"ANALYSIS OF POWER QUALITY PROBLEMS AND SUBSYNCHRONOUS RESONANCE IN 25 KV AC TRACTION POWER SUPPLY SYSTEM IN DELHI METRO RAIL NETWORK LINE-2 AND PROPOSED IMPROVEMENTS USING STATCOM - DYNAMIC REACTIVE POWER COMPENSATORS"

A DISSERTATION SUBMITTED TOWARDS THE PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
POWER ELECTRONICS SYSTEM (PES)
(2013-2016)

SUBMITTED BY:
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UNDER THE GUIDANCE OF
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DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(FORMERLY DELHI COLLEGE OF ENGINEERING)
DELHI
AUGUST 2016

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(FORMERLY DELHI COLLEGE OF ENGINEERING)

CERTIFICATE

This is to certify that this project titled "**ANALYSIS OF POWER QUALITY PROBLEMS AND SUBSYNCHRONOUS RESONANCE IN 25 KV AC TRACTION POWER SUPPLY SYSTEM IN DELHI METRO RAIL NETWORK LINE-2 AND PROPOSED IMPROVEMENTS USING STATCOM - DYNAMIC REACTIVE POWER COMPENSATORS**" submitted in partial fulfillment of the requirements for the Degree of Master of Technology by **Sh. Ashish Arora** at Delhi Technological University is a record of original research work carried out by him under my guidance. Any material borrowed or referred to is duly acknowledged.

Ashish Arora
2K13/PES/503
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Dr. Vishal Verma
Professor, DTU
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ACKNOWLEDGEMENT

I express my sincere thanks to my project guide **Dr. Vishal Verma**, for providing me an opportunity to work under his guidance and tireless support during the course of the project. His continued cooperation, never-ending encouragement, meticulous guidance and uninhibited support at various stages helped me in preparation of this research study.

I would also like to thank **Mr. Amritesh Kumar**, Faculty of DTU, for their cooperation and support.

I would also like to acknowledge the vital role of my superiors and colleagues from present organization **Delhi Metro Rail Corporation Limited**, in providing me with the opportunity to gain insight into the existing Power Supply System and its technical and failure details.

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M. Tech., Power Electronics
Semester VI
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Delhi Metro Rail Corporation Ltd.

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Chapter -1

INTRODUCTION

1 INTRODUCTION

1.1 Introduction:

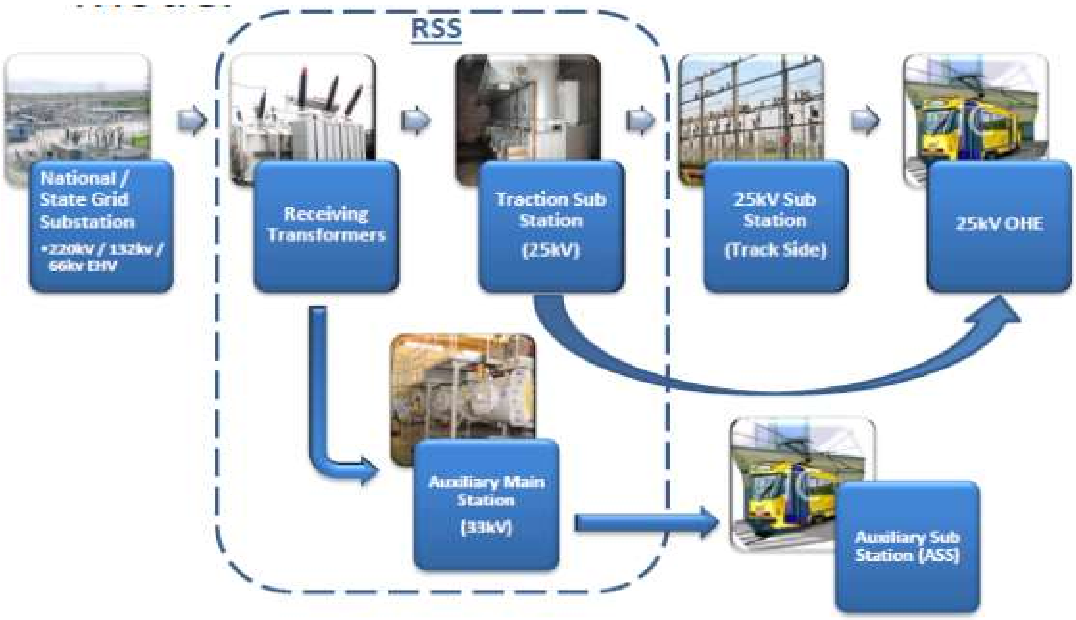
Delhi Metro Railway Corporation is providing metro services over a network of more than 213 route km. with 160 stations, which also include 54 route km under-ground portions. DMRC runs almost 216 rakes consisting of 4/6/8 coaches for transporting about 2.8 million passengers everyday with peak headway of 138 sec. Punctuality on Delhi Metro is measured with a least count of 60 sec and on most days, it has been achieving 100% punctuality making it one of the most punctual metros in the world.

Delhi Metro Rail Corporation Limited has adopted 25 KV AC Traction Power supply network for Trains and 33 kV AC distribution network for supplying the auxiliary load requirements at various stations where the voltage is step down to 415 V for feeding the auxiliary equipments. This system is typical than the utility distribution network as redundancies have to be catered for making the supply reliable.

The popularity of DMRC can be gauged as even occasional disruption to train operation, due to any failure in equipments causes inconvenience to passengers and invites severe criticism from public and media.

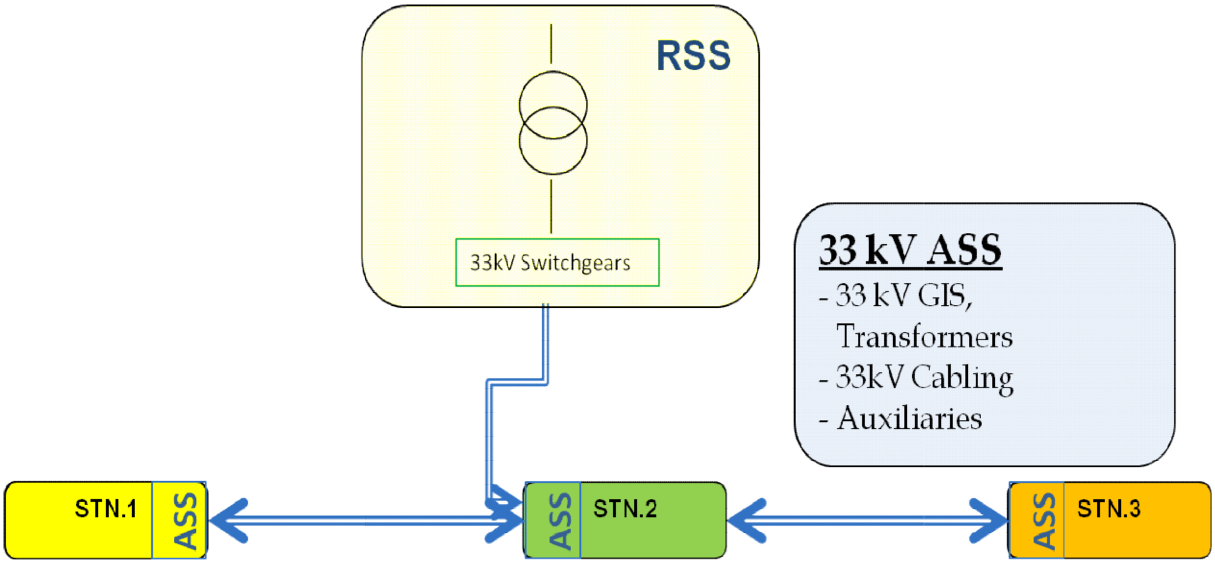
1.2 Layout of Power Supply in Delhi Metro

For any Metro Rail Transit System (MRTS) availability of un-interrupted power supply is an essential requirement. Delhi Metro Rail Corporation (DMRC) receives EHV power supply at 220/132/66kV from different supplying authorities/DISCOMS (DTL/DISCOMS) at Receiving Substations (RSS) consisting of Traction Substations (TSS) and Auxiliary Main Substations (AMS). Every metro line is planned with two or more Receiving Sub Stations (RSS)

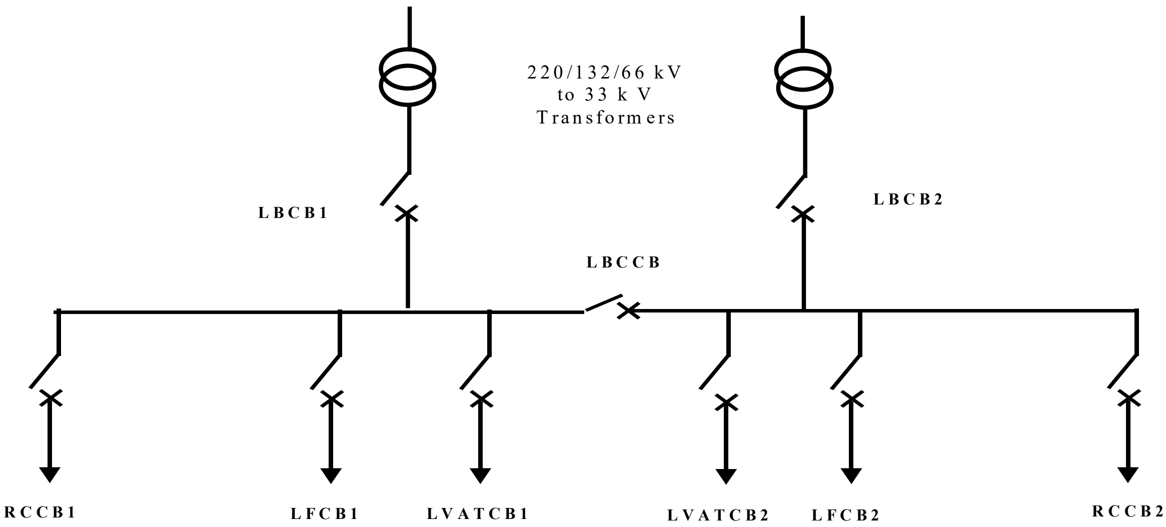


Inside RSS, there are two substations namely the Traction Sub Station (TSS) and the Auxiliary Main Substation (AMS). While the output of TSS is 25 kV single phase AC, which is used to feed the OHE; the output of AMS is 33 kV three phase AC fed to the ASS. Each Station has an ASS, in which this 33 kV three phase is further stepped down to 415 V three phase for the local supply to the station.

The RSS feeds auxiliary power at stations and en-route, through an Auxiliary Main Substation (AMS), duplicate 33kV cable network (in ring formation) and Auxiliary Substations (ASS) at each underground and elevated station. The power received at ASS is distributed to the auxiliary loads of the stations through LV distribution system.

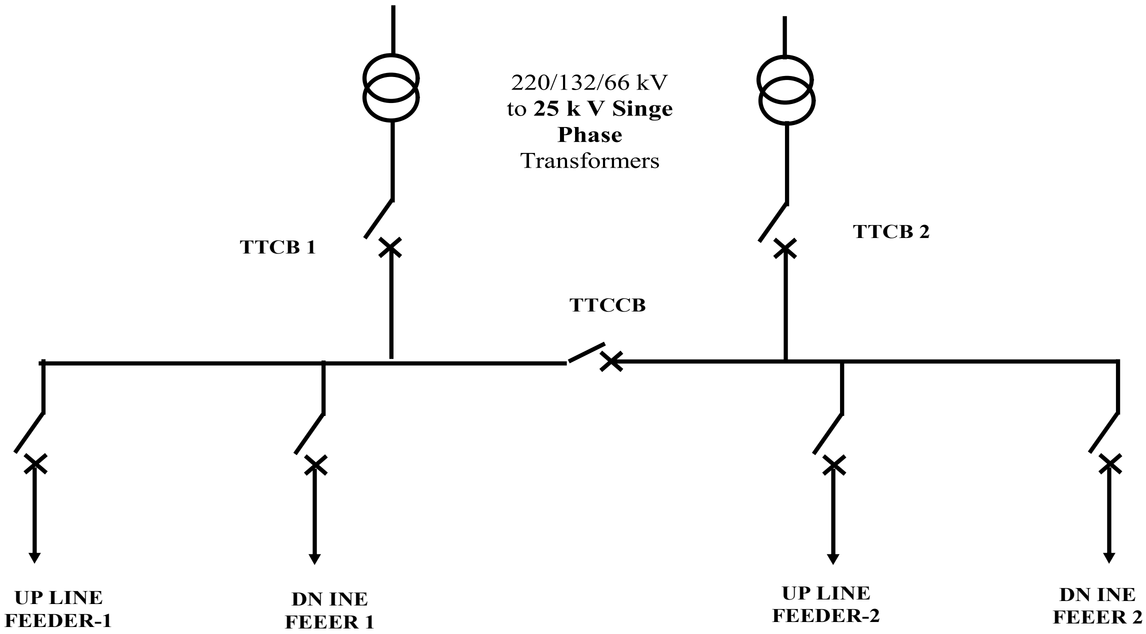


Typical SLD of the AMS and ASS are shown below.



AMS Simplified Diagram

Typical SLD of the Traction Substation is shown below.



1.3 Description of Traction Power supply in DMRC LIne-2

DMRC Line-2 is of 45 kms length and are having four Traction Substations at

- Jahangirpuri
- New Delhi
- Chattarpur
- Huda City Centre

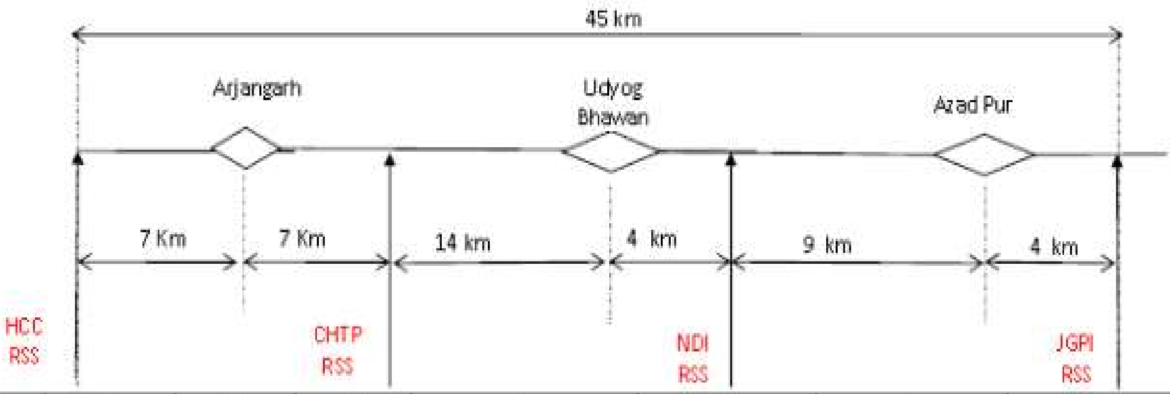
Three neutral sections are located between each pair of Traction Substations to segreegate the power supplies at

- Azadpur
- Udyog Bhawan
- Arjan Garh

The location of Traction Substations and Neutral sections is shown below with their normal feeding zone and extended feeding zone.

As shown in the figure, during extended feeding conditions, the RSS at Chattarpur feeds 14 km on Left side, and 27 kms on Right side , a total of 41 kms.

LINE 2



Type	FP	SP	FP	SP	FP	SP	FP
Stn	HCC	AJ	CHTP	UB	NDI	AZU	JGPI
Name	Huda city Centre	Arjangarh	Chattar Pur	Udyog Bhawan	New Delhi	Azad Pur	Jahangir Puri
Ch.	0 km	7 Km	14 km	28 Km	32 Km	41 Km	45 Km
Loc	Elevated	Elevated	Elevated	UG	UG	Elevated	Elevated

RSS	Total feeding zone		Total feeding zone	
	NORMAL		EXTENDED TO ADJACENT SECTION	
	Left Side	Right side	Left Side	Right side
HCC	0	7	0	28
CHTP	7	14	14	27
NDI	4	9	25	13
JGPI	4	0	17	0

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Chapter -2

BACKGROUND OF THE POWER QUALITY PROBLEMS

2 BACKGROUND OF THE POWER QUALITY PROBLEMS

2.1 Background

Line 2 of DMRC extends from Jahangir Puri (JGPI) – Huda City Centre (HCC) with following Traction Substations (TSS) –

- Jahangirpuri
- New Delhi
- Chattarpur
- Huda City Centre

Each of the substations has been designed as a back up of the adjacent substation. The Traction Transformers have the following characteristics –

- HV level – 66 kV
- LV Level – 27.5 kV
- MVA rating – 30 MVA
- % Impedence – 13.8%
- Overloading characteristics - +50% for 15 minutes
  +100 % for 5 minutes

With the introduction of 8 car trains the traction load has increased and during extended feed condition, traction loads of up to 200% of transformer capacity are being observed. During such scenario following abnormal behavior have been observed:

1. The voltage drops as low as 17 kV, and jerks in trains are being experienced in some running trains
2. Loud noise in transformer
3. Frequent OLTC operation in the Transformer due to AVR

2.2 Site measurements

In view of the above, earlier to this various site measurements have been undertaken by DMRC/O&M and Project Team along with the team of manufacturer M/s EMCO.

The Subject Transformer was dismantled, taken back to factory of the manufacturer, and tested again for all the recommended tests as per IEC 60076.

The results were normal, and no abnormality in construction of transformer was reported.

A site measurement was undertaken on 27/12/2013 and power analyzers were installed. DMRC O&M, Project Team and DTU representatives were present. The observations are represented below.

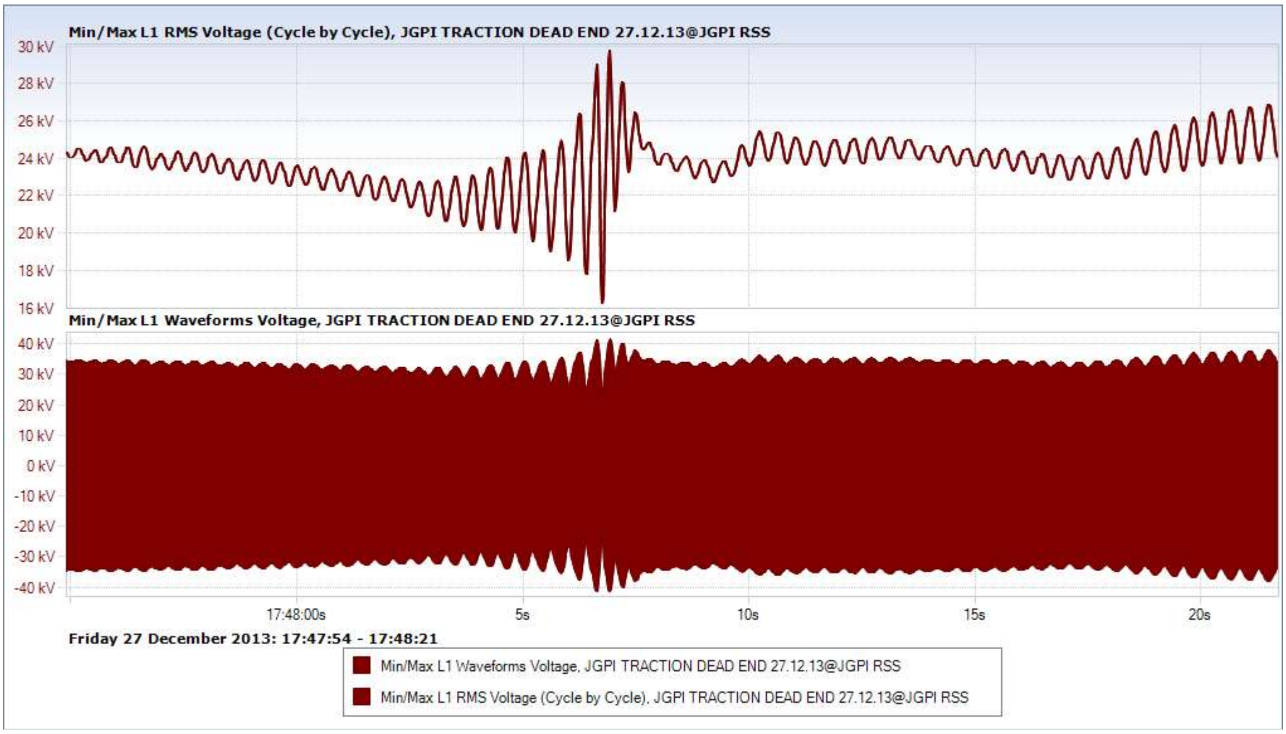


Fig 2.1 (a) The Sub synchronous resonance observed in the traction power supply at Line end with variations from 17 kV to 29 kV.

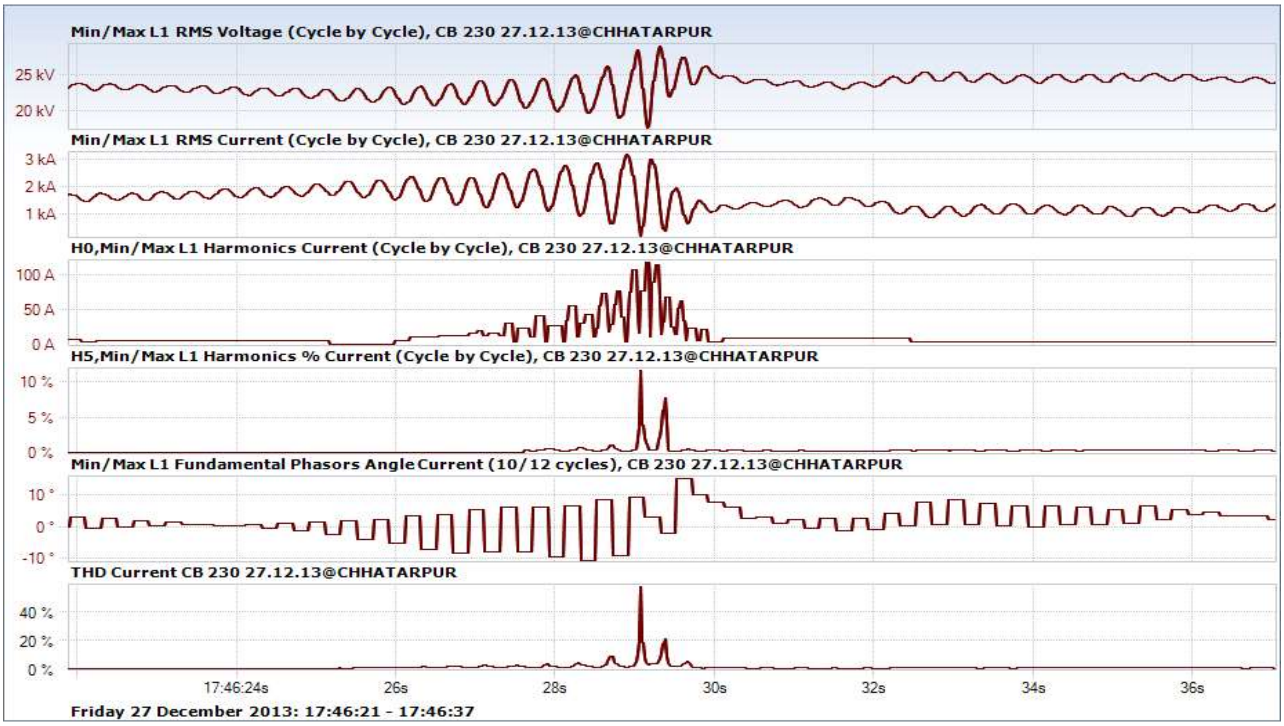


Fig 2.1 (b) The Sub synchronous resonance observed in the traction power supply at Line end with variations from 17 kV to 29 kV.

Further site measurements were undertaken on 28/01/2014 and power analyzers were installed. **Wide Voltage and current pulsations** along with jerks in trains are observed. The observations are represented below**.**

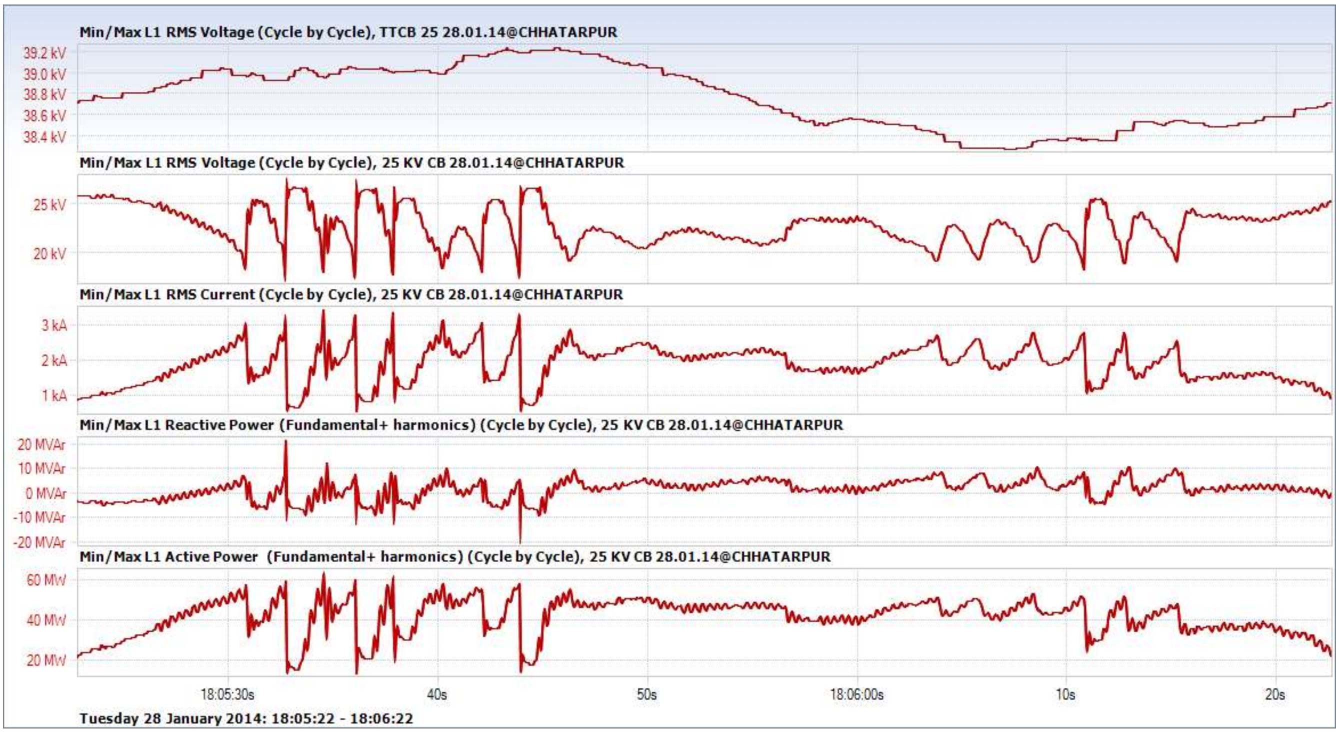


Fig 2.2 Wide Voltage and current pulsations along with jerks in trains are observed in the traction power supply

2.3 Preliminary Observations

It was observed that during high load conditions around 2000 A (>175%) of rated load, wide voltage fluctuations were observed.

During site measurements, it has been observed that variation of load current and load voltage to the extent of 29 kV to 16 kV and current variation at the sending end to the extent of 3 kA up to 400 A had been observed. The waveforms are shown below.

This is due to the **SUBSYNCHRONOUS RESONANCE** happening in the system between transformer inductance and capacitive load in the system.

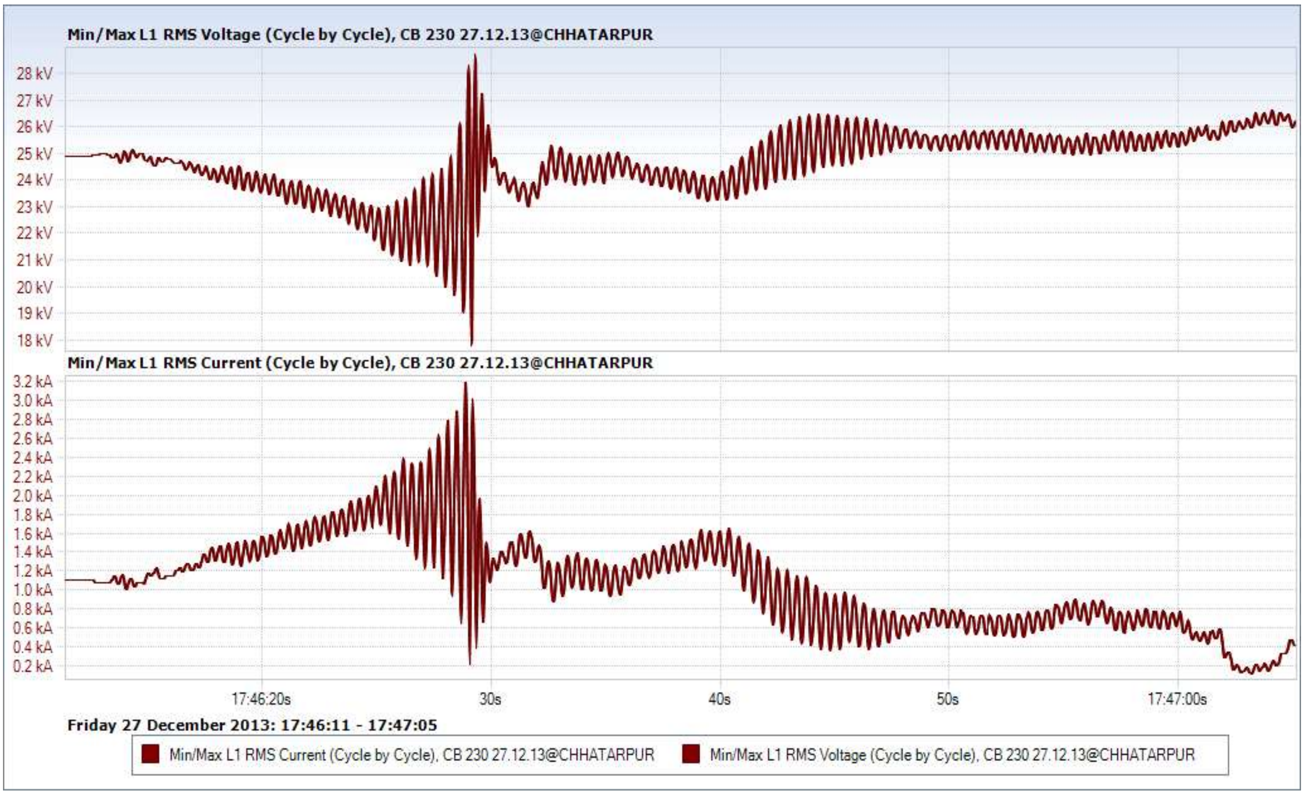


Fig 2.3 The Sub synchronous resonance observed in the traction power supply at TRACTION SUBSTATION AT CHATARPUR with variations from 17 kV to 29 kV, and current variations from 400 A to 3100 A

This phenomenon is unlike the gradual voltage and load variation as observed in the normal load condition even up to the extent of load conditions of 1250 A as observed at 1745 hrs in the observation report, and at 2100 A at 21 kV no resonance was observed which is the % of rated capacity of the transformer **(Fig 2.4)**.

It is pertinent to note that the reactive power requirement in the system is also of the pulsating nature during the resonance phenomenon varying up to the range of 19 MVAR up to – 27 MVAR.

During this phenomenon a large pulsating noise and wide voltage fluctuations resulting in jerks in the train are clearly observed and established. Total harmonics distortion up to the range of 57% has been observed in this phenomena reaching up to 11.69%.

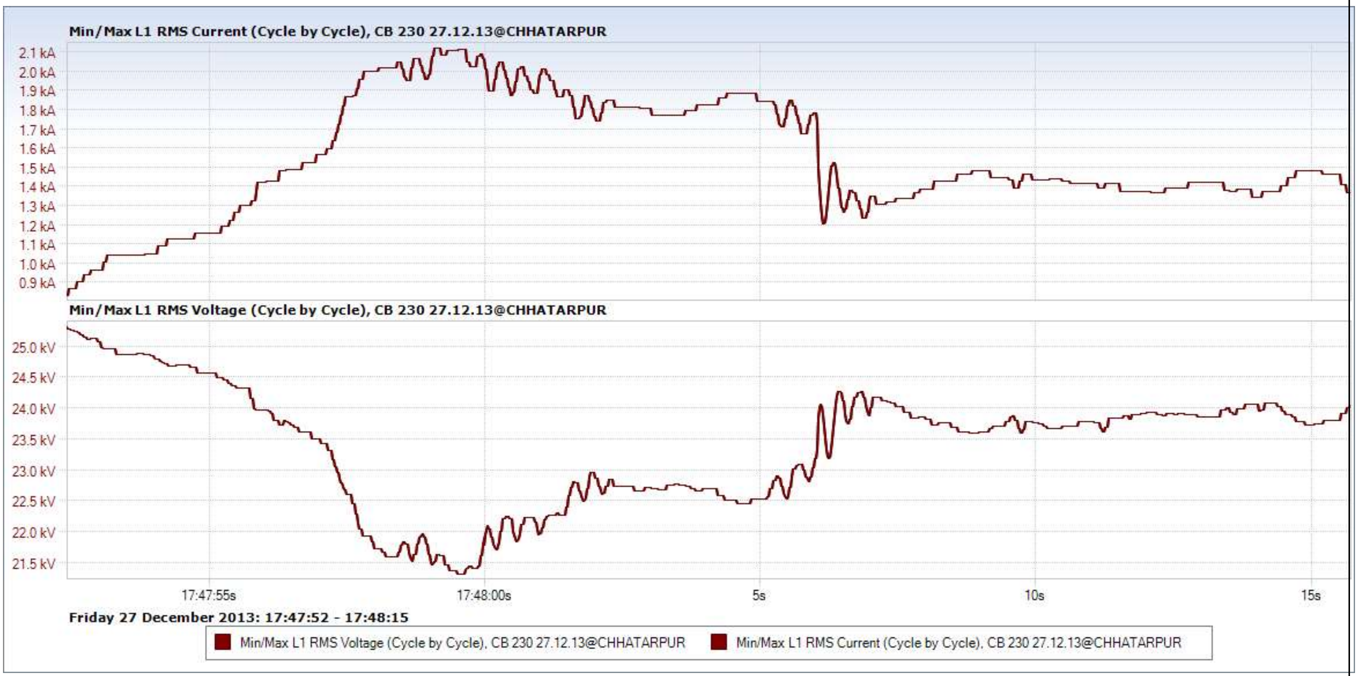


Fig 2.4 The Normal Load variations upto 2000 A, the Voltages drop up to 21 kV only and NO resonance is observed

2.4 Probable Causes

The following probable causes were suggested by–

It has been observed in this case that at a load of around 1300 A – 1400 A (120%) equal to 36 MVA, the impedance of transformer starts resonance with the load reactance.

With this Sub synchronous resonance Phenomenon, wide variation in load current & thereby load voltage is observed.

2.5 Way forward

2.5.1 Equivalent Lab Model for simulation

A lab model for simulating the characteristics along with STATCOM characteristics before the actual implementation.

2.5.2 Static Compensator (STATCOM)

Static compensators have been installed in various traction and power utility applications world wide. A similar static reactive power compensator has been suggested which monitors and supplies the reactive power compensation using IGBT Switches. Reactive power requirement is compensated dynamically by these compensators. The manufacturers like Hitachi, ABB are providing these compensators world wide.

The compensator can benefit in following ways:

1. Providing reactive power VAr as required during normal feed condition as well as overload conditions.

   This will continuously support the VAR requirements and resonance stage is not likely to reach.
2. Improve voltage profile by minimizing voltage drops due to reactive and harmonic current transformers.
3. VAr requirement from Grid will not be required so a saving in Electricity bill in normal course.
4. Helps in increasing life of system components i.e. transformer from overloading

Chapter -3

REVIEW OF AVAILABLE RESEARCH LITERATURE

3 REVIEW OF AVAILABLE RESEARCH LITERATURE

3.1 Review of Relevant Literature or Research Publications

3.1.1 "Selective Compensation of Power-Quality Problems Through Active Power Filter by Current Decomposition" by Bhim Singh, Senior Member, IEEE, and Vishal Verma, Member, IEEE

Active Power filters like STATCOM as proposed here as a likely solution to the voltage unbalances, and pulsations, and resulting Sub synchronous resonance.

The paper describes the scheme for control strategy for compensation of harmonics by active power filters like STATCOM by decomposition of load current into positive, negative sequence components in SRF, and also harmonics and reactive components.

3.1.2 " STATCOM to enhance power quality and security of rail traction supply" by Grunbaum, R. ; AB/FACTS, ABB, Vasteras, Sweden ; Hasler, J.-P. ; Larsson, T. ; Meslay, M.

Published in:

Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on Date of Conference: 1-3 July 2009

This paper describes that the railway traction systems are heavy and complex loads on the grids and being connected to only two phases, they cause heavy unbalance in the power supply network of the grid.

This not only causes the system to be harmful for traction purpose but also for the other users connected to the power supply network.

With ever increasing network of traction as well as the grid, the power quality as per the codes ad rules is difficult to maintain in such scenarios.

The paper treats STATCOM as a means for power quality improvement in grids dominated by high speed rail traction.

3.1.3 "A Novel Control Scheme of the Statcom for Power Quality Improvement in Electrified Railways" by Hosseini, S.H. ; Fac. of Electr. & Comput. Eng., Tabriz Univ. ; Sarhangzadeh, M. ; Shahnia, F.

Published in:

Power Electronics Specialists Conference, 2006. PESC '06. 37th IEEE

Date of Conference:

18-22 June 2006

This Paper describes that the Electrified railways are necessary for the metropolitan cities which are predominantly relying on the mass rapid transit systems such as metro or sub urban trains, which can carry more passengers at high efficiency and faster mode.

However, the electric traction power systems cause power quality damage to the grid by creating harmonics, unbalances, power factor problems, sudden loadings, non uniform loadings.

these problems can be overcome by using STATCOM in the Traction Substations.

this paper describes method for the control of STATCOM. it also compares the efficiency of statcom with other types filters used in the systems.

3.1.4 "A study on system stability improvement of distribution system with high speed electric railway using STATCOM"

BY Seoung Hyuk Lee ; Han Yang Univ., Seoul, South Korea ; In Soo Bae ; Chang Ho Jung ; Jin-O Kim

Published in:

Transmission and Distribution Conference and Exposition, 2003 IEEE PES (Volume:1)

Date of Conference: 7-12 Sept. 2003

This paper examines the stability of transmission line due to loading of High speed rail. the transmission line is at 154 kV.

The paper presents a method to evaluate the system stability.

the method describes the relation between stability and power losses, and the assessment of stability is done by numerical methods.

This paper discusses the increase of the stability by using STATCOM as it reduces the losses, and supplies reactive power .

Furthermore, it proves that the compensation of voltage drop and its by-product, loss reduction is closely related to improvement of system stability.

3.1.5 APPLICATION OF MULTILEVEL ACTIVE POWER FILTERING TO A 25kV TRACTION SYSTEM

by P C Tan, P C Loh, D G Holmes and R E Morrison

This paper describes that The Traction power supply systems are mostly prone to the harmonics and unbalances, and power quality distortions.

these power supply disturbances create situations which reduces Traction voltages and hence effect the Locomotive / Train performances.

it is an established fact that using of Active filter on Traction power supplies by minimising harmonics is an effective way of improving the voltage profile of the traction power systems.

this also compensates Reactive power on the grid.

This paper now extends this work to consider the further performance improvement that can be achieved using a multilevel converter as the shunt active filter.

3.1.6 "The State-of-the-Art of Power Electronics in Japan"

by Hirofumi Akagi, Fellow, IEEE

"IX. ACTIVE FILTERS FOR POWER CONDITIONING

This paper describes the use of active filters in high speed rail networks in Japan.

Active power filters have been used for all power quality problems like harmonics, reactive power compensation, unbalances, flickers, voltage regulation, pf improvements.

Shunt active filters have been used in Japanese railways for compensation of reactive power and unbalance currents.

these active filters use voltage fed PWM inverters with GTO thyristors.

the High speed trains generate a variable unbalance load , with variable reactive power requirements and harmonics on the line. in a day many such trains pass through the line.

this will cause voltage unbalances at the grid resulting in to power quality problems to the other systems connected to the common grid.

the active filter compensates for the reactive power, unbalance loadings, negative sequence components and harmonics thereby resulting in withdrawal of only pure fundamental power from the grid without any fluctuations.

At present, several active filters in a range of 40–60 MVA have been installed in substations along the Tokaido Shinkansen.

Chapter -4

MODELLING

4 MODELLING

4.1 Model of Traction Power supply

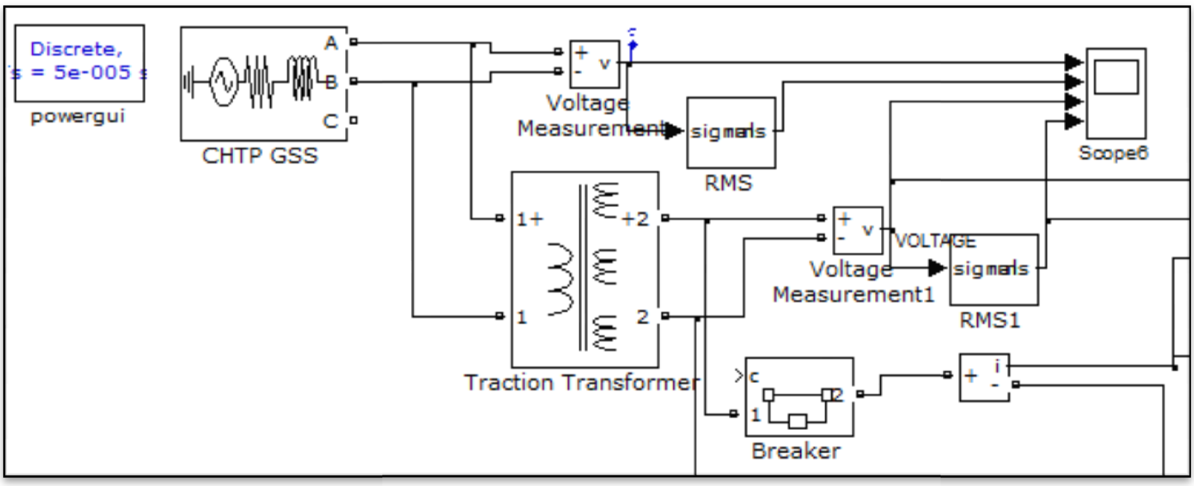
A MATLAB model of Traction Power supply of Line-2 of Delhi Metro has been developed to simulate the conditions of Power supply feed to the trains running in the configuration as existed in the subject conditions where the actual site measurements were under taken.

4.2 Traction Transformer

Two winding traction Transformer has been considered of 30 MVA with voltage ratio of 66 kV / 27.5 kV. For the sake of simplicity, taps have not been used.

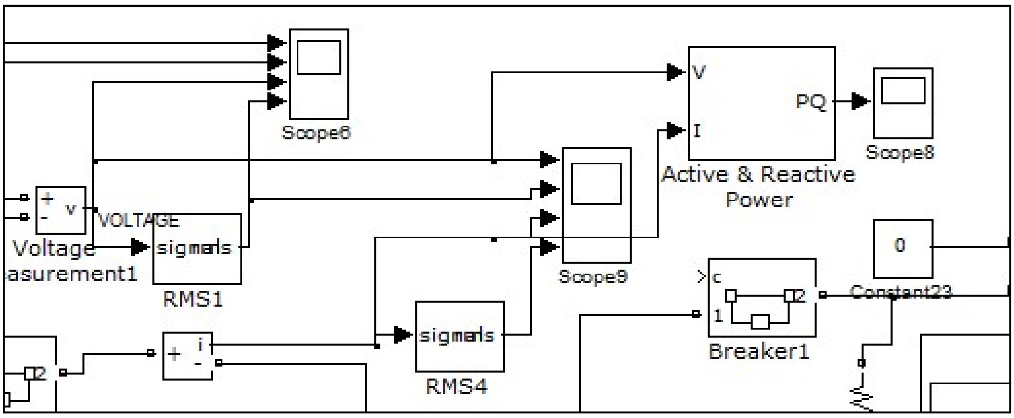
A normally closed circuit breaker has been used on the secondary side of 27.5 kV which feeds the overhead Catenary system of 25 kV , for supply of power to the trains.

Voltage measurement blocks for primary and secondary voltages has been provided which measure and record actual waveforms as well as their rms values.



4.3 V-I and P-Q measurements

Voltage and Current measurement blocks , for measurement and recordin of waveforms as well as rms values are added. For P-Q measuremnts and recording a separate scope has been added.



4.4 OHE Modeling

For every 2 km, a train has been considered. The OHE has been modeled as series R- L element.

The values of OHE Impedances are considered from the Indian railway AC Traction Manual.

As per ACTM, the per km impedance of " Single Track OHE with RC" has been considered as 0.70 < 70 degree.

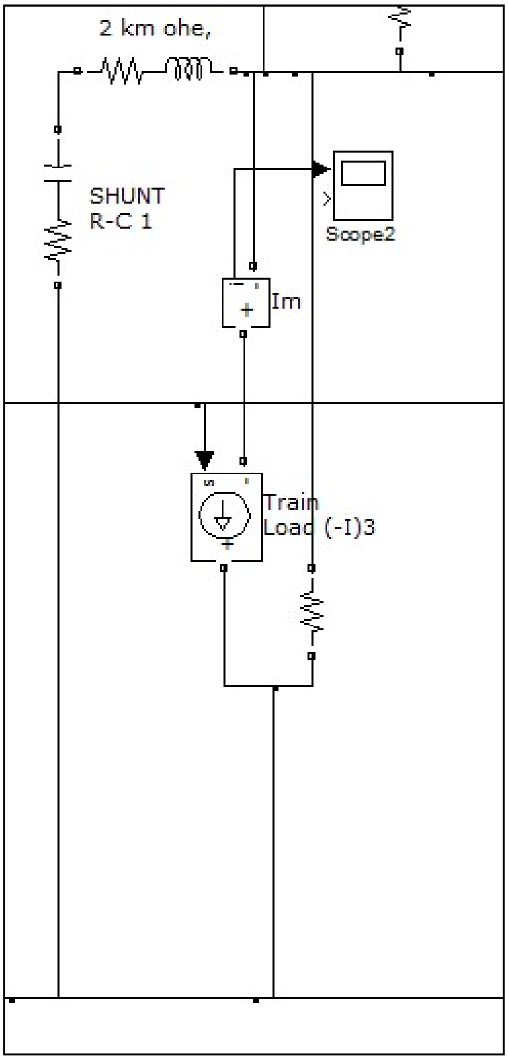
Both the UP and DN lines have been considered separately.

Shunt capacitance of OHE has been considered as

Line capacitance = 0.011 μF/km [ref 7]

5.3.1 The OHE is made up of a stranded cadmium copper catenary of 65 mm^2 cross section or a stranded aluminum alloy catenary of 116 mm^2 cross section and a grooved contact wire of 107 mm^2 or 150 mm^2 cross section, making up a total of 150 mm^2 or 210mm^2 copper equivalent. The OHE impedance values are generally taken as under:

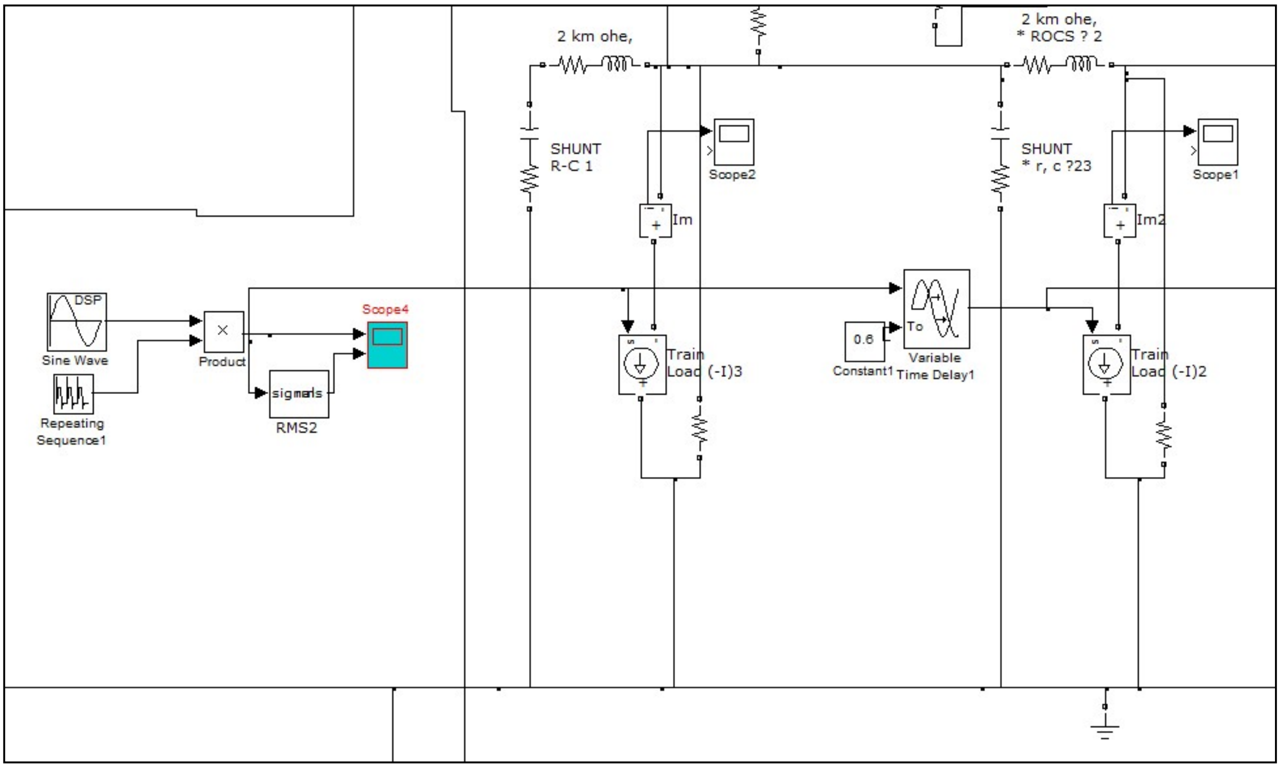
(i)	Single track OHE without return conductor	0.41 ∠ 70° Ohm/km
(ii)	Double track OHE without return conductor	0.24 ∠ 70° Ohm/km
(iii)	Single track OHE with return conductor	0.70 ∠ 70° Ohm/km
(iv)	Double track OHE with return conductor	0.43 ∠ 70° Ohm/km
(v)	Add booster transformer impedance where these are provided	@ 0.15 Ohms per booster transformer.
(vi)	Percentage impedance of traction transformer at 27 kV.	(12 +/- 0.5)% (21.6 MVA base)



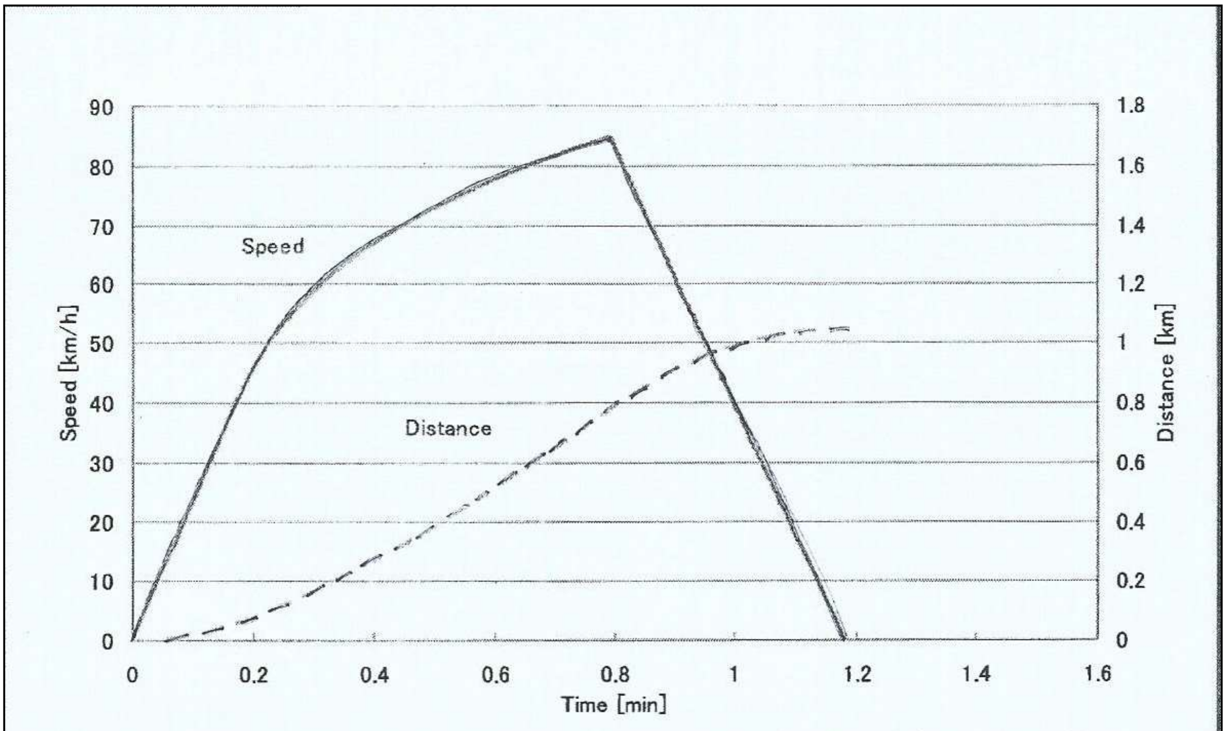
4.5 Model of Train

The Train has been modeled as a controlled current source. The Cureent wave form is controlled by a repeating sequence as per the current - time curve of the train between two stations over a span of approx 120 seconds, after which the cycle repeats again.

A delay of 6 seconds has been considered between start of every subsequent train for segregation purposes.

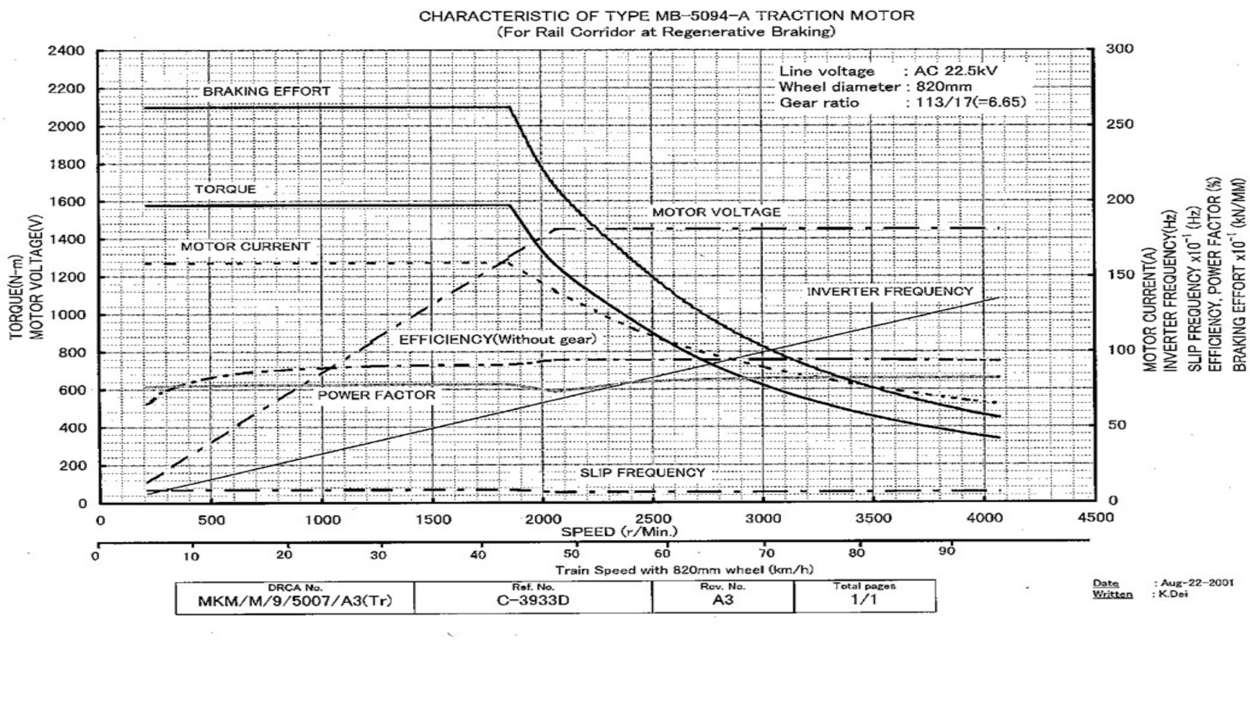


The Train running data in terms of Speed vs Time over a span between two stations in elevated section is represented as below:-

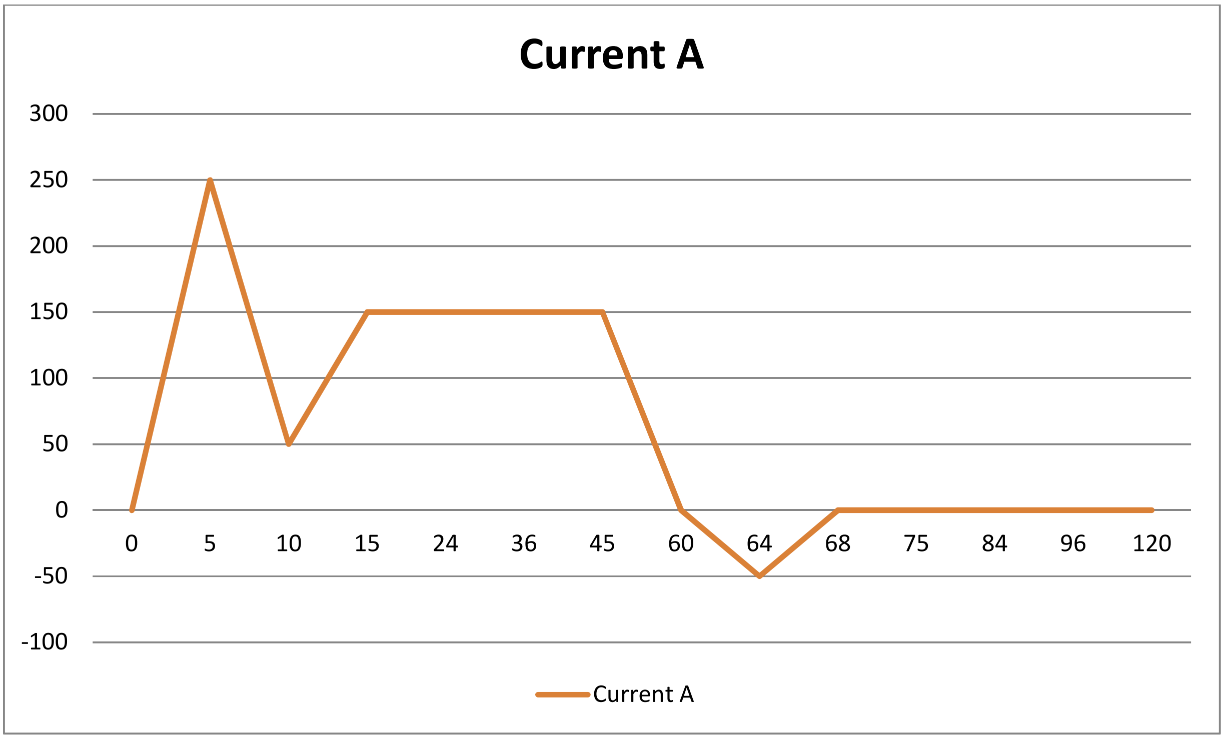


. The speed-time and distance-time of AW3 at -grade and elevated corridor.

The Characteristics of Traction motor represents the current at different speeds as follows:-



Combining both the above characteristics, the curve for train current vs time over a span between two stations in elevated section can be worked out as follows:-



The above current time curve has been used as repeating sequence in the model used for the train.

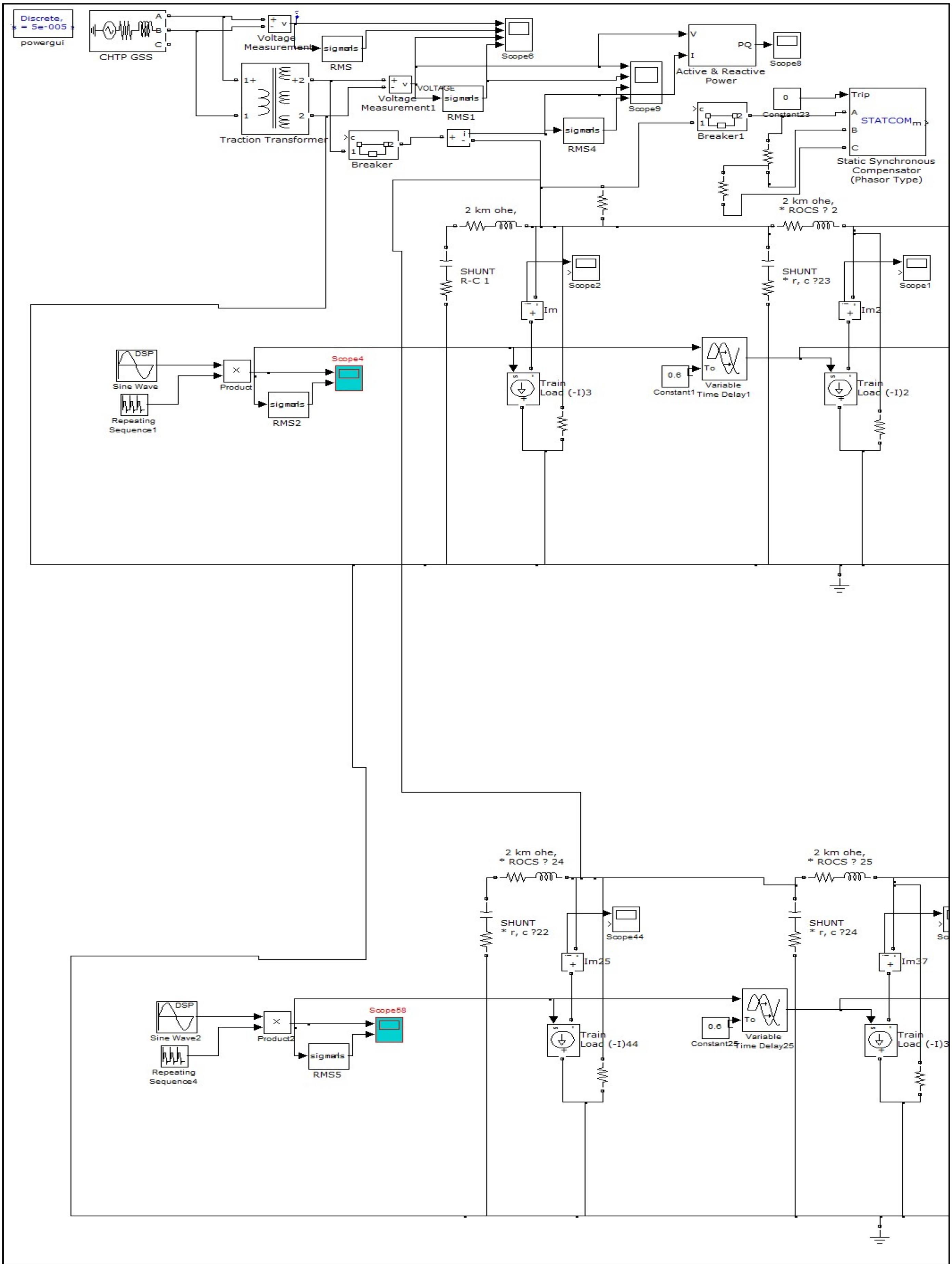
A small negative current zone represents the regenerative mode.

A total of 46 Trains has been considered in the complete line with 23 trains in each of the UP and DOWN Lines.

4.6 Model of STATCOM BLOCK

Static Synchronous compensator is added (phasor type) in shunt to the 25 kV supply.

The curtailed Model is shown below. Only two trains per line are shown. Model of Other Trains are on the left side of main model.


Discrete, s = 5e-005 s
powergui
CHTP GSS
Voltage Measurement
RMS
Scope6
Active & Reactive Power
Scope8
Traction Transformer
Voltage Measurement1
VOLTAGE
RMS1
Scope9
Breaker
RMS4
Breaker1
Constant23
STATCOM
Static Synchronous Compensator (Phasor Type)
2 km ohe,
2 km ohe, * ROCS ? 2
SHUNT R-C 1
Scope2
SHUNT * r, c ?23
Scope1
Im
Im2
Sine Wave
Product
Scope4
Repeating Sequence1
RMS2
Train Load (-I)3
Constant1
Variable Time Delay1
Train Load (-I)2
2 km ohe, * ROCS ? 24
2 km ohe, * ROCS ? 25
SHUNT * r, c ?22
Scope44
SHUNT * r, c ?24
Im25
Im37
Sine Wave2
Product2
Scope58
Repeating Sequence4
RMS5
Train Load (-I)44
Constant25
Variable Time Delay25

4.7 Results of Simulation

The Simulation is run for one compete cycle so that all trains have run to their full one span. the voltage and current waveforms of 25 kV are recorded and measured.

The Following figure Shows the results of simulation with wide voltage variations up to 17 kV.

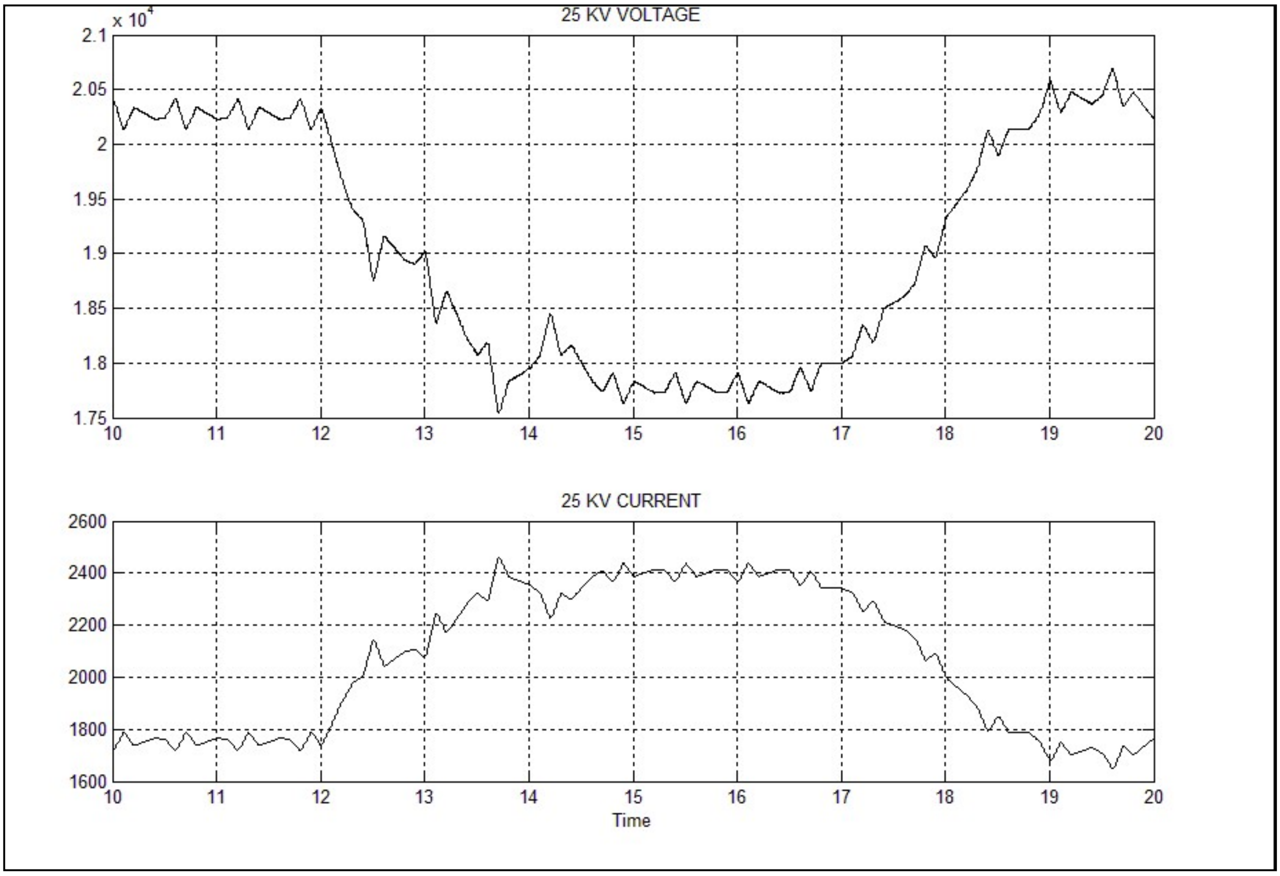
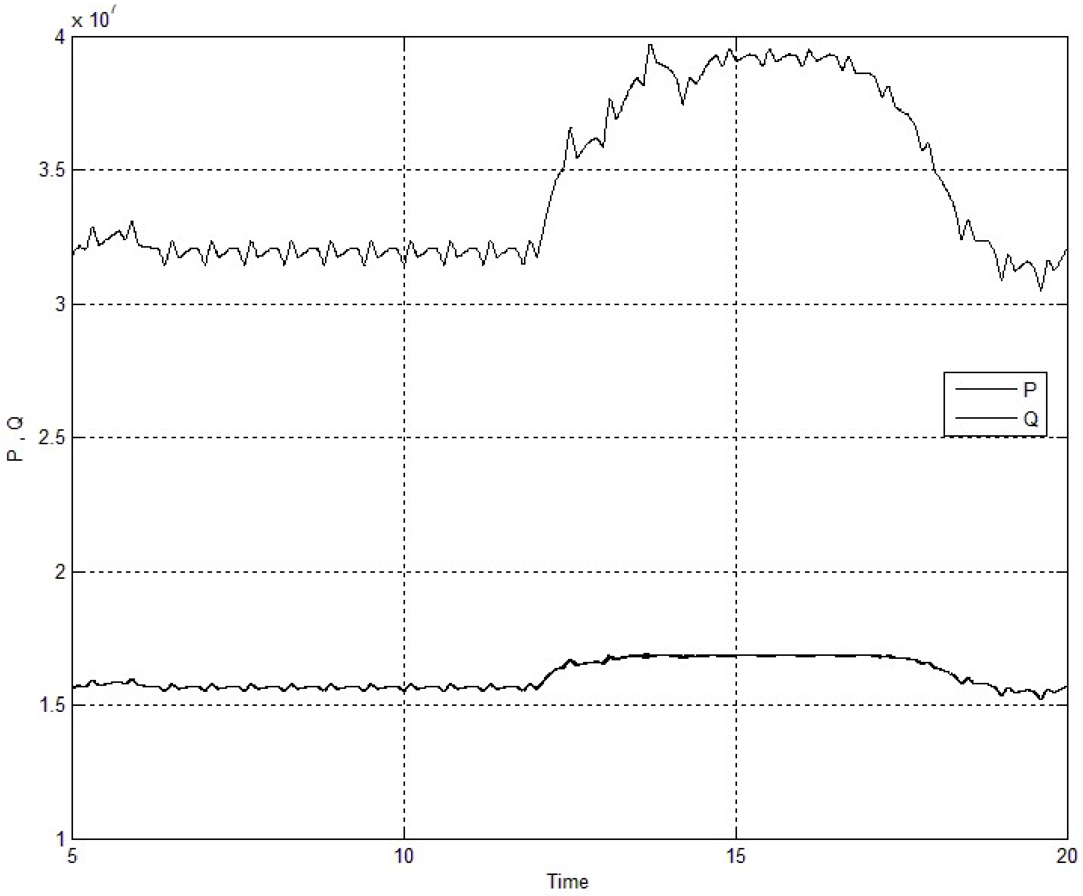


Fig 4.1 Results of simulation with wide voltage variations up to 17 kV.

The Following figure Shows the results of simulation for P-Q measurements, with P varying up to 40 MVA.



<u>Fig 4.2 Results of simulation for P-Q measurements, with P varying up to 40 MVA</u>

Chapter - 5

CONCLUSIONS AND RECOMMENDATIONS

5 CONCLUSIONS AND RECOMMENDATIONS

1. The power supply disturbances in Line-2 have been studied and analysed by several site measurements by using power analysers under the extended feed conditions from the Chattarpur RSS.
2. At all instances sudden increase in reactive power demand has been noticed, thereby resulting in dip in voltages available at 25 kV OHE for traction purposes.
3. This disturbance results in Trains losing their voltages and few of them start going to off mode thereby reducing the load and immediate improvement in voltages. This repeated cyclic phenomena results in repeated voltage pulsations and jerks in trains.
4. At certain instances wide amplitude SUB SYNCHRONOUS RESONANCE at certain load combination has been observed.
5. STATCOM of the capacity of 5 MVAr as per the average requirement is being considered for reactive power compensation.
6. Need be, the capacity will augmented based on study and use. The compensator can benefit in following ways:
7. Providing reactive power VAr as required during normal feed condition as well as overload conditions. This will continuously support the VAR requirements and resonance stage is not likely to reach.
8. Improve voltage profile by minimizing voltage drops due to reactive and harmonic current transformers.
9. VAr requirement from Grid will not be required so a saving in Electricity bill in normal course.
10. Helps in increasing life of system components i.e. transformer from overloading.

References

1. "Selective Compensation of Power-Quality Problems Through Active Power Filter by Current Decomposition"

   By Bhim Singh, Senior Member, IEEE, and Vishal Verma, Member, IEEE

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