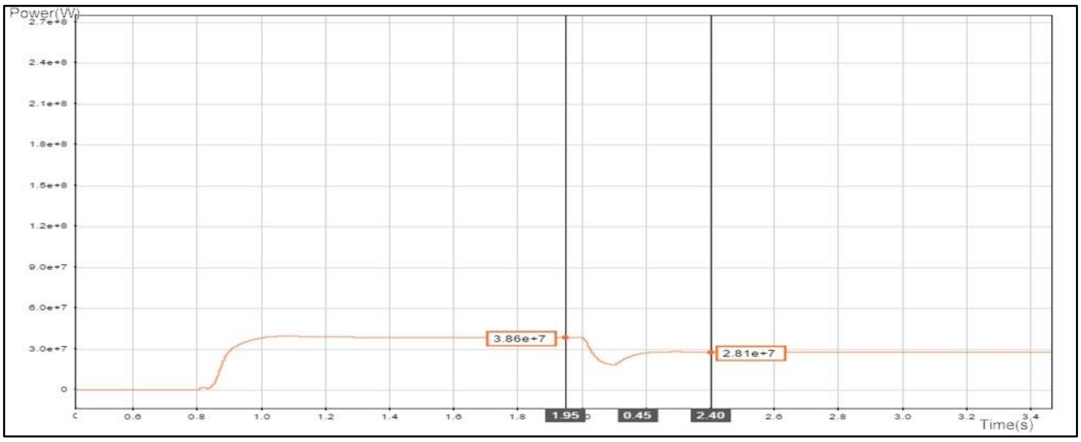


Figure 55: Active power variation of 15kV/50Hz system

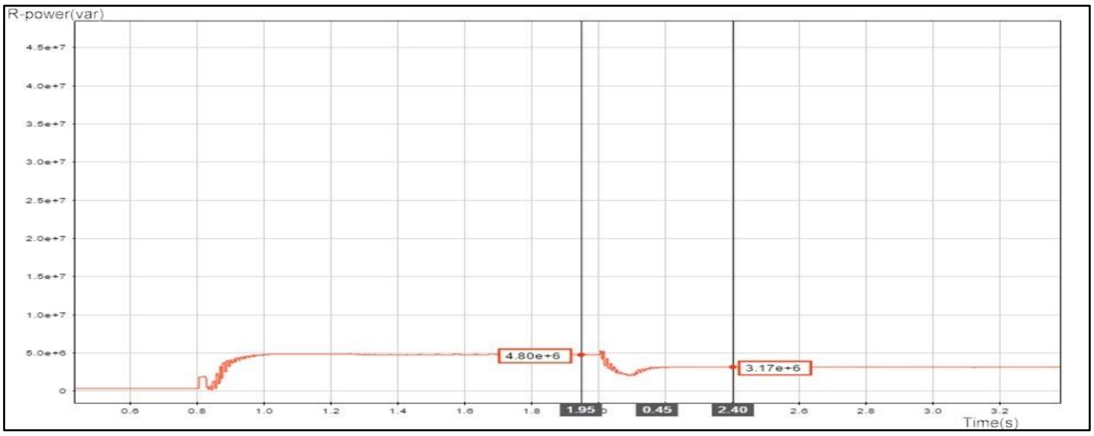


Figure 56: Reactive power variation of 15kV/50Hz system

The active power variation at 2s is 38.64MW to 28.14MW and reactive power variation at 2s is 4.80Mvar to 3.17Mvar. The maximum active power requirement is 38.64MW and maximum reactive power requirement is 4.80 Mvar.

5.2.1.2 132 kV voltage variation

The voltage variations in 132kV transmission network in critical time are shown in following Figures.

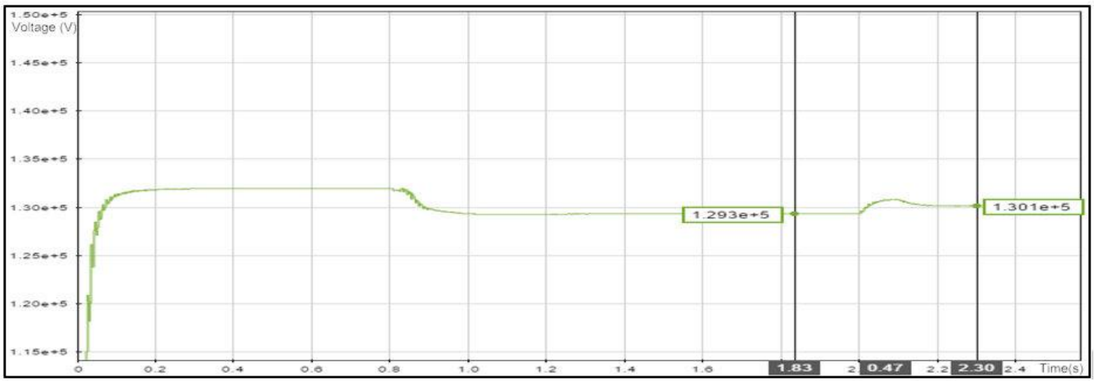


Figure 57: 25kV/50Hz system

The Voltage drop is 2.65kV and 132kV line voltage dropped to 129.346kV.

Figure 58: 15kV/16.7Hz system

The Voltage drop is 0.89kV and 132kV line voltage dropped to 131.111kV.

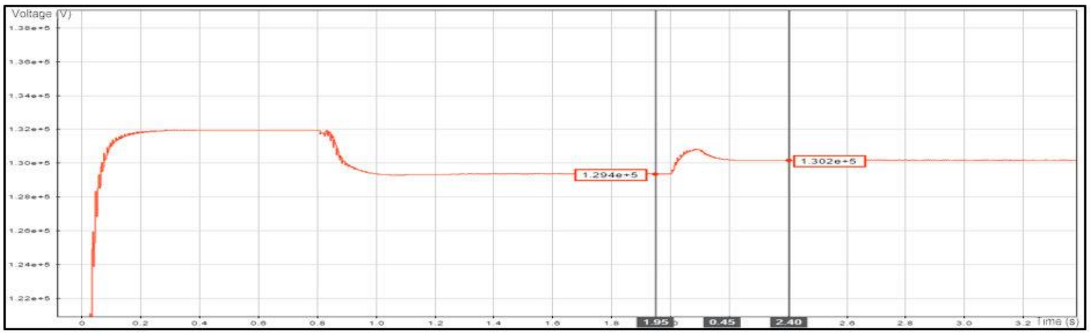


Figure 59: 15kV/50Hz system

The Voltage drop is 2.63kV and 132kV line voltage dropped to 129.368kV.

5.2.1.3 132kV line current variation

The current variations in 132kV transmission network in critical time are shown in following Figures.

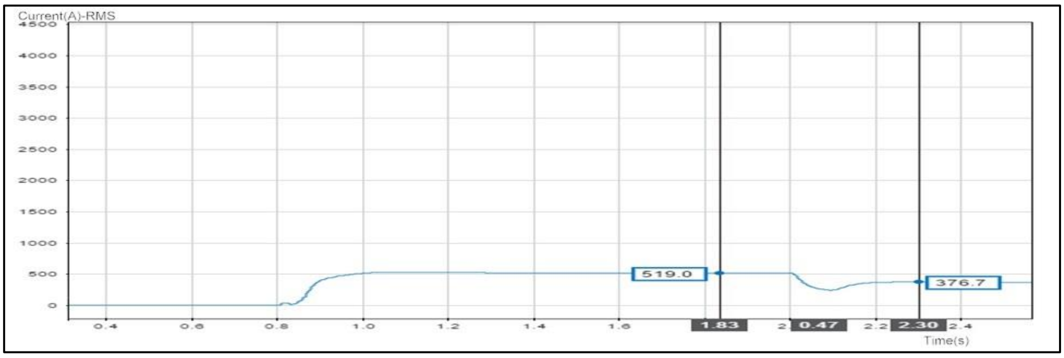


Figure 60: 25kV/50Hz system

The maximum current in 132kV transmission line is 519.227A.

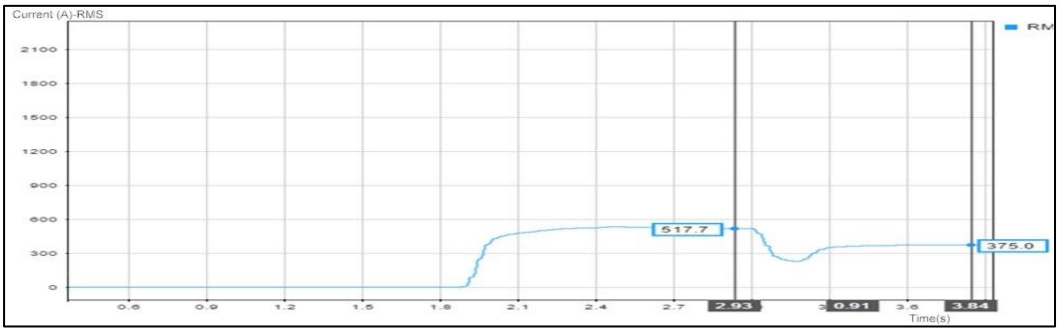


Figure 61: 15kV/16.7Hz system

The maximum current in 132kV transmission line is 517.71A.

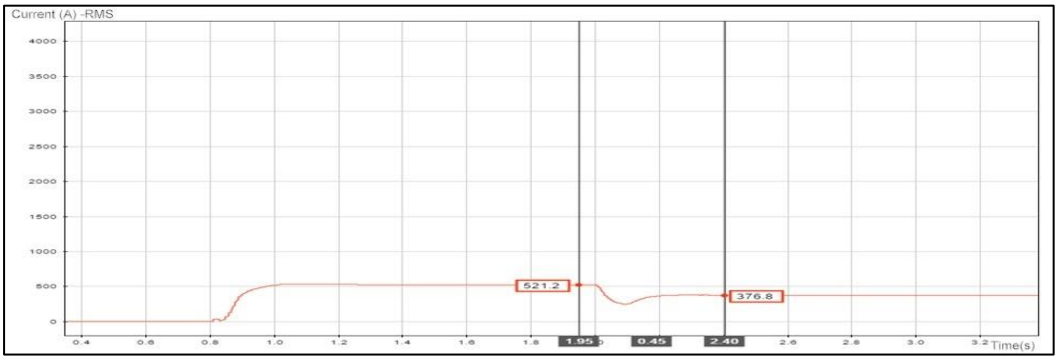


Figure 62: 15kV/50Hz system

The maximum current in 132kV transmission line is 521.32 A.

5.2.1.4 Total harmonic distortion of current in transmission side

The total harmonic distortions of current in 132kV transmission network are shown in following figures. According to the results, the THD% is less than 10% in critical time period.

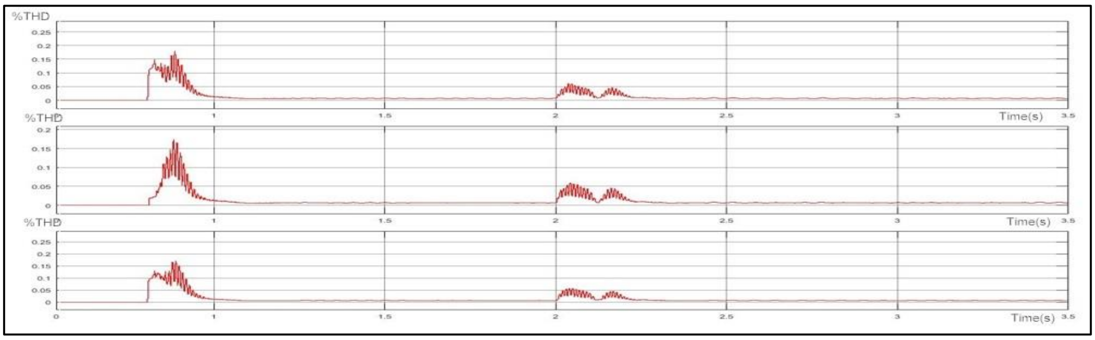


Figure 63: 25kV/50Hz system

Table 19 : THD in current at 132kV transmission line for 25kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	0.58%	4.27%

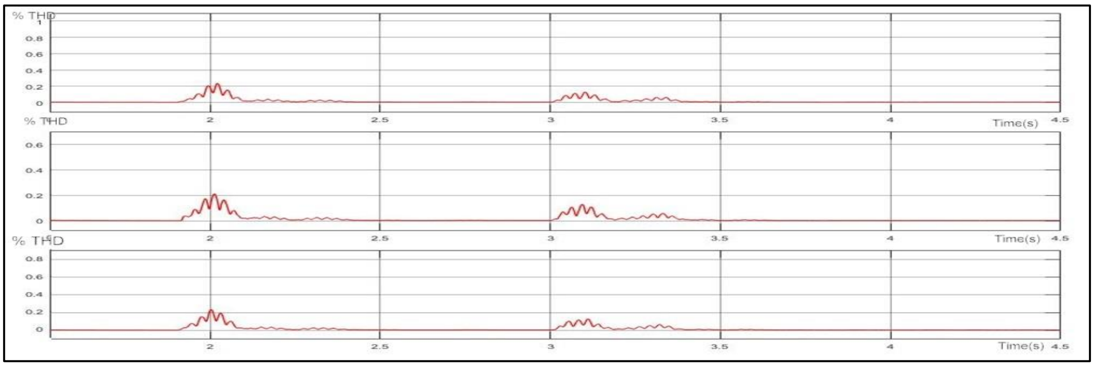


Figure 64: 15kV/16.7Hz system

Table 20: THD in current at 132kV transmission line for 15kV/16.7Hz system

	Just before 3s (t=2.9s)	Just after 3s (t=3.05s)
Maximum THD%	0.49%	5.27%

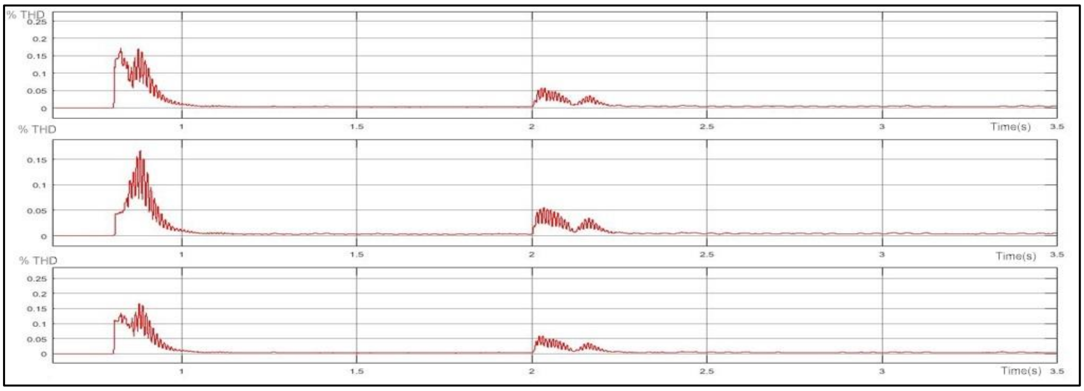


Figure 65: 15kV/50Hz system

Table 21: THD in current at 132kV transmission line for 15kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	**0.39%**	**4.71%**

5.2.1.5 Total harmonic distortion of voltage in 132kV transmission network side

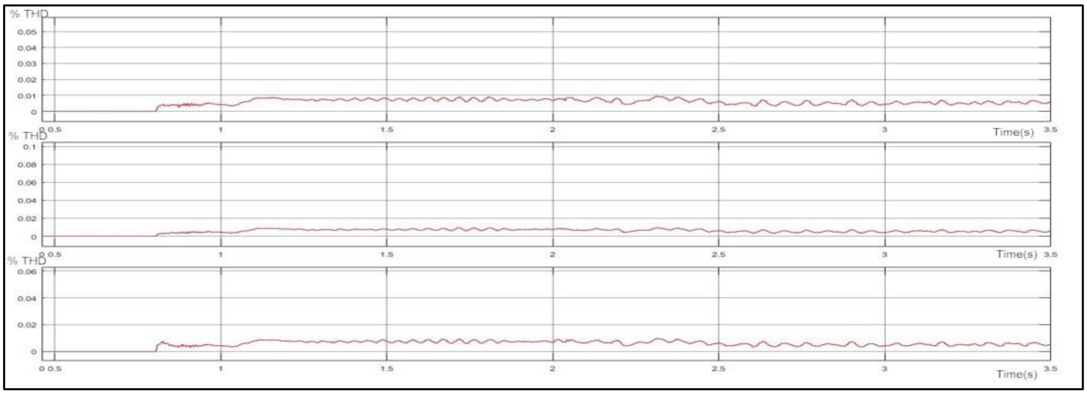


Figure 66: 25kV/50Hz system

Table 22 : THD in voltage at 132kV transmission line for 25kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	**0.66%**	**0.76%**

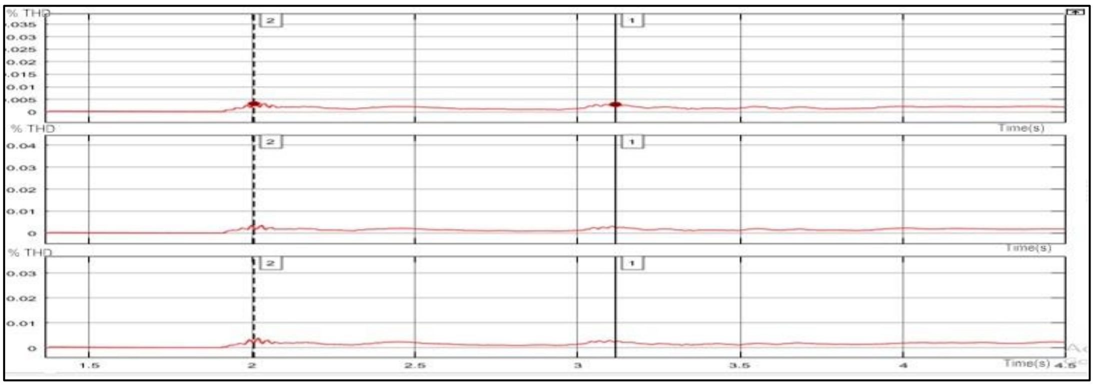


Figure 67: 15kV/16.7Hz system

Table 23: THD in voltage at 132kV transmission line for 15kV/16.7Hz system

	Just before 3s (t=2.9s)	Just after 3s (t=3.05s)
Maximum THD%	**0.17%**	**0.32%**

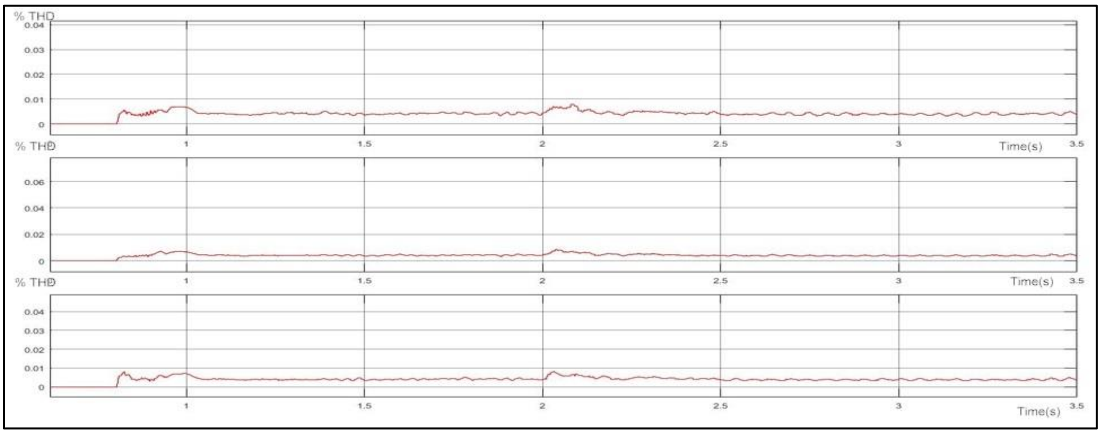


Figure 68: 15kV/50Hz system

Table 24: THD in voltage at 132kV transmission line for 15kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	**0.39%**	**0.6%**

5.2.2 Case 02 : Ragama Railway Substation

The Mat lab model was simulated with the identified critical situation within the time table of Colombo Fort to Veyangoda sector as shown in following Table.

Table 25: Train status in critical time in Ragama substation

Train No	Time	Location	Feeding station	Distance (km)	Status
1020	18:19	Ganemulla	Ragama	7 km	Full speed
1006	18:19	Bemmulla	Ragama	16.3 km	Full speed
1581	18:19	Dematagoda	Ragama	11.5 km	Slowdown
1577	18:19	Hunupitiya	Ragama	5.5 km	Accelerating
1569	18:19	Veyangoda	Ragama	21.7 km	Accelerating
1173	18:19	Veyangoda	Ragama	22 km	Slowdown
1039	18:19	Gampaha	Ragama	12 km	Slowdown
1578	18:19	Gampaha	Ragama	11.9 km	Slowdown
1176	18:19	Ragama	Ragama	0.5 km	Accelerating
1177	18:19	Maradana	Dehiwala	Different feeder	Slowdown
4078	18:19	Kelaniya	Ragama	8.67 km	Full speed

In this simulation, critical time period 18:19 hrs is represent at 2s point of the time axis for 50Hz and 3s for 16.7Hz .Therefore the variations of the selected parameters before and after the 2s is consider for 50Hz systems and the variations of the selected parameters before and after the 3s is consider for 16.7Hz systems in this study.

5.2.2.1 Active power variation

The active power and reactive power variation for 25kV/50Hz voltage configuration around 18:19 hrs are shown in following Figures 69 and 70.

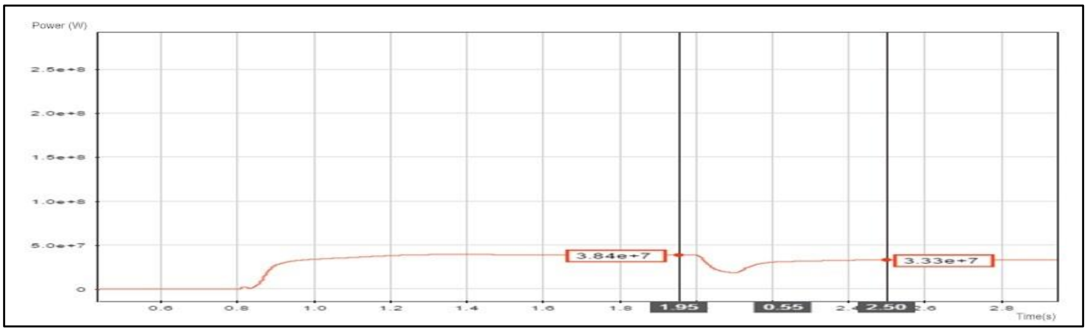


Figure 69: Active power variation -25kV/50Hz system

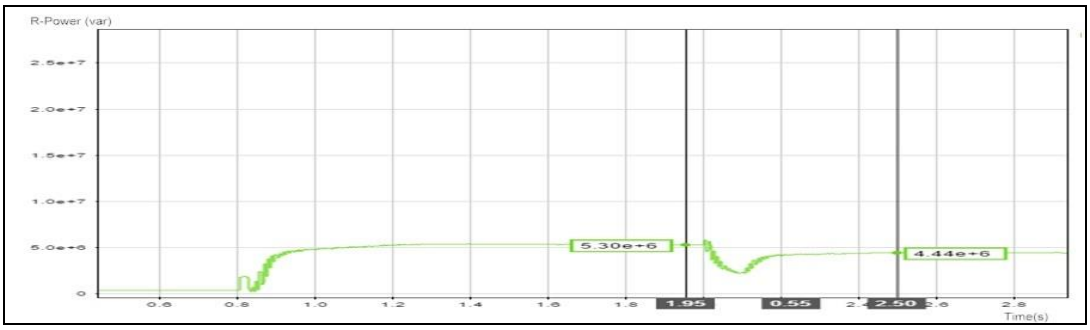


Figure 70: Reactive power variation -25kV/50Hz system

The active power variation is 38.39MW to 33.25MW and reactive power variation at 2s is 5.30 Mvar to 4.44Mvar. The maximum active power requirement is 38.39MW and maximum reactive power requirement is 5.30 Mvar.

The active power and reactive power variation for 15kV/16.7Hz voltage configuration around 18:19 hrs hrs are shown in following Figures 71 and 72.

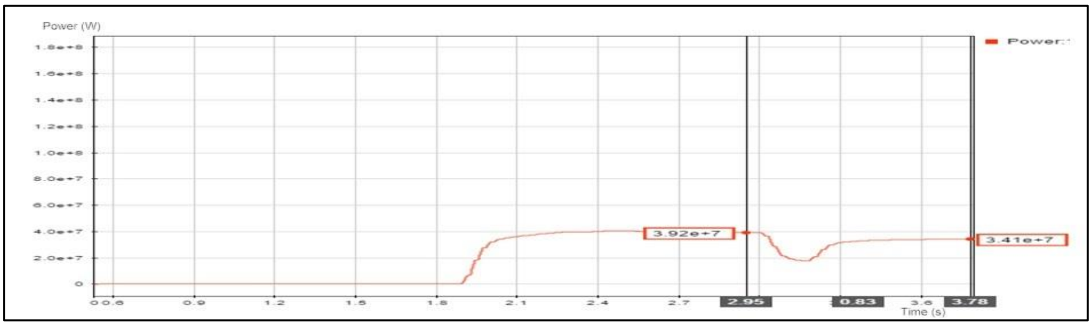


Figure 71: Active power variation 15kV/16.7Hz system

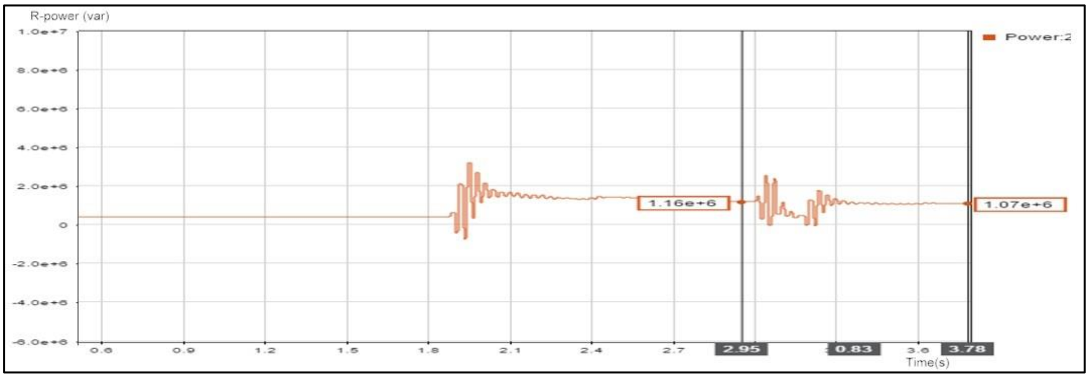


Figure 72: Reactive power variation 15kV/16.7Hz system

The active power variation at is 39.22MW to 34.14MW and reactive power variation at is 1.16Mvar to1.07Mvar.The maximum active power requirement is 39.22MW and maximum reactive power requirement is 1.16 Mvar.

The active power and reactive power variation for 15kV/50Hz voltage configuration around 18:19 hrs hrs are shown in following Figures 73 and 74.

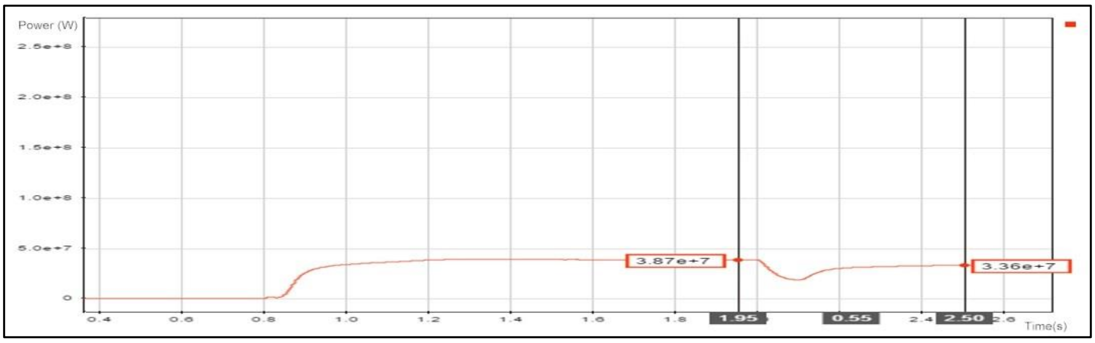


Figure 73: Active power variation of 15kV/50Hz system

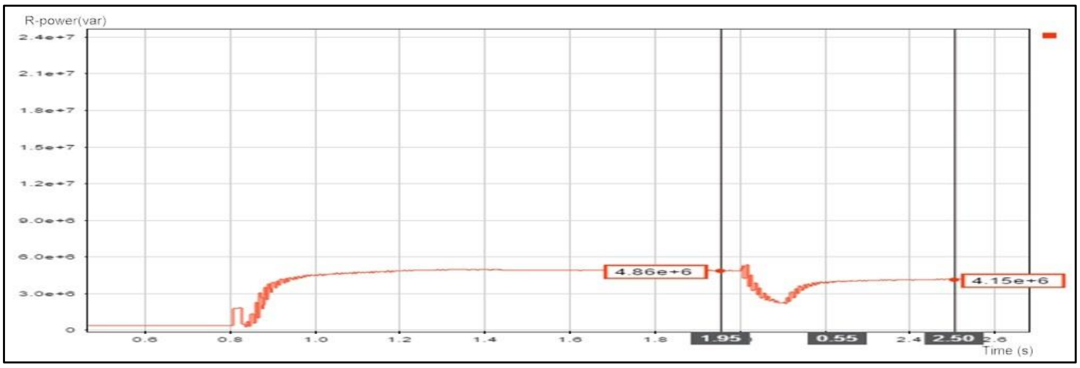


Figure 74: Reactive power variation of 15kV/50Hz system

The active power variation is 38.69 MW to 33.55MW and reactive power variation is 4.85 Mvar to 4.14 Mvar. The maximum active power requirement is 38.69MW and maximum reactive power requirement is 4.85 Mvar.

5.2.2.2 132 kV voltage variation

The voltage variations in 132kV transmission network in critical time are shown in following Figures.

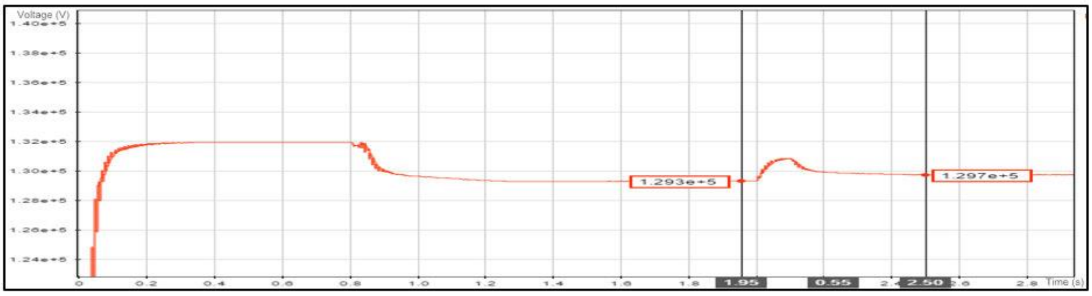


Figure 75: 25kV/50Hz system

The Voltage drop is 2.68kV and 132kV line voltage dropped to 129.32kV.

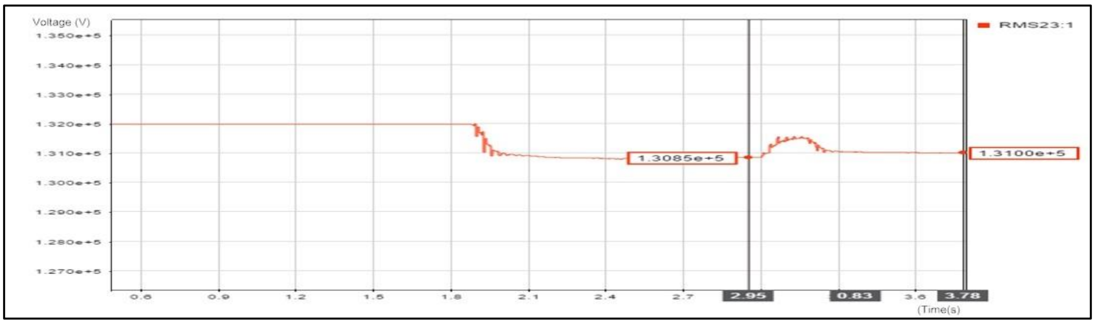


Figure 76: 15kV/16.7Hz system

The Voltage drop is 1.15kV and 132kV line voltage dropped to 130.85kV.

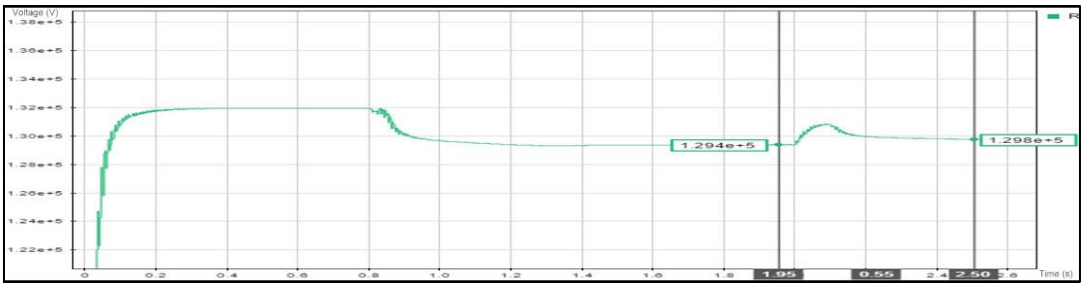


Figure 77: 15kV/50Hz system

The Voltage drop is 2.61kV and 132kV line voltage dropped to 129.38kV.

5.2.2.3 132kV line current variation

The current variations in 132kV transmission network in critical time are shown in following Figures.

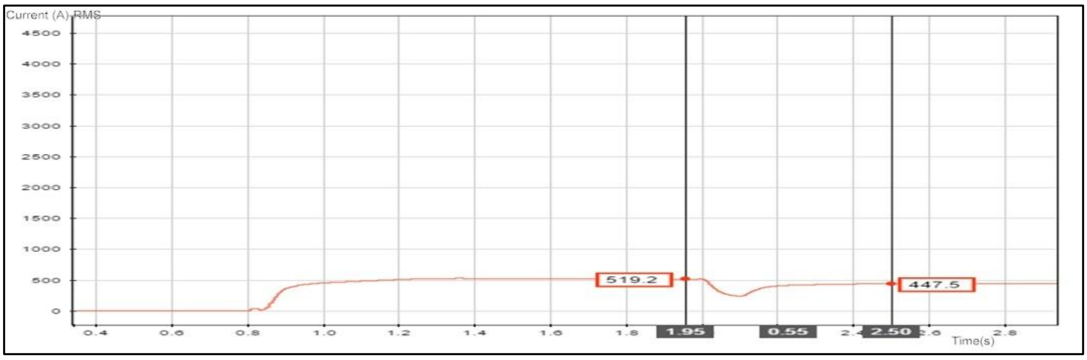


Figure 78: 25kV/50Hz system

The maximum current in 132kV transmission line is 519.17A.

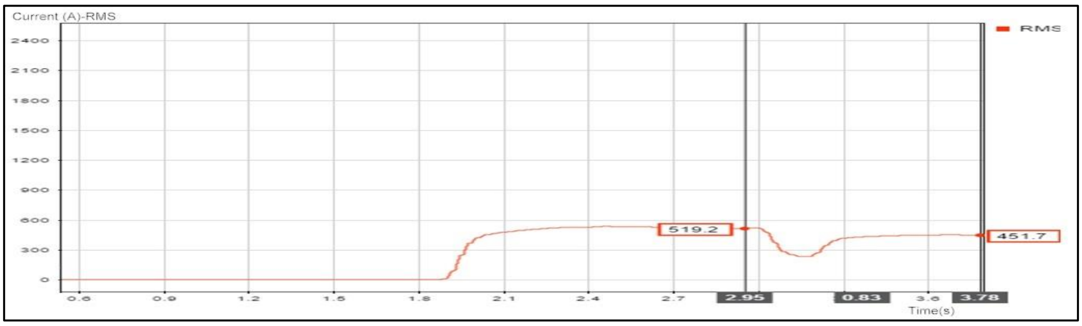


Figure 79: 15kV/16.7Hz system

The maximum current in 132kV transmission line is 519.23A.

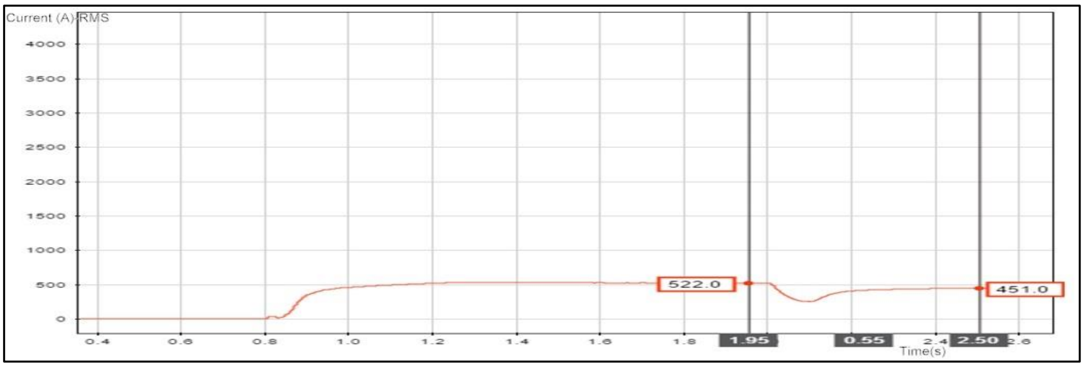


Figure 80: 15kV/50Hz system

The maximum current in 132kV transmission line is 522.03A.

5.2.2.4 Total harmonic distortion of current in transmission side

The total harmonic distortions of current in 132kV transmission network are shown in following Figures.

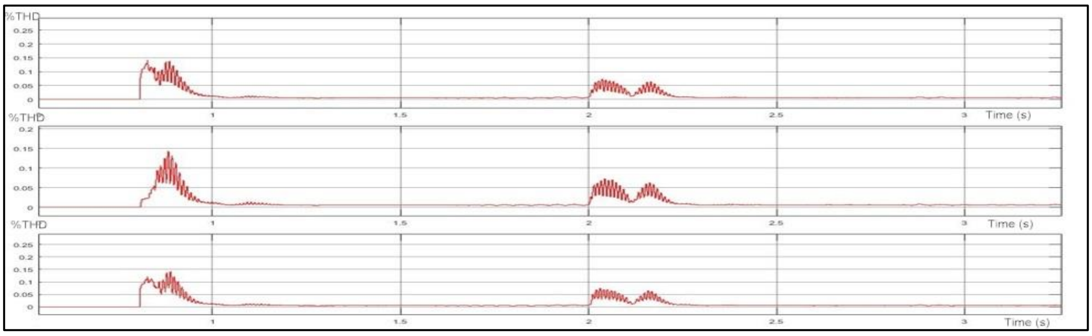


Figure 81: 25kV/50Hz system

Table 26 : THD in current at 132kV transmission line for 25kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	**0.52%**	**5.83%**

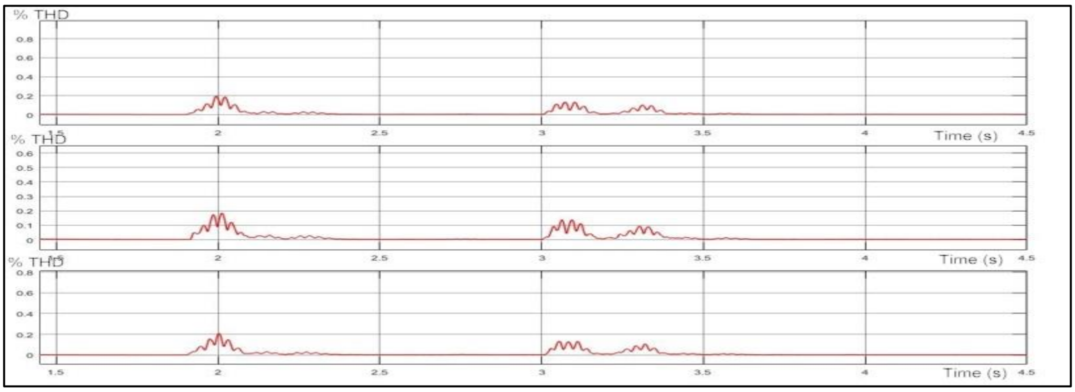


Figure 82: 15kV/16.7Hz system

Table 27: THD in current at 132kV transmission line for 15kV/16.7Hz system

	Just before 3s (t=2.9s)	Just after 3s (t=3.05s)
Maximum THD%	**0.33%**	**6.82%**

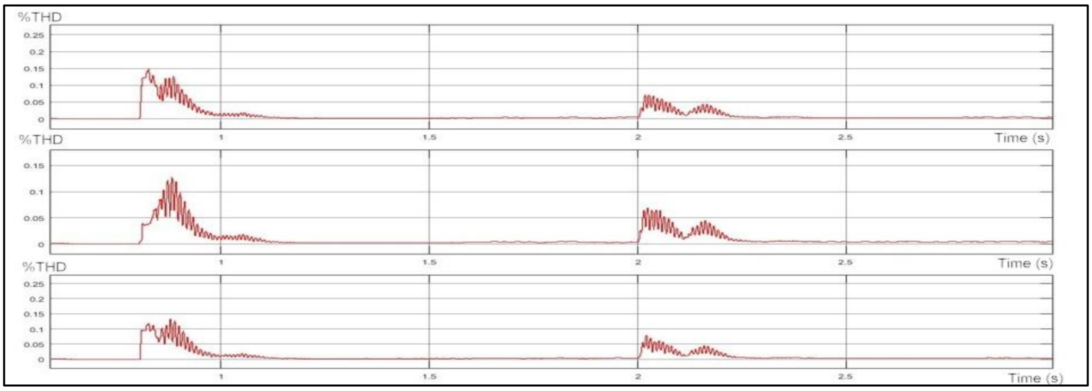


Figure 83: 15kV/50Hz system

Table 28: THD in current at 132kV transmission line for 15kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	0.27%	5.72%

5.2.2.5 Total harmonic distortion of voltage in 132kV transmission network side

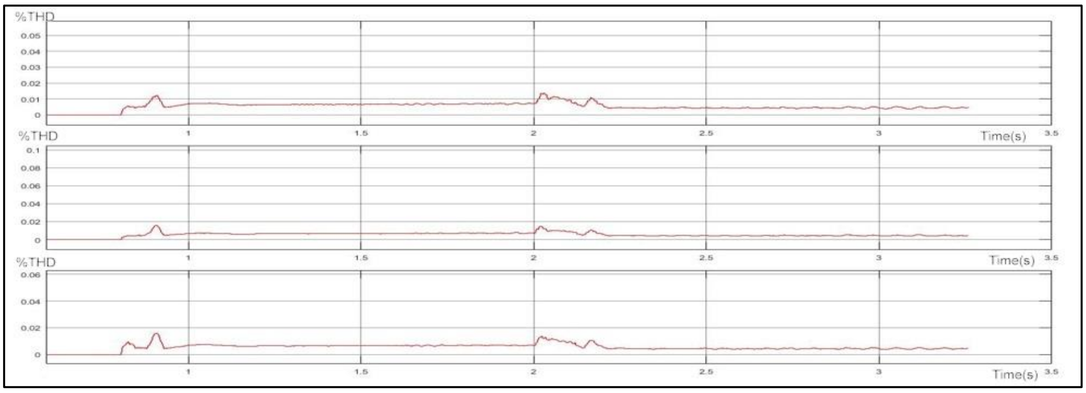


Figure 84: 25kV/50Hz system

Table 29 : THD in voltage at 132kV transmission line for 25kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
Maximum THD%	0.66%	1.32%

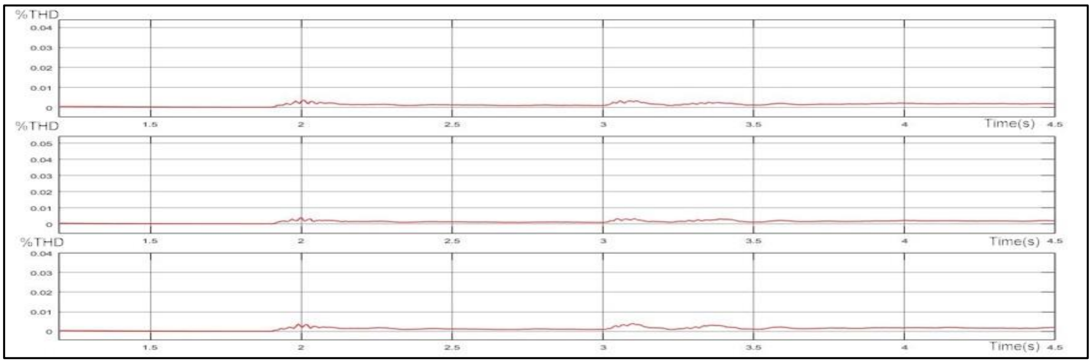


Figure 85: 15kV/16.7Hz system

Table 30: THD in voltage at 132kV transmission line for 15kV/16.7Hz system

	Just before 3s (t=2.9s)	Just after 3s (t=3.05s)
Maximum THD%	0.12%	0.31%

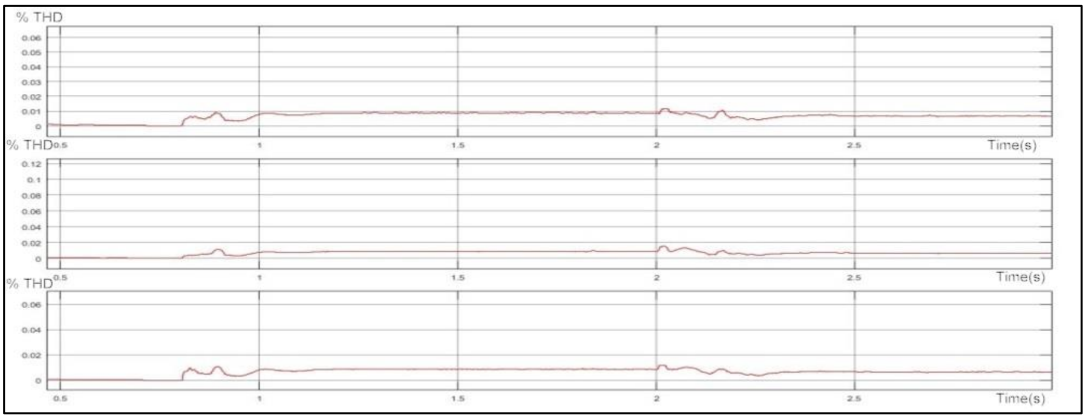


Figure 86: 15kV/50Hz system

Table 31: THD in voltage at 132kV transmission line for 15kV/50Hz system

	Just before 2s (t=1.9s)	Just after 2s (t=2.05s)
THD%	0.87%	1.17%

5.3 Results Analysis

In this section, the obtained results for the critical time period for two railway substations were summarized separately for the analysis.

5.3.1 Results analysis of Dehiwala Substation

Table 32: Results analysis of Dehiwala Substation

Parameter	Dehiwala Substation (critical time 07:06hrs)		
	25kV-50Hz	**15kV-16.7Hz**	**15kV -50Hz**
Maximum Active power	**38.44MW**	39.17MW	38.64MW
Maximum Reactive power	5.067var	**1.25Mvar**	4.80Mvar
Maximum Voltage drop	2.65 kV	**0.89kV**	2.63kV
Minimum 132kV Voltage	129.35kV	**131.11kV**	129.37kV
Maximum 132kV Current	519.23A	**517.71A**	521.38A
Current THD%	4.27%	5.27%	**4.11%**
Voltage THD%	0.76%	**0.32%**	0.6%

According to the results,

- The 132kV transmission line minimum voltage drop in critical time is 0.89kV observed in 15kV-16.7Hz system and second lowest value is 2.63 kV observed in 15kV-50Hz system.

- The 132kV transmission line minimum current in critical time is 517.71A observed in 15kV-16.7Hz system. The second lowest value is 519.23A observed in 25kV-50Hz system.
- The minimum active power observed in 25kV-50Hz system and minimum reactive power observed in 15kV-16.7Hz system.
- The voltage Total Harmonic Distortion is minimum in the 15kV-16.7Hz system and second lowest values observed in 15kV-50Hz system.
- The current total harmonic distortion in 25 kV-50Hz system is 4.27% ,15kV-16.7Hz system is 5.27% and the minimum value 4.11% is obtain in 15kV-50Hz system.

5.3.2 5.3.2 Results analysis of Ragama Substation

Table 33: Results analysis of Ragama Substation

Parameter	**Ragama Substation (critical time 18:19hrs)**		
	25kV-50Hz	**15kV-16.7Hz**	**15kV -50Hz**
Maximum Active power	**38.39MW**	39.22MW	38.69MW
Maximum Reactive power	5.30Mvar	**1.16Mvar**	4.85Mvar
Maximum Voltage drop	2.68kV	**1.15kV**	2.61kV
Minimum 132kV Voltage	129.32kV	**130.85kV**	129.39kV
Maximum 132kV Current	519.17A	**518.25A**	522.03A
Maximum Current THD%	5.83%	6.82%	**5.72%**
Maximum Voltage THD%	1.32%	**0.31%**	1.17%

According to the results,

- The 132kV transmission line minimum voltage drop in critical time is 1.15kV observed in 15kV-16.7Hz system and second lowest value is 2.61 kV observed in 15kV-50Hz system.
- The 132kV transmission line minimum current in critical time is 517.71 A observed in 15kV-16.7Hz system. The second lowest value is 519.23 A observed in 25kV-50Hz system.
- The minimum active power and reactive power variation observed in 25kV-50Hz system and 15kV-16.7Hz system respectively.
- The voltage Total Harmonic Distortion at critical time is minimum in the 15kV-16.7Hz system and second lowest values observed in 15kV-50Hz system.
- The current total harmonic distortion in 25 kV-50Hz system is 5.83% ,15kV-16.7Hz system is 6.82% and the minimum value 5.72% is obtain in 15kV-50Hz system.

DISCUSSION AND CONCLUSION

6.1 Discussion

In this thesis, proposed Sri Lankan railway electrification with overhead AC catenary feeding systems has been considered. In this study, 3 different voltage configurations of 25kV-50Hz,15kV-16.7Hz and 15kV-50Hz were considered .The critical time periods were observed by analyzed present railway time table for Panadura-Maradana and Colombo Fort to Veyangoda at 07:06 hrs in morning and 18:19hrs in evening respectively. In that critical time periods, the train locations, their running status and distances from the proposed railway substations were obtained.In this study, electric train model was consider with 06 number of 2 pole induction motors with conventional breaking choppers. The regenerative braking power is dissipating through these breaking choppers and avoids increase of DC link voltage.

With the using of all above data and assumptions Mat lab simulation was carried out to find out the optimum railway network configuration to minimize power quality issues in proposed Sri Lankan railway electrification system based on following parameters.

- 132kV voltage drop at grid interconnection point in both Dehiwala and Ragama railway substations.
- Maximum current drawn from the 132kV feeding transmission network from Dehiwala grid to Dehiwala railway substation and Aniyakanda grid to Ragama railway substation.
- Current and voltage THD% at grid inter connection point in both Dehiwala and Ragama railway substations.
- Maximum active and reactive power requirement in both Dehiwala and Ragama railway substations.

By analyzing the results, 15kV system having minimum parameter variation under the analysis criteria as shown in Table 34.

Table 34: Result analysis for optimum voltage configuration

Parameter	Dehiwala substation	Ragama Substation
Minimum active power requirement	25kV-50Hz	25kV-50Hz
Minimum reactive power requirement	15kV-16.7Hz	15kV-16.7Hz
Minimum Voltage drop	15kV-16.7Hz	15kV-16.7Hz
Minimum 132kV line current	15kV-16.7Hz	15kV-16.7Hz
Minimum voltage THD%	15kV-16.7Hz	15kV-16.7Hz
Minimum Current THD%	15kV-50Hz	15kV-50Hz

In present 132kV transmission system, voltage drop and the reactive power variation in morning peak are critical issues that should address. The harmonic penetration to the 132 kV network is also should be minimize to improve the power quality in the transmission system. In present Sri Lankan power system, frequency controlling generator capable of fulfilling the sudden active power variation but reactive power variation caused transmission line voltage drop in both 220kV and 132 kV system was experienced in present situation.

Therefore, 15kV voltage configuration which having the minimum reactive power variation, minimum transmission line current variation and minimum voltage and current total harmonic distortion is best solution for the present Sri Lankan power system to mitigate power quality issues with proposed railway electrification system.

This study based on the electrical parameters of the railway system and not considers economic parameters such like cost of frequency conversion from the existing 50Hz system, cost of the newly proposed substations and cost of railway electrical distribution systems and associate infrastructure.

6.2 Conclusion

According to the results obtain, the minimum power quality issues were observed in 15kV system. The frequency of 16.7Hz system is having lowest values in 132kV network voltage drop, reactive power variation, 132kV line current variation and total voltage harmonic variation. Therefore according to this technical parameter analysis, 15kV-16.7Hz system is optimum voltage configuration to electrify the railway track from Panadura to Veyangoda as proposed Sri Lankan railway electrification. In the other hand, there is another research gap to identify the economic viability on changing voltage and frequency from existing 50 Hz system.

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ANNEX 1

Table A1.1 Daily time table of Panadura to Maradana

Train number	Arrival time (hrs)	Departure time (hrs)	Destination time (hrs)
	04:19	04:20	05:16
	04:49	04:50	05:45
	05:29	05:30	06:27
8311	06:02	06:03	06:58
8310	06:10	06:10	07:07
8317	06:25	06:27	07:28
8316	06:30	06:30	07:41
8320	06:42	06:44	07:45
	06:55	06:55	08:04
8063	07:01	07:02	07:50
8324	07:05	07:11	08:08
8327	07:05	07:06	07:54
	07:19	07:21	08:10
8097	07:28	07:30	08:23
8328	07:30	07:30	08:28
8335	08:05	08:05	09:07
8342	08:33	08:34	09:30
8057	08:51	08:52	09:38
8339	09:15	09:15	10:13

8336	09:35	09:35	10:41
8344	11:11	11:12	12:10
8350	12:48	13:05	14:15
8352	14:05	14:06	15:01
8363	14:49	14:50	15:41
8335	15:00	15:00	15:55
	17:05	17:05	18:10
8051	17:21	17:25	18:12
	18:00	18:01	19:09
8375	18:39	18:40	19:35
8390	22:38	22:39	23:21

Table A1.2 Daily time table of Maradana to Panadura

Train number	Arrival time (hrs)	Departure time (hrs)	Destination time (hrs)
8710	04:30	04:30	05:25
8711	05:05	05:05	05:53
8716	05:37	05:37	06:33
8717	05:52	05:52	06:47
8724	06:26	06:26	07:21
8050	06:30	06:30	07:34
8723	07:00	07:00	07:51
8727	07:32	07:32	08:41
8729	07:54	07:54	08:51
8040	08:10	08:10	09:12

8736	08:35	08:35	09:34
8741	09:05	09:05	10:45
	10:12	10:15	11:05
8742	11:10	11:10	12:06
8744	12:05	12:05	13:02
8748	13:30	13:30	14:25
8751	14:00	14:00	14:56
8056	14:15	14:15	14:59
8749	14:30	14:30	15:35
8756	15:20	15:20	16:27
8757	16:00	16:02	16:50
8765	16:10	16:10	16:53
8761	16:15	16:15	17:12
8763	16:25	16:25	17:15
8096	16:40	16:40	17:21
8758	16:45	16:45	17:38
8062	16:55	16:55	17:35
8759	17:10	17:10	18:07
8764	17:30	17:30	18:27
8772	17:40	17:40	18:37
8766	17:50	17:50	18:46
8773	18:10	18:10	19:07
8774	18:25	18:25	19:38
8775	15:45	18:45	20:09

8780	19:45	19:45	20:40
8782	20:35	20:35	21:30
8783	21:30	21:30	22:25

ANNEX 2

Table A2.1 Daily time table of Colombo Fort to Veyangoda

Train number	Arrival time (hrs)	Departure time (hrs)	Destination time (hrs)
1109	03:00	03:00	04:15
1125	04:40	04:40	05:48
1124	05:10	05:12	06:17
1005	05:55	05:55	06:42
6011	06:05	06:05	06:49
4077	06:17	06:35	07:20
1135	07:02	07:02	08:14
1133	07:35	07:35	08:26
1136	08:00	08:00	09:09
1015	08:30	08:30	09:11
1140	08:35	08:35	09:26
5452	08:50	08:50	09:45
1141	08:55	08:55	10:07
1146	09:30	09:30	10:19
1007	09:45	09:45	10:30
4000	09:50	09:50	10:40
1143	10:10	10:10	11:18
1019	10:35	10:35	11:22
1144	11:35	11:35	12:49
1147	12:05	12:05	13:13

1023	12:40	12:40	13:25
1150	12:50	12:50	14:02
1151	13:25	13:25	14:41
1152	13:40	13:40	15:11
4085	13:45	13:45	14:32
1154	13:55	13:55	15:07
1158	14:20	14:20	15:26
1162	14:50	14:50	15:58
1163	15:20	15:20	16:45
1170	15:45	15:45	16:55
1169	16:25	16:25	17:19
1172	16:42	16:42	17:40
1164	16:50	16:50	17:35
1168	16:50	16:50	18:01
4469	17:15	17:15	17:59
1173	17:20	17:20	18:20
1175	17:40	17:40	18:55
1039	17:45	17:45	18:30
1176	17:55	17:55	18:43
1177	18:15	18:15	19:23
1183	18:35	18:35	19:30
1184	18:45	18:45	20:00
5067	19:15	19:15	20:02
1186	19:20	19:20	20:28

1191	19:50	19:50	20:59
1045	20:00	20:00	20:47
1192	20:45	20:45	21:53
7083	21:30	21:30	22:19
1196	21:45	21:45	22:57
1194	23:00	23:00	00:08

Table A2.2 Daily time table of Veyangoda to Colombo Fort

Train number	Arrival time (hrs)	Departure time (hrs)	Destination time (hrs)
1046	04:17	04:20	05:17
1507	04:28	04:29	05:36
1512	24:48	04:49	05:50
1516	05:33	05:34	06:35
1518	05:18	05:19	06:34
1527	06:04	06:06	07:11
1528	06:14	06:15	07:27
1525	06:49	06:59	07:58
1525A	05:44	05:45	06:57
1531	06:53	06:54	07:44
1535	06:29	06:30	07:30
1526	07:09	07:10	07:58
1526A	07:13	07:14	08:06
1537	06:39	06:40	07:52
1537A	06:42	06:43	08:02

1542	07:29	07:30	08:30
1542A	07:18	07;27	08:33
1538	07:48	07:53	09:10
1536	08:36	08:37	09:51
1539	09:35	09:35	10:45
1549	09:42	09:43	10:55
1550	11:12	11:13	12:21
1547	10:33	10:34	11:42
1546	11:00	11:01	11:52
1551	12:12	12:22	13:30
1552	13:58	13:59	15:11
1565	14:38	14:44	15:56
1553	13:30	13:30	14:38
1566	15:29	15:38	16:46
1568	16;03	16:04	17:16
1574	15:17	15:17	16:15
1575	16:44	16:52	18:01
1581	17:20	17:21	18:29
1576	20:34	20:38	22:20
1577	17:30	17;30	18:47
1569	18:18	18:19	19:22
1570	19:02	19:03	20:16
1578	18:06	18:07	19:02
1578A	19:34	19:35	20:49

1592	20:13	20:14	21:10
1592A	20:57	20:58	22:07
1584	19:55	19:55	21:11
1585	21:16	21:17	22:10
1589	21:30	21:31	22:33
1591	22:08	22:09	23:17
4086	09:24	09:26	10:20
4856	05:47	05:48	06:53
4857	06:50	PASS	07:46
4004	09:51	PASS	10:36
4859	07:40	PASS	08:35
4018	12:19	PASS	13:05
4078	17:37	17:39	18:58
4094	15:34	15:36	16:25
4022	19:19	PASS	20:00
4090	03:02	03:05	04:05
4851	22:20	PASS	23:30
6012	14:18	14:20	15:15
6080	04:03	PASS	04:53
7084	02:30	02:33	03:30
3868	15:11	15:13	16:05
5068	04:56	05:00	6:00
1024	13:12	13:13	14:03
2026	10:22	10:23	11:15

1008	20:02	20:03	20:53
1040	07:16	07:17	08:05
1040A	07:23	07:24	08:13
1034	07:50	PASS	08:42
1016	14:41	14:42	15:27
1030	08:07	PASS	08:52
1036	08:53	08:54	09:45
1006	18:09	18:11	18:57
1010	16:50	PASS	17:36
1020	17:58	17:59	18:50
1032	18:46	PASS	17:30