

**A Study on the Modelling and Controlling of a Smart Grid for
Railway Power Supply
A Case Study: Ethio-Djibouti Railway Line**

Mebratu Delelegn Endalemaw



A Dissertation Submitted to

**The Department of Electrical Power & Control Engineering
College of Electrical Engineering & Computing**

**Submitted in Fulfillment of the Requirement for the Degree of Doctor of
Philosophy in Electrical Power Engineering
Office of Graduate Studies**

Adama Science and Technology University

October ,2024

Adama, Ethiopia

**A Study on the Modelling and Controlling of a Smart Grid
for Railway Power Supply
A Case Study: Ethio-Djibouti Railway Line**

Mebratu Delelegn Endalemaw

Supervisors

Dr. CS.Reddy (Associate Professor)

Dr. Endalew Ayenew (Assistant Professor)

A Dissertation Submitted to

The Department of Electrical Power & Control Engineering

College of Electrical Engineering & Computing

**Submitted in Fulfillment of the Requirement for the Degree of Doctor
of Philosophy in Electrical Engineering**

Office of Graduate Studies

Adama Science and Technology University

October ,2024

Adama, Ethiopia

Declaration

I hereby declare that this Dissertation entitled “A **Study on the Modelling and Controlling of a Smart Grid for Railway Power Supply**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials used for this thesis have been duly acknowledged through appropriate citations.

Mebratu Delelegn

Name of student

Signature

Date

Recommendation

We, the supervisors of this dissertation, hereby certify that we have read and revised the dissertation entitled “**A Study on the Modelling and Controlling of a Smart Grid for Railway Power Supply**” prepared under our guidance by Mebratu Delelegn Endalemaw submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering. Therefore, we recommend the submission of the dissertation to the department for further review and defense.

Dr. CS.Reddy

Major Supervisor

Signature

Date

Dr. Endalew Ayenew

Co- Supervisor

Signature

Date

Approval Page of Ph.D. Dissertation

We hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled **“A Study on the Modelling and Controlling of a Smart Grid for Railway Power Supply”** by Mebratu Delelegn Endalemaw.

Dr. CS.Reddy

Major Supervisor

Signature

Date

Dr. Endalew Ayenew

Co- Supervisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the dissertation open defense by Mebratu Delelegn Endalemaw have read and evaluated the dissertation entitled **“A Study on the Modelling and Controlling of a Smart Grid for Railway Power Supply”** and examined the candidate during open defense. This is, therefore, to certify that the dissertation is accepted for partial fulfillment of the requirement of the **Degree of Doctor of Philosophy in Electrical Engineering**.

Dr. Kenna Likasa

Chair Person

Signature

Date

Dr. Negasa Muleta

Internal Examiner

Signature

Date

Dr. Santosh Kumar

External Examiner 1

Signature

October 28, 2024

Date

Dr. Mengesha Mamo

External Examiner 2

Signature

October 28, 2024

Date

Finally, approval and acceptance of the dissertation is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the candidate's Department Graduate Council (DGC) and School Graduate Committee (SGC).

Département Head

Signature

Date

School Dean

Signature

Date

Office of Post graduate Studies, Dean

Signature

Date

Acknowledgments

I want to express my sincere gratitude to my main supervisor Dr. CS Reddy and my co-supervisor Dr. Endalew Ayenew for their invaluable advice, continuous support, and patience during my PhD study. I sincerely thank the School of Electrical and Computer Engineering for the opportunity to undertake my studies at Adama Science and Technology University. I am immensely grateful and owe a lot to ASTU Electrical Power Engineering Department staff and management Mr. Mesfin Mergea, Mr. Adisu Safo, Dr. Tefera T., Prof. Jin, and Dr. Negasa Muleta for their continuous support, understanding, and suggestions throughout my PhD. I thank you for the trust you put in me. Many thanks also go to Ethio Djibouti Railway Share Company for providing the necessary data during my study. I want to thank my family: My mother Almaz Demisse and my father Delelegn Endalemaw for their great support, endless love, and belief in me during this journey.

Lastly, but not least , I would like to express my gratitude to my amazing wife Seble Tesfu for her decision to join me in this adventure, and for her support, sacrifices, and care, for me, and our lovely sons Aron, Yafet and Eyosias. Without your help, this research would not have been possible. This thesis is also dedicated to them.

Table of Contents

Acknowledgments	iii
List of Table	vii
List of Figure	ix
Abbreviation and Acronym	xiii
Abstract	xv
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background	1
1.2 Motivation of Research	2
1.3 Scope of Work	4
1.4 Statement of the Problem	4
1.5 Objective of the Study	7
1.5.1 General objectives:	7
1.5.2 Specific objectives	7
1.6 Research Questions	8
1.7. Research Methodology Approach	8
1.8 Main contributions	9
1.9 Publications	10
1.9.1 Journal articles	10
1.9.2 Conference paper	10
1.10 Organization of the Thesis	10
CHAPTER TWO	12
LITERATURE REVIEW	12
2.1 Introduction	12
2.2. Railway Traction Power Supply Systems	12
2.2.1 Railway electrification system	12
2.2.2 Traction Power Supply Mode	16
2.2.3 Composition of railway traction power supply system	18
2.3 Power Quality in Electrified Railway System	22
2.3.1 Power Quality	22
2.3.2 Composition of System Voltage Loss	29
2.4 Smart Grid for Railway Power Supply System	34

2.4.1 Introduction.....	34
2.4.2 Overview Smart grid.....	34
2.4.3 Smart Grid Communication Architecture	39
2.4.4 Smart Grid for railway Power supply System	45
2.4.5 Smart grid SCADA Systems in Railways.....	52
2.4.6 SCADA for Wind Energy	56
2.5 Artificial intelligence in smart grid.....	58
2.5.1 Introduction.....	58
2.5.2 Overview of Artificial Neural Network.....	59
CHAPTER THREE	69
POWER FLOW ANALYSIS OF ETHIO-DJIBOUTI RAILWAY LINE ..	69
3.1 Introduction.....	69
3.3 Modeling and Methodology.....	74
3.4.2 Analysis of power supply scheme from Sirba Kunkur to Milo Section	87
3.4.3 Analysis of power supply scheme for three traction substations Hurso,Lonnis , and Milo	97
3.4.4 Analysis of Power Supply for Adigala, Aysha and Dewanle Substations	104
3.5. Power quality Measurement	113
3.5.1. Voltage Measurement Awash Traction substation	114
3.5.2 Voltage and Current Unbalance measurement	118
3.5.3 Voltage Measurement Adegala Traction substation	119
3.5.4. Voltage and current harmonic measurement Adegala Traction substation	119
3.6 Power Quality Measurement of Hurso Traction substation.....	124
3.6.1 Voltage Measurement Hurso Traction substation	124
3.6.2 Voltage and Current Harmonics Hurso Traction substation.....	125
3.6.3 Voltage and Current Unbalance measurement	126
3.7 Power Quality Measurement of Aysha Traction substation	127
3.7.1 Voltage Measurement Aysha Traction substation	127
3.7.2 Voltage and Current Harmonics Hurso Traction substation.....	127
3.7. 3 Voltage and Current Unbalance measurement	130
CHAPTER FOUR.....	141
STUDY AND ANALYSIS OF SMART GRID INTEGRATION WITH RAILWAY POWER SUPPLY	141

4.1 Introduction.....	141
4.2 Design and Analysis of RBFN Based MPPT controller for wind energy Integrated with Traction power supply System.	141
4.2.1 Introduction.....	141
4.2.2 Design of Wind Energy Integrated with Traction System.....	152
4.3 RBFN -based MPPT control algorithm of wind energy system	155
4.3.1 DC-DC Converter Modeling	158
4.3.2 Voltage Source Inverters Modeling	159
4.3.3 Energy management in wind energy integrated with traction power supply system.....	160
4.4 Simulation and Result Discussion	163
4.5 Analysis of Wind Energy Integration with railway Power supply	171
4.5.1 Grid connected mode	172
4.5.2 Island connected mode	173
CHAPTER FIVE	176
CONCLUSION AND RECOMMENDATIONS	176
5.1 Conclusion	176
5.2 Recommendation	177
Referances.....	179

List of Table

Table 1. Sation and Traction power substation power cut data.....	5
Table 2. 1 Monthly highest and lowest temperature.....	68
Table 2.2 Monthly average wind Speed	68
Table 2.3 Measured Wind Speed	68
Table 2.4 The Monthly wind Power Density	68
Table 2.5 Technical parameters of Aysha Wind Farm	69
Table 3.1 Supply voltage and connection points of traction substation	72
Table 3.2 Technical Parameters of Mojo and Wulenchit	79
Table 3.3 load flow analysis result	80
Table 3.4 N-1 fault of Nazareth 2-line fault result.....	81
Table 3.5 Awash 7-kilo line fault result.....	82
Table 3.6. Negative-sequence analysis result	82
Table 3.7 Short circuit analysis result.....	83
Table 3.8 Voltage harmonic distortion IEEE 519-2014 standard.....	84
Table 3.9. Total voltage and current distortion simulation result	85
Table 3.10 Negative-sequence results.....	89
Table 3.11 Technical Parameters of Traction Substations.....	90
Table 3.12 load flow analysis result	91
Table 3.13 AsebeTeferi line fault result	92
Table 3.14 N-1 fault of Awash 7 kilo line.	93
Table 3.15 Negative Sequence analysis.....	94
Table 3.16. Short circuit analysis result.....	95
Table 3.17 Total voltage and current distortion simulation result	95
Table 3.18. Negative-sequence results.....	99
Table 3.19 The schematic diagram for the relevant access system	100
Table 3.20 load flow analysis result	101
Table 3.21 Hurso line fault result	101
Table 3.22 Adegala line fault result.....	102

Table 3.23 Negative sequence Analysis	102
Table 3.24 Negative sequence Analysis	103
Table 3.25 Total voltage and current distortion simulation result	104
Table 3.26. Negative-sequence results.....	106
Table 3.27 load flow analysis result	107
Table 3.28. Hurso line fault result	108
Table 3.29. Adegala line fault result	109
Table 3.30 Negative-sequence analysis	110
Table 3.31. Short circuit analysis result.....	110
Table 3.32. Total voltage and current distortion simulation result	112
Table 4.1: Output power in different wind speed.....	171
Table 4.2 Load flow analysis result	178
Table 4.3 Load flow analysis result	175

List of Figure

Figure 2.1 Single phase AC System	16
Figure 2.2 One-way feeding	17
Figure 2.3 Double line feeding	17
Figure 2.4 Two-way feeding.....	18
Figure 2.5 Over Zone feeding.....	18
Figure 2.6 Composition of Traction Power	19
Figure 2.7 Traction substation	19
Figure 2.8 Traction Network.....	20
Figure 2.9 Three phase voltage wave form.....	25
Figure 2.10 Three phase symmetric voltage	26
Figure 2.11 Three-Phase Symmetric Voltage.....	29
Figure 2.12 Impedance traction network	30
Figure 2.13 Impedance traction network	30
Figure 2.14 Reactance of traction transformer	32
Figure 2.15 Traction substation loss	32
Figure 2.16 Voltage loss of Traction substation	33
Figure 2.17 Total Voltage loss.....	34
Figure 2.18 Communication architecture	41
Figure 2:19 Smart grid architecture	42
Figure 2:20 Ethernet Passive Optical Net.....	45
Figure 2:21 The Smart Grid Communication	47
Figure 2:22 Railway communication system.....	51
Figure 2:23Railway transmission communication.....	52
Figure 2.24 SCADA for Wind Energy	59
Figure 2:25 Communication networks.....	60
Figure 2.26 Artificial Neural Network	62
Figure 2:27 Aysha wind farm Layout.....	67
Figure 2:28 Monthly wind Speed.....	70
Figure 2:29 Monthly wind temperature.....	70

Figure 2:29 Monthly wind Temperature	70
Figure 3.1 A 25 kV, 50 Hz electric traction system.....	74
Figure.3.2 Ethio-Djibouti Traction Power Supply System.....	75
Figure 3.3 AC-DC-AC traction locomotive.....	78
Figure 3.4. An illustration showing how an energy source and transportation unit are coupled.....	79
Figure 3.5 Traction power supply	80
Figure 3.6 Schematic diagram of power flow analysis in normal operation mode	86
Figure. 3.7 Voltage Harmonic at 132kV side of Methera substation	87
Figure. 3.8 Voltage Harmonic at 132kV side of Melkajilo Traction	88
Figure. 3.9 Voltage Harmonic at 132kV side of Awash Traction	89
Figure 3.10 Traction substation layout	91
Figure 3.11 Schematic diagram of power flow analysis in normal operation mode....	96
Figure. 3.12 Voltage Harmonic at 132kV side of Sirbakunkuer Traction.....	97
Figure. 3.13 Voltage Harmonic at 132kV side of Meiso Traction	97
Figure. 3.14 Voltage Harmonic at 132kV side of Afedem Traction	98
Figure. 3.15 Voltage Harmonic at 132kV side of Gota Traction.....	99
Figure 3.16 Traction substation layout	100
Figure 3.17 Schematic diagram of power flow analysis in normal operation mod	104
Figure 3.18 Voltage Harmonic at 230kV side of Milo substation	105
Figure 3.19 Voltage Harmonic at 230kV side of Lonnis substation.....	105
Figure 3.20 Voltage Harmonic at 230kV side of Adegala substation	106
Figure 3.21 A Schematic diagram of a traction system connected to a power supply system.	107
Figure 3.22 Schematic diagram of power flow analysis in normal operation mode.....	113
Figure. 3.23 Voltage Harmonic at 230kV side of Adegala substation	113
Figure 3.24 Voltage Harmonic at 230kV side of Aysha Traction	114
Figure .3.25 Voltage Harmonic at 230kV side of Dewanle Substation.....	114
Figure 3.26 Voltage Harmonic at 230kV side of Hurso Substation	115
Figure. 3.27 Voltage Harmonic at 230kV side of lonnis Substation	115
Figure 3.28 Voltage Harmonic at 230kV side of Milo Substation	116
Figure 3.29 Voltage and Current harmonics Measurement Awash Traction substation.....	117
Figure 3.30 3 rd Voltage harmonics at 25kV side of railway substation.....	117
Figure 3.31 5 th Voltage harmonics at 25kV side of railway substation.....	118

Figure 3.32 7 th Voltage harmonics at 25kV side of railway substation	118
Figure 3.33 13 th Voltage harmonics at 25kV side of railway substation	119
Figure 3.34 15 th Voltage harmonics at 25kV side	119
Figure.3.35 23 rd Voltage harmonics at 25kV side of railway substation.....	120
Figure 3.36 3 rd Current harmonics at 25kV side of railway substation	120
Figure 3.37 7 th Current harmonics at 25kV side of railway substation	121
Figure 3.38 Voltage and Current Unbalance measurement	121
Figure 3.39 Voltage measurement	122
Figure 3.40 3 rd Voltage harmonics at 25kV side of railway substation.....	122
Figure 3. 41 15 th Voltage harmonics at 25kV side of railway substation	123
Figure 3. 42 15 th Voltage harmonics at 25kV side of railway substation	124
Figure 3.43 3 rd Voltage harmonics at 25kV side of railway substation.....	124
Figure 3.44 3 rd Current harmonics at 25kV side of railway substation	125
Figure 3.45 5 th Current harmonics at 25kV side of railway substation	125
Figure 3.46 7 th Current harmonics at 25kV side of railway substation	126
Figure 3.47 Voltage Measurement Hurso Traction substation	126
Figure 3.48 3 rd Voltage harmonics at 25kV side of railway substation.....	127
Figure 3.49 5 th Voltage harmonics at 25kV side of railway substation.....	128
Figure 3.50 7 th Current harmonics at 25kV side of railway substation	128
Figure 3.51 9 th Current harmonics at 25kV side of railway substation	128
Figure 3.52 Voltage Unbalance	129
Figure 3.53 Voltage measurement	129
Figure 3.54. 3 rd Voltage harmonics at 25kV side of railway substation.....	130
Figure 3.55 5 th Voltage harmonics at 25kV side of railway substation.....	131
Figure 3.56 3 rd Current harmonics at 25kV side.....	131
Figure 3.57 5 th Current harmonics at 25kV side	132
Figure 3.58 7 th Current harmonics at 25kV side	133
Figure 3.59 Voltage and Current unbalance Measurement	133
Figure 3.60 Increased output voltage	134
Figure 3.61 Reducing voltage loss	135
Figure 6.63 End parallel connection.....	142
Figure 3.64 Capacitance compensation device.....	143
Figure 4.1 ANN model	143

Figure 4.2 Block diagram topology of the hybrid system	144
Figure 4.3 RBFN Architecture.....	145
Figure.4:4 RBFN-based single MPPT architecture for the wind energy system	158
Figure.4:5 Grid tied wind energy system	160
Figure 4.6 Fly wheel Energy Storage System	160
Figure 4.7 Architecture of Energy Management system	162
Figure 4.8 Simulation of Wind Energy system integrated with	166
Figure 4.9 Validation Performance of RBFN wind with MPPT controller	167
Figure 4.10 Training data of RBFN with MPPT controller	168
Figure 4.11Regression plot for training, validation, test of RBFN wind with MPPT controller	169
Figure 4.12 Output power with MPPT at 18m/sec	169
Figure.4.13 Output Voltage with MPPT at 18m/sec	170
Figure. 4.14 Output current with MPPT at 18m/sec	172
Figure 4.15 Output Power without MPPT at 18m/sec	172
Figure.4.16 Output voltage without MPPT at 18m/sec	172
Figure 4.17 Output current without MPPT at 18m/sec	173
Figure 4.18 Output Power without MPPT at 20m/sec	173
Figure 4.19 Output current wave form without MPPT at 20m/sec	173
Figure 4.20 Output Power with MPPT at 20m/sec	174
Figure 4.21 Output voltage with MPPT at 20m/sec	174
Figure 4.22 Output current with MPPT at 20m/sec	175
Figure 4.23 Wind energy system integrated with traction power supply. By using the suggested MPPT control strategy, the AC train electrical power	175
Figure 4.24 Schematic diagram of power flow analysis in grid-connected mode	178
Figure 4.25 Schematic diagram of power flow analysis in Island mode	179

Abbreviation and Acronym

AC	Alternating Current
ADM	Add-drop multiplexer
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
ANN	Artificial Neural Network
BR	Bayesian Regularization
CTC	Centralized Traffic Control
DC	Direct Current
DAS	Distribution Automation System
DDF	Digital Distribution Frame
DES	Distributed Energy Resources
EDF	Ethernet Distribution Frame
EMU	Electric Locomotives Motor Unit
ESS	Energy Storage System
EPON	Ethernet Passive Optical Network
FAN	Field Area Networks (and
GPS	Global Positioning System
HAN	Home Area Networks
INC	Incremental conductance computation
LM	Levenberg-Marquardt
LTE	Long Term Evolutions
MLP	Multilayer Perceptron's
MSTP	Multi-Service Transmission Platform
MPPT	Maximum Power Point Tracking
OAN	Optical Access Network
OCS	Overhead Catenary System
ODF	Light Distribution Frame
OLT	Optical Line Termination
ONU	Optical Network Units
ODN	Optical Distribution Network

PCC	Point of Common Connection.
PMSG	Permanent Magnet Synchronous Generator
PMU	Phasor Measurement Unit
PON	Passive Optical Networks
P&O	Perturbation and observation
PQ	Power quality
RBFN	Radial Basis-Function Network
RCC	Remote Control Centre
R	Regression
RBE	Railway Battery Equipment
RMS	Root Mean Square error
RTU	Remote Terminal Unit
RPC	Railway Power Conditioner
SCADA	Supervisory Control and Data Acquisition
SCG	Scaled Conjugate Gradient
SG	Smart Grid
SOC	State of Charge
SPC	Program-Controlled Switch
SVG	Static Var Generator
THD	Total Harmonic Distortion
TPS	Traction Power Systems (TPS)
TPC	Traction Power Controller
TPSS	Traction Power Supply System
VSI	Variable speed inverter
WAN	Wide Area Networks
WECS	Wind Energy Conversion System

.

Abstract

Power quality analysis is a crucial aspect of managing railway power supply systems. These complex networks must maintain consistent, reliable electricity to power the various components essential for efficient and safe train operations. Analyzing power quality involves closely monitoring a range of electrical parameters, such as voltage, current, frequency, and waveform distortions, to identify any anomalies or deviations from optimal performance. The Ethio Djibouti railway line, a critical transportation link connecting the landlocked nation of Ethiopia to the port city of Djibouti, has been the subject of a comprehensive power quality analysis. This in-depth investigation sought to thoroughly examine the electrical systems and infrastructure supporting this vital rail network, ensuring reliable and efficient operation. Power quality is crucial for any railway, as consistent and stable electricity is required to power the locomotives, signaling systems, and other electrified components. The analysis delved into factors such as voltage regulation, harmonic distortion, power factor, and load balancing across the railway's distribution network. By closely monitoring these parameters, the study was able to identify any inconsistencies, anomalies, or areas for improvement, providing valuable insights to the railway operators. This research delves into investigating power quality phenomena on the Ethiopia-Djibouti railway line, specifically focusing on the Adegala and Aysha 230kV traction substations. Through the utilization of a power quality analyzer, measurements were taken at both 230kV and 25 kV to analyze the harmonic currents, power quantity, and overall distortion of voltage and current. The results of the measurements and simulations point towards exceeding IEEE standard 519-1992 limitations in terms of current and voltage harmonics. Significant voltage imbalances were detected within the train supply network's connecting spot, with the imbalance on the 230kV side surpassing 2%, failing to meet IEEE standard 1159-2009. Considering this, the research focuses on exploring the smart grid integration of wind energy with the railway's power supply. This study examines and maximizes the power generation from wind energy sources using artificial intelligence technique radial basis function network based maximum power point tracking controller to extract maximum power. The proposed MPPT controller design is applied to a 300kW wind energy structure, utilizing a conventional boost converter to maximize power output. The simulation is conducted in MATLAB and integrated with the railway power supply system to evaluate performance. The mean square error (MSE) obtained from the simulation results helps to validate the effectiveness of the control algorithm. Testing the MPPT approach under various wind speeds using MATLAB/Simulink shows promising results, with the system achieving an average

maximum power of 289.3 kW at a wind speed of 20 m/sec. The low MSE value of 0.012 indicates the suitability of this MPPT controller for practical applications. The research delves into the intricate relationship between wind energy integration and railway power supply, exploring its viability in both grid-connected and island modes. By harnessing the power of the wind, this innovative approach aims to supplement the energy needs of railway infrastructure, reducing reliance on traditional fossil fuel-based sources and promoting sustainable transportation. In the grid-connected mode, the study analyzes how wind turbines can be seamlessly integrated into the existing power grid, allowing for the bidirectional flow of electricity and ensuring a reliable and uninterrupted supply of power to railway operations. All traction substations connected to the power grid in grid-connected mode are experiencing overload conditions. The recorded bus voltage fluctuates between 239kV and 249.9kV, failing to comply with the IEEE standard, which stipulates an acceptable voltage range of +5% and -5% of the nominal voltage and all traction substations connected to the power grid supply side operate underloaded when in island mode. The bus voltage at the traction load side ranges from 20.71 kV to 26.3 kV, adhering to European standards EN50163: 2004. According to these standards, the maximum non-permanent voltage permitted for short durations is 29 kV, while the minimum permanent voltage must not fall below 19.0 kV. This compliance ensures that the voltage levels remain within safe and efficient operational limits, thereby maintaining the reliability and stability of the traction power system. This research not only addresses the issue of unreliable electricity supply, but it also contributes to the development of railway power systems by introducing renewable energy sources for railway electrification. By incorporating smart grid technology, efficient energy management and utilization can be achieved, ensuring a more reliable and sustainable power supply for the railway line.

Keywords: Power quality, Smart grid, RBFN, MPPT, Railway power supply

CHAPTER ONE

INTRODUCTION

In this chapter, the dissertation work is introduced in relation to traction power systems. Based on an examination of prior research as well as the history of the work, objectives and research questions are formulated. The overview is completed with the main contributions of the report and a synopsis of the publications.

1.1 Background

Absurd power quality (PQ) issues plague electric railway power networks worldwide, which are among the most important and high-power end-user loads of utility grids. Significant and diverse types of distortions in network voltage and current have been seen in all connected power systems and adjacent consumers because of the development and evolution of different supply topologies for these systems (Santiyanon et al.,2016). All around the world, railway traffic is increasing these days, which suggests that the amount of electric power consumed is also rising. One common type of railway power supply is the single-phase,25 kV/50 Hz AC traction power supply system. Owing to the contemporary trains' enormous loads, nonlinearity, and dynamic load fluctuation, the traction power supply system regularly has some power quality problems. Modern trains have enormous loads, are nonlinear, and have dynamic load fluctuations, which commonly lead to power quality problems in the traction power supply system (Sayed Moha et al.,2015). Power quality problems, including harmonics, uneven voltage, voltage swings, and poor power factor, have garnered more focus because of their detrimental impacts on utility power systems and traction electrical devices. Furthermore, issues with power quality could also affect the railway's control system, train signaling and communication, and upstream power system. To get around this, it's critical to focus on developing new, effective railway substation power systems with various architectural styles and increased power electronic devices that don't interfere with train traffic or the energy quality of railroad lines. Additionally, as the power market becomes more liberalized, railroad players are resolved to look for techno-economic ways to deal with the anticipated rise in energy demand. To address environmental issues, lower Co₂ emissions, satisfy expanding energy demand, and enhance power quality, renewable energy is predicted to be essential in the future. Integrating storage devices and renewable energy sources into train electrical power systems is one option to solve the problem. More intelligence is needed in the current electric power grid to ensure a consistent, affordable, and sustainable supply of

electricity (Li Xuebin.,2014). Electricity networks struggle to manage the backflow of power from distributed generation sources like wind and solar because the traditional power grid is not built to handle bidirectional power flow. The power grid of today still consists of a highly mechanical network of transformers, circuit breakers, and transmission and distribution lines. Throughout the entire system, the use of sensing, monitoring, communication, and control devices is restricted. Using a range of information and communication technologies, the smart grid paradigm has emerged as a viable way to address these issues. These technologies can enhance the conventional power grid's efficiency, security, stability, and scalability. The study and modeling of a smart grid for Africa's railway power supply system are pivotal in addressing the continent's transportation and environmental challenges. The potential of rail transport in Africa, with its advantages of energy efficiency, reduced greenhouse gas emissions, and minimized road damage, is immense. The ability of trains to move large loads and connect major urban centers efficiently can transform the continent's logistics and passenger transportation landscape. Railways, being the most environmentally friendly mode of transport, offer a cleaner alternative that can significantly improve air quality and reduce health risks associated with emissions from road transport.

However, the realization of these benefits in Africa is hindered by the low level of railway electrification, with just 15% of the continent's railways currently electrified. This gap presents a unique opportunity for the integration of smart grid technologies. Smart grids, with their advanced control, operation, and communication capabilities, can revolutionize the power supply systems of African railways. By enabling more efficient management and distribution of electricity, these grids can facilitate the electrification of railways across the continent. The African Integrated High-Speed Railway Network (AIHSRN), a key part of the African Union's Agenda 2063, underscores the continent's ambition to overhaul its transportation infrastructure. The plan to develop an extensive, electrified railway network connecting cities and regions is both bold and transformative (V. N. Olievschi,2013, R. Bullock,2019). It envisages a future where rail transport plays a central role in Africa's socio-economic development, making the study and modeling of smart grids for railway power supply even more critical.

1.2 Motivation of Research

In the railway system, power quality is a growing issue as it can impact performance and reliability, as well as affect equipment connected to the local distribution network. It is important to analyze the power quality of the railway system to understand train performance

and how it affects the nearby distribution network. Power outages in the railway line are common due to various reasons, which can have negative effects. It is crucial to enhance the dependability and excellence of energy by incorporating wind and solar power as renewable sources. To address these obstacles, the concept of the smart grid has emerged as a hopeful remedy, utilizing different information and communication technologies. These innovations can enhance the efficiency, reliability, security, sustainability, stability, and expandability of the classic power grid. The rise in the integration of renewable energy into the electrical system will help to tackle these challenges.

The study of smart grid integration in railway power supply systems is important for ensuring efficient and reliable energy distribution to trains. By implementing smart grid technology, railway systems can better manage their power supply, leading to cost savings and reduced environmental impact. Understanding this integration motivates researchers and engineers to develop innovative solutions that enhance the overall performance of railway networks. Through this study, advancements can be made in energy efficiency and sustainability within the transportation sector, ultimately benefiting both the railway industry and the environment.

The motivation for the study of smart grid integration with railway power supply system from a variety of important factors. First and foremost, the development of smart grids aims to ensure the stable, reliable, efficient, economical, and sustainable generation, distribution, and usage of both conventional and renewable power sources. With a global rise in the consumption of renewable energy, notably solar and wind power, there is a significant potential for utilizing wind power along railway corridors, particularly in areas like Adama and Aysha in Ethio-Djibouti, as well as tapping into solar energy across the entire railway line. Furthermore, the increasing demand for electricity worldwide has led to high power system loading, placing stress on system equipment. Public interest groups advocating for reduced carbon dioxide emissions and the necessity for a more reliable power supply are also driving forces behind the push for smart grid integration.

The integration of smart grid technologies with railway power supply systems has emerged as a critical area of research, yet a noticeable gap persists in the study and analysis of this integration, particularly in comparison to the well-explored integration of wind energy within other industrial contexts. While significant advancements have been made in various sectors regarding the incorporation of renewable energy sources, the specific application within railway systems, such as the Ethio-Djibouti Railway line, remains largely uncharted territory. This research uniquely addresses this gap by focusing on a Radial Basis Function Network

(RBFN)-based Maximum Power Point Tracking (MPPT) controller, emphasizing its application in both grid-connected and island mode wind energy systems aligned with railway power supply networks.

By exploring these novel concepts, the research offers a fresh perspective on the analysis of power quality within existing railway lines, while also studying the synergies that can be achieved through the connection of wind energy to railway power supplies. Such integration not only holds the potential to enhance the reliability and efficiency of power systems in the rail sector but also promotes the transition towards sustainable energy sources. By investigating this integration, the study contributes to the broader dialogue regarding renewable energy adoption in transport infrastructures, paving the way for future research and development initiatives that can lead to smarter, greener railway systems. Ultimately, this work is positioned at the intersection of renewable energy innovation and railway electrification, making its findings vital for enhancing the energy paradigms of modern rail networks.

1.3 Scope of Work

In this dissertation work, the focus was placed on the monitoring of power quality parameters at the point where the electric railway system connects to the transmission system. The operational details of the electric traction system, specifically the 25 kV, 50 Hz supply from the 230kV/132kV traction substation, were outlined. Through the investigation of power quality parameters such as THD, unbalance, and short circuit, the research delved into analyzing the power quality issues within the railway power supply system. The scope of this dissertation is to explore these power quality challenges and delve into the design, modeling, and analysis of a smart grid for railway power supply systems. It's important to note that while this study comprehensively covers power quality concerns, it intentionally doesn't address stability problems related to integrating renewable energy sources.

1.4 Statement of the Problem

The Ethio Djibouti railway line currently faces frequent power cuts that disrupt train operations. To address this issue, a study on power quality is necessary to identify and solve the power quality problem. A study on the modelling of a smart grid for railway power supply focuses on addressing the frequent power cuts that plague the Ethio-Djibouti railway line, which significantly disrupt train operations. The research aims to analyze the power quality issues currently affecting the railway and propose solutions to enhance the reliability of its electrical supply. The Ethio-Djibouti Railway line is currently facing power cuts from the

main grid, particularly from Hurso to Dewanle Line. This poses a significant operational challenge, as the single-track line makes it impossible to cross trains in both the Ethiopia and Djibouti sections during a power outage. As a result, train operations may be halted for more than 4 hours on average daily. During power outages, trains are often forced to halt in their tracks, disrupting service and causing delays for subsequent trains until power is restored. In some sections, such as the Hurso to Adegala section, this issue is particularly prevalent, with repeated power outages hindering train operations. The current infrastructure lacks backup power systems or rescue trains capable of removing stalled trains from these sections, exacerbating the problem. This reliance on a single power source makes the railway system vulnerable to grid failures and power shortages. Frequent power outages along the main line and at the stations have posed significant challenges over the past six operational years. These interruptions not only disrupt train schedules but also diminish the overall reliability of the transportation system, leading to increased frustration among passengers and logistical complications for operators. The detailed data outlining the frequency and duration of these power outages provides a clearer picture of the severity of the situation. Each instance of power failure affects not only the immediate line but can also have ripple effects on connected services, ultimately hampering the efficiency of the entire network.

As illustrated in the table below, the frequency of outages has shown a concerning trend, with certain periods experiencing spikes in power interruptions. The duration of these outages further compounds the issue, resulting in prolonged delays and unpredictable service patterns. Understanding this data is critical to implement effective solutions, such as investing in infrastructure upgrades, exploring alternative energy sources, or enhancing backup power systems. Addressing the root causes of these outages will be imperative to restore confidence in the system and ensure a reliable transportation service for all.

Table 1. Station and Traction power substation power cut data

Year	Station Power cut		Traction Power cut	
	Occurrences in number	Power cut duration (hr)	Occurrences in number	Power cut duration (hr)
2018	3436 times	22,625	769 times	2290
2019	8599 times	34,060	4192 times	8357
2020	2928 times	33,323	795 times	2143
2021	2385 times	34,989	538 times	1218
2022	2841 times	35,351	525 times	1384
Average	4038 times	32,069	309 times	1368

To address this issue, integrating smart grid technology with renewable energy sources, such as wind energy, into the railway power supply system offers a promising solution. By incorporating wind turbines, the railway system can generate its own electricity, reducing reliance on the main grid and providing an alternative power source during outages. Smart grid technology can optimize the distribution and utilization of this renewable energy, ensuring a stable and reliable power supply. This integration would not only mitigate the impact of power cuts but also contribute to environmental sustainability by reducing carbon emissions associated with traditional power generation.

The integration of a smart grid with wind energy could provide a solution to supply power for the train in grid connected or island mode, ensuring smoother operations in the event of a power cut. Integrating wind energy with a railway power supply system offers dual benefits. In standby state, the Energy Storage System (ESS) remains idle, as the substation can supply sufficient power to meet traction demands. However, in operation mode, the substation power demand surges, the ESS, and traction substations, Renewable Energy Source, and Railway Battery Equipment work together to provide traction power. Interestingly, even in operation mode, the substation can revert to standby mode if the combined power supply from RES and RBE exceeds traction power demand, allowing excess energy to be stored in the ESS. A study on the modelling of a smart grid for railway power supply focuses on addressing the frequent power cuts that plague the Ethio-Djibouti railway line, which significantly disrupt train operations. The research aims to analyze the power quality issues currently affecting the railway and propose solutions to enhance the reliability of its electrical supply. A crucial part of the study involves integrating wind energy as an alternative power source, providing a sustainable and stable backup to the traditional grid. By developing a smart grid system, the study intends to optimize power distribution and manage the intermittent nature of renewable energy sources efficiently. Ultimately, the goal is to ensure a consistent and reliable power supply to the railway, minimizing operational disruptions and improving overall efficiency. The modelling of smart grids for railway power supply is a critical area of research and development, as the efficient and reliable delivery of electricity is essential for the operation of modern rail transportation systems. This complex topic involves the integration of various technologies and systems to create an intelligent, adaptive power network that can meet the dynamic demands of railway operations. At the core of this model is the ability to monitor, control, and optimize the flow of electricity, drawing from a diverse array of generation sources, including renewable energy, to power the trains, stations, and ancillary infrastructure.

Through the implementation of advanced sensors, communication protocols, and data analytics, the smart grid can respond in real-time to changes in load, weather conditions, and other variables, ensuring a consistent and uninterrupted supply of power. Additionally, the modelling process must account for the unique requirements of railway electrification, such as the need for high-voltage, high-capacity transmission, as well as the integration of energy storage systems to provide backup power and load balancing. By leveraging the capabilities of smart grid technology, railway operators can improve the efficiency, reliability, and sustainability of their power systems, ultimately enhancing the overall performance and environmental impact of their transportation network. The ongoing research and development in this field represents a pivotal step towards the realization of truly intelligent, eco-friendly, and technologically advanced railway power networks of the future.

1.5 Objective of the Study

In this dissertation study focusing on the integration of smart grids with railway power supply systems, the overarching goal is to delve deep into the power quality aspects of traction power systems. The core aim driving this dissertation work is the study and modeling of smart grid for railway power supply system, a concept that holds immense potential for enhancing the efficiency and reliability of railway power networks.

The overall goal of this dissertation work is to obtain knowledge about the power quality of traction power systems and to study and model the smart grid for the railway power supply system. The study aims to investigate the general and specific objectives of using an RBFN-based MPPT controller for wind energy in combination with the traction power supply system. The research will focus on understanding how this controller helps to optimize power generation efficiency and stabilize the power supply for traction systems. By analyzing the performance and behavior of this system, researchers hope to improve its overall reliability and effectiveness. The goal is to enhance the integration of wind energy into traction power systems, leading to more sustainable and efficient transportation systems.

1.5.1 General objectives:

The general objective of this research is:

- To Study on the Modelling and Controlling of a Smart Grid for Railway Power Supply.

1.5.2 Specific objectives

To realize the objective of studying and modeling smart grid for railway power supply systems, the following are the specific objectives:

- To Study the Power Quality Analysis of the Ethio-Djibouti Railway Power Supply System
- To Study and Analysis of RBFN-based MPPT controller for wind energy integrated with the Traction Power Supply System.
- To identify the improvement of integrating the smart grid into the existing railway power supply system.

1.6 Research Questions

Based on this background, previous research, and the general problem formulation mentioned above, the following questions may be established:

- What are the main power quality problems of the electrified railway and their solutions?
- How can power quality problems of the electrified railway improve and optimize power quality to make train operations more stable?
- What is the impact of integrating wind with railway traction substations?
- What key technologies have enabled an efficient integration of smart grid for railway power supply?
- How can standalone and grid connected wind energy systems be integrated in a railway power supply system?

1.7. Research Methodology Approach

The methodology for studying and analyzing the integration of smart grid technology with railway traction power supply systems is a multi-faceted approach that seeks to enhance both efficiency and reliability. Central to this investigation is the Power Quality Analysis of the Ethio-Djibouti Railway Power Supply System. This phase begins with a systematic collection of data, particularly focusing on the evaluation of power quality. Utilizing a power analyzer device, researchers can accurately measure fluctuations and disturbances within the existing power supply system. These empirical findings are subsequently validated through the use of sophisticated simulation tools such as MATLAB Simulink and ETAP software. This detailed analysis is crucial for understanding how variations in power quality can impact the overall performance of the railway system.

A complementary aspect of the research involves the development of an RBFN-based MPPT (Radial Basis Function Network-based Maximum Power Point Tracking) controller for wind energy integrated into the traction power supply system. This segment of the study employs a

systematic methodology that begins with extensive data collection regarding the controller's performance under various wind conditions. The focus here is to analyze how effectively the controller can optimize power output to the traction power supply system. The results obtained from this analysis will be compared with existing power control methods, offering insights into potential improvements or ongoing challenges.

To achieve the proposed objectives, this study is structured around key components of modeling, control design, and the application of industry-standard software tools such as MATLAB Simulink and ETAP for simulation purposes. The research methodology is delineated into several steps: first, a comprehensive literature review to assess the state of power quality and smart grid technologies, identifying opportunities for innovative contributions to existing knowledge. Following this, data collection on critical railway traction parameters alongside wind energy input parameters will be conducted to ensure a well-founded analysis. Researchers will then develop a mathematical model that effectively characterizes the power supply for trains, with an emphasis on integrating renewable energy sources like wind. Lastly, an architectural framework for smart grid integration will be crafted, facilitating a comprehensive analysis of power quality issues through simulations, which will be validated by real-time measurements taken during actual railway operations. This structured approach not only contributes to the field of transportation energy management but also advances the dialogue on sustainable railway systems.

1.8 Main contributions

This PhD dissertation work focuses on the important connection between smart grids and railway power supply integration. The primary contribution of this research lies in the innovative study and design approaches developed. These approaches aim to enhance the efficiency and reliability of power supply systems within the railway network. By combining smart grid technologies with railway systems, this study seeks to optimize energy usage and improve overall sustainability in transportation infrastructure.

To resolve the electrified railway's power quality issues

- **Increased Integration of Renewable Energy:** To increase the penetration and utilization of clean energy, electrical engineers are working to integrate renewable energy sources into the smart grid. This helps to lessen reliance on fossil fuels and carbon emissions.
- **Enhanced Reliability and Resiliency:** Smart grids can minimize downtime during outages by detecting faults, rerouting power, and restoring service quickly thanks to advanced

automation and monitoring. Experience in electrical engineering guarantees a stable power supply and a strong grid infrastructure.

- Stable voltage and frequency maintenance is essential for electric locomotives to run effectively. Precise control mechanisms provided by smart grids guarantee that the power supplied satisfies the exacting requirements of rail traction systems. The Traction Electricity Supply Network gains real-time monitoring and control capabilities from Smart Grids. This guarantees the best possible energy use, fewer losses, and immediate responses to fluctuations in demand or supply.

1.9 Publications

The work undertaken during this PhD process has contributed to the following Publications.

1.9.1 Journal articles

- Mebratu Delelegn¹, Ravikumar Hiremath², Chandra Sekhar Reddy³, "Power Quality Analysis of Ethio-Djibouti Railway Power Supply System, "SSRG International Journal of Electrical and Electronics Engineering, "Volume 11 Issue 3,2024. [International Journal of Electrical and Electronics Engineering is a Scopus-indexed open-access, double-blind peer-reviewed journal]
- Mebratu Delelegn¹, Ravikumar Hiremath², Chandra Sekhar Reddy³, "Study and Analysis of RBFN based MPPT controller for wind energy integrated with Traction Power Supply System, "Journal of Electrical System (JES), Vol. 20 No. 7s (2024). [JES is indexed in UGC CARE, Scopus, and Web of Science (ESCI)]

1.9.2 Conference paper

- Mebratu Delelegn¹, Ravikumar Hiremath², Chandra Sekhar Reddy³, "Power Flow Analysis of Addis-Djibouti Railway Power Supply System Using ETAP,"2021 IEEE Southern Power Electronics Conference (SPEC), December 2021.

1.10 Organization of the Thesis

The thesis is organized into 5 chapters. The outline of the thesis is as follows:

Chapter 1 Presents the past research studies and delves into the background of the topic. I create goals and pose research questions to guide my study.

Chapter 2 provides a detailed look at railway power supply systems. It explains how the railway traction power supply system is structured and highlights the integration of smart grid technology in the railway power supply. The chapter also delves into the role of Supervisory

Control and Data Acquisition (SCADA) systems in smart grids and explores the concept of Artificial Intelligence within smart grid applications. The information presented in this chapter offers a comprehensive understanding of the evolving technology landscape within railway power systems.

Chapter 3 focuses on explaining the methods and methodology used to study power quality analysis of the Ethio Djibouti railway line. It highlights the approach taken to investigate and analyze the RBFN based MPPT controller for wind energy integration with the Traction Power Supply System. The discussion provides a detailed overview of how these methods are applied in the study and analysis of power systems within the railway infrastructure. By understanding these methodologies, researchers can gain insights into optimizing power supply efficiency for sustainable energy use in transportation systems.

Chapter 4 analyzes the results and discussions of integrating smart grids into railway power supply. The study looks at analyzing the power quality of the Ethio Djibouti railway line using MATLAB and ETAP software and validating the findings using a power analyzer device. Moreover, the chapter delves into examining an RBFN-based MPPT controller for wind energy using simulation and compares the results obtained from the analysis. This chapter provides valuable insights into the application of smart grid technology in the railway sector.

In the final Chapter 5 of this study, I discuss the results found in the previous chapters and provide answers to the questions explored. It also draws conclusions and suggest areas for future research. Each chapter discusses the work did and the results achieved. Overall, it analyzes and conclude the work conducted in this study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides a general explanation of railway power supply systems and focuses on the composition of the railway traction power supply system. It includes a review of recent progress in electrified railway networks from existing research. The chapter commences by identifying the different traction power supply system's being utilized and then analyzes the advancements in this field. The incorporation of smart grid technology into railway power supply system's plays a crucial role in guaranteeing a dependable, effective, and environmentally friendly energy network for the railway industry. With the increasing need for electrified rail networks, the older grid systems are under immense strain, causing worries about the quality of the power supply (R.E.Morrison et al.,2000). By embracing smart grid technology, railways can better manage their power needs, optimize energy usage, and enhance overall operational efficiency. This technological breakthrough not only solves the problems that traditional grid systems are currently facing but also opens the door for the rail industry to have a resilient and sustainable energy future. This chapter will cover the application of artificial intelligence to smart grid systems, the integration of smart grid technology for railway power supply, and the function of SCADA (Supervisory Control and Data Acquisition) in managing and optimizing smart grid operations. The transportation industry could benefit from increased sustainability, dependability, and efficiency if smart grid technology is applied to railway power supply. Furthermore, advanced predictive analytics, real-time decision-making, and automation of grid operations are made possible using artificial intelligence in smart grid systems, which enhances efficiency and lowers costs. Moreover, SCADA is essential for observing, managing, and maximizing the performance of smart grid infrastructure since it makes intercomponent communication and coordination easier. We hope to offer a thorough grasp of the developments and implications of smart grid technologies in the context of railway power supply by examining these important areas.

2.2. Railway Traction Power Supply Systems

2.2.1 Railway electrification system

For over a century, railways have served as the backbone of transportation in Africa, playing a pivotal role in the development of the continent. Their history is intertwined with colonialism, with European powers constructing railways to facilitate military operations and extract resources from the interior. These networks were designed to transport primary

commodities from the hinterland to ports, enabling their export to Europe. After gaining independence, African nations took control of their railway systems, but many struggled to maintain them effectively. Inadequate investment and competition from road transportation led to a decline in the quality and efficiency of African railways. However, in recent years, the continent has witnessed a resurgence of interest in railway development. Economic growth, increasing trade, and urbanization have spurred the need for efficient transportation systems. Social factors, such as population growth and the desire for improved mobility, have also contributed to the demand for railway services. Additionally, institutional reforms and increased foreign investment have facilitated the revitalization of African railways. Several African countries have recently undertaken ambitious railway projects, including the construction of new lines and the renovation of existing ones. These projects aim to improve connectivity, reduce transportation costs, and boost economic growth. The African Union's African Integrated High-Speed Railway Network (AIHSRN) project, part of its Agenda 2063, envisions a continent-wide high-speed rail system. These developments signal a bright future for African railways, promising to enhance the continent's economic and social prosperity. The African railway network currently spans just over 85,000-line km (although only 70% is fully operational), using multiple track and loading gauges, traction systems, and other technical parameters couplers, maximum permissible axle load, etc. Africa has the lowest railway network density in the world compared to its landmass and population. Despite covering 23% of the world's surface area and being home to approximately 18% of the global population, the continent accounts for only around 8% of the world's total railway length. This disparity highlights the need for concerted efforts to improve and expand Africa's railway infrastructure to support economic growth and connectivity. Most countries in Africa use diesel traction, while only 8 countries have electrified lines, representing approximately 15% of all lines in Africa. A3 kV direct current (DC) is the most common standard followed by 25 kV alternating current, while 50 kV AC is only used in South Africa. Most railways in Africa are diesel-operated, but electrification where it exists mostly conforms to the modern standard of 25 kV AC, with some obsolete systems using the older 3 kV DC (M.B. Bouraima et al. ,2020). Africa's railway electrification presents a significant shift towards sustainable and efficient transportation across the continent. Despite the prevalent use of diesel-operated trains, the move to electrify railways is gaining momentum, primarily adhering to the modern standard of 25 kV AC. This transition reflects a broader effort to modernize infrastructure, reduce greenhouse gas emissions, and cut operational costs. Electrification offers numerous advantages, including lower energy consumption, reduced dependency on fossil fuels, and

decreased air pollution, benefiting both the environment and public health. Historically, some railways in Africa utilized the older 3 kV DC system, which, although revolutionary at the time, is now considered obsolete due to its lower efficiency and higher maintenance costs compared to the 25 kV AC standard. The push towards the 25 kV AC standard is part of a global trend in railway electrification, chosen for its higher power-to-weight ratio, greater efficiency, and compatibility with high-speed rail operations. Several African countries are at the forefront of this transition, investing in extensive electrification projects to revamp their existing railway networks. South Africa, for instance, has made significant strides in electrifying its rail system, particularly around urban areas to support commuter services. Ethiopia's electrified rail project, linking Addis Ababa to Djibouti, represents a remarkable advancement in cross-border infrastructure, enhancing trade and mobility.

The challenges of railway electrification in Africa are multifaceted, involving substantial financial investments, technological transfer, and capacity-building. However, international partnerships and funding from development banks are playing a crucial role in overcoming these barriers. Electrification projects are not only about upgrading rails but also about transforming stations, training personnel, and adopting new maintenance practices to accommodate electric trains. The environmental impact of railway electrification in Africa cannot be overstated. By shifting from diesel to electric trains, African nations can significantly contribute to global efforts to combat climate change. Moreover, the reliability and efficiency gained through electrification can boost the appeal of railways, potentially shifting freight and passenger traffic from road to rail, further reducing overall carbon emissions. In conclusion, while the journey towards full electrification of Africa's railways is still underway, the progress made thus far indicates a promising direction. The transition to the 25 kV AC standard exemplifies a commitment to embracing modern, sustainable technologies that can drive economic growth, enhance connectivity, and protect the environment. As more countries join this initiative, the vision of an interconnected, electrified railway network across Africa becomes increasingly attainable, heralding a new era in the continent's transportation landscape (De Bod, A., & Havenga, J. H., 2010).

Electric locomotives in electrified railways rely solely on traction power systems (TPS) to receive uninterrupted electric energy from the utility grid. Electric railways, with their advantages such as high traffic capacity, efficiency, minimal pollution, and economical transportation costs, serve as the backbone of modern transport networks. Due to economic expansion, the global electrified railway network is expanding. There's a variety of

configurations used to deliver electricity to railway networks. These configurations depend on several factors, including the type of train service (tram, subway, commuter rail, freight), expected electrical load, and the specific train technology in operation. Here's a look at the main railway electrification schemes commonly used worldwide:

i. DC Electrification System

DC electrification system offers various advantages, such as addressing weight and space limitations, allowing for rapid acceleration and deceleration of DC electric motors, being cheaper than AC systems, reducing energy consumption, and providing other benefits. This type of system utilizes rectifiers and power-electronic converters to change three-phase electricity from power grids into DC power at a lower voltage. This lower voltage can be achieved through a third or fourth rail system or an overhead rail system.

ii. AC Electrification System

These days, AC traction systems are very common. Most traction systems use them because of their many benefits, which include easy controllability of AC motors, quick availability and generation of AC that can be stepped up or down, fewer substation requirements, and the presence of light overhead catenaries that transfer low currents at high voltages, among other benefits. Selecting the type of electrification depends on several factors like availability of supply, type of application area, or on the services like urban, suburban, and main line services, etc.

a. Low-frequency single-phase AC system: 16.7Hz, rated voltage of 15kV. Frequency is inconsistent with the power grid, requiring a special frequency converter, rarely used.

b. Power frequency single-phase AC system: 50Hz, rated voltage of 25kV, widely used main railway line.

Electric trains rely on a special electrical grid called the traction power supply system to keep them running. This system takes high-voltage electricity from the regular power grid and converts it to the specific format that electric trains, like locomotives and EMUs, need to operate. The traction power supply system is made up of several key parts, including traction substations and the traction network itself. Its composition is shown in Figure 2.1.

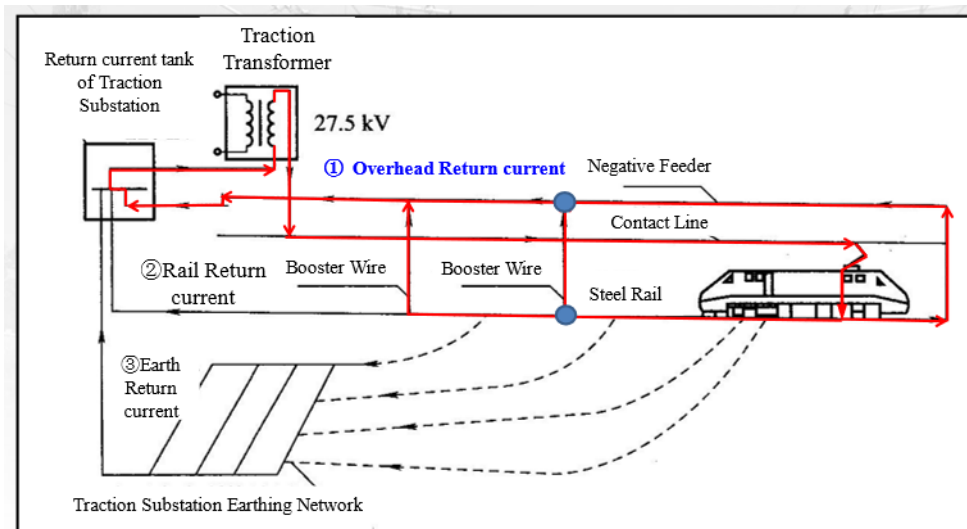


Figure 2.1 Single phase AC System

c. Three-phase AC system: The Catenary line is very complicated and has not been adopted.

2.2.2 Traction Power Supply Mode

The term "power supply mode" describes how the traction substation and the power system are connected. Level 1 loads include traction loads, and significant losses will result from a power outage. Due to the high demand for external power supply reliability at the traction substation, two separate power supply sources ought to be installed. The standby power supply should start up right away if one of the sources fails. Numerous power supply modes have emerged with the advancement of the traction power supply system. The power supply modes and TPS structures have an impact on the performance of electrified railways. Multiple feeding modes can be used with a traction power supply system, including one-way, two-way, double-way, and more (Abbas et al.,2007, Han. et al.,2011).

a. One-way feeding

Electric locomotives draw power from a single side of the traction substation. This design limits outages to one section of the power supply during breakdowns. As a result, traction substations can rely on simpler protective measures. However, for maximum reliability, utilizing two independent supply lines is recommended.

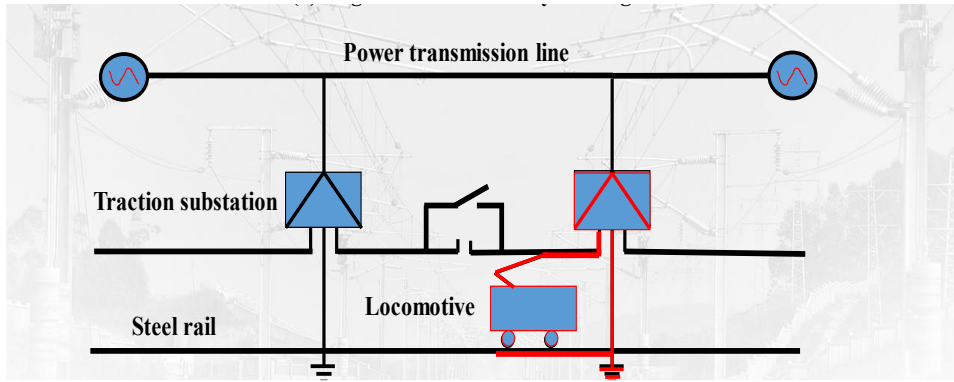


Figure 2.2 One-way feeding

b. Double line feeding

Double end feeding means that both power sources of a traction substation are supplied by the power sources from two ends of a public grid as shown in Figure 2.3.

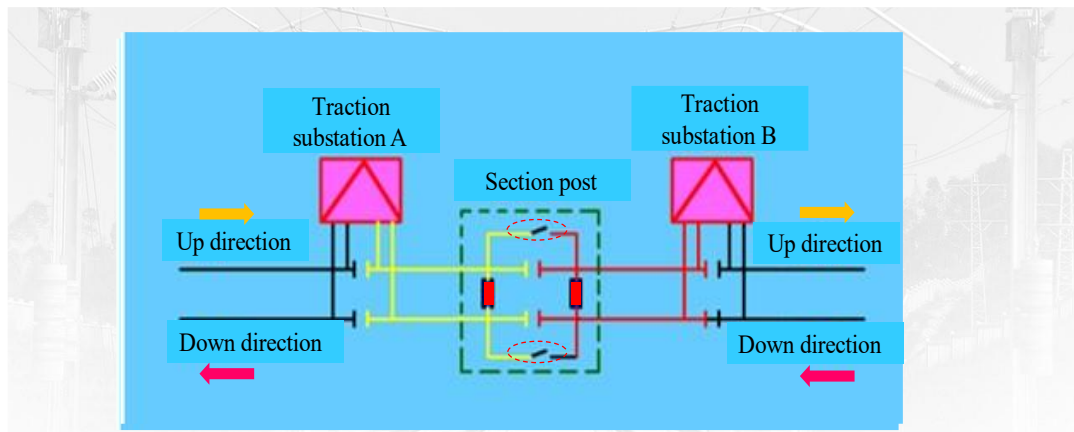


Figure 2.3 Double line feeding

C-Two-way feeding

The electric locomotives can receive electricity from the traction substations on both sides. It can help increase the power supply voltage of the OCS and reduce electricity loss. However, the impact of breakdown is high, and the complex protective devices are required for substations. This type of power supply is mainly used for urban rail systems.

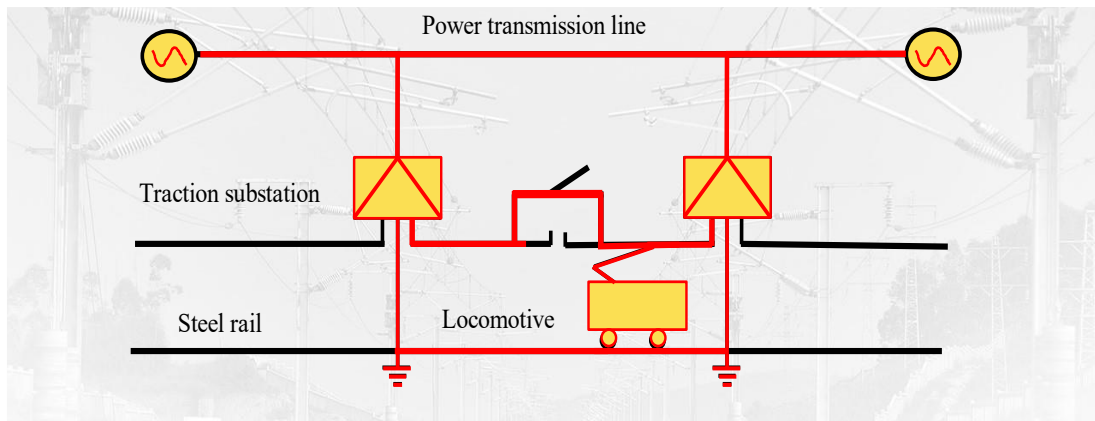


Figure 2.4 Two-way feeding

D. Over Zone feeding

When a traction substation has serious faults, it cannot supply power normally and cannot be restored in a short time, it needs to adopt over zone feeding mode, and the faulty substation is withdrawn from operation and supplied by two adjacent traction substations. When over zone feeding is adopted the power supply distance is doubled and the power capacity is reduced, so the number of trains must be reduced.

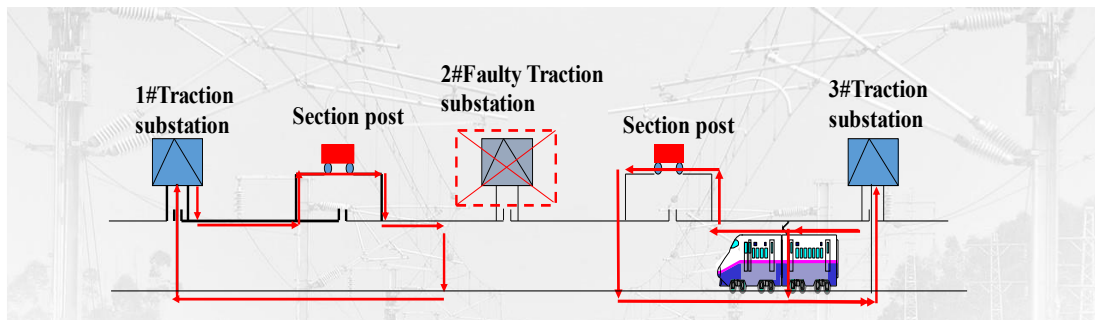


Figure 2.5 Over Zone feeding

2.2.3 Composition of railway traction power supply system

Traction substations, a traction network, and additional auxiliary power supply facilities make up an electric traction power supply system. An essential component of electrified railroads is this system. It is utilized to provide traction power, particularly for EMUs, or electric locomotives. The traction power supply system is an electrical power network that is used to receive power from the three-phase power transmission system and supply power for the train operating on the single-phase AC electric power system. Traction power systems (TPS) are the only means of power supply for electric locomotives on electrified railways, giving them continuous access to electricity from the utility grid. Transformers, overhead catenary wires,

and substations make up a typical traction power supply. Its composition is shown in Figure 2.6.

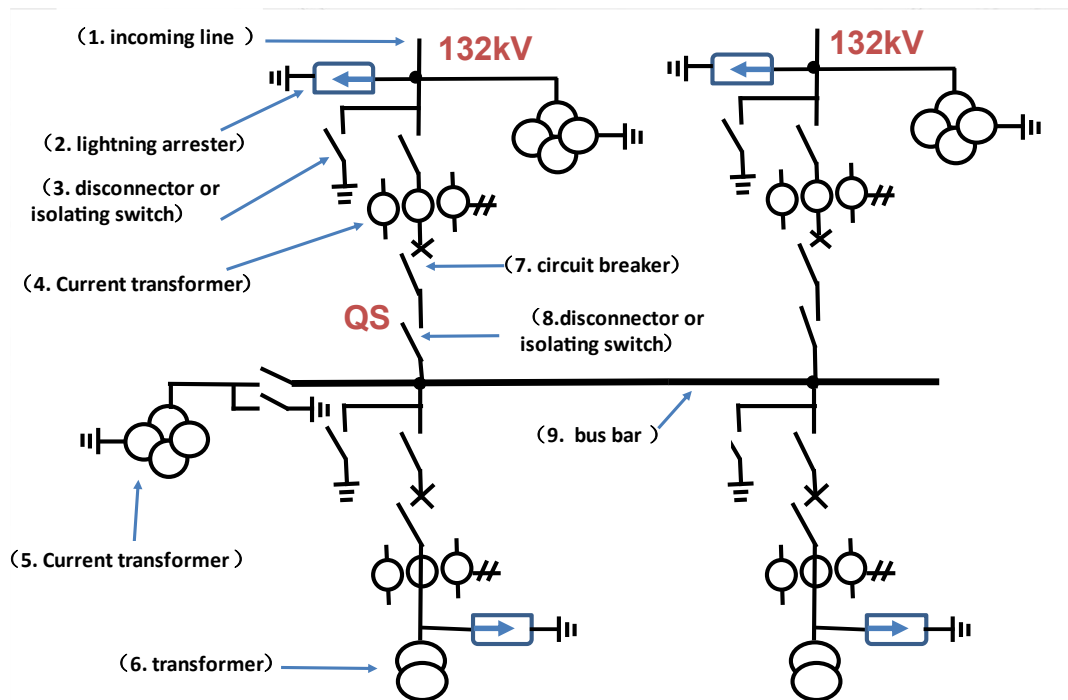


Figure 2.6 Composition of Traction Power

A. Traction substation

Traction stations are a very important part of electrified railways, and the function is to turn the 132kV or 230kV power frequency AC high voltage into 27.5kV single-phase power frequency AC which is suitable for electric locomotives (Jinhao et al.,2007, M. Aeberhard et.al,2010).

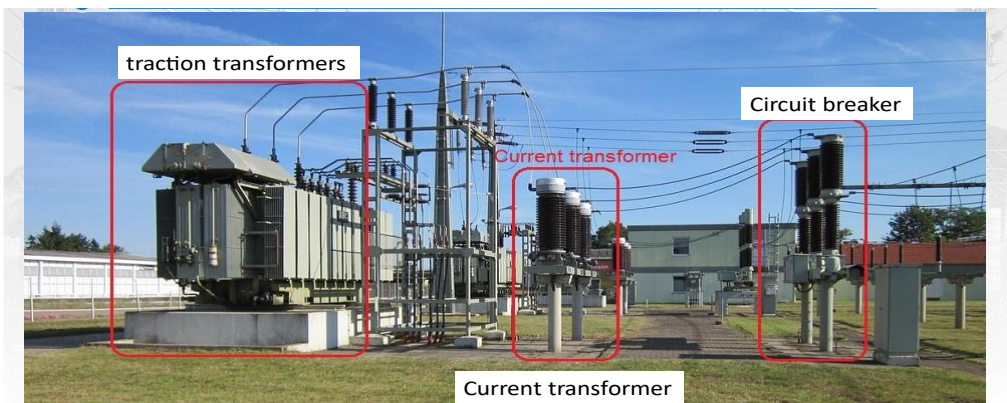


Figure 2.7 Traction substation

The traction substation shall adopt 132kV of power resource for incoming transmission and adopt the mode of branch connection with a connection strap diagram shown in above Figure 2.7.

- The traction substation shall adopt 132kV of power resources for incoming transmission and adopt the mode of branch connection with a connection strap.
- The 27.5kV side shall adopt a single bus-bar segment for connection.
- Main transformers of traction substations adopt an operation mode consisting of a master transformer and a spare transformer.
- Automatic switching devices for the main transformer and the power sources are used.
- The feeder circuit breakers adopt the fixed reserve.

B. Traction Network

After the current flows from the traction transformer to the electric locomotive through feeder lines and OCS, it then flows back to the traction transformer by steel rail, booster wire, and negative feeder, earth. This circuit is called a traction network. It includes:

- Feeder line
- OCS
- Steel rail
- Negative feeder
- Booster wire

- Earth wire

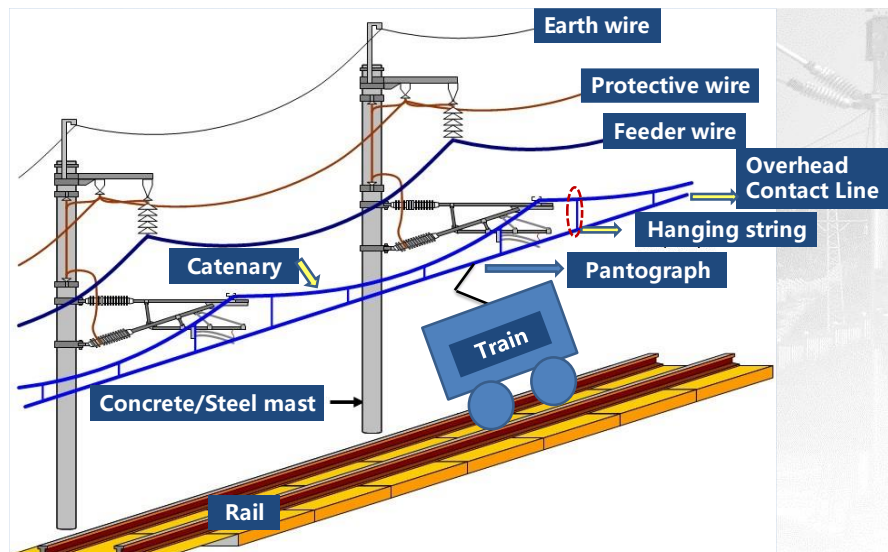


Figure 2.8 Traction Network

C. Switchgear

High-voltage switch devices are important components of the traction power supply system. These devices have the role of controlling and protecting the main transformers and high-voltage transmission equipment. The main switch devices are the circuit breakers, isolating switches, load switches, etc. These devices have the role of controlling and protecting the main transformers and high-voltage transmission equipment. The main switch devices are the circuit breakers, isolating switches, load switches, etc.

D. Electrical disconnect

Disconnect switches, also called isolator switches, are like safety switches for electrical circuits. Their main job is to completely cut off power to a circuit for maintenance or repairs. This ensures a safer work environment for technicians. These switches are common in electrical distribution systems and industrial settings. Imagine a giant machine needing a tune-up-a disconnect switch to isolate it from the power source, preventing accidental energization during work. Even in high-voltage substations, disconnect switches play a crucial role. They allow technicians to safely isolate equipment like circuit breakers, transformers, and entire transmission lines for maintenance.

2.3 Power Quality in Electrified Railway System

2.3.1 Power Quality

The electrified railway system has emerged as a pivotal component in the development of the railway industry, contributing significantly to the enhancement and sustainability of the national economy. By facilitating efficient, high-capacity transportation of goods and passengers, electrified railways help reduce traffic congestion, lower carbon emissions, and promote integration among various modes of transport, thereby strengthening economic activities. However, the operational efficiency of electric railway power supply systems can be severely compromised by power quality issues, which include negative sequence currents, harmonic distortions, and voltage fluctuations (U. J. Shenoy et al., 2004). These power quality problems arise in real-time operations due to factors such as variable load conditions, interactions between electrical equipment, and the influence of external grid disturbances. Negative sequence components can lead to overheating and inefficient electrical performance, while harmonics can result in increased losses and reduced lifespan of critical railway components, such as transformers and motors. Furthermore, voltage fluctuations can cause interruptions and instabilities in the power supply, directly impacting the reliability of train services. Collectively, these issues not only hinder the operational efficiency of electric railway systems but can also lead to increased operational costs, delayed services, and reduced attractiveness of rail transport as a viable alternative for freight and passenger movement. Consequently, addressing these power quality challenges is essential for optimizing the electrified railway's performance and realizing its full potential as a driver of economic growth, making research and investment into advanced power supply technologies and maintenance strategies a pressing priority for stakeholders in the railway industry. These issues negatively impact the grid's stability and efficiency (Mariscotti, A., & Sandrolini, L., 2021). Researchers have been investigating solutions to these power quality problems for several decades. Many studies focus on traction systems, measurement analysis, and the causes and effects of power quality issues.

Railway power conditioner (RPC): Several studies recommend RPCs to address power quality problems (Pei Luo Zhang, 2023). RPCs have been thoroughly analyzed and compared to other methods for correcting harmonic currents and negative sequences. An RPC converter includes a DC link and a back-to-back connection. The controller regulates the DC link voltage, providing both dynamic and reactive power compensation. Therefore, RPCs can effectively mitigate power quality issues caused by grid traction systems. Different literatures

reviews on power quality problems in electric train systems and proposes a solution using a Reactive Power Compensator. The RPC's effectiveness is compared to traditional methods for handling harmonic currents and negative sequences. An RPC converter includes a DC link and a back-to-back connection. Its controller dynamically maintains a stable DC link voltage, improving overall power quality by mitigating issues caused by grid traction. The controller ensures both responsiveness and continuous operation. A Pulse Width Modulation (PWM) rectifier serves as the front-end converter, transforming single-phase AC electricity into DC for the link. Additionally, battery storage systems or passive/active filtering techniques can be used to address power quality concerns (D. Paice ,1996). The researchers analyze the voltages and currents in both the 110 kV and 25 kV lines to understand the impact of electric trains on the power grid's performance. Their findings help us understand how these trains can influence the overall stability of the electrical system. In this study, power quality measurements were conducted at substations operating at 110/35/25 kV, and their results were compared to the IEC 61000-3-6 standard. The findings of this literature review, conducted by Arrillaga, J. & Watson, N.R. ,2003, offer a comprehensive overview of the environmental impact and power quality assessment of railway operations. Noteworthy conclusions and insights were derived from this research, shedding light on the importance of maintaining high standards in power quality within railway systems. These conclusions provide valuable information for further improving the efficiency and sustainability of railway networks. The article examines the important effects on the environment and power quality caused by railway traction power substations. Many power issues arise due to the electrical disturbances caused by the negative charge buildup of the electrified railway system. Researchers (Fini et al.,2016, Xiaohong et al.,2022, Lin wei Li, Mingli Wu.,2020),closely examined different power quality problems linked to traction transformers. Their study delves into how the system copes when experiencing heavy loads. (Sy-Ruen Huang and Bing-Nan Chen ,2002) conducted research on the harmonic distortion caused by electric locomotives on the utility supply network. Their study focused on determining the levels of specific frequencies present in the potential and energy, as well as the overall percentage of harmonic distortion in current and voltage. Through tests and analysis, they aimed to understand how electric locomotives impact the quality of power in the supply network (Luo et al.,2011, Tanta et al. ,2020). In the realm of electrified railways, power electronic devices play a pivotal role in enhancing the efficiency and performance of electric locomotives, serving as the crucial link between the DC power supply and the main traction circuit. These devices, which include converters, inverters, and rectifiers, facilitate the conversion and control of electrical power, enabling the

locomotives to operate seamlessly across varying operational demands and conditions. For instance, while rectifying the alternating current (AC) from overhead lines into usable direct current (DC) is foundational for maintaining optimal power flow within the traction system, the inverters allow for the modulation of this power, effectively managing speed and torque while ensuring smooth acceleration and deceleration. Moreover, the incorporation of advanced power electronic components enhances the train's overall energy efficiency, enabling regenerative braking, where braking energy is converted back into electricity and fed into the supply network or reused for subsequent acceleration. This not only reduces power consumption but also minimizes wear and tear on mechanical components, leading to decreased maintenance costs and improved reliability. Furthermore, the use of sophisticated control algorithms in conjunction with these power electronic devices allows for precise real-time adjustments to the power delivery, optimizing the performance of the electric locomotive under varying load conditions, gradients, and track configurations. This intricate interplay of technology and engineering not only represents a significant advancement in railway technology but also contributes to the overall sustainability of the transport sector by reducing carbon emissions and energy consumption, making electrified railways a more viable and eco-friendlier alternative to conventional diesel-powered trains. Therefore, the integration of power electronic devices into electric locomotives is indispensable for ensuring efficient, flexible, and reliable rail transport that meets the ever-increasing demands of modern infrastructure while supporting environmental goals (G.W. et al.,2004, Alexander et al.,2010). The electrified railway system is plagued by a host of power quality issues that stem from the inherent defects and characteristics of the traction load itself. These power quality problems are multifaceted in nature, encompassing nonlinearity, asymmetry, fluctuation, and significant impact on the overall power system. The nonlinear behavior of the traction load, which is driven by the complex electronic components and control systems, introduces harmonics and distortions that can wreak havoc on the clean sinusoidal waveform of the power supply. This, in turn, leads to increased heating in motors, transformers, and other equipment, as well as potential interference with sensitive electronic systems. (R. Lamedica et al. ,2020, P. Ladoux et al.,2010).The asymmetry of the traction load, often caused by unbalanced single-phase traction motors, creates an imbalance in the three-phase supply, leading to negative sequence currents and voltages that can accelerate the aging of insulation and cause vibrations in rotating machinery. The inherent fluctuations in the traction load, driven by the intermittent acceleration and braking of the trains, result in rapid and significant changes in power demand, leading to voltage instability, flicker, and potential tripping of protective devices. Perhaps

most concerning are the high-impact transients and spikes that can occur in the electrified railway system, often due to the switching of large inductive loads or the energization of traction transformers. These abrupt power surges can not only damage sensitive electronic equipment but also pose a serious safety hazard, potentially leading to arcing, insulation breakdown, and even catastrophic failures that can endanger both infrastructure and human life(Linya Liu, Zifeng Zhong. 2024.Yijie et al,2013 M. Aeberhard, et al.,2010).

a. Voltage Unbalance

Unbalanced load might result in voltage imbalance in an electrical utility system. Because electrified trains are by nature single phase loads, connecting these high speed, high power, time-varying loads to a three-phase power supply will result in a significant power imbalance. Two phases of the three-phase power system, running at industrial frequency through specialized substations, supply the traction loads.

Electrical imbalances in power grids can stem from two main causes: unequal demand on the system or a lack of transposition in transmission lines. Electric trains, with their single-phase, high-power, and constantly changing nature, are inherently imbalanced loads. When connected to a three-phase system through specialized substations, they can significantly disrupt the power balance. These dedicated substations typically use two out of the three phases to supply the trains, and the severity of the imbalance depends on factors like train movement, power needs, and grid configuration. When analyzing these imbalances, engineers consider two key aspects: the effect on equipment operating under the imbalanced voltage and the impact on the entire network's health, including generators, transmission lines, and distribution systems (An Luo et al.,2011, Linwei Li et al. ,2019).

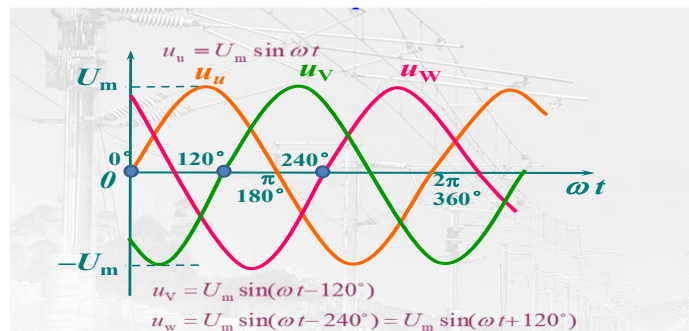


Figure 2.9 Three phase voltage wave form

The three-phase symmetrical voltage is usually used in power systems. As shown in the figures, the three-phase voltage has the same amplitude and frequency, and the phase difference between them is 12 degrees as shown in Figure 2.9 and Figure 2.10.

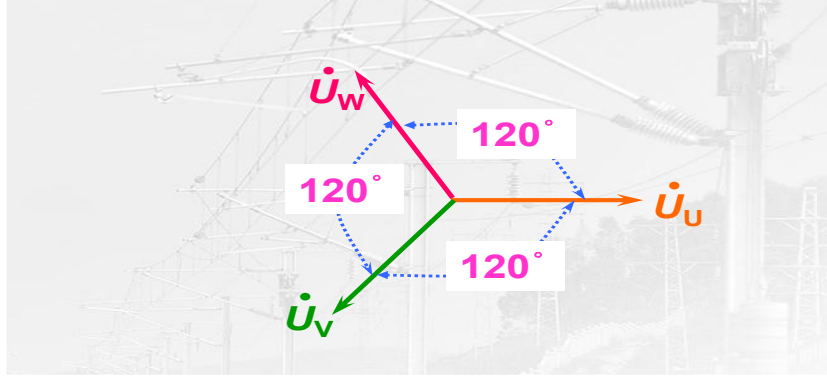


Figure 2.10 Three phase symmetric voltage

The sequence of three -phase alternating current in phase is called phase sequence. The phase sequence of the three-phase power supply is U, V, and W. In power systems, yellow, green, and red are commonly used to distinguish U, V and W phases.

Voltage Unbalance Voltage asymmetry (k) of a three-phase system is defined as a relation of positive and negative sequence components according to IEC 61000-2-12:

$$K = \frac{U_1}{U_2} \quad (2.1)$$

Where: U_1 positive sequence component of voltage

U_2 negative sequence component of voltage

The extra loss and vibration of the accessory due to the voltage will also lead to a decrease in how well the synchronous motor works. Since the electric train's power load is uneven and this uneven load is unstable, the negative sequence current, which can quickly change and spread throughout the power system, is more likely to cause the relay protection device in the system to decide whether to activate or not because of a malfunction in the negative sequence component, making the relay protection device more complex and less reliable, and possibly leading to a widespread power failure. Negative sequence current also has some negative impacts on the power transformer (Qianming et al.,2017, G.W. et al.,2004). Due to the uneven distribution of current, one phase current in the power transformer becomes too large, which decreases its efficiency in use (the rated output is not fully utilized), causes extra energy loss, and compromises the safety of the equipment. When the current passes through the transmission line, the negative sequence power fails to function, resulting in power loss and a decrease in the power transmission capacity and economic advantages.

b. Harmonics

It is important to consider the supply authorities' criteria for harmonic currents and harmonic voltage distortion at the point of common connection (PCC) to the high voltage network. An analysis of the harmonic distortion has been conducted using a calculation that takes the peak timetable into account. Voltage harmonic analysis is done in compliance with IEC 61000-3-6. The EMU's harmonic currents and the outcomes of the network computation with simulated train movement serve as the foundation for the computations (M. Goto et al.,1995, Y.E. et al.,2000). An EMU operating at full traction load has taken into consideration the following harmonic currents.

Harmonic Currents: Each train will feed the harmonic currents into the catenary system, which will then use the substation transformer to transfer them into the high-voltage grid. Trains supply the catenary system with harmonic currents at various sites, with varying phase angles and magnitude. For every train, the harmonic currents have a different phase angle.

Harmonic Voltage Distortion: When the traction power supply system is connected to the grid, it is necessary to compute the distortions of harmonic voltage and current on PCC that either comply or do not comply with the harmonic norms. An essential metric for assessing the quality of traction power supply systems is harmonic voltage distortion.

Total harmonic voltage distortion: the total harmonic voltage distortion factor can be calculated according to IEC 61000-3-6:

$$THV_D = \sqrt{\sum_{V=2}^N \left(\frac{U_N}{V_1}\right)^2} \quad (2.2)$$

Where: THVD Total harmonic voltage distortion magnitude of harmonic order v for x trains

V harmonic order

N number of harmonic order

c. Voltage Fluctuation

To guarantee the speed of the electric traction locomotive, great power is a prerequisite. Furthermore, it guarantees that, under the traction voltage grade, the load current can reach hundreds of thousands of amps. This means that a larger load current will result in a larger voltage drop during peak hours or fewer traction substations connected to the electrical grid due to the larger impedance of the traction net and traction transformer. It will significantly

affect the system and is particularly noticeable when the load power factor is low, which is the primary cause of the traction feeder voltage sag. Second, when the position of the locomotive changes continuously, so does the traction network access impedance and the associated line voltage drop. When a locomotive that runs on AC-DC-AC electricity absorbs the same amount of power, the load current increases, leading to a significant loss of active power and reducing the overall efficiency of the system. When it comes to AC-DC electric locomotives, low traction voltage can lead to a corresponding drop in DC voltage, which can cause the system to slow down or even halt. This can have an impact on the system's overall operational capacity and efficiency. The system's harmonic amplification, operating overvoltage, or lightning overvoltage are the usual causes of high voltages, which can result in equipment damage or locomotive protective actions, and the stability and safety of locomotive operation cannot always be ensured (Farhad Shahnian, Rasoul Esmaeilzadeh, 2005, Kaleybar et al., 2017, Michele et al., 2022).

d. Voltage Loss

The voltage drop experienced in traction supply systems is a critical aspect that must be carefully considered in the design and operation of electrified railway networks. This phenomenon is influenced by various factors, primarily the current flow on the alternating current (AC) power supply side, but also, and perhaps equally importantly, the current flow through the substations that distribute this electricity to the overhead lines. When electric trains draw power, they create a considerable load, which causes a drop in voltage along the supply lines; this drop can be exacerbated by the impedance presented by the cables and transformers in the network. As the current travels from the main power source to the substation, it encounters resistance, leading to a significant reduction in voltage, which can adversely affect the performance of the trains, especially during peak demand times when multiple trains are operating simultaneously. Furthermore, the current that flows through the substation itself contributes to additional voltage drops due to similar resistive losses occurring in the equipment that regulates and transforms the voltage to levels suitable for train operation. This interaction highlights the necessity for strategically placed substations and the adoption of technologies designed to minimize these voltage losses, such as high-voltage transmission lines and capacitive voltage support systems. Ultimately, a comprehensive understanding of both the supply side and substation dynamics is essential in optimizing the efficiency and reliability of traction supply systems, ensuring that trains receive a stable and adequate power supply critical for their safe and efficient operation. After the current flows

from the traction transformer to the electric locomotive through feeder lines and OCS, it then flows back to the traction transformer by steel rail, booster wire and negative feeder, earth.

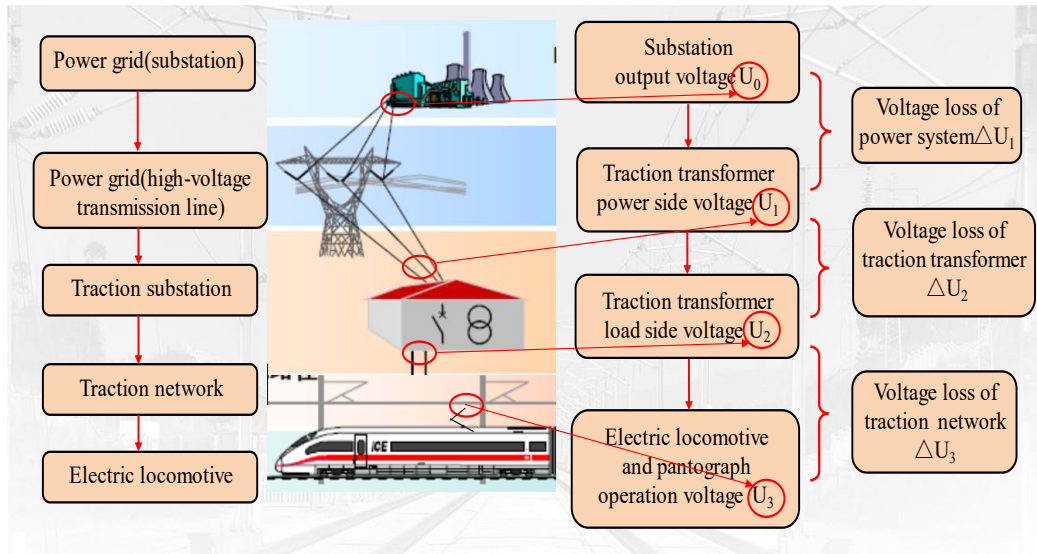


Figure 2.11 Three-Phase Symmetric Voltage

Because the resistance R of substation and high voltage transmission line is far less than reactance X , reactance can be used instead of impedance to analyze the composition of voltage loss, as shown in Figure 2.12.

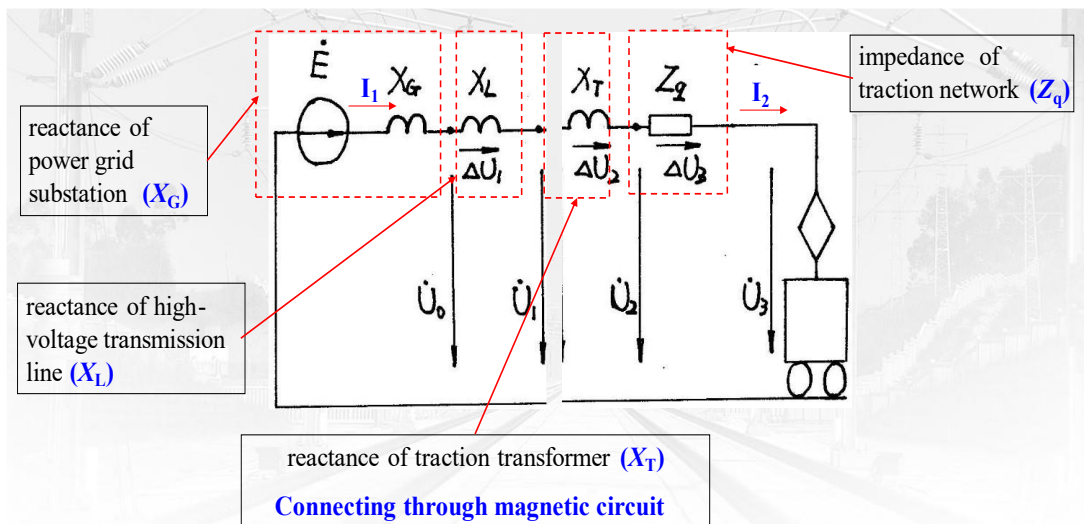


Figure 2.12 Impedance traction network

2.3.2 Composition of System Voltage Loss

Voltage drops $\Delta \dot{U}$ is defined as the difference of voltage phasor between the two ends of the line, whose modulus ΔU is called the voltage losses. It includes:

- Substation output voltage loss

- Traction transformer power side voltage loss
- Traction transformer load side voltage loss
- Electric locomotive and pantograph operation

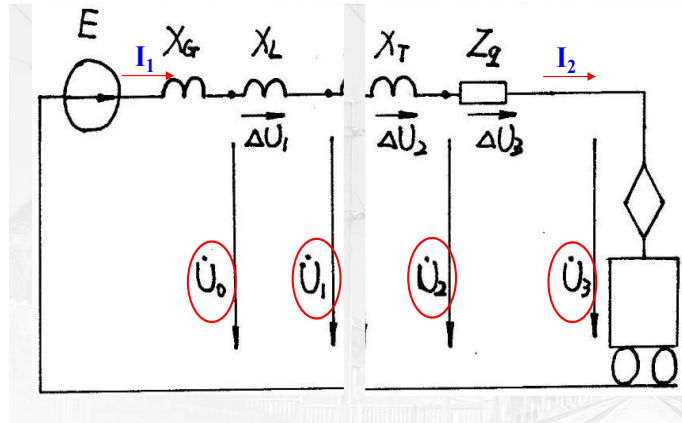


Figure 2.13 Impedance traction network

a. Substation output voltage loss

When no load, $I=0A$

$$\Delta U_1 = I_1 * X_L \quad (2.3)$$

$$\Delta U_2 = I_2 * X_T \quad (2.4)$$

$$\Delta U_3 = I_2 * Z_g \quad (2.5)$$

$$\Delta U_1 = \Delta U_2 = \Delta U_3 = 0 \quad (2.6)$$

When there is no load

$U_0 = U_1 = KU_2 = KU_3$, it can be considered that there is no voltage loss in the system.

When there's no load,

X_T is the reaction of the traction transform and the voltage loss Concentrates on the traction transformer.

When loaded, $I > 0A$

- $\Delta U_1 = I_1 * X_L > 0$
- $U_1 = U_0 - \Delta U_1 < U_0$
- $\Delta U_2 = I_2 * X_T > 0, U_2 = ((U_0 - \Delta U_1)/K) - \Delta U_2$

- $\Delta U_3 = I_2 X_q > 0$
- $U_3 = (U_0 - \Delta U_1)/k - \Delta U_2 - \Delta U_3$

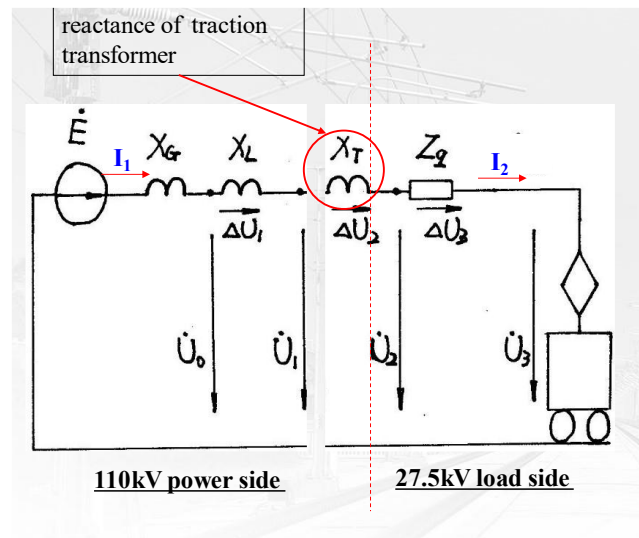


Figure 2.14 Reactance of traction transformer

Voltage loss of traction substation is defined as the difference between traction substation power side voltage.

$$\Delta U_2 = I_2 * X_T \quad (2.7)$$

Where: X_T is the reaction of traction transform and the voltage loss

I_2 is the load current

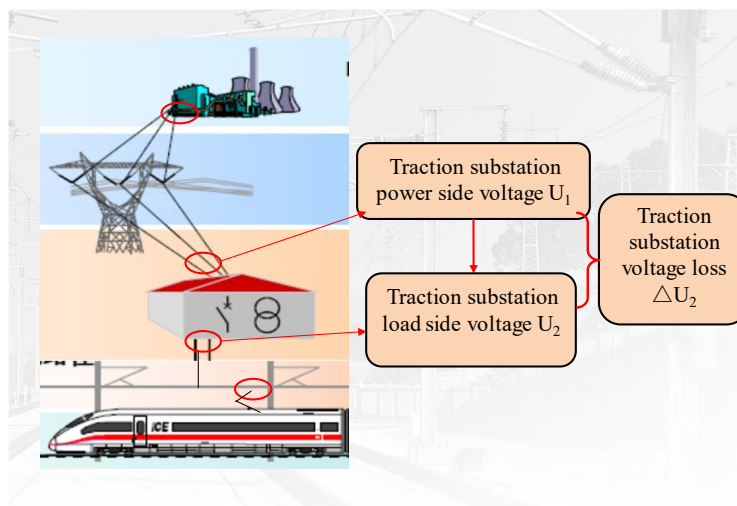


Figure 2.15 Traction substation loss

Voltage loss of the traction substation ΔU_2

The output end of the transformer as shown in the figure is short-connected, and a rated current is input at the power side. At this time, the voltage U_k added by the power supply is the short-circuit voltage of the transformer. U_k is the voltage loss generated by the rated current inside the transformer. i.e. ΔU_2

$$\Delta U_2 = I_2 * X_T U_k \quad (2.8)$$

Voltage loss of the traction substation ΔU_3

Voltage loss of the traction substation is the difference between traction substation load side voltage U_2 and electric locomotive pantograph operation voltage U_3 . It is given by the equation:

$$\Delta U_3 = I_2 * Z_q = I_2 x (R + jX) \quad (2.9)$$

Where: R is the resistant of traction network and.

X is the reactions of the traction network.

ΔU_3 is the Voltage loss caused by the traction current flowing through the traction network.

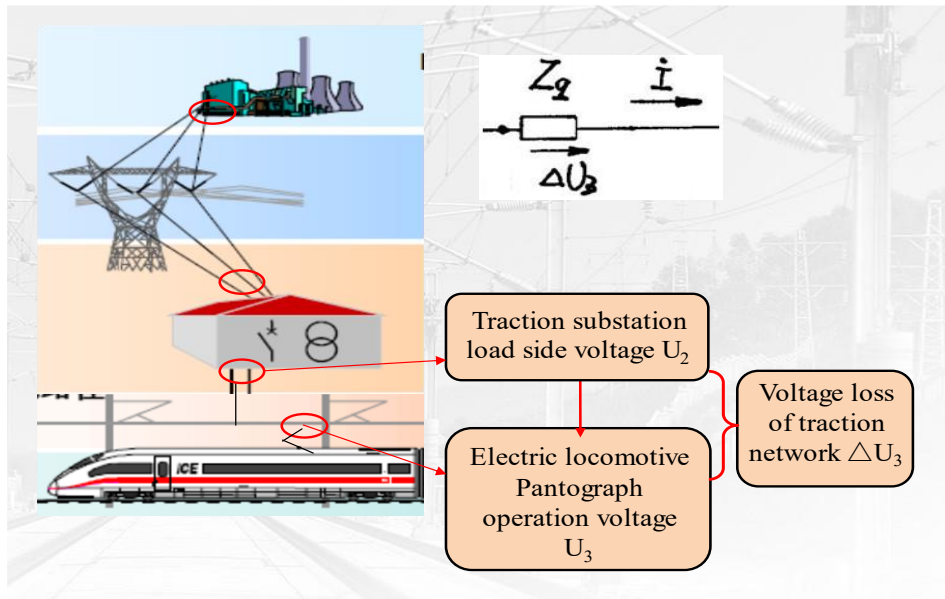


Figure 2.16 Voltage loss of traction substation

c. Analysis of Total Voltage loss

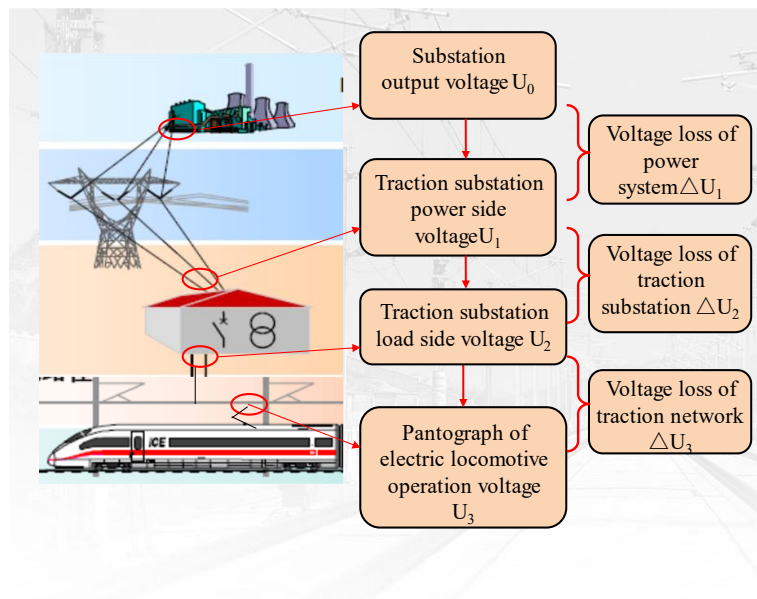


Figure 2.17 Total voltage loss

Under heavy load, the total voltage loss is the end of the power supply arm is ΔU .

$$\Delta U = \Delta U_1 + \Delta U_2 + \Delta U_3 \quad (2.10)$$

Which lowers the voltage at the end of the power supply arm, resulting in the reducing of locomotive speed and even the difficulty of starting.

2.4 Smart Grid for Railway Power Supply System

2.4.1 Introduction

The integration of smart grid technology into railway power supply systems is a pivotal step towards ensuring a reliable, efficient, and sustainable energy infrastructure for the rail sector. As the demand for electrified rail networks continues to grow, traditional grid systems are facing unprecedented pressure, leading to concerns over power quality, stability, and environmental impact. A smart grid for railway power supply systems offers a transformative solution, leveraging advanced technologies such as IoT sensors, artificial intelligence, and real-time monitoring to optimize energy distribution, minimize energy waste, and reduce greenhouse gas emissions. By harnessing the potential of smart grids, railway operators can enhance the overall performance of their power supply systems, improve passenger safety, and contribute to a more environmentally friendly transportation ecosystem (Hossain et.al,2012, Ma et al.,2013).

2.4.2 Overview Smart grid

The next generation of electric grid, known as the smart grid (SG), combines control systems, information and communication technologies (ICT) with the electrical grid (Kabalcı et al.,2019, D. Fan et al.,2021, C. Feng et al.,2021). The Smart Grid, which promises self-healing, resilience, sustainability, and efficiency to the energy-critical infrastructure, is regarded as the next generation power system due to its integration of advanced computing and communication technology. When the SG fully supports two-way energy flows that are effectively managed based on real-time information as well as two-way information (communication) flows, it is "smart". The term "smart grid" refers to an electrical power system that combines a two-way communication network with artificial intelligence to provide both energy and information. This technology allows for real-time feedback on how the electrical grid is operating via a variety of sensors and equipment (W. Wang et al.,2011, S.R. Salkuti et al.,2021).

The concept of a smart grid for a railway power supply system represents a cutting-edge advancement in the realm of energy management and distribution. At its core, the smart grid leverages sophisticated digital technology to create a highly efficient, reliable, and responsive electrical network that powers the railway infrastructure. By integrating real-time data monitoring, advanced analytics, and automated control systems, the smart grid optimizes the generation, transmission, and consumption of electrical energy across the railway network.

This allows for dynamic load balancing, minimized power losses, and rapid response to fluctuations in demand ensuring a stable and uninterrupted supply of electricity to keep trains running smoothly and on schedule. Moreover, the smart grid's two-way communication capabilities enable seamless integration with renewable energy sources, such as solar panels and wind turbines installed along the railway lines, allowing for the incorporation of clean, sustainable power generation. This holistic, intelligent approach to railway electrification not only enhances energy efficiency and reduces environmental impact, but also provides railway operators with granular insights and the ability to make data-driven decisions for proactive maintenance and capacity planning. Ultimately, the smart grid for railway power supply represents a transformative technology that is poised to revolutionize the way we power our modern rail transportation networks, ushering in a new era of reliability, sustainability, and operational optimization (Zhang, P. et al., 2010, Dileep, G.,2020).

The key features of a smart grid include:

- **Advanced Metering Infrastructure (AMI):**

Smart grids represent a transformative advancement in modern energy management, serving as the backbone of an intelligent, interconnected power system. At their core, these grids facilitate sophisticated bidirectional communication between utility companies and their customers, establishing a dynamic, data-driven framework that optimizes energy production, distribution, and consumption.

Integral to this data-driven approach are smart meters, which offer consumers detailed, instantaneous insights into their own energy consumption. These intelligent devices facilitate two-way communication, allowing customers to not only monitor their usage but also interact with utility providers, potentially adjusting their demand in response to dynamic pricing signals or grid conditions. This heightened transparency and control ultimately empowers consumers to make more informed decisions about their energy use, playing an active role in optimizing the grid's performance. Leveraging the wealth of data generated by smart grids, utility companies can also implement advanced analytics to forecast demand, optimize asset management, and enhance predictive maintenance all of which contribute to a more resilient, sustainable power infrastructure. As the global transition to renewable energy sources accelerates, smart grids will prove increasingly essential, serving as the adaptive, responsive nervous system that enables the seamless integration of distributed generation, storage, and load-balancing capabilities. Through their ability to facilitate real-time, intelligent

coordination between all stakeholders, these innovative power networks are poised to revolutionize the way we generate, distribute, and consume electricity, ushering in a new era of energy efficiency, reliability, and sustainability.

Smart grids are an essential component of modern energy management systems, offering advanced bidirectional communication between utility companies and customers. These grids provide comprehensive data on energy usage, allowing for remote monitoring and accurate billing in real-time. Using sophisticated sensors, automation, and monitoring systems, smart grids collect vital information on power production, transmission, and distribution. This data enables grid managers to identify and respond to variations in voltage levels, potential problems, and electricity consumption. With this knowledge, they can optimize the grid's efficiency and improve its reliability. Smart grids also utilize smart meters that offer detailed insights into energy consumption and allow for two-way communication between utility providers and consumers. Overall, these innovative grids play a crucial role in promoting efficient energy use while enabling seamless communication between all parties involved (J.R. Anam Malik ,2016).

• **Distributed Energy Resources (DERs):** A major development in the way we distribute and control electricity throughout our contemporary infrastructure is the idea of smart grids. The fundamental component of this novel strategy is the smooth integration of various distributed energy resources into the grid's structure, such as solar panels, wind turbines, energy storage devices, and electric cars. Smart grids make it possible to achieve a level of flexibility and responsiveness that was previously unthinkable by utilizing this integrated network of decentralized and renewable energy sources. Smart grids enable us to utilize the natural intermittent of renewable energy sources, such the sun and wind, and more precisely manage their variations, freeing us from the constraints of centralized, fossil fuel-dependent power generation. This is accomplished by carefully deploying cutting-edge energy storage technologies, which serve as a buffer to even out fluctuations in the output of renewable energy sources and provide a steady, dependable supply of electricity to end users. Moreover, bidirectional power exchange in which cars can use stored energy to return to the grid during periods of high demand is made possible by the integration of electric vehicles into the smart grid infrastructure, which increases the resilience and efficiency of the grid. Smart grids open the door to a more flexible, decentralized, and sustainable power infrastructure that is better suited to fulfill the changing energy demands of our contemporary civilization by integrating these various dispersed energy resources with ease.

- **Demand Response and Energy Efficiency:**

The implementation of a smart grid infrastructure allows consumers to take a more active role in managing their energy consumption patterns and usage. With a smart grid, consumers are provided with real-time access to detailed information about current energy pricing, enabling them to make more informed decisions about when and how they utilize electricity. This visibility into real-time pricing incentivizes consumers to adjust their energy usage behaviors, such as by shifting high-consumption activities to off-peak hours when rates are lower. Additionally, smart grid technologies provide automated feedback to consumers about their moment-to-moment energy usage, allowing them to track their consumption patterns and adjust accordingly. For example, smart meters and in-home displays can give consumers a granular, up-to-the-minute accounting of their electricity usage, empowering them to identify opportunities to reduce consumption during periods of high demand or when prices are at their peak. This two-way communication between the grid and consumers also facilitates demand response programs, where consumers voluntarily agree to temporarily scale back their electricity usage during times of peak grid strain, such as extreme weather events. By having the ability to dynamically modify their energy consumption, consumers play a critical role in helping to balance the grid and prevent service disruptions or blackouts. Overall, the smart grid enables a new era of consumer energy management and participation, ultimately creating a more resilient, efficient, and sustainable electricity system (Nico et al.,2012).

- **Grid Resilience and Self-Healing:** Smart grids represent a transformative evolution in the management and delivery of electrical power, designed specifically to enhance resilience against power outages and faults—challenges that have long plagued traditional grid systems. By incorporating advanced monitoring and control technologies, smart grids can swiftly identify and isolate affected areas when issues arise, such as equipment failures or severe weather impacts. This rapid response capability allows for the rerouting of power flows and expedites the restoration of service, significantly boosting overall grid reliability and minimizing downtime. In practical terms, this means that outages become shorter and less frequent, ensuring that consumers and businesses alike can depend on a stable supply of electricity. Moreover, smart grids excel at integrating renewable energy sources—such as solar, wind, and hydro—into the existing electrical framework, a critical factor in the push toward cleaner energy solutions. With real-time monitoring and sophisticated control mechanisms, smart grids can adeptly manage the intermittent that often characterizes renewable energy production, allowing for greater flexibility and efficiency in energy

deployment. This functionality not only promotes the use of environmentally friendly energy resources but also aids in optimizing electricity delivery, thereby reducing energy waste across the system. The overarching goal of implementing smart grids is to create a more sustainable and efficient electrical infrastructure, one that not only accommodates the growing demand for clean energy but also enhances the reliability and resilience of the entire electrical grid, ultimately fostering a greener and more robust energy future (Prashant et al.,2023, Ataul et al.,2014).

- **Renewable Energy Integration:** The smart grid facilitates the integration of these intermittent energy sources into the grid by leveraging technologies such as energy storage systems, smart inverters, and microgrids. This integration helps balance the grid, manage power fluctuations, and optimize the utilization of renewable resources (Sun et al.,2013, Chen et al.,2021).

- **Grid Automation and Control:**

The electrical grid is the vast network of power lines, transformers, and other infrastructure that delivers electricity from power plants to homes and businesses. Smart grid technologies have revolutionized the way this critical system is monitored and controlled. At the heart of the smart grid are advanced Supervisory Control and Data Acquisition (SCADA) systems, which use a network of intelligent sensors to continuously gather data on the grid's operations. This real-time information is fed into sophisticated analytics platforms that can detect emerging issues or inefficiencies with incredible speed and precision. For example, if a fallen tree branch causes a power line to short circuit, the SCADA system will instantly pinpoint the location of the fault and automatically reroute power to minimize the number of affected customers. Similarly, the analytics can optimize energy flow across the grid, ensuring that electricity is being delivered as efficiently as possible and reducing overall energy waste. This level of automated control and monitoring dramatically enhances the reliability of the electrical system, minimizing the duration and scope of power outages. If an outage does occur, the smart grid's rapid fault detection and isolation capabilities enable faster service restoration, getting the lights back on for impacted communities in a fraction of the time it would have taken with legacy grid infrastructure. Overall, the integration of smart grid technologies represents a quantum leap forward in the electricity industry's efforts to build a more resilient, responsive, and sustainable power delivery system (K.Sayed,H.A. Gabbar.,2017).

Phasor Measurement Unit (PMU): Phasor Measurement Units (PMUs), when integrated with GPS technology, serve as highly advanced and sophisticated measuring instruments that enable the comprehensive monitoring and precise measurement of critical system parameters across the entire power network. By collecting high-frequency, time-synchronized measurement data from various points throughout the electrical grid, PMUs provide system operators with an unprecedented level of real-time visibility into the dynamic state and health of the power network. This powerful capability allows operators to quickly identify and diagnose any abnormalities or disturbances, empowering them to immediately initiate the necessary protective and corrective measures to maintain the efficient and reliable operation of the grid. The high-resolution data gathered by PMUs, sampled at rates up to 60 times per second, offers an unparalleled level of granularity that far exceeds the capabilities of conventional, slower-responding monitoring equipment. This enables the rapid detection of transient events and dynamic phenomena that would otherwise go unnoticed, giving operators the actionable intelligence required to dynamically control and stabilize the power system. By integrating PMU technology with the precision timing provided by GPS, the measurements from dispersed PMUs can be perfectly synchronized, allowing for the accurate analysis of system-wide conditions and the identification of complex inter-area interactions. This holistic, interconnected view of the power network, made possible by PMUs, is a critical enabler for enhancing the dynamic stability, security, and resilience of the grid in the face of ever-increasing operational challenges and the integration of renewable energy sources (C. C. R. Dehulls et. al. ,2015, P. Lopes et. al.,2015, M. Lange et al.,2006).

2.4.3 Smart Grid Communication Architecture

Modern electric systems, known as smart grids, have greatly improved the flexibility, security, dependability, efficiency, and safety of the electrical system using computers, automation, sensors, and communications (P. Zhang et al.,2011, Chen et al.,2009).This has allowed consumers to actively manage their electricity consumption and respond to fluctuations in electricity prices by adjusting their usage, giving them more choices and control over their energy consumption. With the integration of electric vehicle charging and various distributed energy resources, a smart grid streamlines operations and makes it easier to link and manage different components of the system. It bridges the gap between electricity production, delivery, and consumption to enhance overall system performance for the benefit of both customers and the environment. The smart grid's automated and distributed energy

system relies on a two-way flow of electricity and data for optimal functioning (Chren S., 2017, Fredrik et al.,2021, Ancelotti al.,2013).

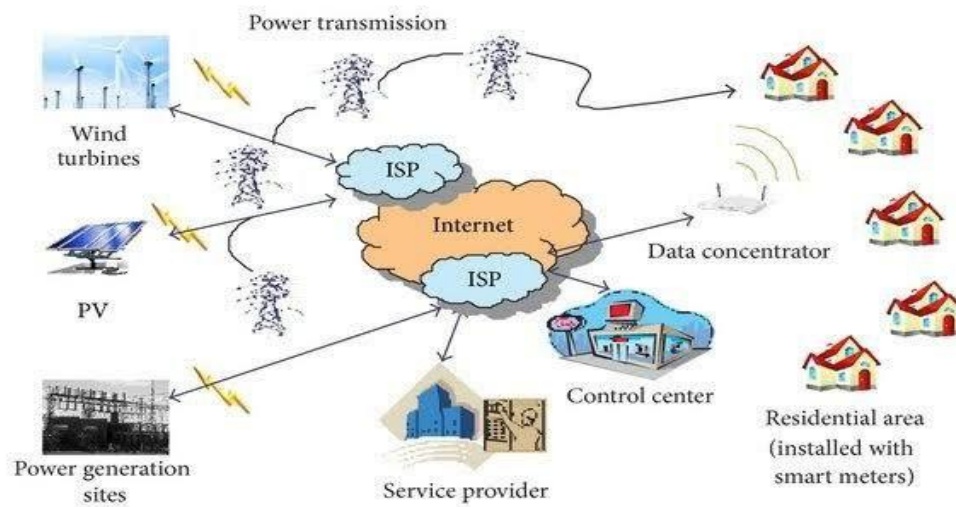


Figure 2.18 Communication architecture [61]

The smart grid communication infrastructure will emerge from the interconnection of many small-scale networks organized into a hierarchical architecture (F. R. Yu et al,2011, B. Heile et al.,2010).

- Home Area Networks (HANs),
- Field Area Networks (FANs) and
- Wide Area Networks (WANs).

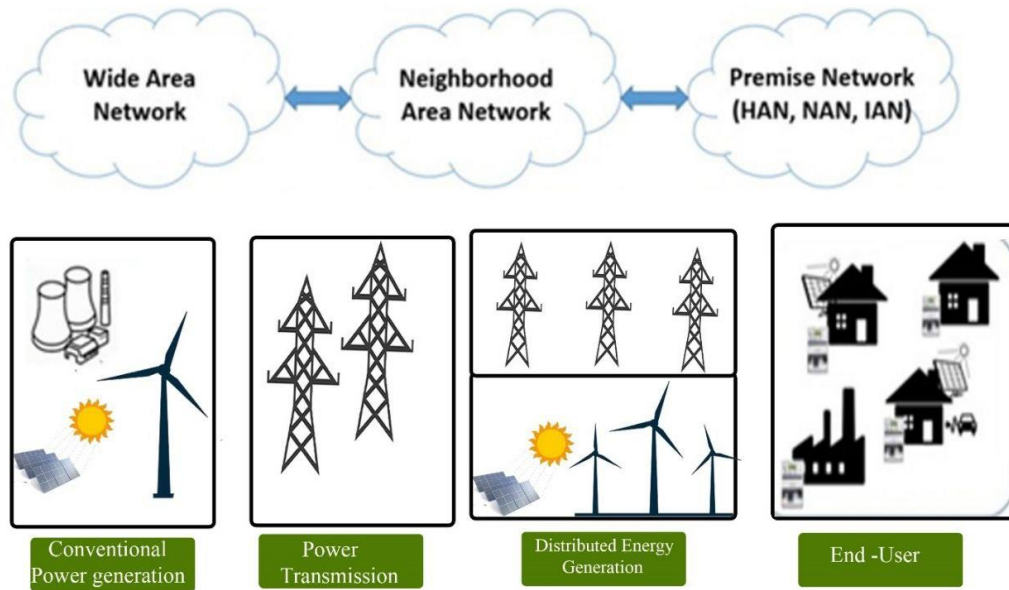


Figure 2.19 Smart grid architecture [61]

1. Home Area Networks (HANs)

A HAN is used to gather sensor information from a variety of devices within the home and deliver control information to these devices to better control energy consumption. In the consumer domain, home area networks (HANs) are required to deploy new functions like DR and AMI as well as to monitor and operate smart devices on the customer's property. Additionally, HANs allow home automation networks to monitor and operate applications for disaster recovery, user comfort, and effective house management (Gapakumar et al.,2016).

2. Field Area Networks (FANs)

Distribution automation and control equipment that communicate over networks between individual service connections and backhaul points to the electric utilities are included in the Field Area Network (FAN), which is referred to as the communication network for power distribution areas. It serves as a link between substations with collectors, access points, and data concentrators and customer premises. Between client premises and substations, intelligent nodes are placed to gather and manage data from nearby data points. Business functional needs, which could comprise the following elements are what drive the requirements for FANs communication.

- Feeder status monitoring
- Feeder voltage quality monitoring

- Reactive power monitoring (capacitor bank monitoring)
- Managing reactive compensation (capacitor bank switching)
- Feeder switch control
- Feeder sectionalized and recloser control.
- Supervisory control of feeder fault isolation schemes
- Provide communication channels for fault isolation schemes.

Many communication technologies can be used for FANs of the smart grid, are:

- (i) Power line communication,
- (ii) Wireline communication,
- (iii) Wireless communication.

- **Power Line Communication:**

Power lines are typically used to transmit electrical power, though they can also be used to transmit data. Using the current power lines, power line communication is a technique that allows high-speed data transmissions between devices. Power line communication systems receive modulated carrier signals transmitted over power transmission cables (F. Camacho, et.al.,2011). Transformers frequently block the propagation of data signals, which restricts power line communication inside each line segment that connects the transformers. A few hundred bits per second to millions of bits per second are the range of data rates on power lines, and the latter are inversely correlated with line spacing.

- **Wireline Network:**

Dedicated wireline cables can be a highly effective solution for constructing robust data communication networks that operate independently from electrical power lines. While this approach does require additional investment in cable deployment, it can yield significant benefits in terms of communication capacity and response times. Depending on the specific transmission medium utilized, these dedicated wireline networks may leverage technologies such as SONET/SDH, Ethernet, coaxial cable access, or Passive Optical Networks (PONs). One prominent example of wireline network architecture is the Ethernet Passive Optical Network (EPON), which integrates the high-bandwidth capabilities of PON technology with the ubiquitous Ethernet protocol. The EPON system consists of a few key components - an Optical Line Termination (OLT) that serves as the central hub, multiple Optical Network

Units (ONUs) installed at end-user locations, and an Optical Distribution Network (ODN) composed of passive optical components that facilitate the connections. This architecture allows for highly efficient, point-to-multipoint data transmission, with the passive optical elements reducing the need for active equipment and power sources along the transmission path. As a result, EPON networks can offer an optimal balance of cost-effectiveness, bandwidth capacity, and low latency for a wide range of broadband connectivity applications. The dedicated nature of the wireline infrastructure, combined with the inherent advantages of PON technology, make EPON a compelling choice for building high-performance data communication networks that are isolated from the electrical power grid (Wenyu an, Z. D. Y. M.,2013). All transmission in the EPON is performed between an OLT and all ONUs connected with the OLT, as shown in Figure 2.24.

Field area networks play a critical role in the electricity distribution systems that power our modern world. These communication networks form the backbone that enables the various power system applications operating within the distribution domain to share and exchange crucial information. These applications can be broadly categorized into two main groups - field-based and customer-based. For field-based applications, a core functional requirement of any Distribution Automation System (DAS) is feeder automation. This allows the electricity distribution network, particularly the loop distribution lines commonly used in urban areas, to be intelligently controlled and optimized. The field area network facilitates the real-time monitoring and automated management of these distribution feeders, enabling faster outage detection, quicker service restoration, and more efficient load balancing across the grid. On the customer-facing side, the field area network integrates with the Advanced Metering Infrastructure (AMI) to enable two-way communication between utility companies and their consumers. This allows for remote meter reading, dynamic pricing, and other advanced smart grid capabilities that empower customers to better monitor and manage their electricity usage. Utility firms have explored both wired and wireless communication technologies to build out these AMI networks, but wired solutions are generally preferred due to their superior reliability, security, and bandwidth capacity. The physical cables are more resistant to interference and eavesdropping compared to wireless signals, providing a more robust and secure data transmission platform for these mission-critical smart grid applications.

Overall, the field area network is the critical connective tissue linking the various operational and customer-oriented components of the modern electricity distribution system, facilitating the real-time data exchange and coordinated control that is essential for delivering reliable,

efficient, and responsive power to end users (Sunkara Pradeep et al.2023, Chren S.et al.,2016,X. Fang et al.2017).

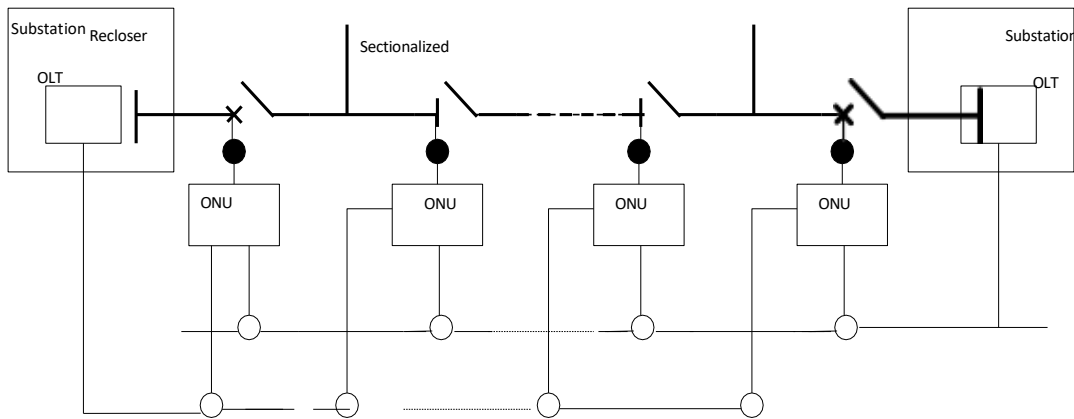


Figure 2.20 Ethernet passive optical net [69]

Wireless Network. Advancement in wireless networking technology has enabled us to connect devices in a wireless way, eliminating the installation of wirelines. IEEE 802.11s, RF Mesh, Worldwide Interoperability for Microwave Access and cellular standards, such as 3G, 4G, and LTE, are some of the stronger candidates for the FANs (Pradeep et al.,2023).

3. Wide Area Network (WAN)

WAN plays a critical role in linking the grid and core utility systems, encompassing core and backhaul networks. It serves as the communication backbone for the power grid, connecting various distributed networks to control centers. With the need for high data rates and long-distance coverage, WAN applications rely on technologies like PLC, fiber optic communication, cellular, WiMAX, and satellite communication for backup in remote areas (Fredrik et al.2021,Song et al.2017, Renbin et al.,2010).This robust infrastructure enables real-time measurements and control instructions to ensure the stability of the power grid.A Wide Area Network (WAN) is the backbone of communication in a Smart Grid. It facilitates the exchange of data between various components of the grid, enabling functionalities like:

- **Centralized Monitoring:** WAN links the grid and core utility systems, providing a central point to monitor power quality, customer usage (total and time-of-use), and control energy consumption.
 - **Network Connectivity:** WAN comprises two sub-networks:
 - **Core Network:** Connects metro networks of the utility and substations, forming the grid's core.

- **Backhaul Network:** Bridges Field Area Networks (FANs) to the core network, ensuring data exchange between remote locations and the central system.

Smart Grid Communication Infrastructure

A Smart Grid relies on a robust communication infrastructure to support its advanced features. WAN technology fulfills this requirement by providing:

- **Wide Area Coverage:** WANs can span vast geographical distances, enabling data exchange between geographically dispersed parts of the grid.
- **Reliable Data Transfer:** WANs ensure reliable transmission of critical data, like meter readings and control signals, between grid components.

By effectively utilizing WANs, Smart Grids can achieve improved efficiency, reliability, and seamless integration of renewable energy sources (Adel Ab-Belk hair et al.,2020, Shaofeng Xie et al.,(2021), Kai Li et al., 2021).

An illustrative example of this architecture is shown in Figure 2.25.

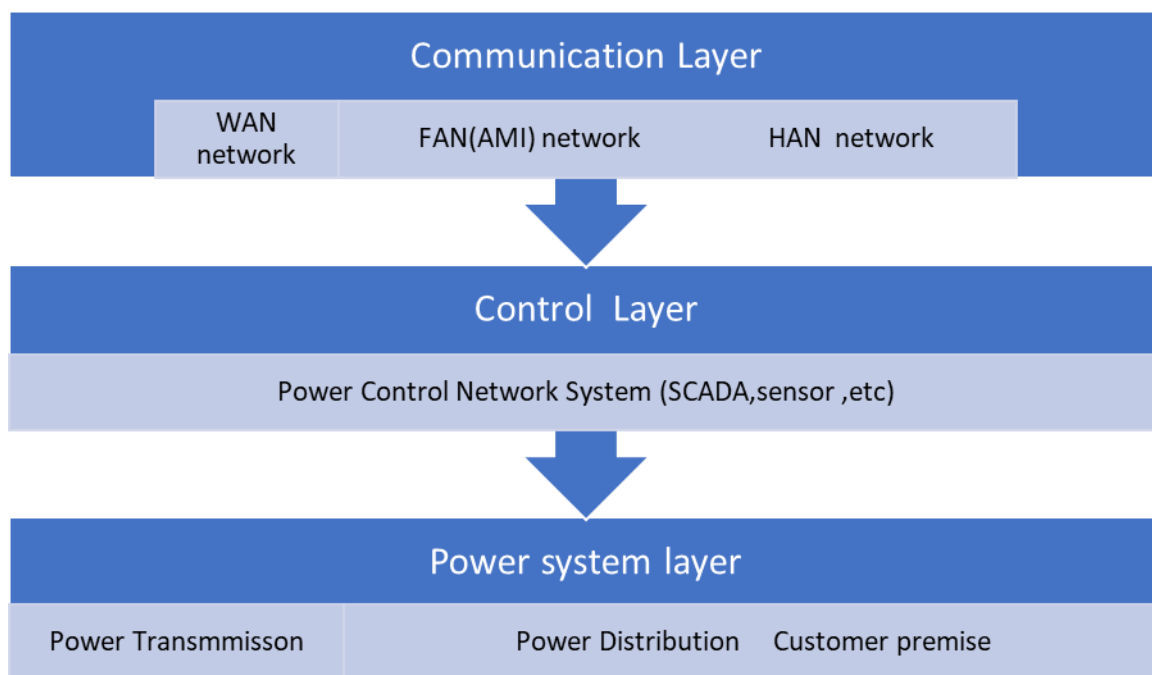


Figure 2.21 The smart grid communication

2.4.4 Smart Grid for railway Power supply System

The development of smart grids (SGs) has been a continuous emphasis because of the expanding complexity of electrical power systems, the rising demand for electricity, and the need for a highly secure, efficient, and dependable power supply. SG is regarded as the next

generation power system that makes use of information and electricity flows in both directions. The capacity to integrate data, monitor systems, communicate data reliably, analyses data securely, and implement local and supervisory controls. Smart grids refer to the trend of modern electricity networks becoming more and more integrated with digital systems that are based on data and communication (Abbas Alizadeh et al.,2007, P. Mohankumar et al.,2023, Zhi Zhang et al.,2020).One of the biggest loads on a national grid is provided by railway power systems, and as technology advances, there will be chances to create cutting-edge power systems that enhance both national grid and railway systems. Railway power systems could undergo a radical transformation if energy storage and renewable energy sources are combined with power electronics. More sophisticated protection and control systems can boost system efficiency and create a railway that operates with greater dependability. The "next generation" of electrical supply systems, or smart grids, use information and communication technologies to improve supply availability, reliability, and energy efficiency. Nevertheless, despite these benefits, the development of smart train networks has trailed behind those of domestic industry and other industries, only recently becoming a focus of the future railway.

i. Smart Grid Railway Communication Systems

Railway is an important infrastructure for the economic and social development of a country and is the pillar industry of a country. Railway communication services mainly include the following types.

1. Voice services

Voice service is a telephone communication service between railway staff. It mainly includes:

- Dispatching telephone communication
- Wireless train dispatching telephone.
- Office phone communication.
- Emergency voice communication.

2. Data services

Data service is the data communication service provided between railway related equipment, mainly including:

- train control information transmission.
- wireless train number transmission.

- wireless dispatching command transmission
- power supply and environment monitoring information.
- network management information transmission.
- ticket information management.
- passenger service information management.
- Freight information management.
- Office information management.
- CTC (centralized traffic control) information transmission.

The communication system of Ethio- Djibouti Railway consists of two communication systems in Ethiopia and Djibouti, with Labu communication station and Nagad communication station as the center respectively. The two systems are all composed of transmission system, telephone exchange and access network, dispatching communication system, wireless dispatching system, synchronous system, network management system, communication power, power supply and environment monitoring system. The transmission system adopts a two-layer network structure of backbone relay layer and access layer. The backbone relay layer adopts STM-16 ADM equipment to build a multi-service transmission platform (MSTP), while the access layer adopts STM-4 ADM equipment to build a MSTP. Telephone switching and access network. Labu communication station set up a new 3000L program-controlled switch (SPC), and Nagad communication station set up a new 500L program-controlled switch, the two switches are interlinked by 2×2M signaling, and the conditions of intercommunication with the local operator's telephone exchange network are reserved. OLT equipment is set up in the two communication stations, and ONU equipment is set up in each station, traction substation, locomotive and vehicle section (turning back section) and comprehensive maintenance center (workshop and work area). The main equipment of the digital dispatching system is in Labu communication station and NAGAD communication station. The sub equipment of the dispatching system is located in the station along the line, the machine and vehicle section. The 450MHz train wireless dispatching system is composed of a dispatching switchboard, monitoring switchboard, station radio, cab radio, fiber optic repeater, antenna, portable radio, etc. In Labu communication station and NAGAD communication station, a new radio train switchboard is set up; station radios are set up along the line; cab radio is set up in the locomotive; ground personnel is equipped with

portable radio. The railway communication system is mainly composed of communication lines, transmission network, telephone exchange system, access network, dispatching communication system, train radio dispatching communication system, power supply and environment monitoring system, communication power supply system, clock synchronous system and network management system.

ii. Composition of Railway Communication system

The composition of the railway communication is mainly composed of communication lines, transmission network, telephone exchange system, access network, dispatching communication system, train radio dispatching communication system, power supply and environment monitoring system, communication power supply system, clock synchronous system and network management system. Communication lines are the basis of the whole system which are responsible for the transmission of various information flows. The transmission system, as information bearing platforms, are responsible for providing transmission channels for various services. The transmission system provides synchronous transmission channels, and the data network system provides asynchronous transmission channels. Other service systems are used for performing railway communication services based on the transmission system or data network system. In addition, the signal system, power supply system, information system, etc. also take the transmission system or data network system as the transmission platform to carry their respective services.

a. Communication Lines

Communication lines are the basic part of railway communication network, which provides reliable and efficient transmission medium for all kinds of information flow. Railway communication lines mainly include optical fiber cable lines, communication cable lines and ancillary facilities which mainly includes cross connecting box, terminal box, optical fiber monitoring system and so on.

b. Transmission System

Railway transmission system is the basic bearing platform for various kinds of information in railway, which provides transmission channels for carrying information come from access network, digital dispatching communication system, train radio dispatching communication system, power supply and environment monitoring system, information system, signaling system, and other systems. Railway transmission system mainly includes digital transmission equipment (SDH/MSTP), transmission system network management and ancillary facilities

which include ODF (light distribution frame), DDF (digital distribution frame), EDF (Ethernet distribution frame), etc.

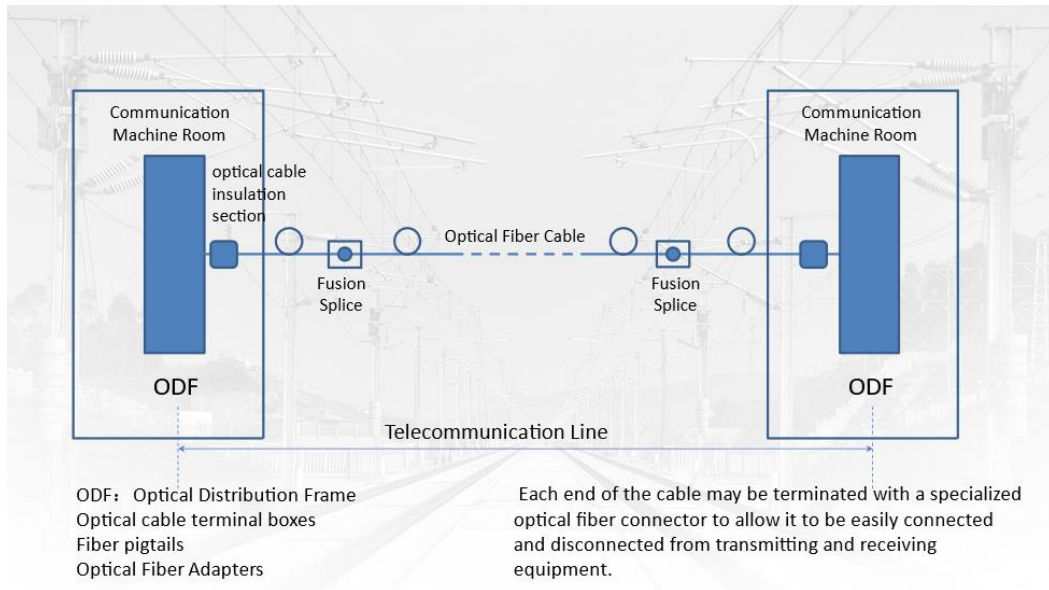


Figure 2.22 Railway communication system

A high-speed railway transmission system is a complex network that monitors and analyzes train and substation data. It consists of four key players (Hongjun et al.,2023, Linwei Li, Mingli Wu.,2020, Daisuke et al.,2014).

Data Collection Layer:

- This layer acts as the information gathering hub.
- Sensors like voltage, current, radar, and navigation systems (BeiDou or GPS) are installed on trains and substations.
- These sensors collect various data, including electrical and non-electrical measurements, simultaneously (data fusion).

Data Communication Layer:

- This layer ensures data transmission from trains and substations to a central data center.
- Communication programs are designed to effectively transmit monitoring results and data recordings.
- This layer serves as the primary channel for data flow.

Data Analysis Layer:

- Here, the collected data undergoes preprocessing and analysis (data mining).

- This analysis allows for a comprehensive evaluation of the traction network, including:
 - Power quality assessment
 - Energy efficiency evaluation
 - Fault detection

Data Visualization Layer:

- This layer focuses on presenting the analyzed data in an easily understandable format.
- It enables real-time monitoring of data and various statistics through a local Apache server.
- This allows for informed decision-making regarding the railway's operation and maintenance.

In simpler terms, the system gathers data from trains and substations, transmits it for analysis, and then displays the results for monitoring purposes. This comprehensive system helps ensure the smooth and efficient operation of high-speed railways.

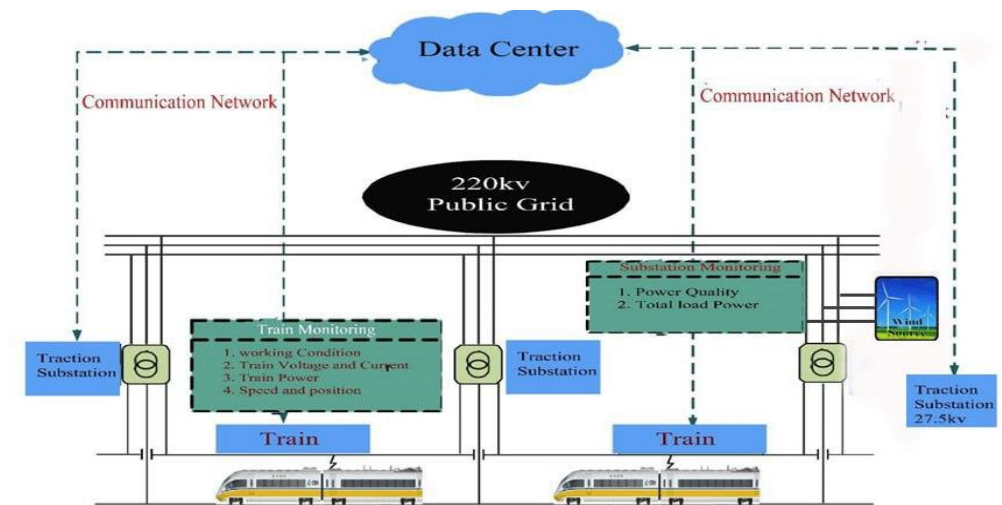


Figure 2.23 Railway transmission communication [83]

c. Telephone Exchange System

The railway telephone switching system provides fixed voice office services and interconnects with the public automatic telephone network. Railway telephone exchange system mainly includes SPC (stored program controlled) exchange, network management and supporting equipment (DDF, VDF, etc.).

d. Access System Railway

Access system is used to connect the user information to the corresponding communication service network node. It mainly realizes the remote access of railway telephone and provides the access of point-to-point data and audio circuit for railway users. Railway access system mainly includes OLT (optical line terminal), ONU (optical network unit), network management equipment and ancillary equipment. Auxiliary equipment mainly includes DDF, VDF (audio distribution frame) and so on. The optical access network (OAN) is a sophisticated and efficient system for transmitting data and communication signals using optical fiber technology. At its core, OAN utilizes optical fiber as the primary transmission medium, harnessing the power of light waves to carry information over long distances with minimal signal degradation. This approach stands in contrast to traditional copper-based access networks, which are more susceptible to interference and signal loss.

The key components of an OAN include the optical line terminal (OLT) and the optical network unit (ONU). The OLT acts as the interface between the broader network infrastructure and the local access network, providing the critical link that enables communication between the service provider and the end user. It is responsible for managing the flow of data, converting electrical signals to optical signals, and coordinating the interactions between the various network elements. On the user side, the ONU serves as the gateway, terminating the optical fiber from the ODN (optical distribution network) and processing the optical signals to provide a seamless business or residential interface. The ODN, in turn, is the optical transmission medium that facilitates the distribution of optical signals between the OLT and the ONU, ensuring the reliable and efficient delivery of data.

The advantages of an OAN are numerous and compelling. By leveraging the inherent bandwidth and low signal loss of optical fiber, these networks are capable of supporting high-speed internet, advanced television services, and sophisticated voice communications, all with exceptional quality and reliability. Moreover, the modular and scalable nature of OAN technology allows for easy upgrades and expansion to meet growing consumer demands, making it an increasingly attractive solution for service providers and communities seeking to future-proof their communication infrastructure.

e. Communication Power Supply System

Communication power supply system provides stable, reliable and uninterrupted power supply for communication equipment. Its capacity and various indexes should meet the

requirements of communication equipment for power supply. The system includes AC and DC power distribution equipment, high frequency switching power supply, UPS, battery group, generator set, power supply line, lightning protection and grounding device.

f. Power Supply and Environment Monitoring System

Power and environment monitoring system is responsible for collecting, transmitting and processing working status information of power supply equipment and air conditioning equipment and environment information (temperature, humidity, smoke, water, access control, etc.) in machine rooms, to ensure machine room and equipment in it safety. Power supply and environment monitoring system consists of monitoring center, monitoring station, monitoring terminal and communication channel.

g. Clock Synchronous Network

The railway synchronous network provides the reference frequency signal for the railway digital communication network. The railway synchronous network is composed of one level clock node, two level clock node, three level clock node, timing link, network management system and supporting equipment.

h. Network Management System

Network management system is used to realize centralized maintenance and management of communication system equipment. Network management equipment generally consists of servers, monitoring terminals, codecs, storage devices and network switches. Network management system mainly includes network management equipment of transmission network, data network, dispatching communication, wireless network, power, and environmental monitoring communication system.

2.4.5 Smart grid SCADA Systems in Railways

SCADA, which stands for Supervisory Control and Data Acquisition, is a computer system that acts as the central nervous system for monitoring and controlling railway traction power supply. It gathers real-time data from various electrical components like circuit breakers, isolators, and interpreters at substations and switching stations. This data is then processed, displayed, and used to control the entire system.

Why is SCADA Important for Railways?

SCADA plays a vital role in ensuring the smooth operation of trains by:

Real-time monitoring: SCADA continuously monitors the health of the traction power supply system, allowing for quick identification and response to any potential issues.

Centralized control: From a central control center, the Traction Power Controller (TPC) can remotely manage switching operations at substations, ensuring efficient power distribution.

Improved decision-making: Real-time data acquisition allows the TPC to make informed decisions about power management and optimize overall system performance.

The SCADA system typically involves a central host computer that communicates with remote units like RTUs (Remote Terminal Units) and PLCs (Programmable Logic Controllers) installed at substations. These remote units collect data from field equipment and transmit it to the central computer for processing and control.

By implementing a SCADA system, railways can ensure a reliable and efficient traction power supply, ultimately contributing to a smoother and safer train operation (Jun Zhu *et al.*,2023, Hu Guozhen *et al.*,2009). Railways rely on SCADA systems for managing their electrical traction power. This technology continuously collects data from various railway substations and switching stations. The data includes the status of circuit breakers, isolators, and other equipment. Railways typically receive electricity through high voltage lines. These lines may be 132kV or 230kV. The electricity is then stepped down to 25kV for powering trains. A Traction Power Controller (TPC) works from a central control center. The SCADA system allows the TPC to see real-time data about the entire traction power system. This includes the status of equipment at substations and switching stations. The TPC can also remotely control the switching operations of this equipment. In simpler terms, SCADA acts like a giant control panel for the railway's electrical system. It gives the TPC a clear view of everything that's happening and the ability to adjust as needed (Anantvalee T, Wu J ,2006, Sunil Kumar *et.*, al,2016,Collier, S. E.,2010).A Supervisory Control and Data Acquisition (SCADA) system is the backbone of a smart grid, enabling real-time monitoring and control of the entire power network. Its core functions include:

Distributed Generation Support: SCADA facilitates the integration and management of renewable energy sources like solar and wind power.

Alarming and Event Logging: The system continuously monitors for anomalies and triggers alerts for operators. It also logs events for historical analysis and future decision-making.

Telemetry: SCADA gathers data from sensors and meters across the grid, providing a comprehensive view of power generation, transmission, and consumption.

Remote Control: Operators can remotely control field equipment, such as circuit breakers and switches, to isolate faults, minimize downtime, and optimize power flow. This includes:

Lockout Release: SCADA allows for the remote release of lockouts on equipment, streamlining maintenance procedures.

Automated Fault Isolation: During outages, the system can automatically trip circuit breakers to isolate faulty sections, protecting healthy parts of the grid and restoring power quickly.

By combining these functionalities, smart grid SCADA systems ensure efficient, reliable, and secure power delivery

The main Data Acquisition functions are as under:

- To acquire real time data regarding the status of all the circuit breakers, interrupters, transformer alarms and faults arising out of excessive transformer winding temperature, transformer Buchholz relay operation, transformer excessive oil temperature, pressure relief device operation etc.
- To acquire data regarding the abnormal and faulty conditions of various equipment's.
- To acquire data regarding the power system measurands like current, voltage, power factor, maximum, demand etc.
- To perform, alarm functions on all the data acquired. Limit violations, abnormal states of status devices, rate-of change violations etc. shall be processed.
- To log and print out all commanded and uncommand changes which take place in the system.
- To print out log sheets and summaries in the desired formats, with station address, item address and time.

The SCADA system acts as the brain of the 25kV electrified traction system, providing centralized monitoring and control capabilities. It's a comprehensive hardware and software solution that allows operators to manage remote field devices from a central location.

The SCADA system can be broken down into two key components:

a. Remote Control Centre (RCC): This is the central hub of the system, providing a user interface for the Traction Power Controller (TPC).

The RCC allows the TPC to:

- Manage the 25kV power supply to the Overhead Equipment (OHE).
- Monitor equipment health at traction substations along the route.
- View real-time data on catenary status, device conditions, and telemetry from control stations.
- Control field equipment remotely, including circuit breakers and transformer tap changers.
- Store historical data on alarms, events, and telemetry for analysis and maintenance purposes. This facilitates faster identification and rectification of faults within the overhead equipment and switching stations.

Main and Standby Computer

- Operator Workstation Computer
- Communication Processors with Modems
- Printer and Print Sharer Switch
- Modem
- UPS
- Battery

The Traction Power Control (TPC) room houses important equipment necessary for the functioning of the smart grid for railway systems. The UPS and batteries have their dedicated space within the TPC room, ensuring a continuous and reliable power supply for the railway operations. Through the implementation of smart grid technologies, the railway system is able to monitor and optimize energy usage, efficiently manage power distribution, and enhance overall system reliability. By integrating renewable energy sources and implementing advanced energy management systems, the smart grid for railway not only improves operational efficiency but also reduces environmental impact, making it a sustainable option for modern transportation network (M. Ismail et al.,2015, T. Chen et al.,2011).

b. Remote Terminal Unit (RTU): It serves as the vital link between field equipment and the Remote-Control Centre, enabling the control and monitoring of various parameters. Operating within a Wide Area Network (WAN), the RTU facilitates the exchange of information between unmanned control stations and the RCC. Through its flexible, modular, and reliable design, the RTU ensures seamless integration with the system, allowing for efficient data acquisition and control functions. With its microprocessor-based logic system and firmware

programming, the RTU is well-equipped to handle complex tasks, making it an indispensable component in modern industrial operations (C. Han et al.2011, J. Wu et al.,2015, M. Erol-Kantarci and H. Mouftah,2015).The RTU accepts digital and analog input signals from Remote locations (TSS / SP / SSP) and receives the control command information from the RCC to perform the following tasks:

- Status input monitoring and change of status
- Control output operation
- Analog input monitoring
- Communication with RCC

RTU can be divided into five parts:

- Logic Chassis
- Interface Unit
- Transducers
- Modem
- Power Supply Unit

2.4.6 SCADA for Wind Energy

In today's world, renewable energy systems are becoming more and more popular due to the necessity of reducing Co₂ emissions and the increasing expenses associated with fossil fuels. Renewable energy plays a significant role in distributed generation systems, where its power can either be added to the current electricity grid or utilized for local microgrid use. SCADA systems, also known as Process Control Systems (PCS), are employed to collect, monitor, and analyze real-time environmental data on a large scale (Niya Chen et al.,2018, R. Palma-Behnke et al.,2011, Hamidi, V., Robinson F. ,2008).

Modern wind farms include different types of measuring tools, SCADA units, and communication systems. To ensure steady, secure, and automated management, the individual wind turbines are equipped with microprocessor controllers that use closed loop control algorithms to govern the internal controllers, such as Pitch, Yaw, Generator, and Supervisory controllers. SCADA is utilized for remote monitoring, supervision, and control of both wind turbines and wind parks. It allows for complete remote management and oversight (B Chen

et al., Yang Hu et al., 2014). The overall control system of wind power plant is shown in Figure 2:28.

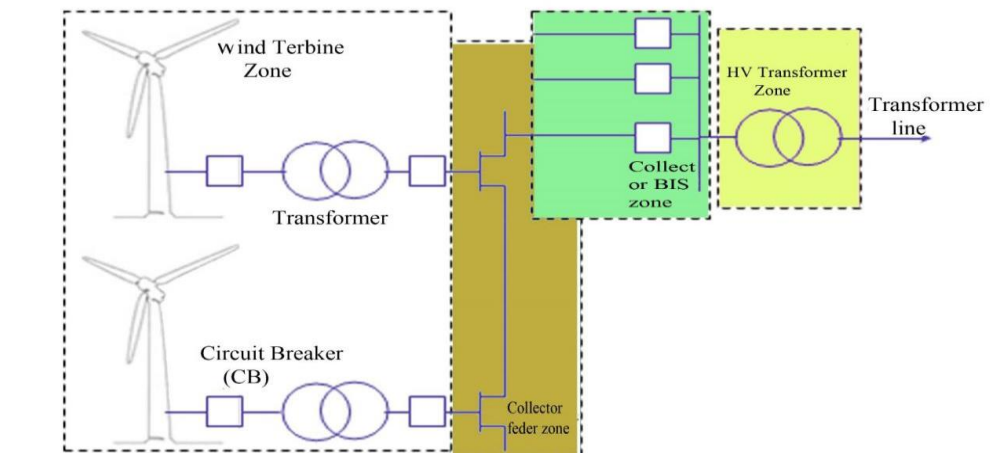


Figure 2.24 SCADA for wind energy [97]

The main functions of the SCADA system can be summarized as follows:

- Wind Park overview.
- Wind Park control
- Turbine overview
- Turbine control
- Log viewer
- Report Generation.

SCADA is a key tool for managing and checking different aspects of the wind turbine generation system (WTGs), typically installed alongside the turbines. This system acts as the main link between the wind power plant operator and the equipment in the wind farm. It facilitates the integration of data on WTGs, meteorological mast, and substation in one control hub, capturing and storing operational data from the WTGs and different alarm signals (Xingzhen Bai et al., 2018, Michael Wilkinson et al., 2014). Wind farm communication networks are crucial for efficient operation. They need to be reliable and cost-effective. Ethernet Passive Optical Network (EPON) offers a promising solution. This fiber-optic technology uses an Optical Line Terminal (OLT) as a central hub connected to Optical Network Units (ONUs) at each wind turbine. Similar to a SCADA system polling data from

remote terminal units (RTUs), the OLT in an EPON system gathers information from the ONUs at frequent intervals(Linas Gelazanskas, Kelum AA Gamage,2016).

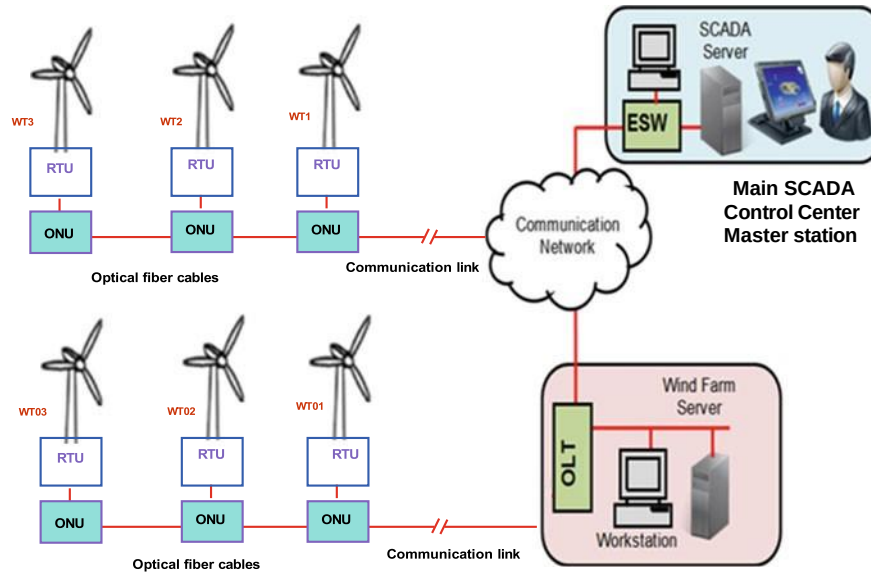


Figure 2.25 Communication networks [97]

2.5 Artificial intelligence in smart grid

2.5.1 Introduction

The smart grid is now able to gather large amounts of diverse and complex data about how the electric power grid operates, thanks to advancements in metering, control, and communication technologies. As traditional methods struggle to effectively analyze this data, there is a growing recognition of the importance of integrating artificial intelligence (AI) techniques into smart grid applications (Shahzad et al.,2020, Gharavi, H., & Ghafurian, R., 2011, Mellit et al.,2014, A. Botterud et al.,2010). The smart grid is a modern electric power system that has AI technology and a network for communication, allowing for the exchange of both energy and data. This innovative system allows for real-time feedback from sensors and devices throughout the power grid. Even though AI is a recent advancement, it has the potential to completely transform how we generate, distribute, and use energy. The power industry has already begun to incorporate AI and similar technologies to facilitate communication among smart grids and meters. The adoption of artificial intelligence in upcoming smart grids may provide effective solutions to improve their efficiency. A key application of AI in this field is to aid in managing dynamic demand response. By analyzing data in real-time, predictive algorithms can forecast shifts in energy usage patterns and

optimize the utilization of renewable energy sources (Hamed et al.,2024). AI integrated into smart grids in the future could provide substantial solutions for enhancing their efficiency. A key application of AI in smart grids is aiding in dynamic demand response. By analyzing data in real-time, predictive algorithms can predict shifts in energy use patterns, as well as provide valuable information on the availability of renewable energy sources.

2.5.2 Overview of Artificial Neural Network

A neural network is an effective tool for modeling data, able to understand and demonstrate intricate relationships between input and output. Artificial Neural Network (ANN) is inspired by how biological nervous systems, like the brain, process information the unique structure of this system consists of many interconnected processing elements, or neurons, working together to solve specific tasks(Reisi et al.,2013).Artificial neural networks (ANNs) function as complex computational models inspired by the biological processes of the human brain, wherein they take a variety of inputs and systematically process these values through a series of mathematical operations. At the core of this operation lies the weighted sum of the inputs, where each input is multiplied by a corresponding weight, reflecting the importance or influence of that specific input on the overall outcome. In addition to these weighted inputs, an additional parameter known as a bias is incorporated into the calculation, allowing the model to shift the activation function to achieve better accuracy and flexibility in its predictions. This computation, effectively a combination of linear transformations, is formally represented in the framework of a transfer function, which serves to encapsulate the processing stage before any nonlinear transformation occurs. Once the weighted total including the bias is obtained, it is fed into an activation function, a crucial component that introduces nonlinearity into the model. This nonlinearity allows ANNs to capture intricate patterns and relationships within the data, which is essential for tackling complex tasks such as image recognition, natural language processing, and a myriad of other applications. The activation function transforms the weighted sum into output values that can be understood and utilized by subsequent layers within the network, ultimately enabling the model to learn from the data presented during training. Through this layered process of weighting, summing, and activation, artificial neural networks can adapt their internal parameters, refining their ability to make predictions and decisions based on the inputs they receive, ultimately mimicking the rich complexity of cognitive processing in brains. A typical artificial neural network looks something like the given Figure 2.30

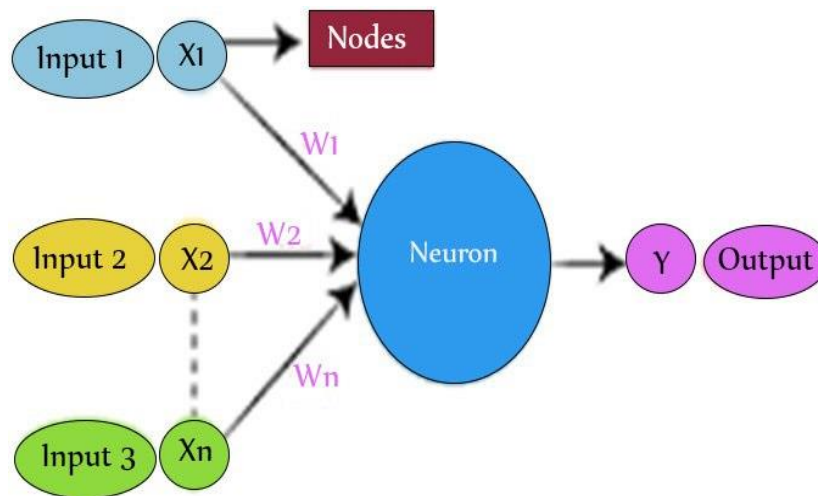


Figure 2.26 Artificial neural network [106]

Artificial Neural Network primarily consists of three layers:

Input Layer: As the name suggests, it accepts inputs in several different formats provided by the programmer.

Hidden Layer: The hidden layer is present in between input and output layers. It performs all the calculations to find hidden features and patterns.

Output Layer: The input goes through a series of transformations using the hidden layer, which finally results in output that is conveyed using this layer. The artificial neural network takes input and computes the weighted sum of the inputs and includes a bias. This computation is represented in the form of a transfer function.

$$\sum_{i=1}^n W_i * X_i + b \quad (2.11)$$

Where: W_i Weighted sum of the inputs

X_i sum of inputs

b the bias

It determines weighted total is passed as an input to an activation function to produce the output. Artificial neural networks are computational models inspired by the human brain processes information, using interconnected nodes called neurons to perform complex tasks such as pattern recognition and decision-making. These networks are trained through a

process called backpropagation, where they adjust the weights of connections between neurons in response to errors, gradually improving their accuracy and performance (Amir et al.,2018, Babaei et al.,2017).By simulating the behavior of neurons and their interconnections, artificial neural networks can learn from data, make predictions, and adapt to new information, making them a powerful tool in machine learning and artificial intelligence applications.

Demand response: This refers to the capacity of customers to change how much electricity they use in reaction to pricing or grid conditions. Utilizing demand response can aid in managing the balance between supply and demand, decreasing peak load, and cutting electricity expenses. For instance, intelligent thermostats can modify temperature settings in homes and buildings automatically according to current electricity prices (E. Koutroulis and K. Kalaitzakis,2006).

Distributed generation: Distributed generation is the process where electricity is produced from small-scale sources that are linked to the grid or operate on their own. This method can lower transmission losses, boost resilience, and vary the energy supply. For instance, rooftop solar panels can create power for use in the nearby area and can also send any extra electricity back to the grid.

Energy storage: Energy storage is a vital component of modern power infrastructure, allowing for the effective conservation of electricity for future use. By harnessing devices or systems to store excess energy, individuals and organizations can ensure a reliable backup power supply, mitigating the impact of fluctuations and grid congestion. For instance, advanced batteries can efficiently store surplus energy generated from solar or wind power during the day, and release it as needed during the night or when the grid is overwhelmed, thereby improving overall power quality and reliability.

Fault Detection and Diagnosis

Neural networks can be trained to recognize patterns associated with faults in the power system. By analyzing smart meter data, neuronal networks can detect and diagnose faults in real-time, reducing downtime and maintenance costs.

Load Forecasting

Accurate load forecasting is essential for effective energy management and planning. Neural networks can analyze historical smart meter data to predict future energy demand, considering factors such as weather patterns and consumer behavior.

Grid Optimization

Neural networks can be used to optimize the operation of smart grids by analyzing data from various sources, such as smart meters, weather forecasts, and renewable energy generation. By optimizing the distribution of energy, neural networks can reduce energy losses and improve the overall efficiency of the power system.

Renewable Energy Integration

The integration of renewable energy sources, such as wind and solar power, into the power grid presents significant challenges due to their intermittent nature. Neural networks can be used to forecast the availability of renewable energy and optimize its integration into the power system.

Neural network control

Neural network control is the application of neural networks to design and implement control strategies for smart grids. Neural networks can adapt to changing grid conditions and learn optimal or near-optimal control actions, such as voltage regulation, frequency stabilization, and load balancing.

2.5.3 Wind Energy System

Wind energy is one of the most important contributors to modern electric grids as clean and environmentally friendly energy resource. Wind energy systems have distinct features, such as being intermittent and using turbine technology, which present challenges for successfully and economically integrating them into the grid. Precise forecasting and dependable predictions of wind power are crucial for the efficient functioning of wind farms and their integration into the power grid (Petr et al.,2023, Tsai et al., 2012, L. Y. Pao and K. E. Johnson ,2009). In wind turbine the kinetic energy in the wind is first convert into rotational kinetic energy in the turbine and then in electrical energy. The energy conversion depends on swept area of blades and wind speed. The swept area is defined as the plane of wind intersected by the generator, and it is calculated from the length of the turbine blades using equation for the area of a circle.

$$A = \pi r^2 \quad (2.12)$$

Where the radius is equal to the blade length. Here it is taken as 113.5 Airflow power is given by following equation:

$$P_m = \frac{1}{2} \rho A V^3 \quad (2.13)$$

Where: ρ is the air density

A is swept area of blade and.

V is the wind speed.

According to German physicist Albert Betz who concluded in 1919, that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. This is called power coefficient.

$$C_p = \frac{P_{wind\ turbine}}{P_{air}} \quad (2.14)$$

Another term that is tip speed ratio (λ) is also essential factor in determining the performance of wind turbine. Coefficient of power is dependent on the value of tip speed ratio (λ) and pitch angle (β).

$$\lambda = \frac{\omega R}{V} \quad (2.15)$$

Where λ is the tip speed ratio, ω is the wind turbine rotational speed, V is the wind speed and R is the blade radius.

Pitch angle (β) depend upon the relation of wind speed with base speed, if wind speed is greater than base speed then β can be controlled, otherwise it is considered as zero. C_p is a non-linear function of λ and β , and it is independent of blade radius.

Wind turbine power is equal to:

$$P_m = \frac{1}{2} C_p (\lambda, \beta) \frac{\rho A}{2} V^3 \quad (2.16)$$

Where: P_m is the mechanical output power of the turbine,

C_p is the performance coefficient of the turbine,

λ is the tip speed ratio of the rotor blade,

β is the blade pitch angle,

ρ is the air density,

A is the turbine swept area, and

V wind speed.

As Ethiopia has good wind resources, wind energy is one of the most significant and rapidly developing renewable energy sources in the world, and it provides a clean energy resource, which is a promising alternative in the short term in Ethiopia. Ethiopia is endowed with various and a diversify renewable energy resources namely, hydro, wind solar, geothermal and biomass. The estimated exploitable potential for hydropower is 45GW, wind is 10 GW, and geothermal is 5GW, solar irradiation ranges from 4.5KWH/m² to 7.5KWH/M²/day(Z. Alnasir and M. Kazerani,2016, S. Pira ,2020).Wind energy energy stands out as one of the most efficient methods for generating electrical power from renewable sources, primarily due to its abundance and low environmental impact. As nations and companies alike seek to transition towards sustainable energy solutions, wind energy offers a compelling alternative, reducing reliance on fossil fuels and mitigating greenhouse gas emissions. However, the inherent volatility of wind power poses significant challenges for the large-scale integration of wind energy into the existing electrical grid. Unlike fossil fuel-based sources, which can deliver a consistent output, wind energy generation is unpredictable and can fluctuate considerably based on various atmospheric conditions, including wind speed and direction. This variability complicates the task of maintaining grid stability and meeting fluctuating electricity demand. Moreover, the efficiency of energy extraction from the wind does not solely depend on wind conditions; it is heavily influenced by the control systems implemented in wind energy conversion systems (WECS). Advanced technologies, such as fully controlled variable speed wind turbine generators, play a crucial role in maximizing power extraction. These systems utilize sophisticated algorithms to adjust the turbine's operational parameters in real-time, optimizing performance across a wide range of wind speeds. Such dynamic control enables these turbines to harness maximum wind energy while simultaneously minimizing mechanical stress, thereby enhancing their operational lifespan and reliability. Despite the challenges presented by the stochastic nature of wind, such innovative solutions pave the way for a more robust and efficient integration of wind energy into the global energy landscape, underscoring its potential as a cornerstone of a sustainable energy future. The ongoing research and development in turbine technology and grid improvements signal a promising trajectory for wind power, as it moves toward overcoming the hurdles of variability and reliability, allowing it to fulfill its role as a key player in the transition to a cleaner energy paradigm

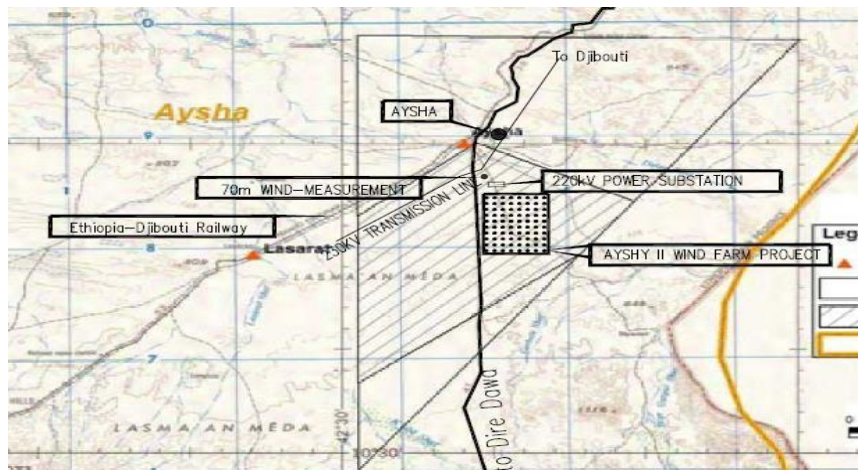


Figure 2.27 Aysha wind farm layout [114]

This research work is done based on the “Aysha II wind farm”, which is in Somali Region, Ethiopia, about 170 kilometers to Dire Dawa, about 150 km from Djibouti, and the Ethio-Djibouti Railway line through the west of wind farm. Ethiopia- Djibouti 230KV transmission line crosses the wind farm and the local 33KV distribution grid is laid along the all-weather road. Aysha wind farm is in north latitude 1029’ 1049’, east longitude 4230’ 4247', which belongs to the semi-desert and semi-gobi area, and the transition zone of plateau in the face of the ocean. Aysha area is in the northern Somali Region and at the end terminal of the national grid, away from the power source center, situated in the tropical desert climate zone without power resources, and is subject to serious shortage of electricity supply due to heavy power loss supplied by the national grid and aging distribution network (Xian,2017).

b. Wind characteristics of the region

According to the meteorological data collected from Aysha weather station in May 2007 - December 2011, the highest temperature of Aysha weather stations in May 2007 - December 2011 is 41.7 °C (June), and the lowest temperature is 12 °C (February); the annual average wind speed is 5.23 m/s, and the dominant wind direction is NE, and secondarily is SW. The highest and lowest temperature statistical results during May 2007 ~ December 2011 are shown in Table 2.1 and Figure 2.2; the monthly average wind speed is shown in Table 2.2, Table 2.3 and Figure 2.3, the monthly wind power measures is shown in Table 2.4.

Table 2. 1 Monthly highest and lowest temperature

Month	1	2	3	4	5	6	7	8	9	10	11	12
Max.Temp(°c)	31.5	33.5	36.5	39.5	40.7	41.7	41	40	40	39	35	32
Min.temp(°c)	14.5	12	12.5	19	19	20.5	18.5	20	19	17.5	13	12.5

Table 2.2 Monthly average wind Speed

Month	1	2	3	4	5	6	7	8	9	10	11	12
Wind Speed(m/sec)	7.03	7.19	6.59	6.01	3.75	3.28	3.89	3.64	3.36	5.13	6.28	6.58

Table 2.3 Measured Wind Speed

Month	1	2	3	4	5	6	7	8	9	10	11	12
10m	8.82	9.65	9.87	8.07	5.18	4.64	5.79	5.74	4.63	7.07	8.46	8.34
30m	9.85	10.66	10.84	8.89	5.86	5.45	6.69	6.64	5.46	8.02	9.45	9.48
60m	10.46	11.19	11.28	9.35	6.18	5.88	7.36	7.35	5.89	8.54	10.04	9.99
70m	10.59	11.39	11.42	9.46	6.32	5.97	7.39	7.35	5.89	8.67	10.21	10.17

Table 2.4 The Monthly wind Power Density

Month	1	2	3	4	5	6	7	8	9	10	11	12
10m	431	529	548	323	123	76	160	153	93	259	389	396
30m	587	704	714	424	169	115	232	221	136	359	528	547
60m	684	807	799	481	197	143	295	283	169	421	619	644
70m	774	852	842	504	208	153	303	289	174	443	654	651

Selected wind turbines

The installed capacity of Aysha II wind farm is 120 MW, the proposed WTGs are 48 sets DEC DF103-2500. The outlet voltage is 0.69 kV, the step-up transformers are 48 sets of box-type transformers with a capacity of 2750 kVA. The connection of WTG and step-up transformer is by unit connection with one WTG with one box-type transformer. The box-type transformer is located about 15~20m beside WTG. 1kV XLPE cable is used to connect

WTG control panel and LV side of box-type transformer. There are 6 circuit 33kV collector lines, and each circuit collector line connects 8 WTGs. The HV side of a 33kV box-type transformer connects to collector line by XLPE insulated cable. The technical characteristics of related turbines are given in Table 2.5.

Table 2.5 Technical parameters of Aysha Wind Farm

Name	DF-103-2500
Rated power	2500kW
Blade Quantity	3
Rotor Diameter	103m
Cut in wind speed	3m/sec
Rated wind speed	10.8m/sec
Cut out wind speed	25m/sec
Hub height	80m
Generator type	Permanent magnet synchronous Generator
Out voltage	690v
Frequency	50Hz

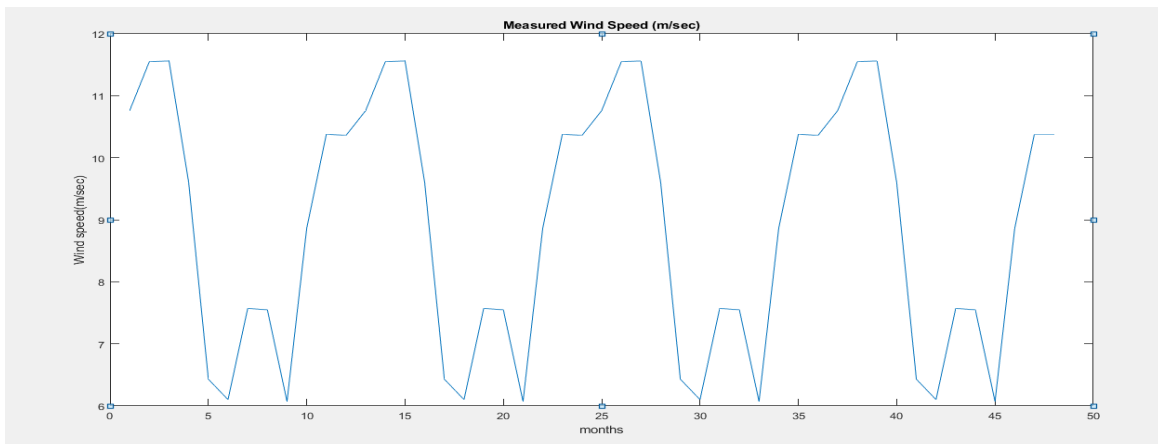


Figure 2:28 Monthly wind speed

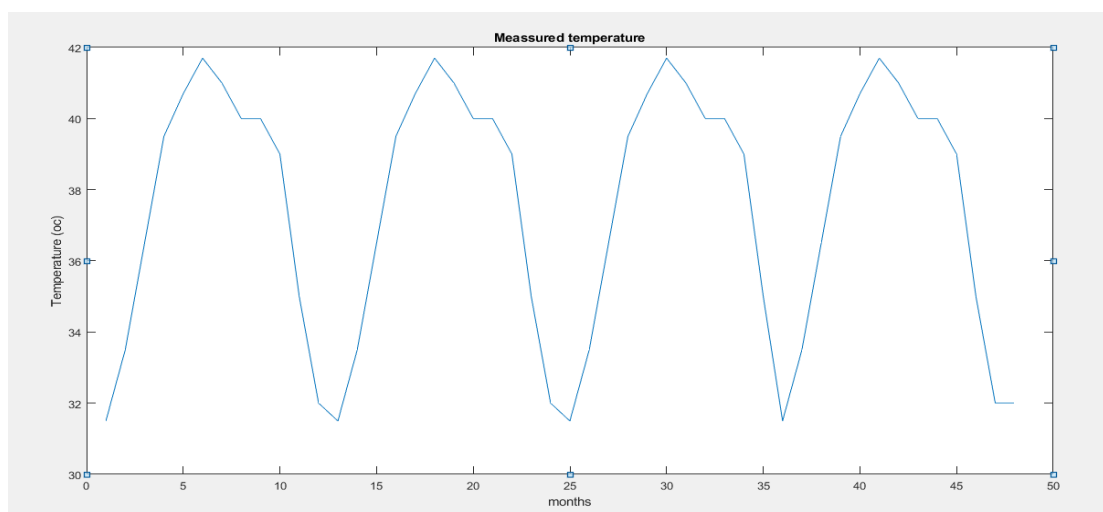


Figure 2:29 Monthly wind temperature.

CHAPTER THREE

POWER FLOW ANALYSIS OF ETHIO-DJIBOUTI RAILWAY LINE

3.1 Introduction

The Ethio-Djibouti railway system, serving as a critical infrastructure link between Ethiopia and Djibouti, relies heavily on the reliability and efficiency of its traction power supply system (TPSS) for smooth operation. Ensuring optimal power quality in the railway's power supply is paramount to maintaining operational efficiency and equipment longevity. Harmonic distortion, one of the most prevalent power quality issues, significantly impacts the traction system's performance (A. Tabakhpour and S. Mousavi, 2016). It can cause overheating in electrical components and miss operation of protective devices, leading to potential system failures. The power flow analysis conducted using ETAP software revealed that certain sections of the railway exhibited high levels of harmonic distortion, exceeding the standard limits. Furthermore, negative sequence currents were detected, indicating asymmetrical load conditions that could lead to motor derating and additional stress on the railway's power infrastructure. Voltage unbalance was another critical issue uncovered during the power quality analysis. Even minor unbalanced conditions can greatly affect the performance of traction motors, reducing their efficiency and lifespan. Addressing these power quality issues requires a comprehensive approach, including the optimization of TPSS design and operation. The analysis suggested that improvements in the distribution network's design could mitigate the observed harmonic distortion and voltage unbalance. Implementations such as harmonic filters and voltage regulators were recommended as potential solutions. Additionally, regular monitoring and maintenance of the traction substations are crucial for early detection and correction of power quality problems (Mtilde Ornkloo, 2016). The study emphasized the importance of adopting advanced simulation tools like ETAP for continuous assessment and optimization of the TPSS to ensure reliable and efficient railway operations. Ultimately, enhancing the power quality of the Ethio-Djibouti railway power supply system will contribute to the sustainability and efficiency of this vital transportation corridor. The efforts to improve power quality not only support the operational needs of the railway but also align with broader goals of energy efficiency and system resilience. Through dedicated analysis and subsequent improvements, the Ethio-Djibouti railway can continue to serve as a backbone for economic development and cooperation between Ethiopia and Djibouti, highlighting the critical role of power quality management in the modern rail transport sector.

3.2 Over-view of Ethio-Djibouti Railway Line

The Ethio-Djibouti Railway is a significant infrastructure project in Eastern Africa, spanning 756km and connecting Djibouti with Ethiopia's capital, Addis Ababa. As the first AC electrical railway in Ethiopia, it plays a crucial role in facilitating the import and export of goods in the region. With 20 traction substations, the railway ensures continuous operation through two independent power supplies. The utilization of a 25 kV AC single-phase power supply for both passenger and cargo locomotives demonstrates the railway's modern and efficient design, making it a vital transport link for the region's economic development. The Ethiopian electric power substations supply each traction substation with 132 kV or 230 kV, which is then transformed to 25 kV using a Vv wire transformer. The train operates on an asymmetric 25 kV AC single-phase power supply, with load varying based on locomotive crew performance. Both passenger and cargo locomotives on the Ethiopia-Djibouti railway utilize the 25 kV, 50 Hz traction power system. This unique power setup enables efficient and flexible operation of the railway network, supporting both passenger and cargo transportation needs.

Table 3.1 Supply voltage and connection points of traction substation

No	Traction substation	Power supply voltage (kV)	Capacity of main transformer (MVA)	Power supply point I	Power Supply Point II
1	Sebeta TS	230	2x20	Sebeta 2	Sebeta 2
2	Indode TS	132	2x20	Kalkti 1	Akaki 2
3	Mojo TS	132	2x20	Nazerti 2	Wulechti TS
4	Wulenchiti TS	132	2x12.5	Mojo TS	Awash TS
5	Melka Jilo TS	132	2x12.5	Methera TS	Methera TS
6	Methera TS	132	2x12.5	MelkajiloTS	Awash TS
7	Awash TS	132	2x12.5	Methera TS	Awash 7kilo
8	Sirba Kunker TS	132	2x12.5	Awash 7 kilo	Mieso TS
9	Mieso TS	132	2x12.5	Sirbakunker TS	AsebeTeferi TS

10	Afedem TS	132	2x12.5	Asebe Teferi	Gota TS
11	Gota TS	132	2x12.5	Afedem TS	Hurso TS
12	Hurso TS	230	2x (12.5+16)	Hurso	Lonnis TS
13	Lonnis TS	230	2x12.5	Hurso TS	Milo TS
14	Milo TS	230	2x12.5	Lonnis TS	Adegala TS
15	Adegala TS	230	2x12.5	Lonnis TS	Adegala
16	Aysha TS	230	2x12.5	Adegala TS	Dewanle TS
17	Dewanle TS	230	2x12.5	Aysha TS	Alisabi TS
18	Alisabil TS	230	2x12.5	Dewanle TS	Holol TS
19	Holol TS	230	2x12.5	Alisabi TS	Negad TS
20	Negad TS	230	2x12.5	Holohol TS	Pk-12

Electric trains offer numerous benefits, including high passenger capacity, efficiency, minimal emissions, and low transportation costs. They are a crucial component of modern transportation networks, using a contact network to transmit electric power to the locomotive. The electrified railway system is comprised of a transmission substation, electric locomotive, and high voltage contact line system. However, the system can experience voltage imbalances, energy factor shifts, and other power-related issues due to unpredictable loads. The electrical supply system of a train track uses one phase 132kV/25kV generators to supply high-voltage power to the cars. The Ethio-Djibouti railway operates on a single-phase power supply with 25 kV and 50 Hz as shown in the Figure 3.1. The network of traction power supplies is divided into portions by a neutral section, each supplied by a different traction substation.

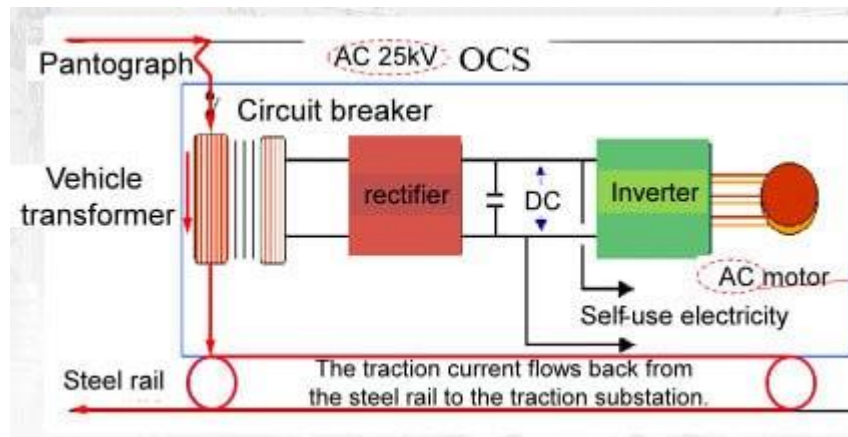


Figure 3.1 A 25 kV, 50 Hz electric traction system

The Ethiopia-Djibouti railway has successfully electrified its entire 756 km track with 20 tractions, each equipped with two independent power supply sources. These tractions output 27.5 kV to the overhead catenary system, employing a single bus-bar segment for connection. The traction substations utilize a master transformer and standby reserve for operation, ensuring efficient and reliable power supply along the railway route.

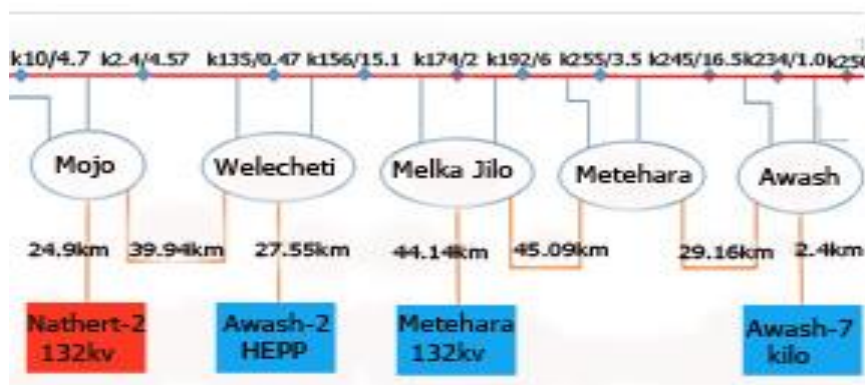


Figure.3.2 Ethio-Djibouti traction power supply system

The local operation control center of every traction substation plays a crucial role in monitoring and managing moving trains and the entire substation. Modern electric drive systems with power electronics components have a significant impact on the power network's operation. Electric locomotives, considered single-phase loads, rely on power transformers and AC-DC rectifiers to power the traction vehicle as shown in Figure 3.3. The conversion of DC voltage through a DC-AC converter powers the induction motor with three-phase electricity. High-power electronics devices in rail line units extensively utilize power electronics converters within the AC-DC traction drive system. This integration of power

electronics and railway systems continues to shape the efficiency and performance of modern transportation networks.

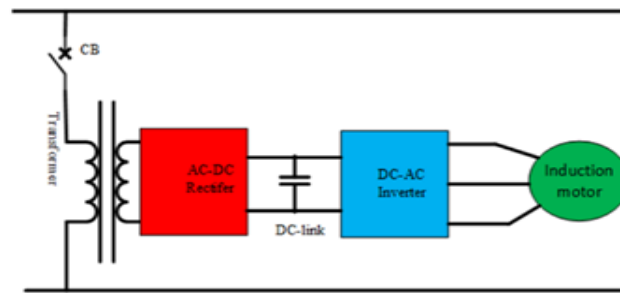


Figure 3.3 AC-DC-AC traction locomotive

The nonlinear features and single-phase nature of AC traction loads cause several power quality issues, such as high reactive power usage, low power factor, harmonic distortion, and notable negative sequence current. These problems are becoming more concerning in the fast-growing area of railway electrification. These challenges impact the efficient and stable operation of the power systems involved in powering trains and railway infrastructure. Addressing these issues is crucial to ensure reliable and effective railway operations (Shu Zeliang, 2010). Extensive research has been conducted to improve railway electrification and power quality analysis techniques. Current research mainly concentrates on power quality analysis through various software simulation methods without proper validation through experiments or measurements. The analysis of power quality in the Ethio-Djibouti railway has not been thoroughly examined in the past. The power supply system is experiencing regular power cuts because of issues with power quality in the local distribution networks. Data from the local SCADA in Ethio-Djibouti traction substations indicates that these power cuts are happening often because of overvoltage and power quality problems, resulting in a power factor that falls below the national standard of 0.9. This situation is affecting the reliability of the electrical supply in the area. Solutions need to be implemented to address these power quality problems and ensure a stable power supply for the railway. Delving into the realm of power quality issues within railway systems, this paper presents a meticulous analysis aimed at ensuring the safe and efficient operation of railways. The primary focus lies in scrutinizing the existing power systems of the Ethio-Djibouti railway line using advanced ETAP software, coupled with the validation of simulation outcomes through real-world data obtained from a power analyzer device. By cross-referencing simulation results with real-time measurements from traction substations, the study aims to establish the credibility and accuracy of the findings. Furthermore, the research is dedicated to exploring methodologies for evaluating

power quality and identifying potential avenues for enhancement. Through a comprehensive investigation, the paper addresses critical aspects of power quality, shedding light on key areas for improvement and optimization within railway operations. This study serves as a valuable resource for professionals and enthusiasts in the railway industry, offering insights into cutting-edge solutions and best practices.

3.3 Modeling and Methodology

The power quality analysis of the Ethio-Djibouti Railway's 25kV, 50Hz traction system involves a comprehensive modeling and methodology approach that addresses various aspects of railway operation and infrastructure efficiency. Given the critical nature of power supply for traction systems, ensuring consistent voltage levels, minimizing harmonic distortion, and maintaining frequency stability are paramount. The modeling phase typically employs advanced simulation tools that represent the railway's electrical network, including traction substations, overhead catenary systems, and the rolling stock that draws power. By utilizing software such as MATLAB/Simulink or ETAP can simulate different operational scenarios to assess how variations in train load, speed, and environmental conditions impact overall power quality.

The methodology for power quality analysis integrates both theoretical modeling and empirical data collection. Initially, baseline measurements of voltage, current, and harmonic levels are gathered through strategic placement of monitoring devices along the railway line. These devices continuously record data during regular operations, capturing transient disturbances and anomalies associated with locomotive activity. Following data collection, advanced analysis is conducted to identify trends and deviations from established power quality standards, such as those outlined by the IEEE 519 guideline for harmonic emissions. This analysis informs targeted mitigation strategies, such as the implementation of reactive power compensation devices, which can improve voltage stability and reduce harmful harmonics that may adversely affect both the railway infrastructure and the surrounding community. The effective modeling and methodology applied in the power quality analysis of the Ethio-Djibouti Railway's traction system are crucial for enhancing operational reliability and efficiency. The outcome not only ensures the safe and efficient movement of trains but also supports sustainable railway operations that align with the growing demand for public transportation in East Africa. Modeling a 25kV, 50Hz railway traction system is essential for understanding and optimizing the performance and efficiency of electric trains. This high-voltage system is designed to provide adequate power for various operational needs, including

traction, auxiliary systems, and on-board equipment. At its core, the system operates by converting electrical energy from a supply source into mechanical energy through traction motors, enabling trains to accelerate and maintain their speed on rail networks. A thorough model typically encompasses key components such as transformers, rectifiers, traction motors, circuit breakers, and various control systems, each functionally interlinked to ensure smooth operation.

The modeling process often employs electrical circuit simulation software to analyze how the system behaves under different conditions, including load variations and fault scenarios. This approach allows engineers to assess parameters like voltage stability, power factor correction, and energy losses throughout the system. Additionally, integrating dynamic models can help simulate the interactions between the train and the track, accounting for factors such as gradient changes and curvature effects. By employing both steady-state and transient analysis, it is possible to evaluate the overall efficiency and reliability of the traction system.

To effectively assess the railway system's power supply and its corresponding impact on the local distribution network, it is imperative to develop a comprehensive model of the entire traction power supply system. This evaluation aims to identify potential areas for improvement or upgrade, with the critical goal of enhancing power quality across the network. The electric railway substation, a pivotal component in this system, is designed as a transformer with ratings of 132kV/230kV/25kV and 20/12.5MVA, establishing a crucial connection to the transmission grid as shown in Figure 3.4. To ensure the uninterrupted operation of locomotives, each traction substation is equipped with two dependable power sources. In this arrangement, the Vv wire transformers are configured in a master-slave setup, which guarantees that in the event of a power source failure, an alternate transmission line is readily available to supply the necessary power. This resilient configuration plays a significant role in maintaining operational efficiency and reliability within the railway system.

The development of a simulation model for electric traction was realized using advanced ETAP software tools, allowing for a detailed analysis of the power dynamics at play. The model serves as a vital resource for identifying potential shortcomings in the current system and evaluating the effectiveness of proposed upgrades or new systems.

circuit 132kV line links the two substations together. Because Mojo and Wulenchiti traction substations rely on each other, the access system layout of both substations is thoroughly studied. Below the figure shows the connection between the two substations.

Table 3.2 Technical parameters of Mojo and Wulenchiti

No	Traction Substation	Mojo(kV)	Wulenchiti(kV)
1	Voltage ratio of transformer	132/27.5	132/27.5
2	Wiring type of transformer	3 Phase Vv	3 Phase Vv
3	Installed Capacity of traction transfer (MVA)	2*(20+20)	2*(12.5+12.5)
4	Phase Sequence of design power incoming line	BCA	BCA

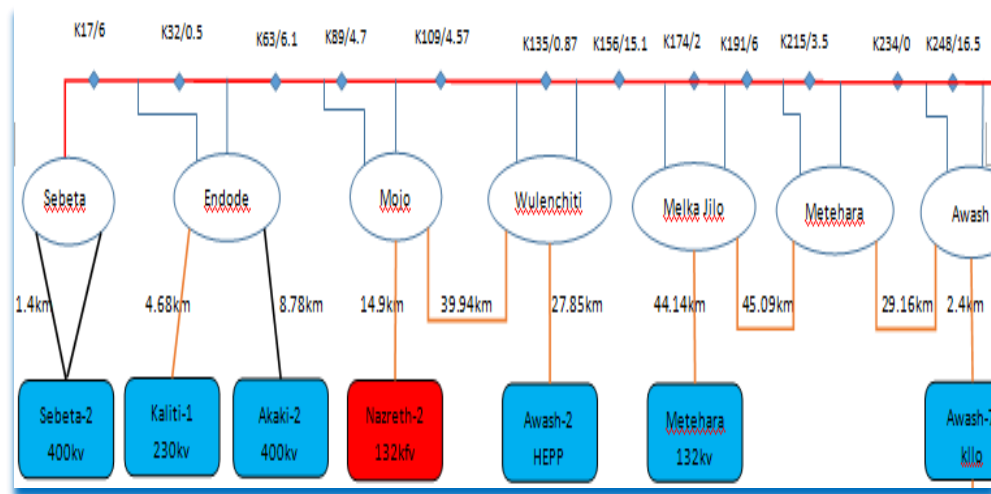


Figure 3.5 Traction power supply

The ETAP software has revolutionized the analysis of power flow and quality in electric traction systems, enabling the development of a robust simulation model. Traction substations are designed for continuous operation with redundant power supplies and Vv wiring transformers, ensuring reliable power distribution. The use of V/V transformers efficiently transforms power, contributing to overall system efficiency. This advanced modeling approach is crucial for understanding traction behavior and its impact on power system supply, highlighting the importance of modern traction power supply systems.

a. Normal operation mode load flow analysis

The analysis of Figure 3.6 and Table 3.3 shows that all traction substations are operating within normal capacity, with no overloading. The bus voltage falls within the range of 132.3kV-137.8kV, meeting the upper and lower limits set by the IEEE standard. This indicates satisfactory performance in normal operation mode, ensuring system reliability and stability.

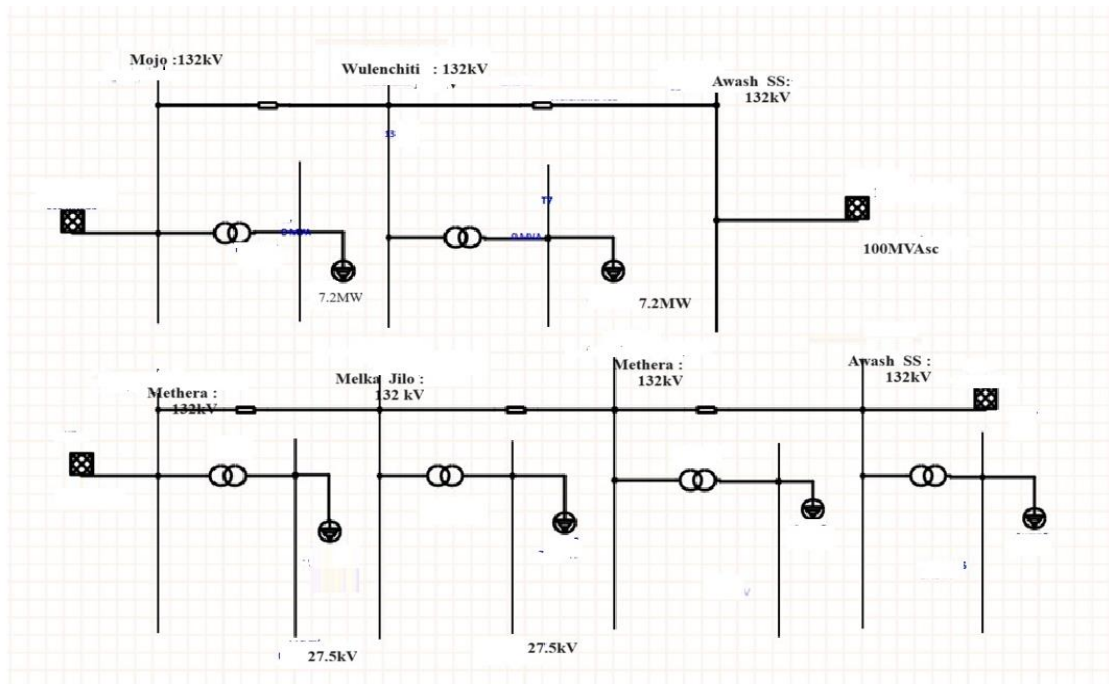


Figure 3.6 Schematic diagram of power flow analysis in normal operation mode

Table 3.3 load flow analysis result

Bus Id	Nominal Voltage(kV)	Bus voltage(kV)
Mojo SS	132	132.3
Wulenchiti TS	132	133.6
Melka Jilo TS	132	137.8
Methera TS	132	137.1
Awash TS	132	133.6

b. Contingency analysis

Contingency analysis plays an important tool in the design and operation of power system networks. By assessing the network's ability to withstand failure, it provides essential insights into feasibility and security. This tool is instrumental in ensuring the reliability and resilience of power systems, making it an indispensable component of network management and planning.

N-1 fault of Nazareth 2 Line

In Table 3.4, the fault of Nazareth -2-line results in Mojo, Wulenchiti Melkajilo, Methera, and Awash traction substations surpassing the recommended limit of the IEEE standard and becoming overloaded. This issue highlights the need for immediate attention and action to prevent potential disruptions to the power supply in these areas.

Table 3.4 N-1 fault of Nazareth 2-line fault result.

Bus Id	Nominal voltage (kV)	Type	Condition	Post contingency (%)
Mojo SS	132	Bus	Overvoltage	105.04%
Wulenchiti TS	132	Bus	Overvoltage	105.04%
Melka Jilo TS	132	Bus	Overvoltage	105.58%
Methera TS	132	Bus	Overvoltage	107.79%
Awash TS	132	Bus	Overvoltage	107.46%

N-1 fault of Awash 7 kilo Line.

In Table 3.5, the fault of the Awash 7 kilo line causes Mojo, Wulenchiti Melkajilo, Methera, and Awash traction substations to exceed the recommended limit of IEEE standard and become overloaded. This issue highlights the need for immediate attention and resolution to prevent further strain on the affected substations.

Table 3.5 Awash 7-kilo line fault result

Bus Id	Nominal voltage(kV)	Type	Condition	Post contingency (%)
Mojo SS	132	Bus	Over voltage	106.4%
Wulenchiti TS	132	Bus	Over voltage	105.4%
Melka Jilo TS	132	Bus	Over voltage	105.8%
Methera TS	132	Bus	Over voltage	106.7%
Awash TS	132	Bus	Over voltage	107.6%

c. Negative-sequence analysis

The voltage imbalance at the 132kV sides of the Methera and Awash substations exceeds the permitted VUF percentage according to IEEE 1159-2009, posing a risk to electrical equipment. The negative sequence current entering the power supply, as shown on table 3.6 does not meet the IEEE standard. This non-compliance highlights the need for corrective measures to ensure the safety and reliability of the power supply system.

Table 3.6. Negative-sequence analysis result

Node	Bus voltage	Voltage unbalanced maximum value (%)
Methera Traction Substation 132kV side	132kV	5.1
Melkajilo Traction substation side	132kV	5.2
Methera Traction Substation	132kV	5.0
Awash Traction Substation 132kV side	132kV	5.2

d. Short circuit current analysis

Short circuit analysis in railway traction is a critical aspect of ensuring the safety and reliability of the electrical systems used in trains. It involves evaluating the potential impact of short circuits on the traction power supply and the associated protection measures. With the increasing complexity of railway traction systems, conducting thorough short circuit analysis is essential for preventing disruptions and hazards. By identifying potential areas of vulnerability and implementing appropriate safeguards, railway operators can maintain the integrity of their power distribution networks and ensure uninterrupted service for passengers and freight. The latest versions of IEC and ANSI/IEEE Standards address fault duties, with specific calculations showing the short circuit current of all traction substation 132kV bus in 2015 within 31.5kA as shown on table 3.7. This analysis provides essential insights for ensuring the reliability and safety of power systems.

Table 3.7 Short circuit analysis result

Name of Substation	Bus Voltage(kV)	Three phase short circuit(kA)
Mojo TS	132	1.273
Wulenchit SS	132	1.273
Melka Jilo TS	132	1.184
Methera TS	132	1.184
Awash TS	132	1.203

e. Harmonic analysis

Harmonics analysis in railway power substations is crucial for ensuring the stability and efficiency of the power system. The presence of harmonics can lead to equipment malfunction and power quality issues, which can disrupt railway operations. By conducting thorough harmonics analysis, engineers can identify and mitigate harmonic distortion, ultimately improving the reliability of the power supply for railway operations. This article explores the importance of harmonics analysis in railway power substations and the measures that can be taken to address harmonic issues. The assessment took place at the connection linked to the electricity plant, with ETAP simulations used to compute voltage levels at 132 kV and 25 kV.

The findings conform to IEC specification 61000-3-14 and IEEE code 519-2014, simulations were run to determine the exact amount of unique voltage and current harmonics at 132kV and 25kV traction substations, as shown in Table 3.8.

Table 3.8 Voltage harmonic distortion IEEE 519-2014 standard

Bus voltage	Voltage distortion (%)	THD (%)
69kV and below	3	5
69001V through 161kV	1.5	2.5
161000V and above	1	1.5

f. Total voltage and current harmonic distortion

The simulation results presented in Table 3.9 paint a concerning picture regarding the power quality issues at the point of common coupling. The data clearly indicates that the harmonic voltage distortion levels exceed the limits set forth by the IEEE 519-1992 standard, which is a widely recognized industry guideline for acceptable levels of voltage harmonics on the grid. Additionally, the total current distortion was found to surpass the thresholds outlined in IEC 61000-3-4, another crucial international standard addressing power quality. These findings, derived from detailed simulations conducted using the industry-leading ETAP software platform at the 132kV voltage level, unveil the presence of problematic individual voltage and current harmonics, as visually depicted in the accompanying figures. Harmonic distortion of this magnitude can have far-reaching consequences, potentially causing equipment malfunction, increased energy losses, and premature asset degradation if left unmitigated. Further analysis will be crucial to pinpoint the root causes driving these power quality deficiencies and develop an effective remediation plan to bring the system back into compliance with the relevant standards and ensure the reliable, efficient operation of the electrical infrastructure.

Table 3.9. Total voltage and current distortion simulation result

Traction Substation	Total Voltage Distortion (THD)%	Total Current Distortion (%)
Mojo TSS	3.21	17.94
Wulenchiti TSS	3.62	54.42
MelkaJilo TSS	3.62	31.57
Methera TSS	3.61	31.57
Awash TSS	2.88	56.04

Individual voltage harmonics

As the simulation results depicted in Figure 3.7 clearly indicate, the 5th and 7th order voltage harmonics have exceeded the 1.5% limit stipulated by the IEEE 519-1992 standards. This is a concerning issue that requires careful consideration, as these voltage harmonics can have detrimental effects on the overall performance and efficiency of the induction motor locomotive. The 5th order voltage harmonic, being a negative sequence harmonic, is particularly problematic. When present in an induction motor, negative sequence harmonics generate a reverse torque that works against the motor's primary rotation, effectively slowing down its operation. This can lead to decreased efficiency, increased energy consumption, and potentially even damage to the motor over time if left unaddressed. Additionally, the 7th order voltage harmonic, classified as a positive sequence harmonic, is also undesirable and can have significant consequences. Positive sequence harmonics are responsible for the overheating of conductors, power lines, and transformers within the system. This occurs due to the additive nature of the waveforms, which results in increased current flow and thermal stress on these critical components. The elevated temperatures can reduce the lifespan of the equipment, increase maintenance requirements, and potentially lead to system failures if the issue is not promptly rectified. Addressing these voltage harmonic concerns is of paramount importance to ensure the reliable and efficient operation of the induction motor locomotive. Implementing appropriate mitigation strategies, such as the installation of harmonic filters or the optimization of the system's design, can help bring the 5th and 7th order voltage harmonics back within the permissible limits set by the industry standards. By taking proactive measures

to address these voltage harmonic issues, the overall performance and longevity of the induction motor locomotive can be significantly improved, leading to enhanced energy efficiency, reduced maintenance costs, and a more reliable transportation solution.

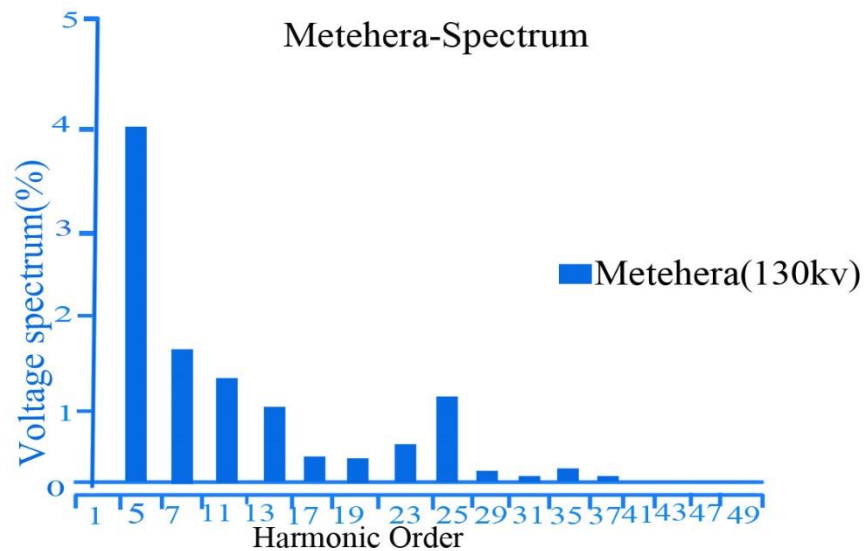


Figure. 3.7 Voltage harmonic at 132kV side of Methera substation

The simulation results depicted in Figure 3.8 reveal that the 5th and 7th individual voltage harmonic orders are exceeding the 1.5% limit specified by the IEEE 519-1992 standards. This is a significant finding, as voltage harmonics can have detrimental effects on electrical systems and equipment. When these higher-order harmonics are present in the voltage waveform, they can cause increased heating in motors and transformers, leading to accelerated insulation breakdown and potential equipment failure over time. Additionally, harmonics of these orders can resonate with power factor correction capacitors, resulting in overvoltage that stress the insulation of those components. This can ultimately lead to capacitor malfunction and power quality issues throughout the distribution system.

Melkajilo TSS-Spectrum

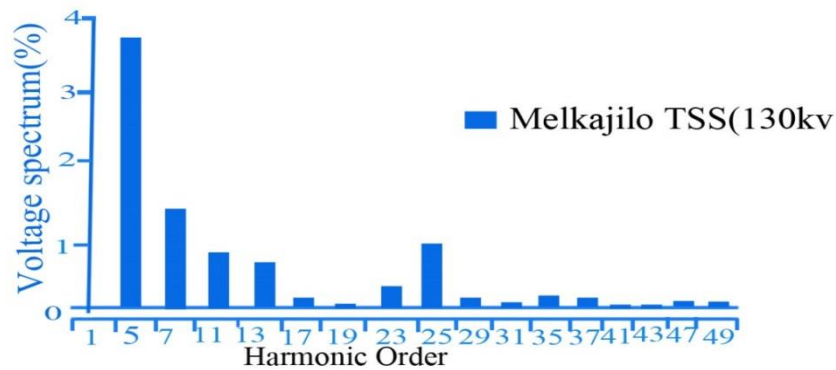


Figure. 3.8 Voltage harmonic at 132kV side of Melkajilo Traction

As per the simulation results in Figure 3.9 below, the 5th and 7th individual voltage harmonics orders are above the limit of 1.5 % specified by IEEE standards 519-1992. The simulation results depicted in Figure 3.9 reveal that two specific voltage harmonic orders are exceeding the permissible limits set forth by the IEEE standards 519-1992. Specifically, the 5th and 7th harmonic orders both surpass the 1.5% threshold established by this industry standard. This is a significant finding, as voltage harmonics refer to distortions in the sinusoidal waveform of the electrical voltage supply. When these harmonic orders rise above recommended levels, it can lead to a range of detrimental effects, including increased power losses, overheating of electrical equipment, and even potential damage to sensitive electronic devices connected to the grid. The 5th harmonic is a common culprit, often arising from the operation of three-phase rectifiers and variable speed drives. Meanwhile, the 7th harmonic may stem from sources such as transformer saturation or the use of power electronics-based equipment. Allowing these harmonics to persist unchecked can compromise power quality, system efficiency, and the lifespan of electrical infrastructure. As such, this simulation data indicates the need for further investigation and implementation of mitigation strategies to bring these harmonic orders back within the prescribed IEEE limits and safeguard the integrity of the overall power system.

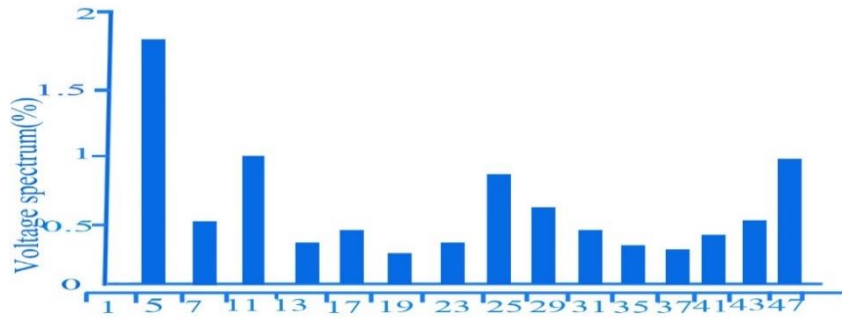


Figure. 3.9 Voltage harmonic at 132kV side of Awash Traction

g. Negative-sequence analysis

The presence of load harmonics in the system due to the non-linearity of traction is a significant concern that can have far-reaching consequences. These load harmonics introduce distortions and imbalances in the power supply, which can have detrimental effects on the overall system performance. Unbalanced systems are a major source of negative sequence current, which can be highly problematic. The injection of large amounts of negative sequence current into the power grid by these unbalanced systems can cause severe damage to electrical devices and equipment. The negative sequence current creates an imbalance in the voltage waveforms, leading to increased stresses and heating in motors, transformers, and other components. This can accelerate insulation breakdown, shorten equipment lifespan, and potentially lead to catastrophic failures if left unchecked.

According to the IEEE 1159-2009 standard, the percentage of voltage unbalance factor (VUF) must not exceed 2% to maintain the integrity and stability of the power system. However, the calculation results presented in Table 3.10 indicate that the assessment of the negative sequence components in the voltage unbalance at the 132kV side is higher than this 2% threshold, failing to meet the IEEE 1159-2009 standard. This non-compliance with the industry standard is a significant concern, as it suggests that the power system is operating outside the acceptable limits for voltage unbalance. The excessive negative sequence current introduced by the unbalanced system can lead to a range of problems, including increased energy losses, reduced efficiency, and potential damage to sensitive electronic equipment connected to the grid. Addressing this issue and bringing the system back within the IEEE 1159-2009 guidelines is crucial to ensure the reliable and safe operation of the power network.

Table 3.10 Negative-sequence results

Node	Bus voltage	Voltage unbalanced maximum value (%)
Mojo Traction substation 132kV side	132kV	5.7
Wulenchiti Traction Substation 132kV side	132kV	7.5
MelkaJilo Traction Substation	132kV	7.5
Methera Traction substation	132kV	5.2

3.4.2 Analysis of power supply scheme from Sirba Kunkur to Milo Section

The power supply voltage grade of Sirba Kunkur, Miesso, Afdem and Gota traction substation is 132kV and the superior power supply points are Awash 7kilo 230kV substation and Hurso 230kV substation. Four traction substations are connected by serial connection to form single chain structure with Asebe Teferi 132kV substation as the public substation. As four traction substations are in the same power supply circuit, the access system scheme of three traction substations is analyzed. The schematic diagram for relevant access system scheme is shown below:

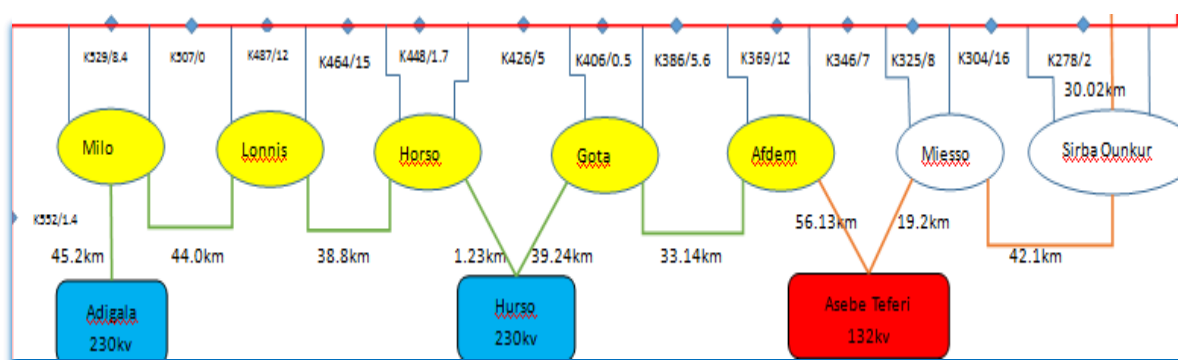


Figure 3.10 Traction substation layout

Table 3.11 Technical parameters of traction substations

Traction Substation	Sirba Kunkuer	Mieso	Afedem	Gota
Voltage ratio of transformer	132/27.5	132/27.5	132/27.5	132/27.5
Wiring type of transformer	3 Phase Vv	3 Phase Vv	3 Phase Vv	3 Phase Vv
Installed Capacity of traction transfer (MVA)	2*(12.5+12.5)	2*(12.5+12.5)	2*(12.5+12.5)	2*(12.5+12.5)
Phase Sequence of design power incoming line	BAC	BCA	ABC	BAC

a. Normal operation mode

The data presented in Figure 3.11 and Table 3.12 clearly demonstrates that during normal operating conditions, the traction substations within this system are not experiencing any overloading issues. This is a crucial finding, as overloaded substations can lead to a variety of problems, including voltage instability, increased power losses, and even potential equipment failure. However, the analysis indicates that the bus voltage across the substations is maintained within a healthy range, falling between 132.8kV and 137.5kV. This voltage profile not only meets but exceeds the IEEE industry standard, which specifies an acceptable upper limit of +5% above the nominal voltage and a lower limit of -5% below it. Operating within these well-defined parameters is essential for ensuring the reliable and efficient transmission of power throughout the traction system. By keeping the bus voltage suitably high but not excessively so, the system can optimize energy delivery while also protecting sensitive electrical components from potentially damaging overvoltage conditions. Overall, the data clearly shows that from a technical standpoint, the traction substations are performing exceptionally well and operating exactly as intended under normal circumstances, a testament to the robust design and careful management of this critical power infrastructure.

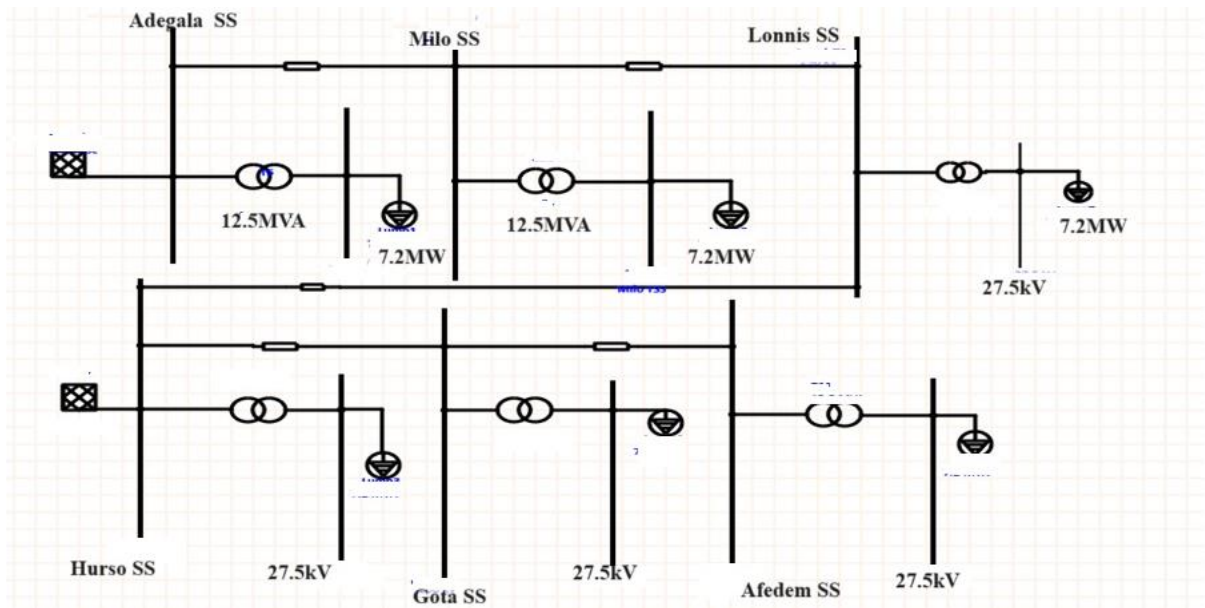


Figure 3.11 Schematic diagram of power flow analysis in normal operation mode

Table 3.12 load flow analysis result

Bus Id	Nominal Voltage (kV)	Bus Voltage (kV)
Sirbakunker TS	132	132.8
Meiseo TS	132	134.6
Afedem TS	132	137.5
Gota TS	132	137.2

b. Contingency analysis

Contingency analysis is an important tool for designing and operating a power system network. It is used to evaluate feasibility and security based on the ability of the network to resist failure.

N-1 fault of AsebeTeferi line.

The fault occurring on the Asebe Teferi transmission line, as clearly shown in the data presented in Table 3.13, is causing significant issues at three critical traction substations within the electrical grid - Sirbakunku, Meiso ,Afedem, and Gota. This fault is resulting in these substations exceeding the recommended load limits specified in the IEEE industry standards, leading to an overload condition that could have serious consequences. When a transmission

line fault occurs, it disrupts the normal flow of electricity through the system, causing voltage fluctuations and uneven power distribution. This imbalance then manifests as excessive loading on the affected substations, pushing them beyond their designed capacity. Such overloading not only risks damage to the substation equipment, but can also lead to unreliable power supply, voltage instability, and potentially even blackouts in the areas served by these critical facilities. Addressing this fault on the Asebe Teferi line is therefore of utmost importance to restore the grid to a stable, balanced state and ensure the traction substations operate within their intended parameters as per the IEEE guidelines. Prompt investigation and remediation of this issue is crucial to maintain the integrity and resilience of the overall electrical network.

Table 3.13 AsebeTeferi line fault result

Bus Id	Nominal Voltage(kV)	Bus Voltage(%)
SirbaKunkuer SS	132	105.4%
Meiso TS	132	106.6%
Afedem TS	132	107.5%
GotaTS	132	107.2%

N-1 fault of Awash 7 kilo line.

The fault on the Asebe Teferi transmission line, as clearly depicted in Table 3.14, is causing significant issues for the Sirbakunkue, Meiso Afedem, and Gota traction substations. This fault has resulted in these critical substations exceeding the recommended limits set forth by the IEEE industry standards. The overloading of these substations is a major concern, as it can lead to a variety of problems, including decreased efficiency, equipment damage, and even potential blackouts or service disruptions for the communities and industries that rely on the power supplied by these facilities. The root cause of this overloading appears to be the fault on the Asebe Teferi line, which is likely causing power fluctuations, voltage drops, or other disturbances that are overwhelming the capacity of the affected substations. This imbalance between supply and demand is placing undue stress on the substation equipment, pushing it beyond its designed limits and risking potential failures or malfunctions. Without intervention to address the line fault and rebalance the loads on the substations, the situation is likely to

deteriorate further, potentially causing cascading issues throughout the regional power grid. Resolving this problem will require a multi-pronged approach. First and foremost, the fault on the Asebe Teferi line must be identified, isolated, and repaired as quickly as possible to restore stability to the affected substations. Additionally, the substations themselves may need to be evaluated to determine if upgrades or expansions are required to bring them back within the IEEE's recommended operating parameters. This could involve installing additional transformers, upgrading switchgear, or implementing advanced control systems to better manage the power flows. Ultimately, addressing this issue is crucial to ensuring the reliable and efficient delivery of power to the communities and industries that depend on these critical energy infrastructure assets.

Table 3.14 N-1 fault of Awash 7 kilo line.

Bus Id	Nominal Voltage(kV)	Bus voltage (%)
Sirbakunkuer SS	132	105.6%
Meiso TS	132	104.8%
Afedem TS	132	107.2%
Gota TS	132	106.2%

c. Negative-sequence analysis

The presence of a negative sequence current entering the power supply can pose a serious threat to the safety and integrity of electrical equipment. As outlined in Table 3.15, this undesirable current can have detrimental effects, potentially endangering the proper functioning of critical components within the system. IEEE standard 1159-2009 explicitly states that a voltage unbalance factor (VUF) percentage exceeding 2% is not permissible, as it can lead to significant imbalances and instabilities. In the case of the 132kV sides of the Asebe Teferi and Awash substations, the voltage imbalance does not meet the requirements set forth in this IEEE standard. The assessment of the negative sequence components at these substations reveals that the criterion of 2% has been surpassed, indicating a clear violation of the established guidelines. This non-compliance can have far-reaching consequences, potentially compromising the reliability, efficiency, and safety of the entire power network.

Addressing and mitigating these voltage imbalance issues is of paramount importance to ensure the continued stable and secure operation of the electrical infrastructure. The negative sequence current to enter the power supply, endangering electrical equipment are as shown in table 3.15. IEEE 1159-2009 states that a VUF percentage of more than 2% is not permitted. The voltage imbalance at the 132kV sides of the AsebeTeferi and Awash substations does not fulfill IEEE standard 1159-2009, because the assessment criterion of negative sequence components is greater than 2%.

Table 3.15 Negative Sequence analysis

Node	Bus voltage	Voltage unbalance maximum value (%)
Serbakunker Traction Substation 132kV side	132kV	5.3
Mieso Traction substation side	132kV	5.2
Afdem Traction Substation	132kV	5.1
Gota Traction Substation 132kV side	132kV	5.8

d. Short circuit current analysis

To establish the protective device implementation and power equipment rating, short-circuit analysis can also be used to examine the voltage profile of a network, especially the buses close to a problem. The most recent versions of the IEC (IEC 60909 and others) and ANSI/IEEE (C37 series) Standards address fault duties. The calculation shows in table 3.16, that the short circuit current of all traction substation 132kV bus in 2015 within 31.5kA.

Table 3.16. Short circuit analysis result

Name of Substation	Bus Voltage(kV)	Three phase short circuit (kA)
Sirbakunker TS	132	1.73
Mieso SS	132	2.3
Afdem TS	132	3.84
Gota TS	132	2.1

e. Harmonic analysis

To determine once the power source trainloads' induced sine waves resulted in insufficient amplitude that the level of shared attaching (PCC), periodic present and voltage studies were performed. The area that has a normal connection linked to the electricity plant serves as the evaluation place for harmonies computations. Total voltage and current harmonic distortion.

Total voltage and current distortion

The simulation results in Table 3.17 indicate that the harmonic voltage distortion at the point of common coupling exceeds the limits set by IEEE519-1992 limits, and the total current distortion exceeds the limit set by IEC 610003-4. The simulations, conducted using ETAP at 132kV levels, revealed the presence of individual voltage and current harmonics as depicted in the figures below.

Table 3.17 Total voltage and current distortion simulation result

Traction Substation	Total Voltage Distortion (%)	Total Current Distortion (%)
Sirba Kunker TSS	3.1	23.9
Mieso TSS	3.2	34.42
Afdem TSS	2.62	37.5
Gota TSS	2.1	38.7

Individual voltage harmonics

As per the simulation results in Figure.3.12 below, the 5th individual voltage harmonics order is above the limit of 1.5% specified by IEEE standards 519-1992. The 5th order voltage harmonic is negative sequence harmonics. The presence of negative sequence harmonics in induction motor locomotive produces a negative torque, which attempts to drive the motor in a reverse direction and slows down its rotation.

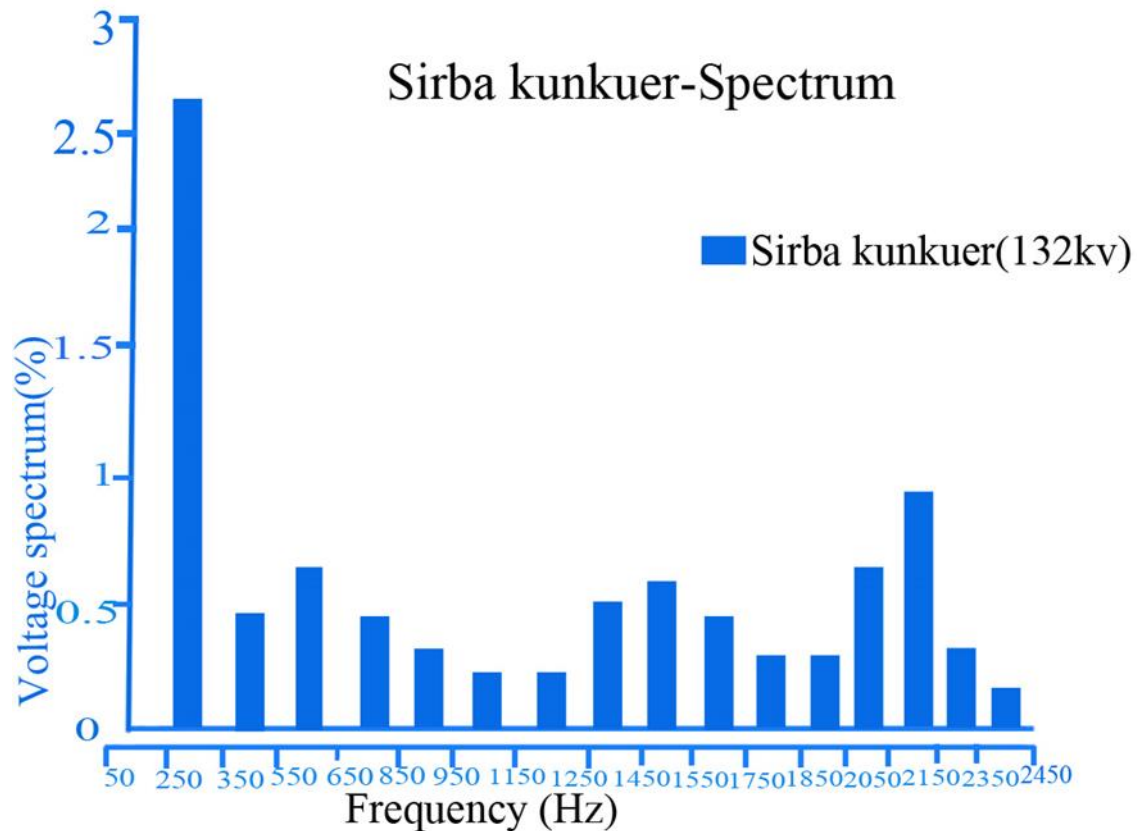


Figure. 3.12 Voltage Harmonic at 132kV side of Sirba kunkuer Traction

As per the simulation results in Figure.3.13 below, the 5th and 7th individual voltage harmonics orders are above the limit of 1.5% specified by IEEE standards 519-1992.

Meiso TSS-Spectrum

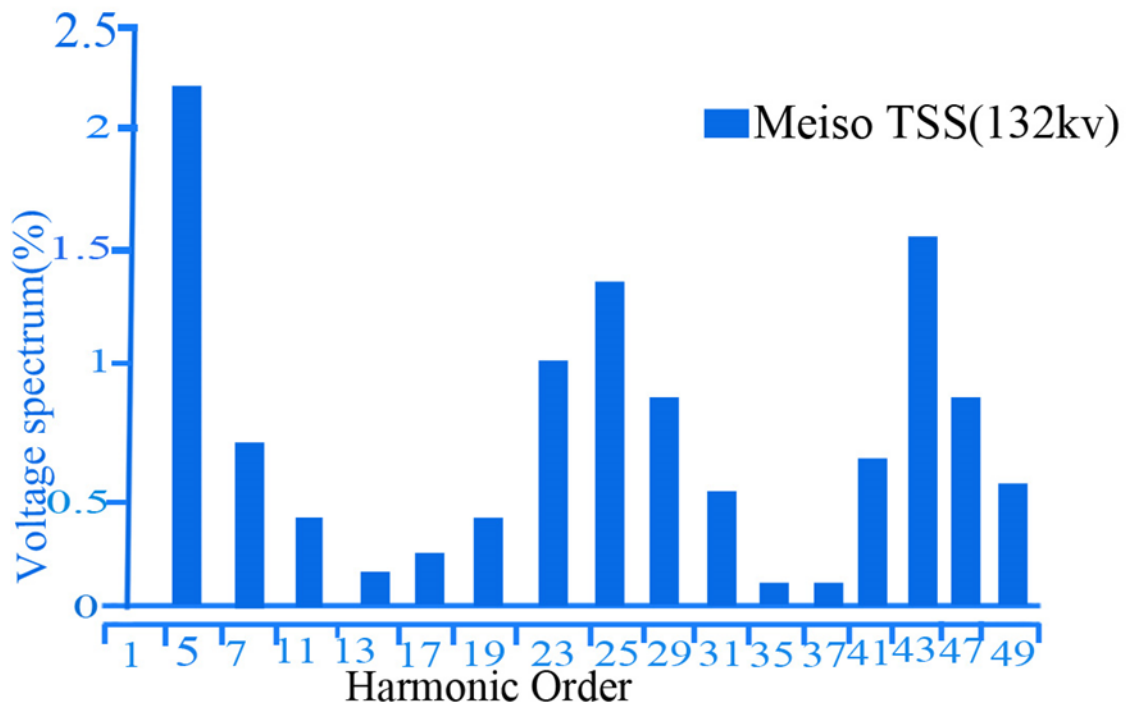


Figure. 3.13 Voltage harmonic at 132kVside of Meiso Traction

As per the simulation results in Figure.3.14 below, the 5th individual voltage harmonics order is above the limit of 1.5% specified by IEEE standards 519-1992.

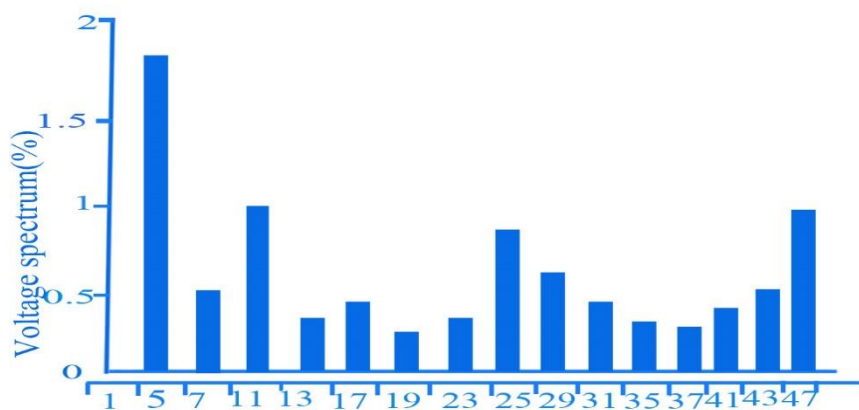


Figure. 3.14 Voltage harmonic at 132kVside of Afedem Traction

As per the simulation results in Figure.3.15 below, the 5th and 7th individual voltage harmonics orders are above the limit of 1.5 % specified by IEEE standards 519-1992.

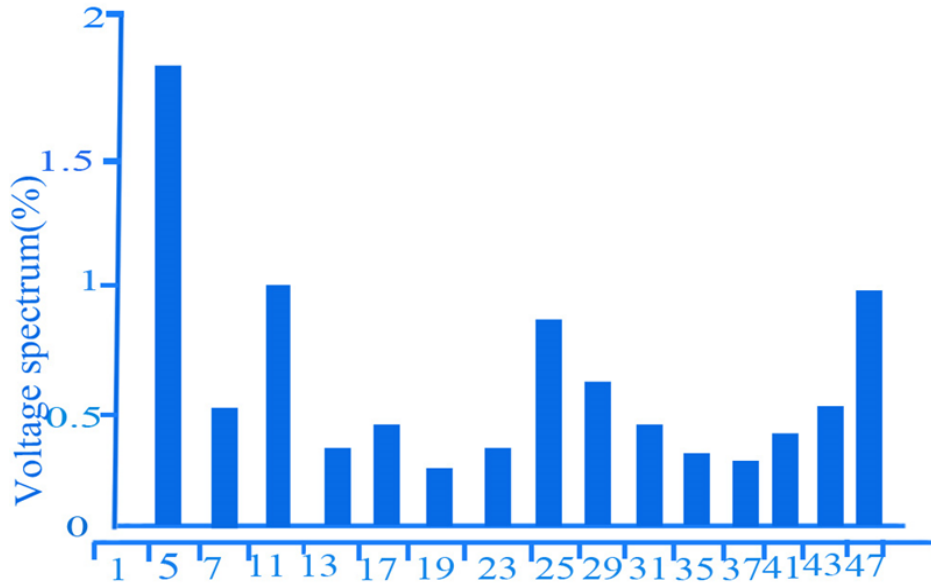


Figure. 3.15 Voltage harmonic at 132kV side of Gota Traction

e. Negative-sequence analysis

Due to non-linearity of traction, load harmonics are present in the system. Unbalance systems are a source of negative sequence current. This unbalance injects large amount of negative sequence current into power grid, causes damage of electrical devices. According to IEEE 1159 –2009 standard, the %VUF must not exceed 2%. As per the calculation results in Table 3.18 below and the assessment standard of negative sequence components in the voltage unbalance at Sirbakunkuer, Mieso, Afedem and Gota substation 132kV Side is higher than 2%, not meeting the IEEE standard 1159-2009.

Table 3.18. Negative-sequence results

Node	Bus voltage	Voltage unbalanced maximum value (%)
Sirba Kunker Traction substation 132kV side	132kV	5.3
Mieso Traction Substation 132kV side	132kV	6.5
Afdem Traction Substation	132kV	7.4
Gota Traction substation	132kV	6.2

3.4.3 Analysis of power supply scheme for three traction substations Hurso, Lonnis , and Milo

The power supply voltage grade of Hurso, Lonnis and Milo traction substation is 230kV and the superior power supply point is Adigala 230kV substation and Hurso 230kV substation. Three traction substations are connected by serial connection to form a single chain structure. As three traction substations are in the same power supply circuit, the access system scheme of three traction substations is analyzed. The schematic diagram for the relevant access system scheme is shown in Figure 3.16 and Table 3.19 below:

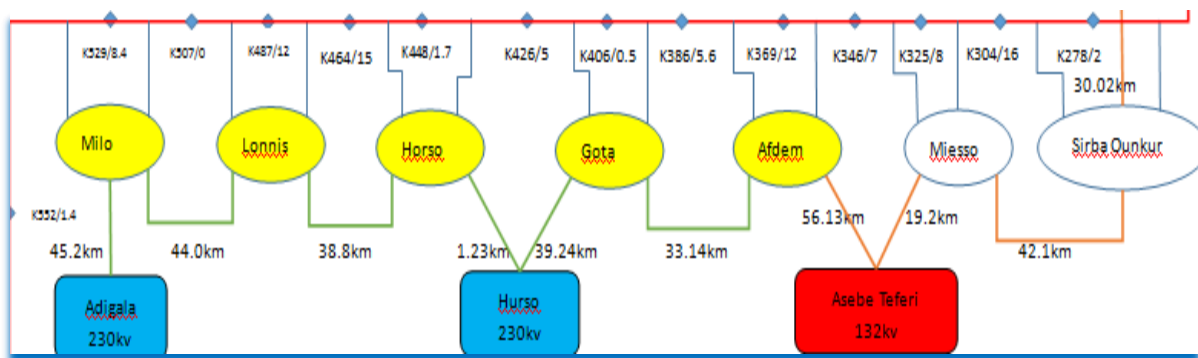


Figure 3.16 Traction substation layout

Table 3.19 The schematic diagram for the relevant access system

Traction Substation	Hurso	Lonnis	Milo
Voltage ratio of transformer	230/27.5	230/27.5	230/27.5
Wiring type of transformer	3 Phase Vv	3 Phase Vv	3 Phase Vv
Installed Capacity of traction transfer (MVA)	2*(12.5+12.5)	2*(12.5+12.5)	2*(12.5+12.5)
Phase Sequence of design power incoming line	BCA	CBA	CAB

a. Normal operation mode

As can be seen in Figure 3.17 and Table 3.20, in normal operation mode all traction substations are not overloaded. The bus voltage is between 234.5kV-236.7kV, which meets the IEEE standard upper +5% and lower -5%.

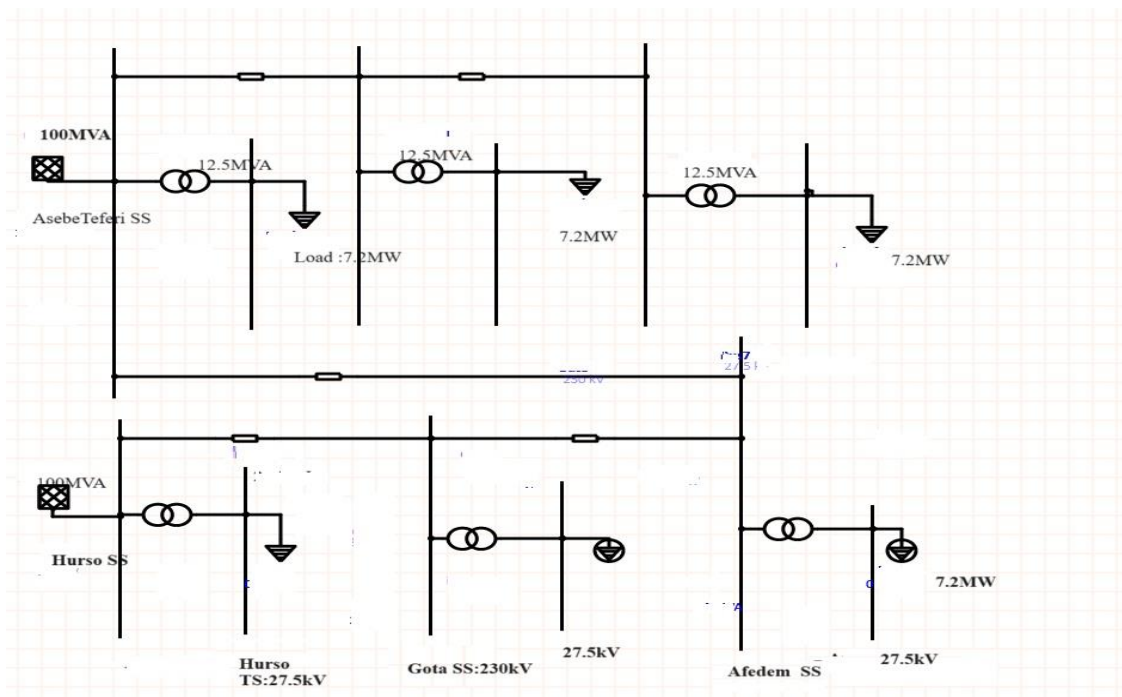


Figure 3.17 Schematic diagram of power flow analysis in normal operation mode

Table 3.20 load flow analysis result

Bus Id	Nominal Voltage(kV)	Bus Voltage(kV)
Afdem TS	132	132.3
Gota TS	1321	135.6
Hurso TS	230	234.5
Lonnis TS	230	235.2
Milo TS	230	236.7

b. Contingency analysis

Contingency analysis is an important tool for designing and operating a power system network. It is used to evaluate feasibility and security based on the ability of the network to resist failure.

N-1 fault of Hurso line.

As it can be seen in Table 3.21 below the fault of Hurso line causes Adegala, Milo, Hurso and Lonnis traction substations to exceed the recommended limit of IEEE standard and overloaded.

Table 3.21 Hurso line fault result

Bus Id	Nominal voltage(kV)	Type	Condition	Post contingency (%)
Adegala TS	230	Bus	Over voltage	104.4%
Milo TS	230	Bus	Over voltage	105.6%
Lonnis TS	230	Bus	Over voltage	105.8%
Hurso TS	230	Bus	Over voltage	106.9%

N-1 fault of Adegala line.

As it can be seen in Table 3.22 below the fault of Hurso line causes Adegala, Milo, Hurso and Lonnis traction substations to exceed the recommended limit of IEEE standard and overloaded.

Table 3.22 Adegala line fault result

Bus Id	Nominal voltage(kV)	Condition	Post contingency (%)
Adegala TS	230	Over voltage	106.4%
Milo TS	230	Over voltage	103.6%
Lonnis TS	230	Over voltage	105.8%
Hurso TS	230	Over voltage	104.7%

c. Negative-sequence analysis

The negative sequence current to enter the power supply, endangering electrical equipment are as shown in Table 3.23, IEEE 1159-2009 states that a VUF percentage of more than 2% is not permitted. The voltage imbalance at the 230kV sides of the Methera and Awash substations does not fulfill IEEE standard 1159-2009, because the assessment criterion of negative sequence components is greater than 2%.

Table 3.23 Negative sequence Analysis

Node	Bus voltage	Voltage unbalance maximum value (%)
Adegala Traction Substation 230kV side	230kV	3.8
Milo Traction substation 230kV side	230 kV	3.2
Lonnis Traction Substation	230kV	4.3
Hurso Traction Substation 230kV side	230 kV	4.2

d. Short circuit current analysis

To establish the protective device implementation and power equipment rating, short-circuit analysis can also be used to examine the voltage profile of a network, especially the buses close to a problem. The most recent versions of the IEC (IEC 60909 and others) and ANSI/IEEE (C37 series) Standards address fault duties. The calculation shows in Table IV that the short circuit current of all traction substation 230kV bus in 2015 within 31.5kA as shown in Table 3.24.

Table 3.24 Negative sequence analysis

Name of Substation	Bus Voltage(kV)	Three phase short circuit(kA)
Adegala TS	230	3.3
Milo TS	230	2.7
Lonnis TS	230	1.8
Hurso TS	230	3.1

e. Harmonic analysis

To determine once the power source trainloads' induced sine waves resulted in insufficient amplitude that the level of shared attaching (PCC), periodic present and voltage studies were performed. The area that has a normal connection linked to the electricity plant serves as the evaluation place for harmonies computations.

Total voltage and current distortion

The simulation results in Table 3.25 indicate that the harmonic voltage distortion at the point of common coupling exceeds the limits set by IEEE519-1992 limits, and the total current distortion exceeds the limit set by IEC 610003-4. The simulations, conducted using ETAP at 230kV levels, revealed the presence of individual voltage and current harmonics.

Table 3.25 Total voltage and current distortion simulation result

Traction Substation	Total Voltage Distortion (%)	Total Current Distortion (%)
Adegala TSS	2.8	33.6
Milo TSS	3.6	34.4
Lonnis TSS	2.6	33.5
Hurso TSS	2.7	36.7

Individual voltage harmonics

As per the simulation results in the figure.3.18 below, the 5th and 11th individual voltage harmonics orders are above the limit of 1% specified by IEEE standards 519-1992.

Milo TS-Spectrum

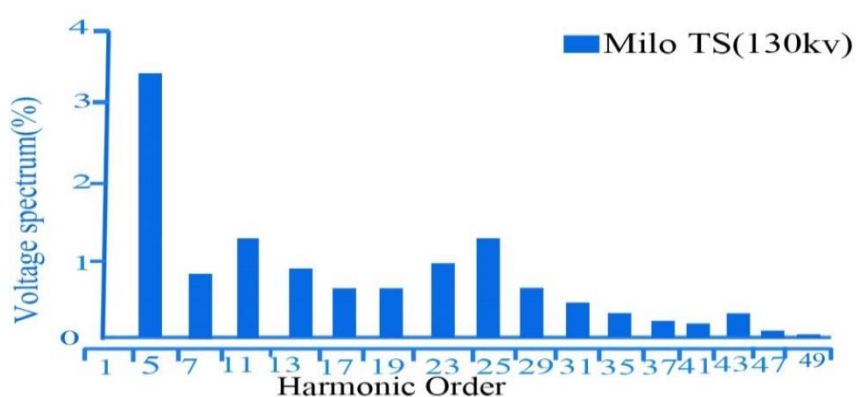


Figure 3.18: Voltage harmonic at 230kV side of Milo substation

As per the simulation results in the Figure 3.19 below, the 5th and 11th individual voltage harmonics orders are above the limit of 1 % specified by IEEE standards 519-1992.

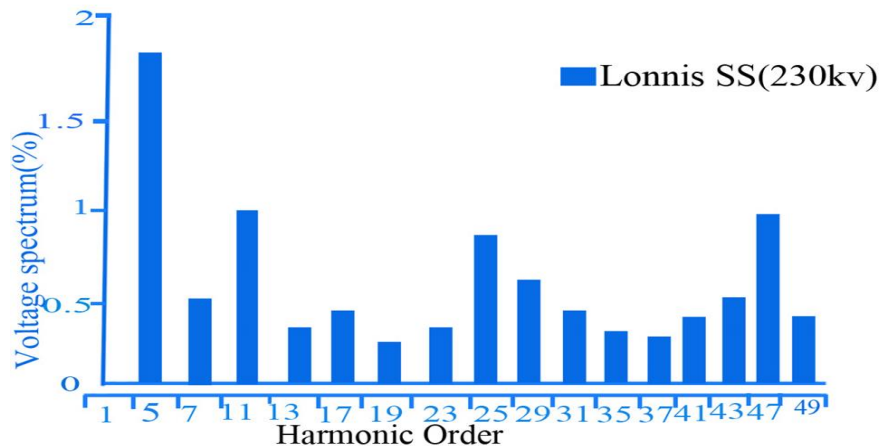


Figure 3.19: Voltage harmonic at 230kV side of Lonnis substation

As per the simulation results in Figure.3.20 below, the 5th and 7th individual voltage harmonics orders are above the limit of 1% specified by IEEE standards 519-1992.

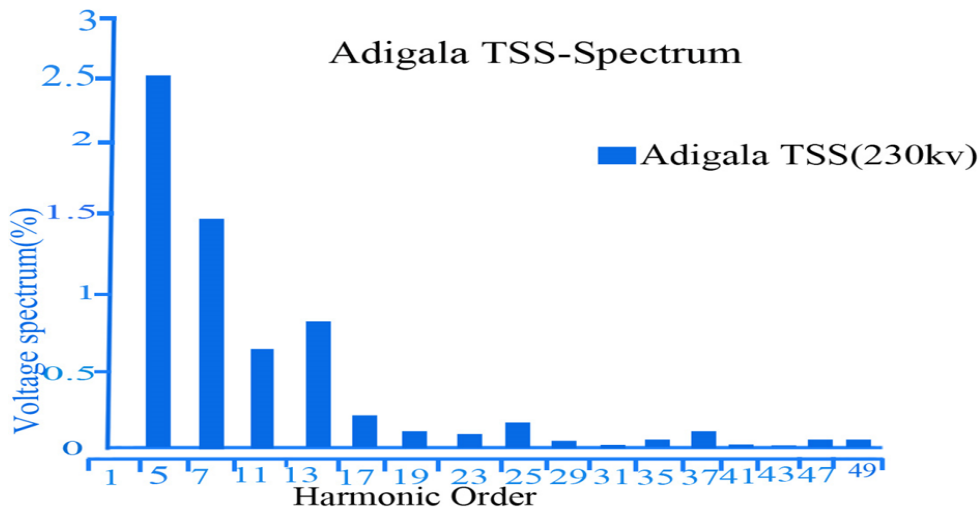


Figure 3.20: Voltage harmonic at 230kV side of Adejala substation

f. Negative-sequence analysis

Due to non-linearity of traction, load harmonics are present in the system. Unbalance system is a source of negative sequence current. This unbalance inject large amount of negative sequence current into power grid, causes damage of electrical devices. According to IEEE 1159 –2009 standard, the %VUF must not exceed 2%. As per the calculation results in the table 3.26 below and the assessment standard of negative sequence components in the voltage unbalance at Adejala substation 230kV side and Hurso Substation 230kV Side is higher than 2%, not meeting the IEEE standard 1159-2009.

Table 3.26. Negative-sequence results

Node	Bus voltage	Voltage unbalance maximum value (%)
Adegala Traction substation 230 kV side	230kV	3.7
Milo Traction Substation 230 kV side	230kV	6.5
Lonnis Traction Substation 230kV side	230kV	7.5
Hurso Traction substation 230 kV side	230kV	6.2

3.4.4 Analysis of Power Supply for Adigala, Aysha and Dewanle Substations

The power supply voltage grade for the Adigala, Ayisha, Dewanle, Ali Sabieh, Holhol, and Nagad traction substations is 230kV. The main power supply points are the Adigala 230kV substation and the Djibouti PK12 230kV substation. These substations are connected in a chain structure. This allows them to work together efficiently and provide electricity to the surrounding areas. The synergy of these substations helps ensure a smooth and reliable power supply for the region.

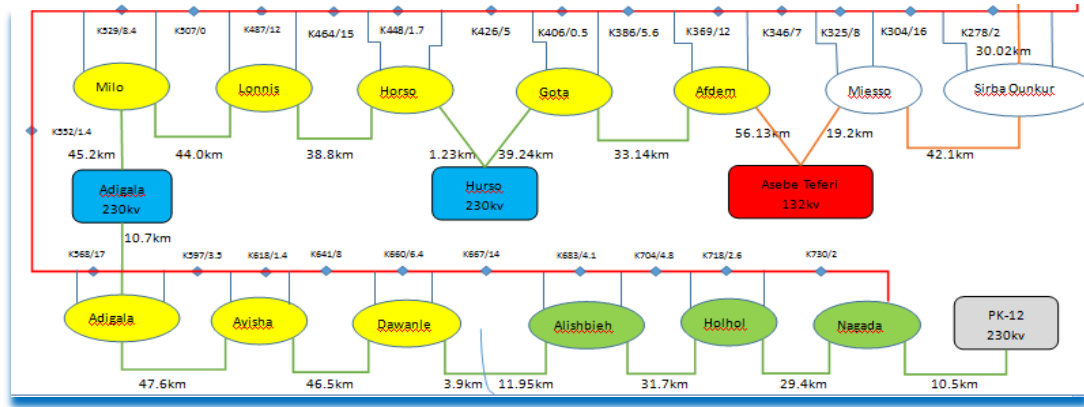


Figure 3.21 A Schematic diagram of a traction system connected to a power supply system.

The AC traction power supply modeling is developed in the block models using ETAP. The model consists of the power grid, transformers, transmission lines, and electric trains. The 230kV three phase AC transmission system is represented by the three phases. The overhead catenary lines and transformer impedances are obtained from the actual design parameter.

a.Normal operation mode

Based on the data presented in Figure 3.22 and Table 3.26, under normal operational conditions, none of the traction substations are experiencing overload. Additionally, the bus voltage readings range between 232.6kV-237.5kV, which falls within the acceptable range set by the IEEE standard, with an upper limit of +5% and a lower limit of -5%. This indicates that the traction substations are operating efficiently and safely within the established parameters.

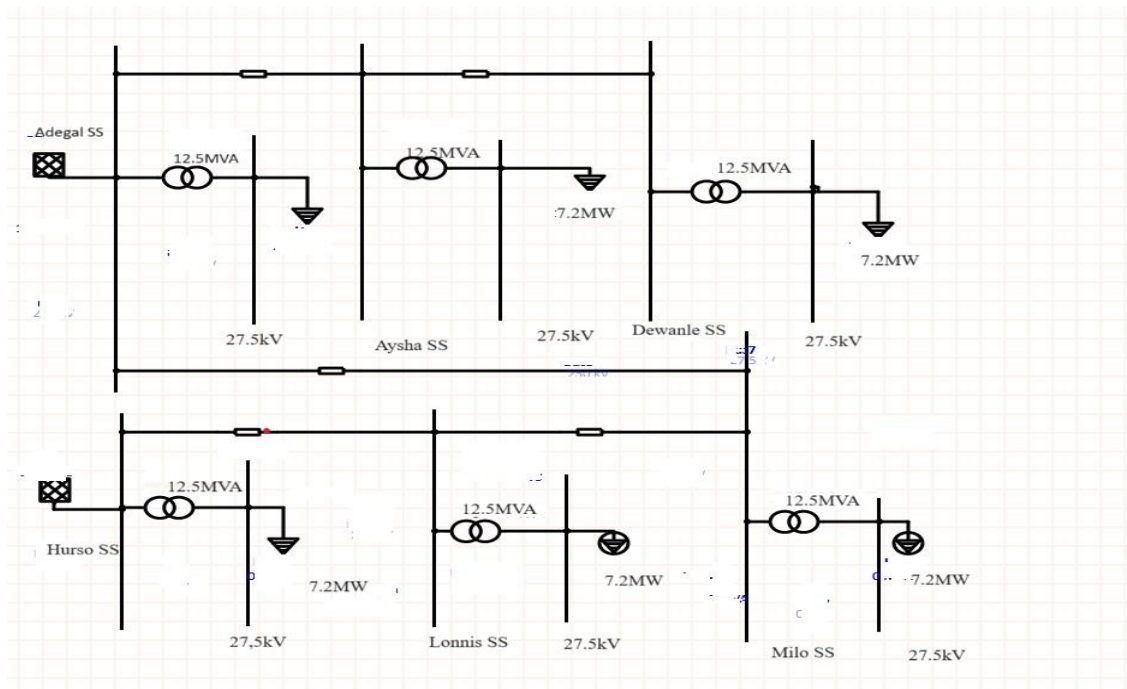


Figure 3.22 Schematic diagram of power flow analysis in normal operation mode

Table 3.27 load flow analysis result

Bus Id	Nominal Voltage(kV)	Bus voltage(kV)
Lonnis TS	230	232.6
Milo TS	230	234.6
Adegala TS	230	237.5
Aysha TS	230	237.2
Dewanle TS	230	235.3

b. Contingency analysis

Contingency analysis stands as a pivotal methodology within the realm of power system engineering, aimed at ensuring the resilience and reliability of electricity networks. This analytical procedure assesses the capability of a power system to withstand unexpected failures, such as the outage of a transmission line or generator, thereby evaluating the network's operational security and feasibility under various scenarios. By simulating different fault conditions, contingency analysis helps in identifying potential vulnerabilities within the system, enabling operators to implement corrective measures proactively. It plays a crucial role in the planning and design phases of power systems, ensuring that they can maintain stable and continuous operation despite unforeseen disturbances. Thus, contingency analysis is instrumental in safeguarding against widespread power outages and in enhancing the overall efficiency and safety of electrical power distribution networks.

N-1 fault of Hurso line.

Contingency analysis is a critical tool used in the power system to assess the stability and reliability of the electrical grid under various fault conditions. The results, as depicted in Table 3.28, demonstrate the impact of a fault occurring on the Hurso line, which precipitates a notable challenge in the grid's operation. Specifically, this fault leads to Afedem, Gota, Hurso, and Lonnis traction substations experiencing loads that surpass the recommended limits set by IEEE standards, indicating a scenario of overloading. Such overloading can potentially lead to equipment failure, reduced system efficiency, and an increased risk of blackout conditions, underscoring the importance of conducting these analyses.

Table 3.28. Hurso line fault result

Bus Id	Nominal voltage(kV)	Condition	Post contingency (%)
Hurso TS	230	Over voltage	106.4%
Milo TS	230	Over voltage	103.6%
Lonnis TS	230	Over voltage	105.8%
Hurso TS	230	Over voltage	104.7%
Adegala TS	230	Over voltage	106.8%
Aysha TS	230	Over voltage	107.2%
Dewanle TS	230	Over voltage	107.1%

N-1 fault of Adegala line.

The results, as depicted in Table 3.29, demonstrate the impact of a fault occurring on the Adegala line, which precipitates a notable challenge in the grid's operation. Specifically, this fault leads to Afedem, Gota, Hurso,Lonnis,Adegala, Aysha and Dewanle traction substations experiencing loads that surpass the recommended limits set by IEEE standards, indicating a scenario of overloading.

Table 3.29. Adegala line fault result

Bus Id	Nominal voltage(kV)	Condition	Post contingency (%)
Hurso TS	230	Over voltage	107.4%
Milo TS	230	Over voltage	106.6%
Lonnis TS	230	Over voltage	105.8%

Hurso TS	230	Over voltage	107.7%
Adegala TS	230	Over voltage	106.2%
Aysha TS	230	Over voltage	107.8%
Dewanle TS	230	Over voltage	107.9%

c. Negative-sequence analysis

Table 3.30 illustrates the negative sequence current entering the power supply, posing a risk to electrical equipment. According to IEEE 1159-2009, a VUF percentage exceeding 2% is not permissible. The voltage imbalance at the 230kV sides of the Hurso and Adegala substations fails to meet the criteria outlined in the standard, with negative sequence components exceeding 2%.

Table 3.30 Negative-sequence analysis

Node	Bus voltage	Voltage unbalanced maximum value (%)
Adegala Traction Substation 230kV side	230kV	5.4
Aysha Traction substation 230kV side	230kV	5.6
Dewanle Traction Substation 230kV	230kV	3.80
Milo Traction Substation 230kV side	230kV	4.9
Lonnis Traction Substation 230kV side	230kV	5.2

c. Short circuit current analysis

Short-circuit analysis helps us understand the power equipment ratings and protective devices needed to keep our electrical networks safe. By using this analysis, we can also check the voltage levels at critical points in our system, like the buses near a potential issue. The latest IEC and ANSI/IEEE standards, such as IEC 60909 and the C37 series, provide guidelines on how to calculate fault duties. The results, as depicted in Table 3.31.

Table 3.31. Short circuit analysis result

Name of Substation	Bus Voltage(kV)	Three phase short circuit(kA)
Adegala TS	230	3.73
Aysha SS	230	2.3
Dewanle TS	230	3.8
Lonnis	230	4.2
Milo TS	230	5.4

d. Harmonic analysis

To determine once the power source trainloads' induced sine waves resulted in insufficient amplitude that the level of shared attaching (PCC), periodic present and voltage studies were performed. The area that has a normal connection linked to the electricity plant serves as the evaluation place for harmonies computations.

i.Total voltage and current harmonic distortion

Voltage and current harmonics are a significant consideration in power systems, referring to the distortion in the voltage and current waveforms from their ideal sinusoidal shape due to non-linear loads. According to the simulation results presented, while the harmonic voltage distortion at the point of common coupling stays within the acceptable range set by IEEE 519-1992 at 1%, the current distortion exceeds the limits outlined by IEC 61000-3-4, indicating a potential issue with power quality. These simulations, conducted using ETAP software at both 230 kV and 27.5 kV levels, help in identifying the presence and magnitude of individual harmonics. The accurate identification of these harmonics is crucial for taking corrective measures to mitigate their impact on the power system. Understanding and managing these harmonics are essential for maintaining the reliability and efficiency of electrical power networks, as excessive harmonics can lead to equipment malfunction, overheating, and other operational issues. The simulation results in table 3.32 indicate that the harmonic voltage distortion at the point of common coupling exceeds the limits set by IEEE519-1992 limits, and the total current distortion exceeds the limit set by IEC 610003-4. The simulations, conducted using ETAP at 230kV levels, revealed the presence of individual voltage and current harmonics.

Table 3.32. Total voltage and current distortion simulation result

Traction Substation	Total Voltage Distortion (%)	Total Current Distortion (%)
Adegal TS	4.21	27.94
Aysha TS	3.6	54.4
Dewanle TS	3.2	41.7
Milo TS	4.1	35.6
Lonnis TS	2.61	38.5

ii. Individual voltage harmonics

Harmonic analysis, as illustrated in the simulation results of Figure 3.23, reveals that the 5th and 7th individual voltage harmonic orders exceed the 1% threshold as mandated by IEEE standards 519-1992, pointing to significant electrical disturbances. Specifically, the 5th order voltage harmonic is identified as a negative sequence harmonic, which poses a unique challenge in induction motor applications, such as locomotives. This type of harmonic generates a counterproductive torque that can reverse the motor's direction or significantly reduce its rotational speed, impairing efficiency, and operational reliability. On the other hand, the 7th order voltage harmonics belong to the positive sequence category, which, while less mechanically detrimental, leads to thermal stress on electrical infrastructure. This stress manifests through the overheating of conductors, power lines, and transformers due to the cumulative effect of waveform distortions, potentially resulting in system failures or reduced lifespan of the equipment.

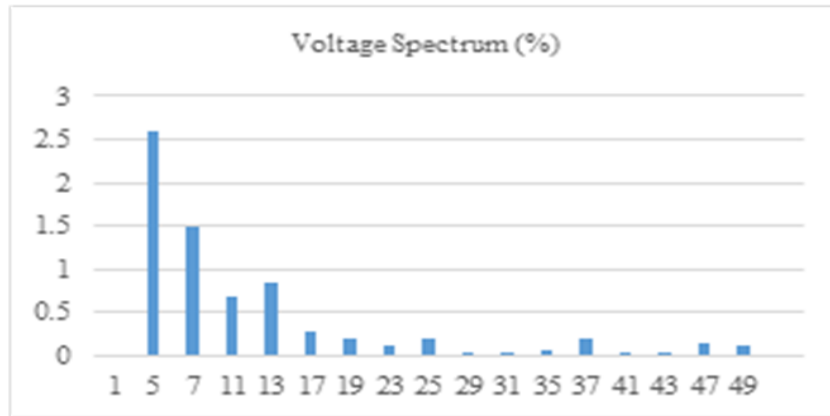


Figure. 3.23 Voltage harmonic at 230kV side of Adegala substation

Voltage and current harmonics are a significant concern in electrical power systems, as they can distort the sinusoidal waveform of electricity, leading to inefficient energy distribution and potential damage to electrical equipment. According to simulation results depicted in Figure 3.24, there is a noticeable deviation from standard electrical performance, especially in terms of individual voltage harmonics. Specifically, the 5th and 7th harmonic orders have been found to exceed the 1% threshold specified by the IEEE standards 519-1992, indicating a problematic level of harmonic distortion. This level of distortion can compromise the reliability of power systems and reduce the lifespan of electronic devices due to the additional stress placed on their components.

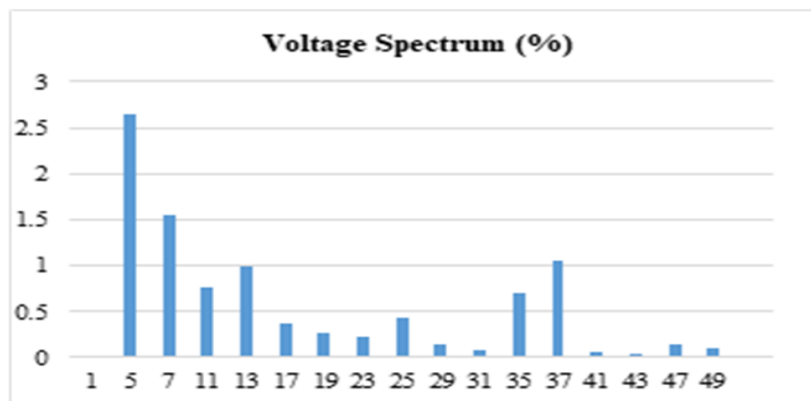


Figure 3.24 Voltage harmonic at 230kV side of Aysha Traction

According to the simulation results depicted in Figure 3.25, the 5th and 7th individual voltage harmonic orders exceed the 1% limit specified by IEEE standards 519-1992, indicating a potentially harmful level of harmonic distortion. This excessive distortion can lead to a variety of issues within electrical systems, including overheating of components, malfunctioning of sensitive equipment, and increased losses in transmission lines. Addressing these harmonic levels is crucial for maintaining system efficiency, reliability, and compliance with industry

standards, necessitating the use of harmonic filters or other mitigation techniques to reduce these harmonics to acceptable levels.

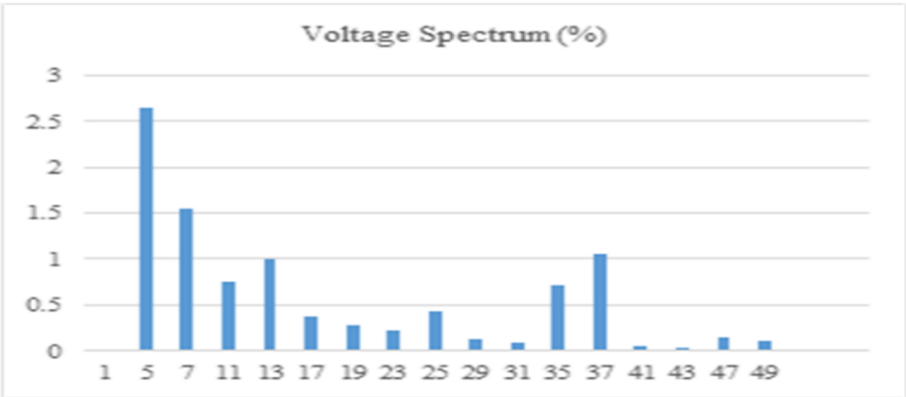


Figure .3.25 Voltage harmonic at 230kVside of Dewanle Substation

Based on the findings shown in the simulation results in Figure 3.26 below, it has been observed that the 5th, 23rd, and 47th negative sequence harmonics orders, as well as the 25th positive sequence order voltage harmonics, exceed the 1% limit set by the IEEE standards 519-1992.

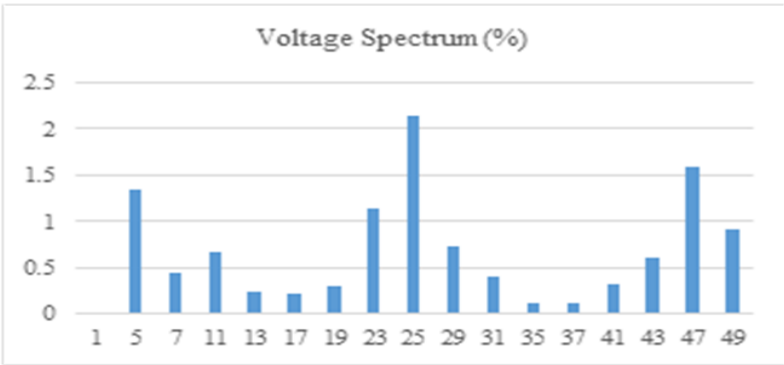


Figure 3.26 Voltage harmonic at 230kVside of Hurso Substation

Based on the simulation results shown in Figure 3.27 below, it is evident that the 5th and 11th order voltage harmonics exceed the 1% threshold set by the IEEE standards 519-1992. This indicates a deviation from the acceptable limits for harmonics levels in the electrical system. It is important to address this issue to ensure compliance with the specified standards and maintain the reliability of the power supply. Further analysis and corrective measures may be necessary to mitigate the impact of these high voltage harmonics.

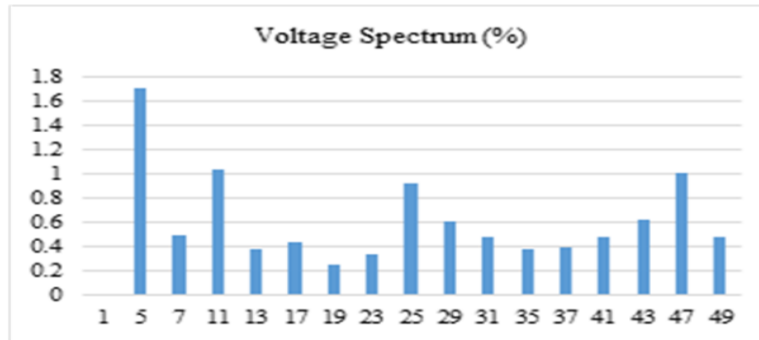


Figure. 3.27 Voltage harmonic at 230kV side of Ionnis Substation

The simulation results in Figure 3.28 indicate that the 5th, 11th, and 25th voltage harmonics exceed the 1% limit specified by IEEE standards 519-1992. This finding highlights the importance of addressing harmonic distortion in electrical systems to ensure compliance with industry regulations and standards. Addressing these harmonics is crucial for maintaining the quality and efficiency of power distribution systems.

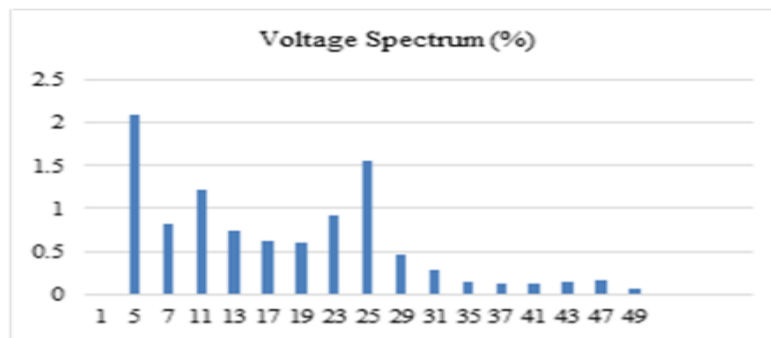


Figure 3.28 Voltage harmonic at 230kV side of Milo Substation

3.5. Power quality Measurement

Electric trains pulling power from a single phase create large, unbalanced currents in the power grid. This imbalance is a major challenge for railway systems, causing issues with power quality. Researchers studied the impact of these imbalances on the Ethio-Djibouti railway route, focusing on the 132/230kV traction substations. The study aimed to analyze the power quality and identify harmonic components (distortions) in both voltage and current that exceed recommended limits set by the IEEE 519-1992 standard. Measurements were taken at the 132 kV/25 kV level to determine the severity of these harmonic distortions. Additionally, simulations were conducted to assess the impact of locomotive-generated harmonics on the upstream 132/230kV grid. The results showed that both measured and simulated values for voltage and current harmonic distortion, at both 132/230kV and 25 kV levels, exceeded the limits set by the IEEE standard.

3.5.1. Voltage Measurement Awash Traction substation

In Figure 3.29, all the voltage values that were measured meet the strict standards set by the IEEE. These values satisfy both the requirement of being within the highest permissible limit of +5% and below the lowest limit of -5%. The data collected demonstrates that the voltage levels are well within the acceptable range outlined by the IEEE guidelines.

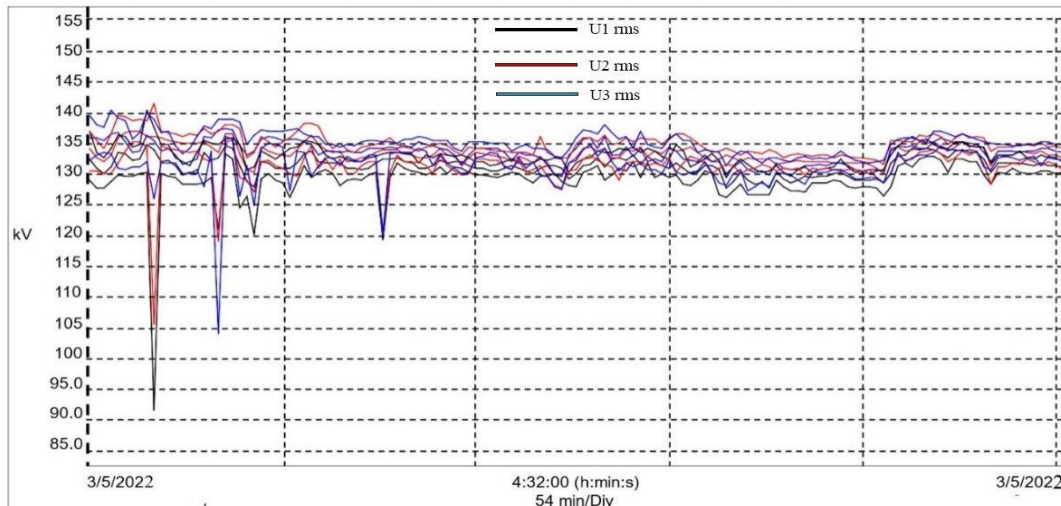


Figure 3.29 Voltage and Current harmonics Measurement Awash Traction substation

Power quality analyzer was attached to the 132 kV transformer's primary side through CT and VT metering. In the following part, the findings of voltage and current harmonic measurements at the transformer's 132 kV main side and 25 kV secondary side are provided. For about 24 hours, measurements were made at 132000:100VTs and 100CTs in the Awash traction substation to ascertain the level of individual harmonic voltage and current present as well as the proportion of total distortion in current and voltage. The 3rd order voltage harmonics in Figure 3.30 have a maximum observed individual voltage harmonic distortion of 12%, above the IEEE 519-1992 standard's 3%.

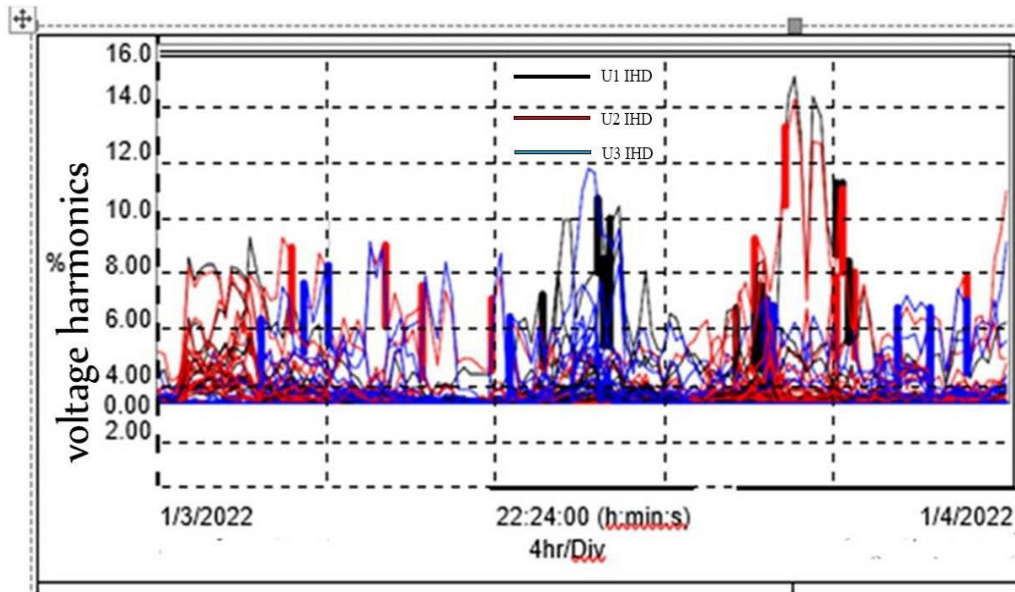


Figure 3.30 3rd Voltage harmonics at 25kV side of railway substation

The voltage harmonic distortion of the 5th order in Figure 3.31 has been measured at a maximum of 10%, exceeding the 3% limit set by the IEEE 519-1992 standard. This means that the level of distortion is higher than what is recommended by the standard. Measurements show that the distortion is beyond the acceptable threshold as per IEEE 519-1992 standard.

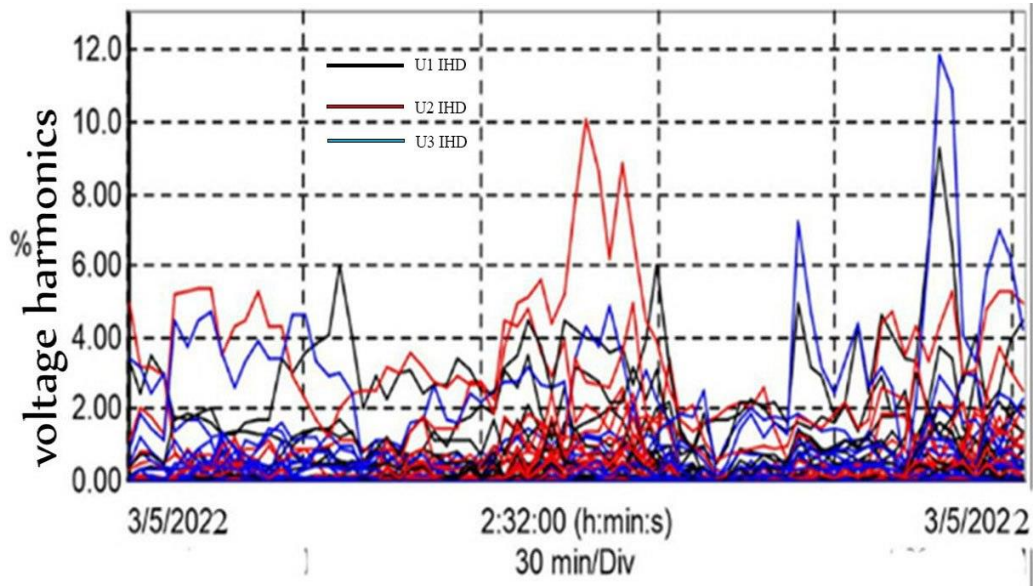


Figure 3.31 5th Voltage harmonics at 25kV side of railway substation

In Figure 3.32, the maximum measured individual voltage harmonic distortion of the 7th order harmonics is reported to be at 5%, exceeding the recommended limit of 3% set by the IEEE 519-1992 standard.

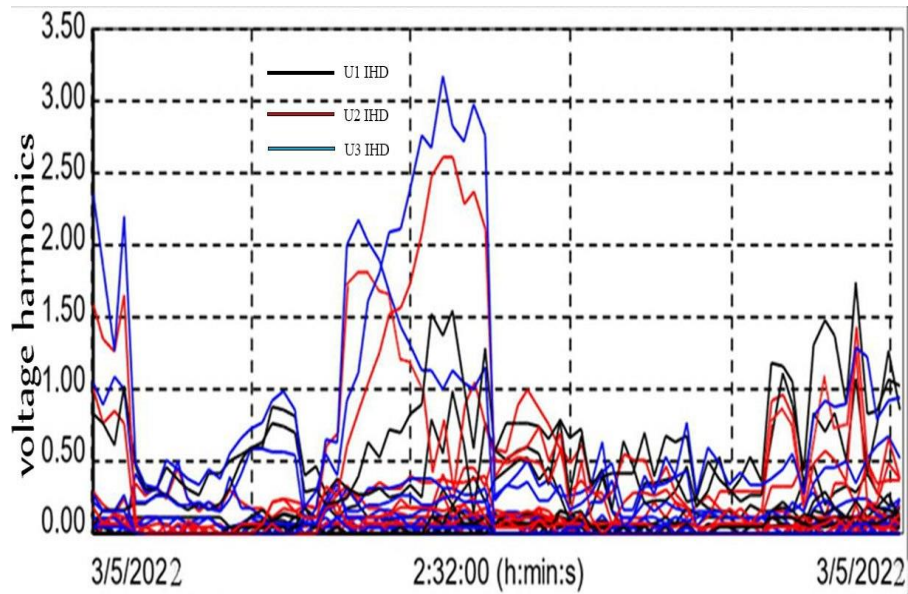


Figure 3.32 7th Voltage harmonics at 25kV side of railway substation

In Figure 3.33, the maximum measured individual voltage harmonic distortion of the 13th order voltage harmonics is noted to be 6%, exceeding the set limit of 3% as per the IEEE 519-1992 standard. This indicates a deviation from the acceptable harmonic levels and may require corrective measures to bring the harmonics within the specified limits.

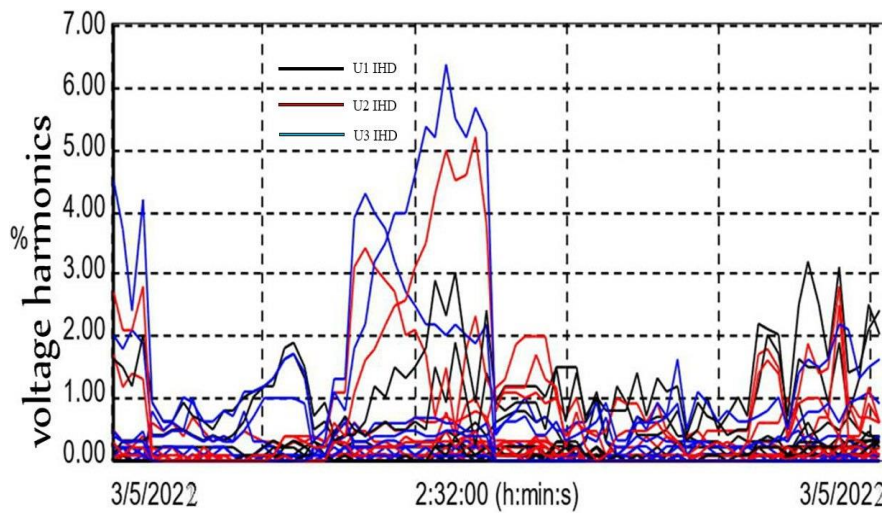


Figure 3.33 13th Voltage harmonics at 25kV side of railway substation

Based on the information provided, it is evident that all the measured individual voltage harmonics levels depicted in Figure 3.34 are adhering to the recommended standard of being below the 3% threshold set by IEEE 519-1992. This signifies a commendable adherence to

industry standards and regulations, ensuring optimal performance and efficiency in the electrical system.

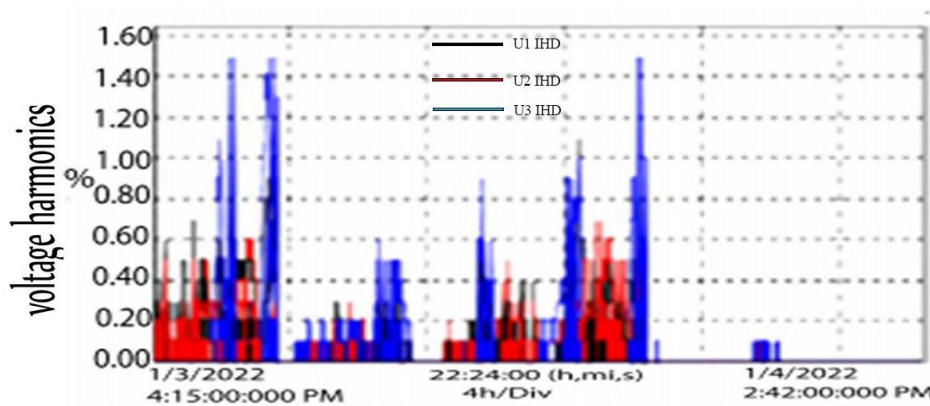


Figure 3.34 15th Voltage harmonics at 25kV side

The measured individual voltage harmonics levels in Figure 3.35 is less than the 3% level recommended by IEEE 519-1992.

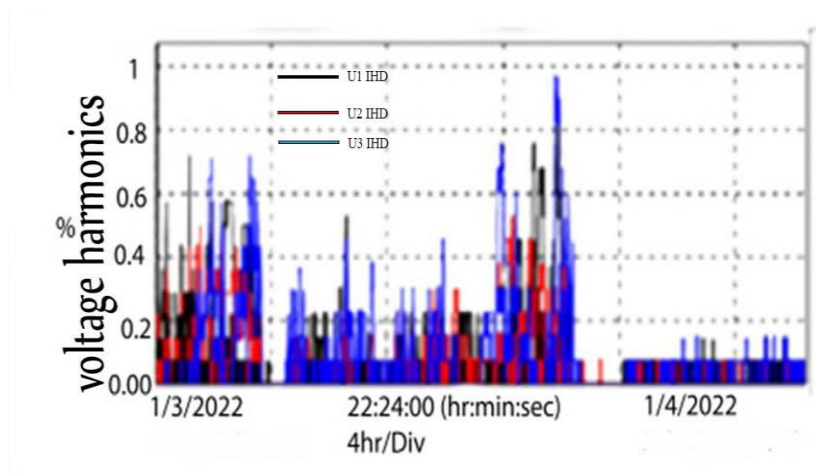


Figure.3.35 23rd Voltage harmonics at 25kV side of railway substation

The result about investigation along with testing from harmonics in Figure 3.36 shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

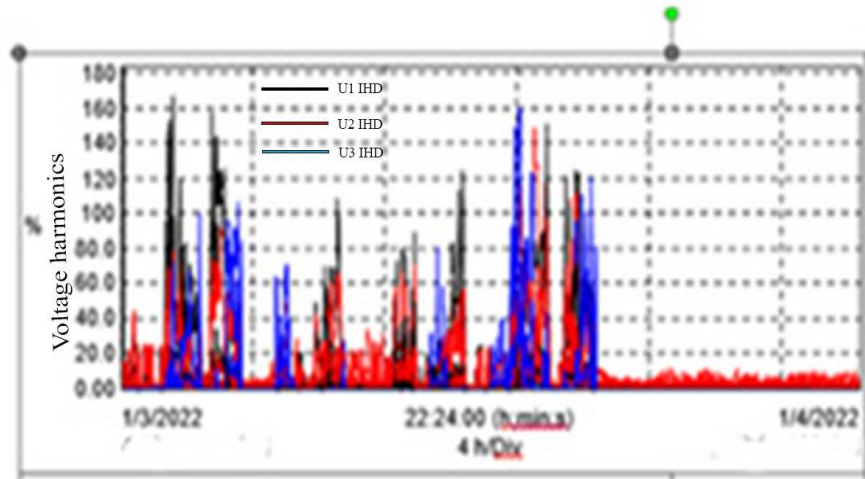


Figure 3.36 3rd Current harmonics at 25kV side of railway substation

The result of the harmonic measurements and analysis for 25kV is as in Figure 3.37 below shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

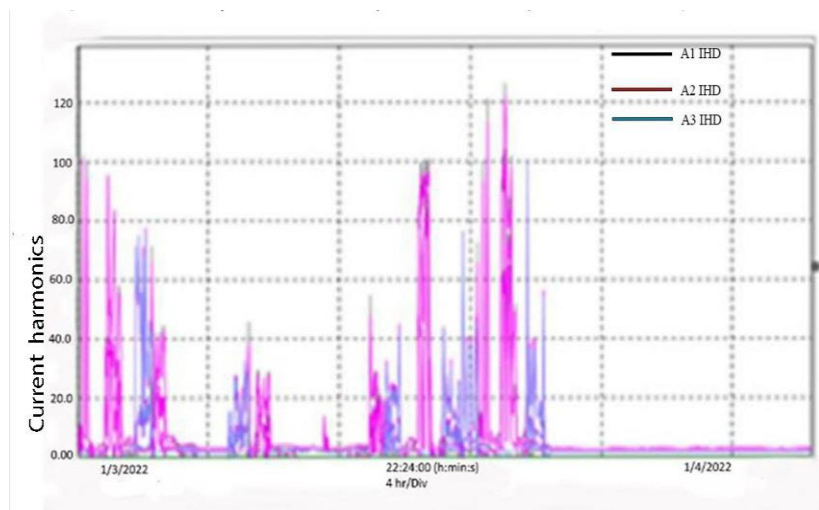


Figure 3.37 7th Current harmonics at 25kV side of railway substation

3.5.2 Voltage and Current Unbalance measurement

Measurements of both the current and the voltage imbalance have been conducted using the 132kV side. The measurements were performed for approximately 24hrs each lasting 2 minutes. The recommended limit for voltage is 2% according to IEEE 1159-2009 standard. The measured voltage unbalance is well within the acceptable range where the current unbalance is above the limit recommended by IEEE standard as shown in Figure 3.38.

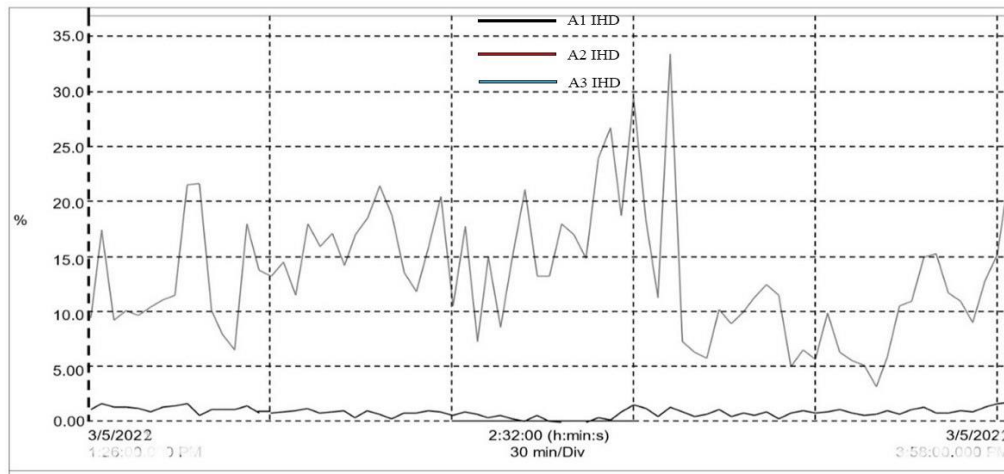


Figure 3.38 Voltage and Current Unbalance measurement

3.5.3 Voltage Measurement Adegala Traction substation

For about 24 hours, measurements were made at 230000:100VTs and 100CTs in the Adegala traction substation to ascertain the level of individual harmonic voltage and current present as well as the proportion of total distortion in current and voltage. In Figure 3.39, all the voltage values that were measured meet the strict standards set by the IEEE. These values satisfy both the requirement of being within the highest permissible limit of +5% and below the lowest limit of -5%. The data collected demonstrates that the voltage levels are well within the acceptable range outlined by the IEEE guidelines.

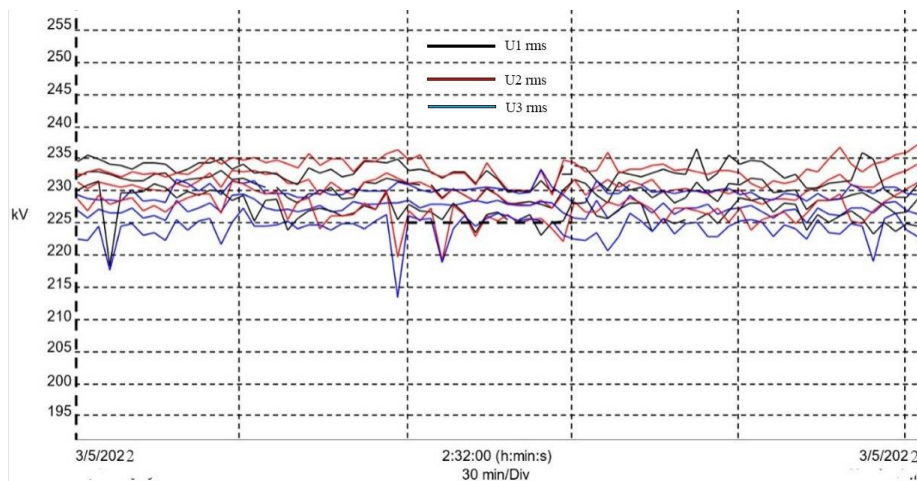


Figure 3.39 Voltage measurement

3.5.4. Voltage and current harmonic measurement Adegala Traction substation

All the measured individual voltage harmonics levels in Figure 3.40 are less than the 3% level recommended by IEEE 519-1992.

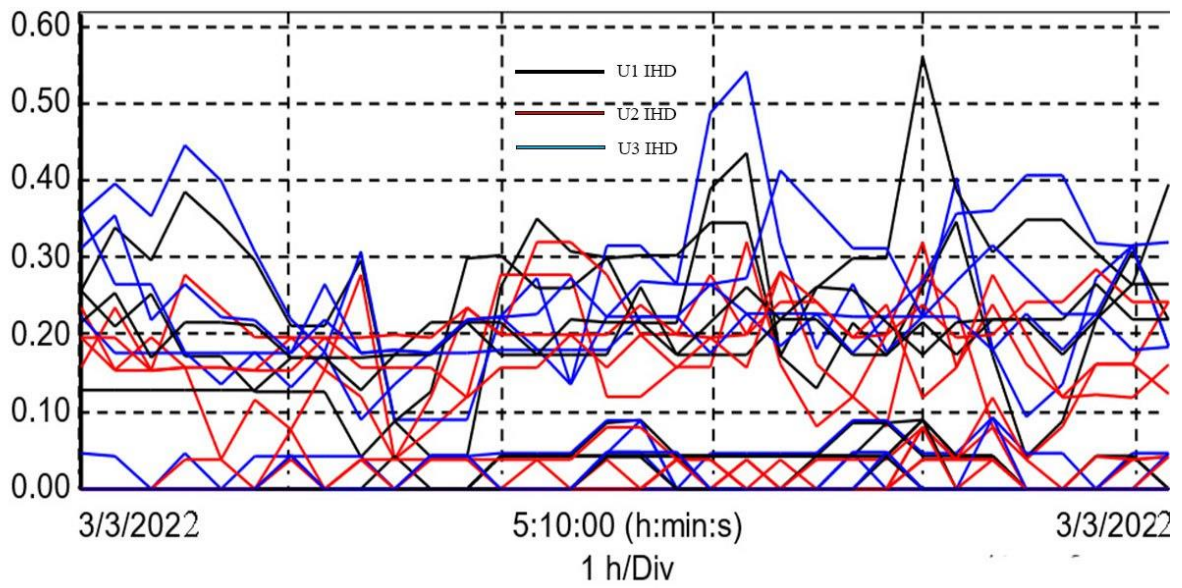


Figure 3.40 3rd Voltage harmonics at 25kV side of railway substation

All the measured individual voltage harmonics levels in Figure 3.41 are less than the 3% level recommended by IEEE 519-1992.

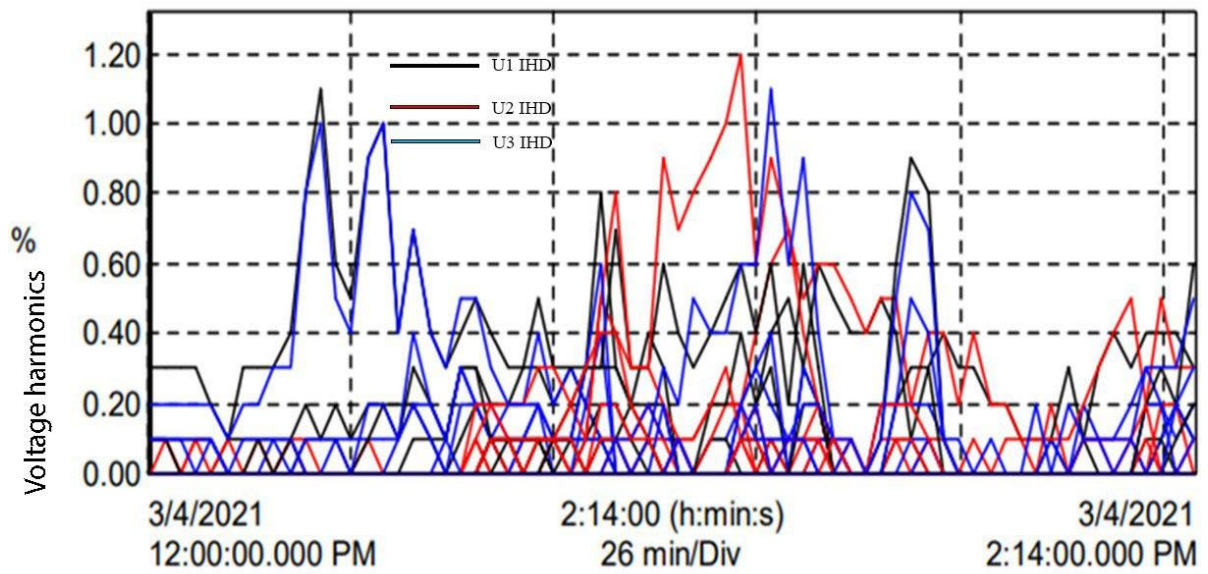


Figure 3. 41 5th Voltage harmonics at 25kV side of railway substation

All the measured individual voltage harmonics levels in Figure 3.42 are less than the 3% level recommended by IEEE 519-1992.

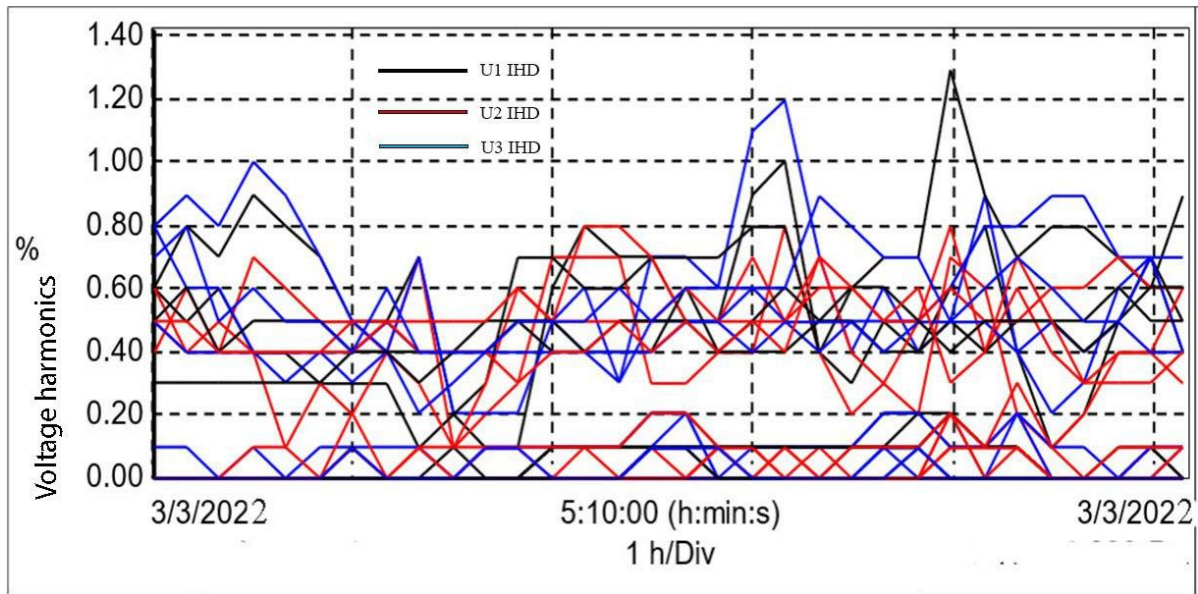


Figure 3. 42 15th Voltage harmonics at 25kV side of railway substation

All the measured individual voltage harmonics levels in Figure 3.43 are less than the 3% level recommended by IEEE 519-1992.

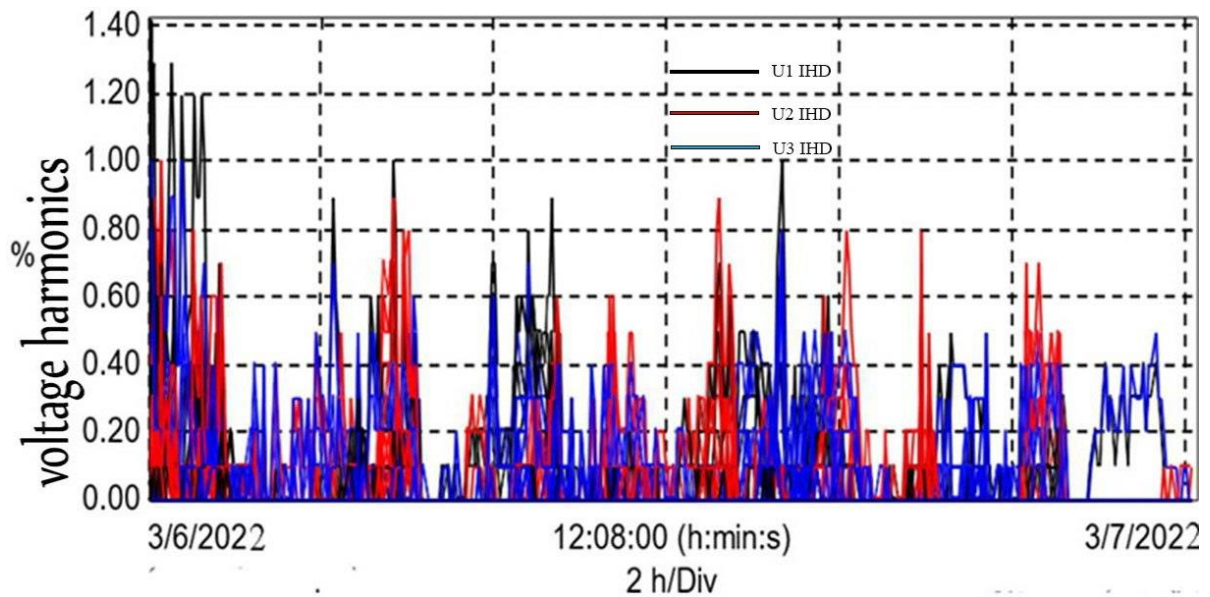


Figure 3.43 3rd Voltage harmonics at 25kV side of railway substation

The result of the harmonic measurements and analysis for 25kV are as in Figure 3.44 Figure 3.45, and Figure 3.46 shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

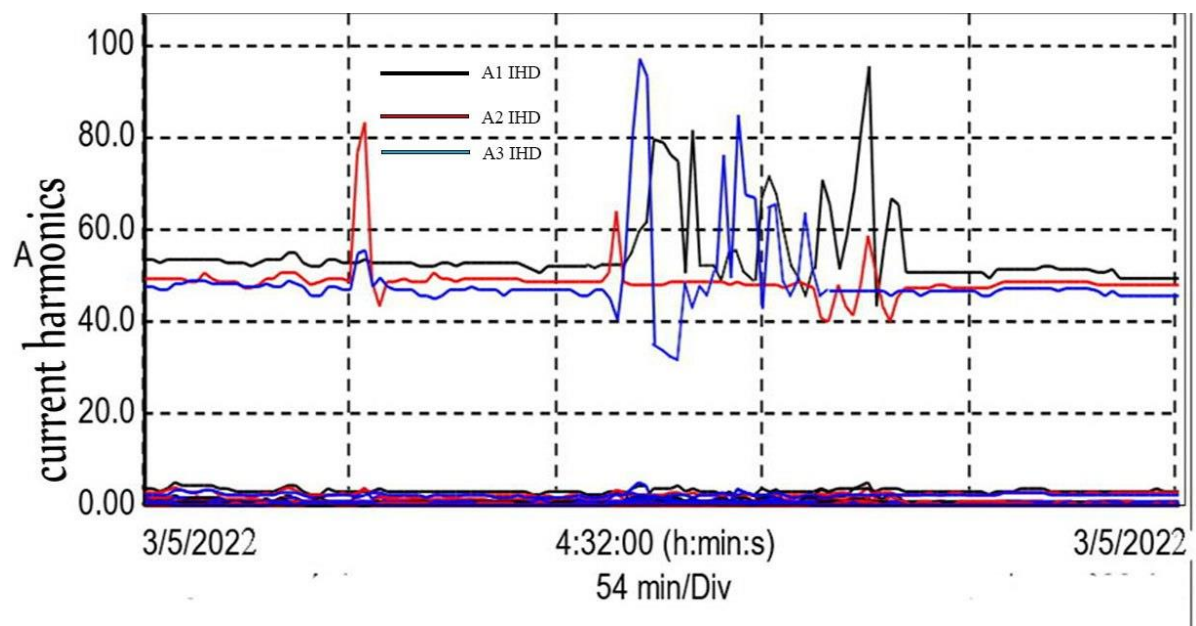


Figure 3.44 3rd Current harmonics at 25kV side of railway substation

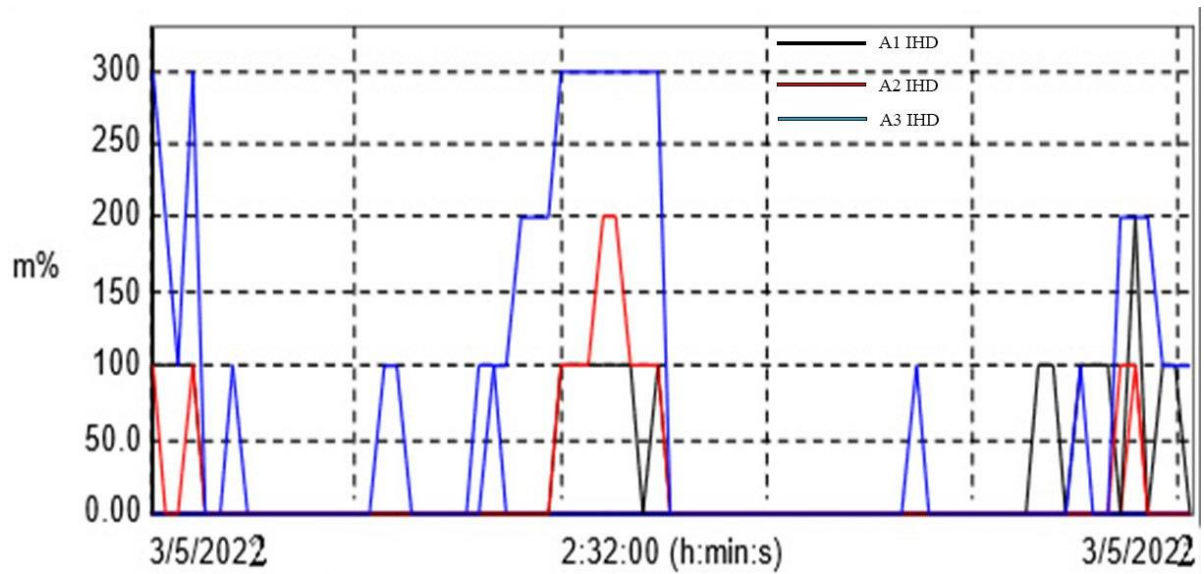


Figure 3.45 5th Current harmonics at 25kV side of railway substation

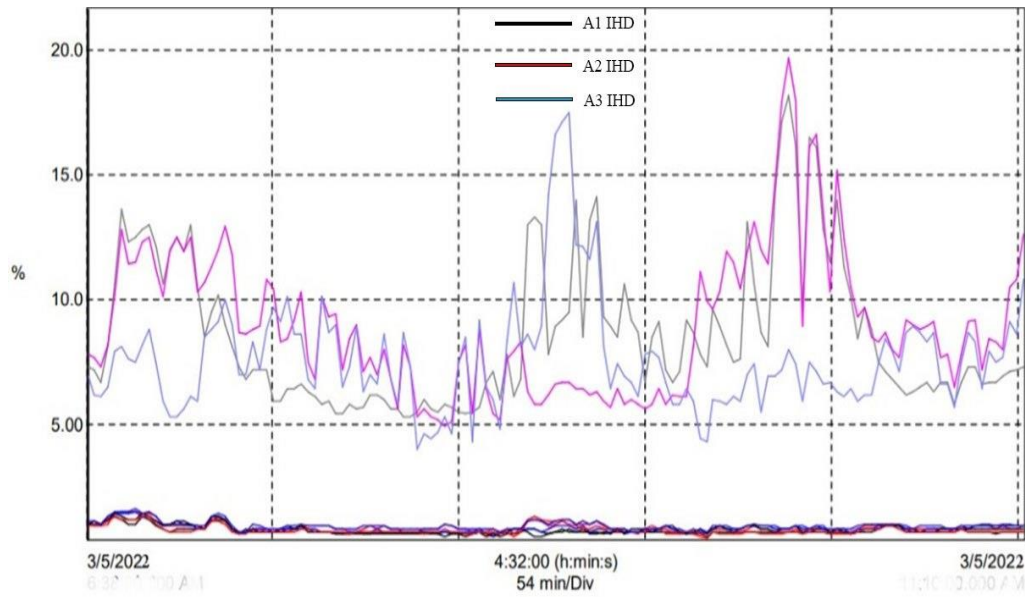


Figure 3.46 7th Current harmonics at 25kV side of railway substation

3.6 Power Quality Measurement of Hurso Traction substation

3.6.1 Voltage Measurement Hurso Traction substation

For about 24 hours, measurements were made at 230000:100VTs and 100CTs in the Hurso traction substation to ascertain the level of individual harmonic voltage and current present as well as the proportion of total distortion in current and voltage. As shown in Figure 3.47 all measured voltage values fulfil both the highest +5% and below -5% requirements of the IEEE.

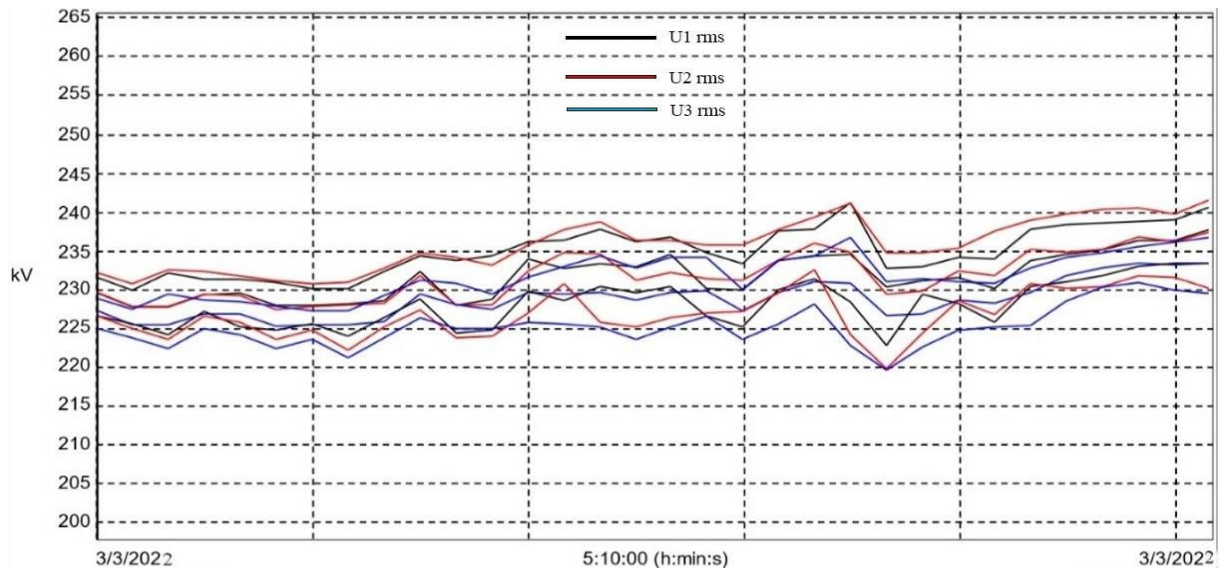


Figure 3.47 Voltage Measurement Hurso Traction substation

3.6.2 Voltage and Current Harmonics Hurso Traction substation

The maximum measured individual voltage harmonic distortion of the 3rd order voltage harmonics in Figure 3.48 is 5%, which is above the limit of 3% IEEE 519-1992 standard.

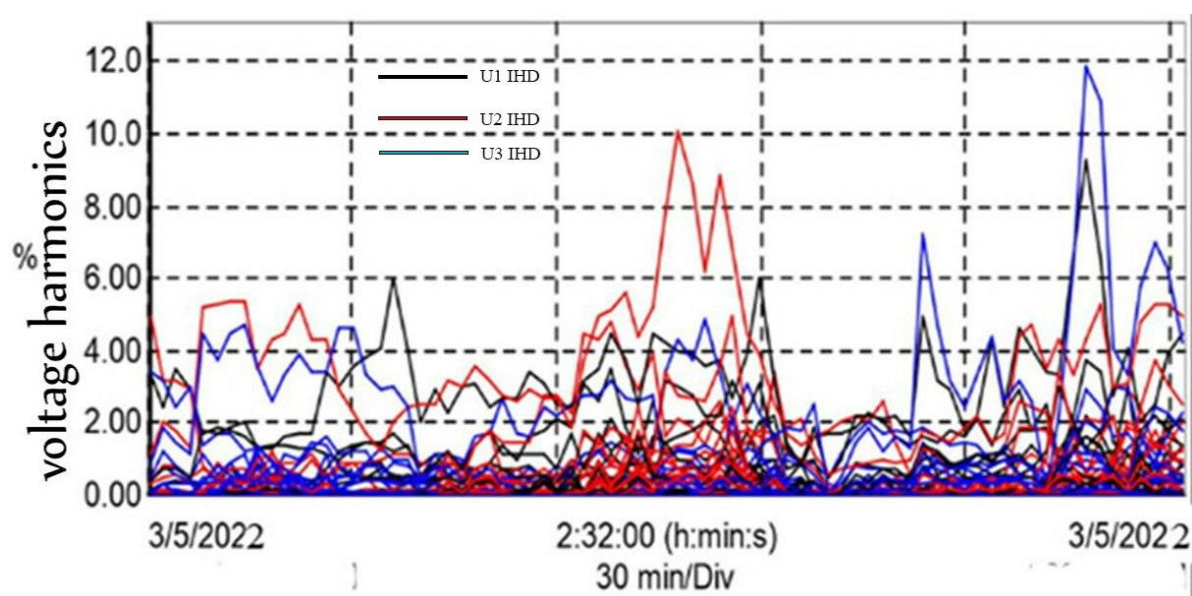


Figure 3.48 3rd Voltage harmonics at 25kV side of railway substation

The maximum measured individual voltage harmonic distortion of the 5th order voltage harmonics in Figure 3.49 is 5%, which is above the limit of 3% IEEE 519-1992 standard.

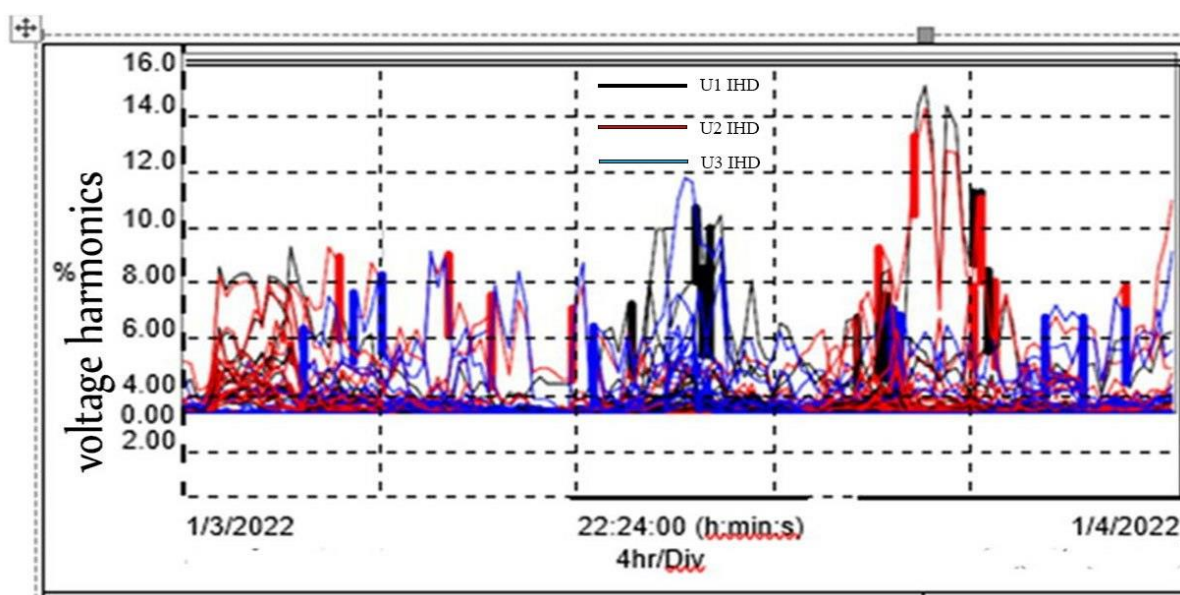


Figure 3.49 5th Voltage harmonics at 25kV side of railway substation

The result of the harmonic measurements and analysis for 25kV is as in Figure 3.50 and Figure 3.51 shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

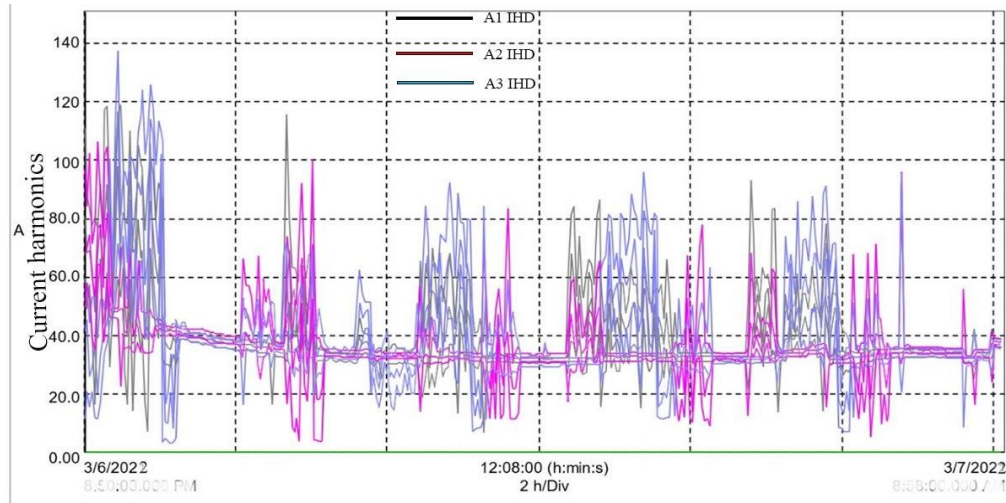


Figure 3.50 7th Current harmonics at 25kV side of railway substation

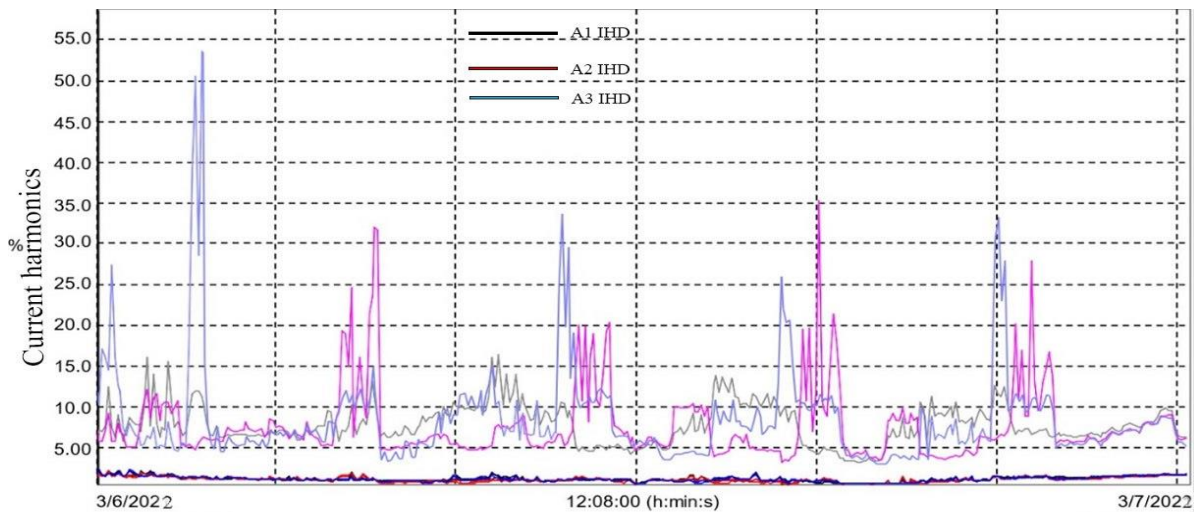


Figure 3.51 9th Current harmonics at 25kV side of railway substation

3.6.3 Voltage and Current Unbalance measurement

Measurements of both the current and the voltage imbalance have been conducted using the 132kV side. The measurements were performed for approximately 24hrs each lasting 2 minutes. The recommended limit for voltage is 2% according to IEEE 1159-2009 standard. The measured voltage unbalance is well within the acceptable range where the current unbalance is above the limit recommended by IEEE standard as shown in Figure 3.52.

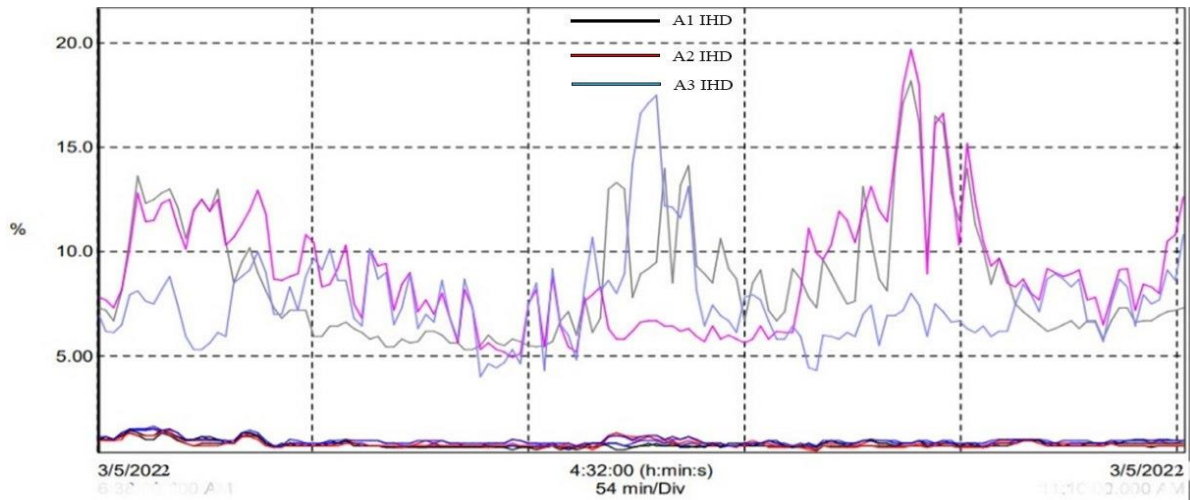


Figure 3.52 Voltage Unbalance

3.7 Power Quality Measurement of Aysha Traction substation

3.7.1 Voltage Measurement Aysha Traction substation

For about 24 hours, measurements were made at 230000:100VTs and 100CTs in the Hurso traction substation to ascertain the level of individual harmonic voltage and current present as well as the proportion of total distortion in current and voltage. As shown in Figure 3.53 all measured voltage values fulfil both the highest +5% and below -5% requirements of the IEEE.

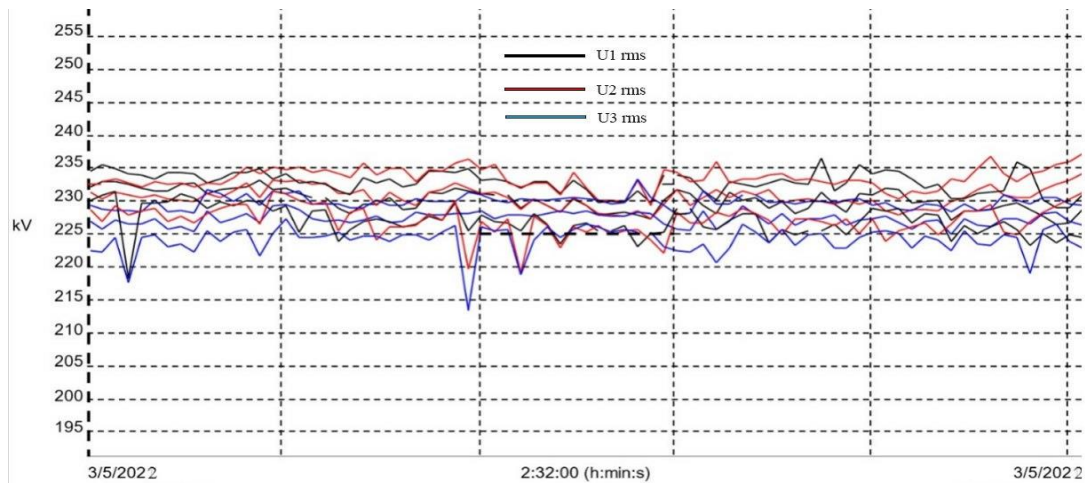


Figure 3.53 Voltage measurement

3.7.2 Voltage and Current Harmonics Hurso Traction substation

The maximum measured individual voltage harmonic distortion of the seventh order voltage harmonics in Figure 3.54 is 6%, which is above the limit of 3% IEEE 519-1992 standard.

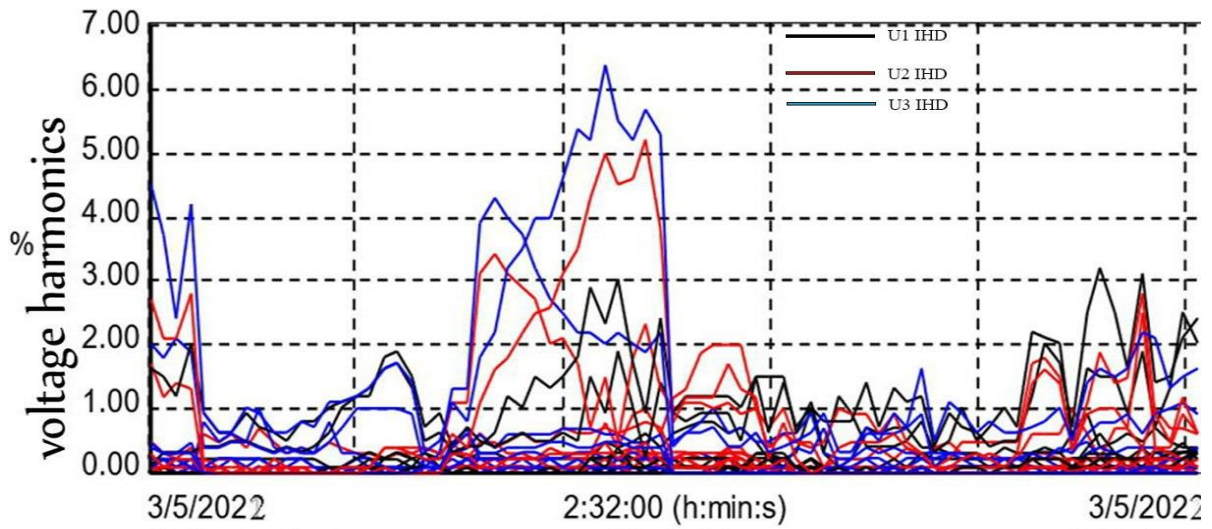


Figure 3.54 3rd Voltage harmonics at 25kV side of railway substation

All the measured individual voltage harmonics levels in Figure 3.55 are less than the 3% level recommended by IEEE 519-1992.

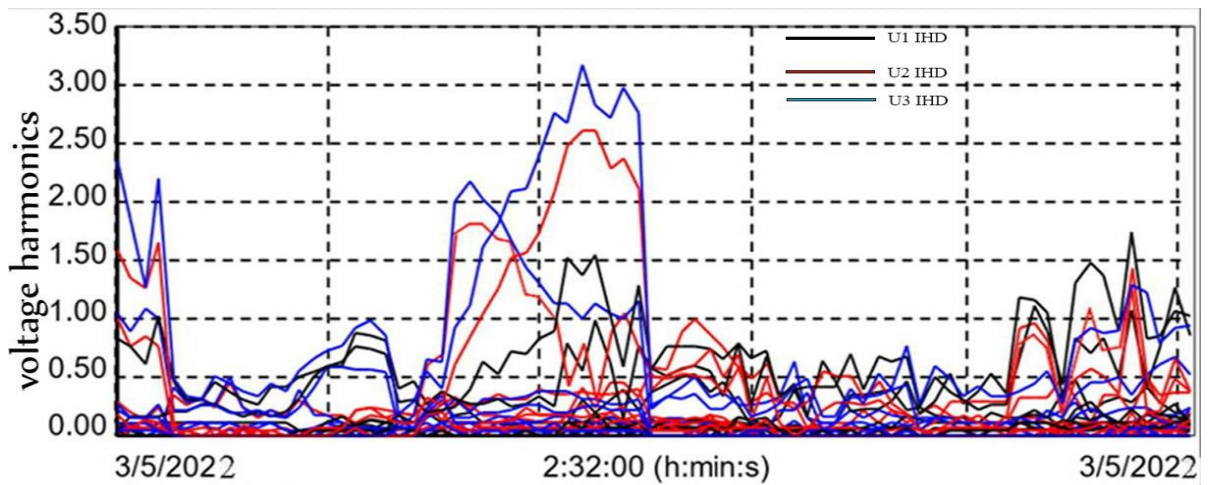


Figure 3.55 5th Voltage harmonics at 25kV side of railway substation

Current harmonics

The result of the current harmonic measurements and analysis for 25kV as shown as in Figure 3.56 that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

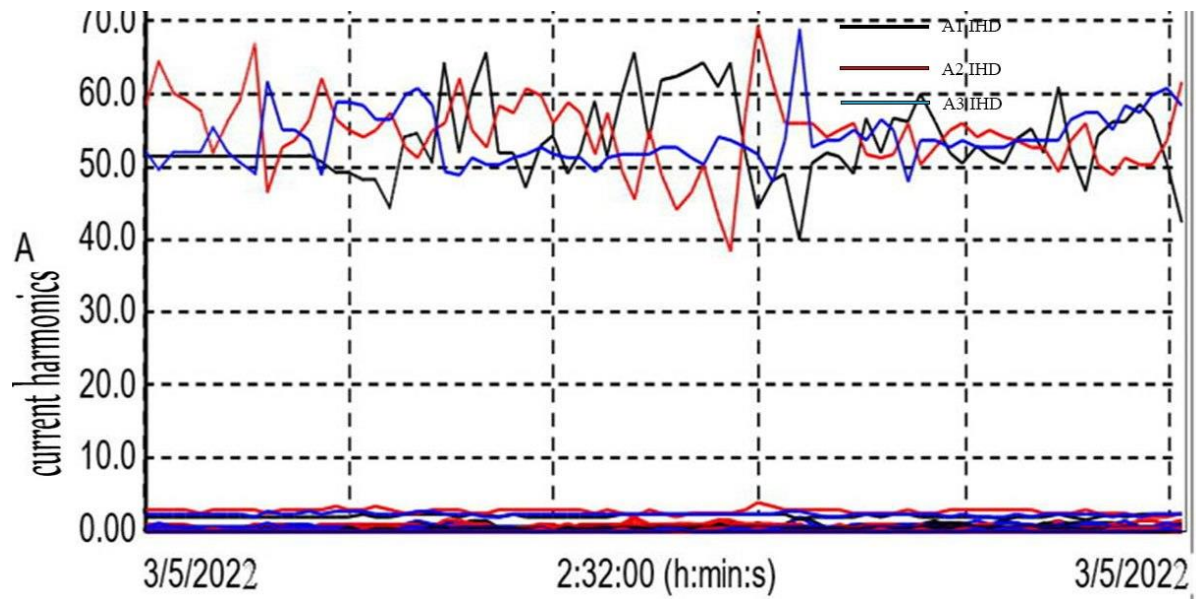
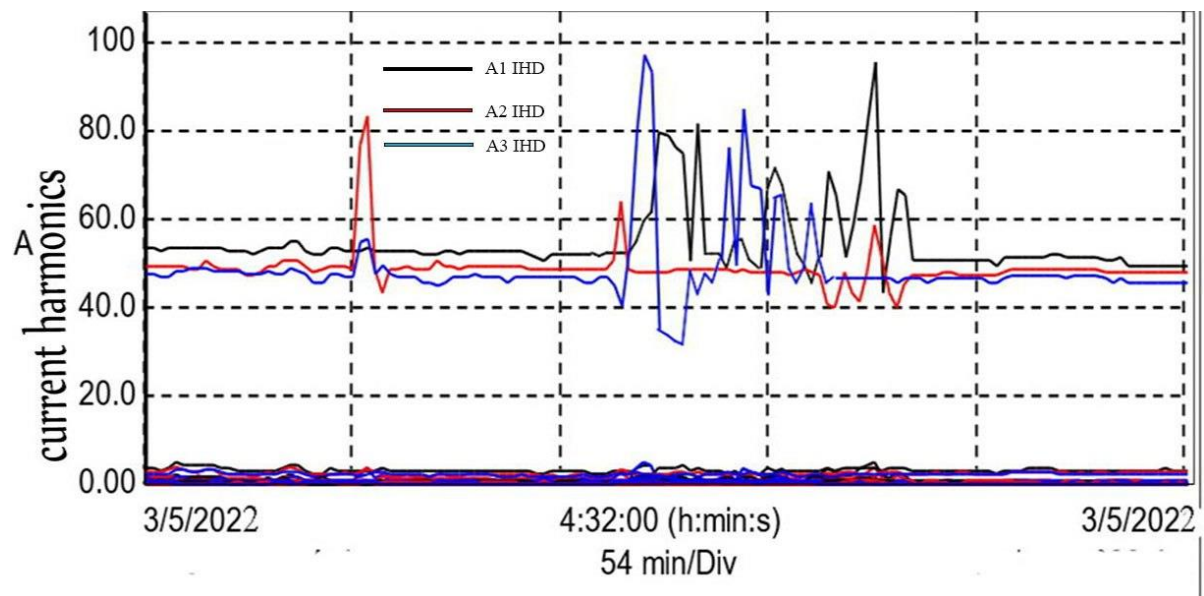


Figure 3.56 3rd Current harmonics at 25kV side

The result of the harmonic measurements and analysis for 25kV is as in Figure 3.57, and Figure 3.58 shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.



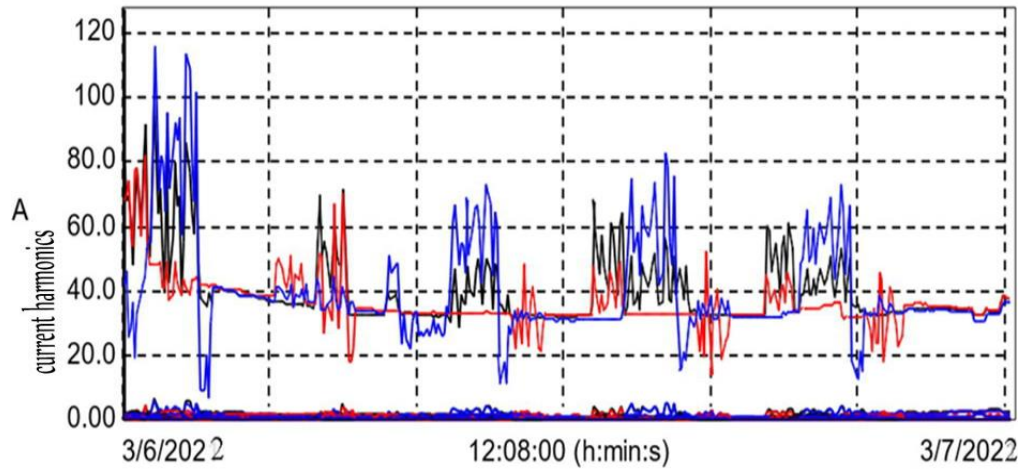


Figure 3.57 5th Current harmonics at 25kV side

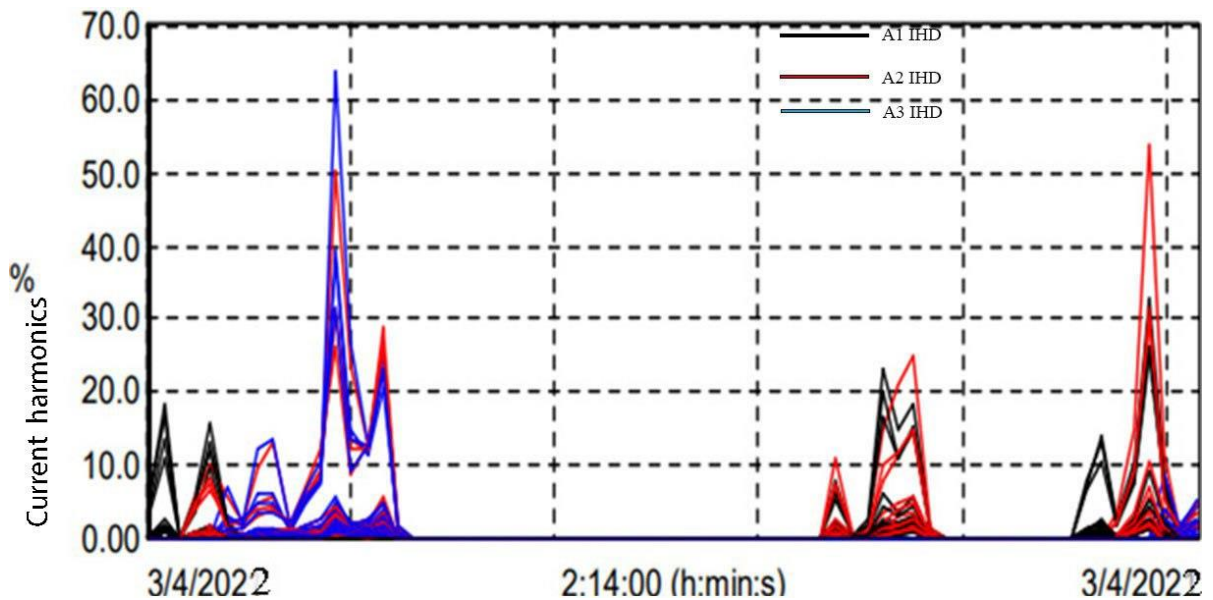


Figure 3.58 7th Current harmonics at 25kV side

3.7. 3 Voltage and Current Unbalance measurement

Measurements of both the current and the voltage imbalance have been conducted using the 132kV side. The measurements were performed for approximately 24hrs each lasting 2 minutes. The recommended limit for voltage is 2% according to IEEE 1159-2009 standard. The measured voltage unbalance is well within the acceptable range where the current unbalance is above the limit recommended by IEEE standard as shown in Figure 3.59.

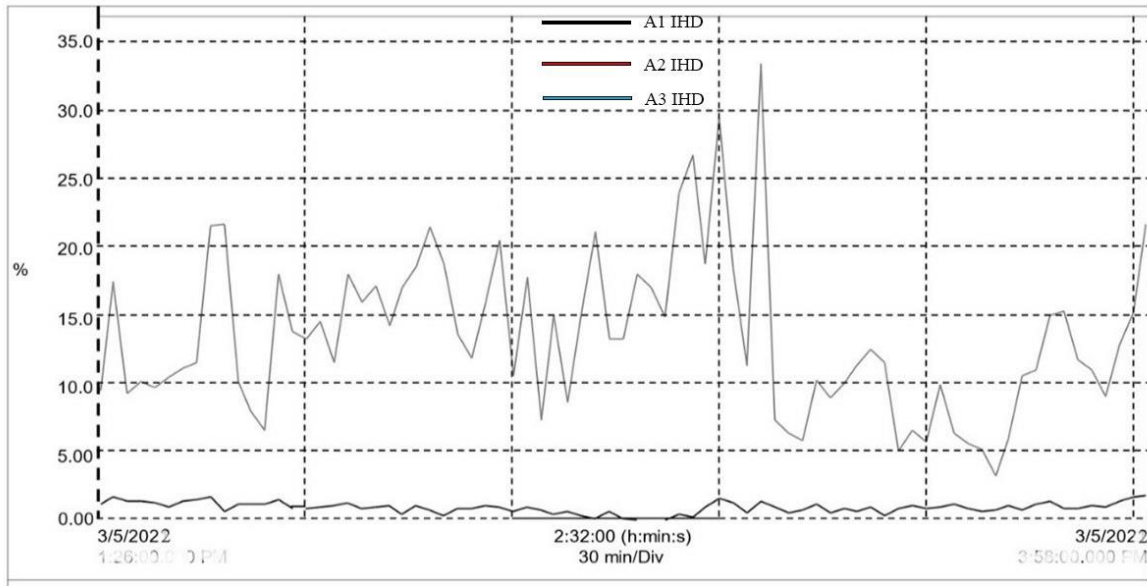


Figure 3.59 Voltage and Current unbalance Measurement

This research delves into the critical issue of power quality phenomena along the vital Ethiopia-Djibouti railway line. By closely examining the Awash and Methera 132kV traction substations, the study provides a comprehensive analysis of the power quality challenges faced within this important transportation infrastructure. Through meticulous measurements at both the 132kV and 25kV voltage levels, the researchers were able to gather detailed data on the harmonic currents, overall power distortion, and other key power quality parameters. The findings indicate that the levels of harmonic currents and voltage distortion exceed the limits set by the IEEE 519-1992 standard, signaling significant problems that must be addressed.

Furthermore, the simulation results specifically, the voltage unbalance on the 132kV side between the Awash and Methera substations is shown to be greater than 2%, which falls outside the acceptable range defined by the IEEE 1159-2009 standard. This unbalance can have serious implications for the reliable and efficient operation of the railway system, potentially leading to equipment malfunctions, reduced efficiency, and other detrimental effects. The comprehensive nature of this research, encompassing both field measurements and simulation modeling, provides a thorough understanding of the power quality challenges faced along the Ethiopia-Djibouti railway line. By delving into the technical details of harmonic distortion, voltage unbalance, and other power quality phenomena, the study offers valuable insights that can inform the development of targeted solutions to improve the reliability, efficiency, and sustainability of this critical transportation link between the two countries. The findings underscore the importance of proactive power quality management in

supporting the growth and development of essential infrastructure projects like the Ethiopia-Djibouti railway.

Harmonic currents and unbalanced voltages can have a detrimental impact on the various components of a power system, causing a wide range of serious problems. These distortions in the electrical waveforms can lead to overheating in equipment like transformers, motors, and generators, as the higher-frequency harmonic currents create additional losses and heating beyond what the system was designed to handle. This excessive heat can then accelerate the degradation of insulation and other materials, shortening the lifespan of crucial power system assets. Additionally, the presence of harmonics and voltage imbalance results in increased transmission line losses, as the distorted currents and voltages create additional resistive and reactive power flows that waste energy. This is particularly problematic for long-distance power transmission, where efficiency is paramount. Furthermore, the harmonics can interfere with sensitive communication systems that rely on the power grid, causing disruptive noise and signal degradation. Protective relays, which are essential for detecting faults and isolating problems, may also malfunction when faced with distorted voltage and current waveforms, potentially failing to operate correctly. Even basic measurement instruments like meters can produce inaccurate readings under these conditions, undermining the ability to properly monitor and control the power system. Given the wide-ranging negative consequences, the modeling and testing conducted to date demonstrates the critical need to mitigate harmonics and voltage imbalance through the application of appropriate mitigation strategies. Continued research in this area is essential to develop more effective solutions and ensure the reliable, efficient, and safe operation of power systems.

3.8 Power Quality Compensation Techniques

Railway power quality compensation techniques are essential for ensuring the efficient and reliable operation of rail systems, which rely heavily on electrical energy for traction and various onboard systems. The growing demand for rail transport has led to increased train frequencies and speeds, consequently imposing higher demands on the power supply. Fluctuations in voltage, harmonics, and other disturbances can significantly affect the performance of both rolling stock and fixed infrastructure. Power quality compensation techniques are employed to mitigate these issues, enhancing the stability of the electrical network and ensuring compliance with stringent power quality standards. The adoption of advanced power quality compensation techniques helps railway operators achieve higher levels of reliability and efficiency, ensuring passengers enjoy a safe and comfortable travel

experience (M. Olofsson, E. Thunberg, 1999, Bharat Bhargava, 1999). The power quality analysis of the Ethio-Djibouti railway line was meticulously conducted through a combination of simulation and actual on-site measurements. The results from both methodologies indicated a satisfactory performance concerning power quality issues, specifically voltage and current harmonics as well as voltage unbalance, which were found to be below the thresholds set by the IEEE standards. Despite these findings, the analysis highlighted the need for compensation strategies to address potential power quality problems, ensuring operational reliability and efficiency.

Furthermore, during the contingency analysis, it became evident that the system exhibited vulnerabilities, lacking resilience to various fault conditions. This underscores the necessity for robust solutions to mitigate risks related to power quality and system stability. To this end, several state-of-the-art compensation techniques are worth considering. These may include the implementation of active power filters, static synchronous compensators (STATCOMs), and harmonic compensators, which can effectively mitigate harmonics, stabilize voltage levels, and enhance the overall resilience of the railway's power supply network. By integrating these advanced technologies, the Ethio-Djibouti railway line can significantly improve its power quality and ensure a more robust, reliable service for its operations. The objective of this dissertation is to explore and recommend effective power quality compensation techniques that can enhance the stability and reliability of electrical systems.

Among the numerous strategies available, this dissertation particularly emphasizes the application of active power filters, static synchronous compensators (STATCOMs), and dynamic voltage restorers (DVRs) as pivotal solutions for power quality improvement. Active power filters are designed to detect and reduce harmonic distortion in electrical systems, ensuring cleaner power delivery. STATCOMs provide reactive power support and voltage regulation, effectively stabilizing the grid during transient events. By systematically analyzing these technologies, this research aims to highlight their effectiveness in various scenarios and provide a comprehensive framework for their optimal deployment.

a. Balance Transformer

Railway power quality is a critical aspect of ensuring efficient and reliable operations, particularly in electric railway systems where disturbances can significantly affect performance. One esteemed technique used in mitigating power quality issues involves balance transformers. These devices play a pivotal role in stabilizing voltage levels and minimizing harmonic distortions, thus enhancing the overall efficiency of the electrical

system. Among the various balance transformers available, the Scott transformer is notable for its ability to convert three-phase power into two-phase systems, facilitating better load balancing. The Le Blanc transformer, on the other hand, excels in managing medium voltage applications and ensures effective voltage transformation with minimal losses. (Y.E. Zhongming,2000).

Another notable type is the impedance-matching balance transformer, which is essential for reducing impedance discrepancies in electrical circuits, thereby improving the transfer of power. This is particularly important in railway systems where different rolling stock may have varying electrical characteristics. Lastly, the wood bridge transformer serves to connect circuits with different voltage levels while maintaining balance, which is crucial for ensuring that all components operate smoothly together. Collectively, these transformers not only enhance the reliability of railway power systems but also contribute to prolonged equipment lifespan and improved energy efficiency, underscoring their importance in modern railway operations

b. Passive filter

In the context of railway power quality compensation techniques, passive filters represent a fundamental solution for enhancing the efficiency of traction power supply systems. These filters are engineered with a precise combination of inductance, capacitance, and resistance, enabling them to address the complex issues associated with power quality. By carefully tuning these reactive components, passive filters can minimize the presence of harmonics, which can adversely affect the performance and longevity of rail infrastructure. (Y.E. Zhongming et al.,2000, Linya et al, 2024, Yujie et al., 2013, Steven et al.,2000). In addition to harmonic reduction, passive filters are instrumental in improving the power factor of the system, thus reducing losses associated with reactive power. Their cost-effective nature makes passive filters particularly appealing for railway operators aiming to implement effective power quality measures without incurring substantial expenditures. This technology is characterized by high-capacity capabilities, allowing it to handle the significant electrical loads encountered in railway systems. By providing a simple yet robust mechanism for compensating reactive power, passive filters not only enhance the reliability and stability of the electrical network but also promote energy efficiency. Consequently, the adoption of passive filters has become increasingly prevalent as rail transport systems strive to meet modern demands for performance and sustainability.

c. Active Power Filter

Active Power Filters (APFs) play a crucial role in enhancing power quality within railway systems, which are often susceptible to various disturbances such as harmonics, voltage sags, and flicker due to the non-linear loads associated with electric trains and associated infrastructure. These filters utilize advanced power electronics technology to actively inject or absorb reactive power and harmonics, thus stabilizing the power system. APFs can dynamically respond to changes in load conditions, providing real-time compensation and improving overall system performance. By mitigating issues such as harmonic distortion, the implementation of APFs not only enhances the efficiency of railway operations but also contributes to the prolonged lifespan of electrical equipment. The versatility of Active Power Filters makes them an attractive option for modern railway networks. They can be integrated into existing systems with minimal disruption, offering a scalable solution to address power quality issues as demand fluctuates over time. Moreover, APFs can be configured to operate in different modes, such as shunt, series, or hybrid arrangements, enabling tailored solutions based on specific railway system requirements. This adaptability allows for more effective management of power quality, ensuring compliance with industry standards and regulations. Furthermore, the deployment of Active Power Filters aligns with the broader trend of sustainable and efficient rail transportation systems. By reducing the impact of harmonic pollution on the grid and enhancing the overall power factor, APFs contribute to lower energy consumption and operational costs. Their capability to improve power quality not only benefits the railway operators but also has positive implications for the connected power grid, ensuring a more reliable and stable energy supply for all users. As railway networks continue to evolve and incorporate more sophisticated technologies, the role of Active Power Filters will likely become even more significant in maintaining optimal power quality and operational efficiency.

d. Static Var Generator

Static Var Generator is a type of dynamic reactive power compensator that can rapidly adjust the amount of reactive power supplied to or absorbed from the power system. This capability proves crucial in addressing the fluctuations and imbalances often encountered in railway networks, particularly those caused by heavy load variations when trains accelerate or decelerate. (G. Celli Member et al.,2000).The SVG utilizes power electronics to provide precise control over reactive power, effectively stabilizing voltage levels and improving the overall power factor. The implementation of Static Var Generators brings several advantages

to railway systems. Firstly, they can eliminate voltage sags and swells, which are detrimental to sensitive equipment onboard trains and at substations. By offering real-time compensation, SVGs enhance the performance of traction systems, enabling smoother train operations and reducing wear on mechanical components. (Omi et al.,2014, Lee et al.,2013). Additionally, SVGs can mitigate harmonics generated by nonlinear loads, promoting compliance with power quality standards and protecting infrastructure from potential damage caused by excessive harmonic distortion. Moreover, the modular nature of Static Var Generators allows for flexible and scalable integration into existing railway infrastructure. As the demand for electrified rail systems continues to grow, SVGs offer a cost-effective solution for modernizing and upgrading power quality management. With their fast response times and ability to operate in a wide range of environmental conditions, SVGs contribute to the reliability and efficiency of railway operations. Overall, embracing Static Var Generator technology is a strategic move towards achieving optimized power quality in railway networks, ultimately leading to improved operational performance.

e. Railway Power Conditioner (RPC)

To enhance the power quality within train traction systems, a pioneering solution known as the Railway Power Conditioner (RPC) has been proposed by researchers in Japan. This sophisticated converter is strategically positioned on the secondary side of a transformer and boasts an adaptable topology, functioning as an ac-dc-ac converter. The RPC's primary objective is to meticulously manage the quality of transferred active power, harmonic power, and reactive power across its two ports. By converting a three-phase 220 kV high-voltage supply into two single-phase 27.5 kV voltages through a V/V linked transformer, the RPC plays a critical role in modernizing train operations. The architecture of the RPC is essentially composed of two back-to-back converters, which are interconnected via a single DC link. This design not only optimizes the transfer of power but also integrates seamlessly with the transformer's secondary side through the use of output reactance and a step-down transformer. By implementing a robust control strategy, researchers have found that the output currents of both converters can be finely tuned. This enables effective transfer of active power between various supply arms, significantly reducing the distortion brought about by harmonics and mitigating the prevalence of non-sinusoidal currents. (Sun et al.,2004,Luo et al.,2009).

In summary, the RPC represents a considerable advancement in addressing power quality concerns in train traction systems. Its ability to balance and refine power flow not only promises to improve the performance of electric trains but also enhances the overall stability

and reliability of railway operations. As train systems continue to evolve toward more efficient and sustainable technologies, innovations like the RPC are instrumental in paving the way for a more resilient infrastructure in public transportation.

f. Voltage loss compensation techniques

Voltage loss compensation techniques are essential in maintaining stable voltage levels across power systems, ensuring that customers receive consistent and reliable electricity. As loads fluctuate throughout the day, variations in voltage can occur, leading to potential disruptions in service. To combat these fluctuations, engineers and operators employ several compensatory methods. One of the primary tools in this approach is voltage regulation equipment, such as transformers with tap-changing capabilities, which can adjust output voltage levels in real-time. These devices not only stabilize the voltage but also enhance the overall efficiency of the power distribution network. In addition to transformers, operators utilize capacitor banks and synchronous condensers to provide voltage support. Capacitor banks inject reactive power into the system, counteracting any inductive loads that may cause voltage drops. Synchronous condensers, on the other hand, can quickly react to voltage changes, supplying or absorbing reactive power as needed to maintain system balance. Furthermore, advanced monitoring systems equipped with real-time analytics allow operators to detect voltage anomalies and respond promptly, ensuring that corrective measures are taken before customers experience any service interruptions.

Moreover, modern advancements in smart grid technology have significantly improved voltage loss compensation techniques. With the integration of automated control systems and sensors, utility operators can enhance voltage regulation, enabling a more proactive approach to managing voltage levels across the network. This technological evolution not only fosters enhanced operational efficiency but also empowers utilities to better manage their resources and respond to shifting demand patterns swiftly. Ultimately, these voltage loss compensation techniques are vital in delivering high-quality power service, ensuring that both the utility and the customers benefit from a reliable and stable electricity supply

i. Increase the Output Voltage of the traction transformer.

Increasing the capacity of the traction transform can effectively reduce X_2 but when the capacity increases it will also reduce the capacity utilization ratio of the transformation and increase the operation cost, which is uneconomical. Therefore, it is not appropriate to simply adopt this method.

$$\Delta U_2 = I_2 * X_T \quad (2.11)$$

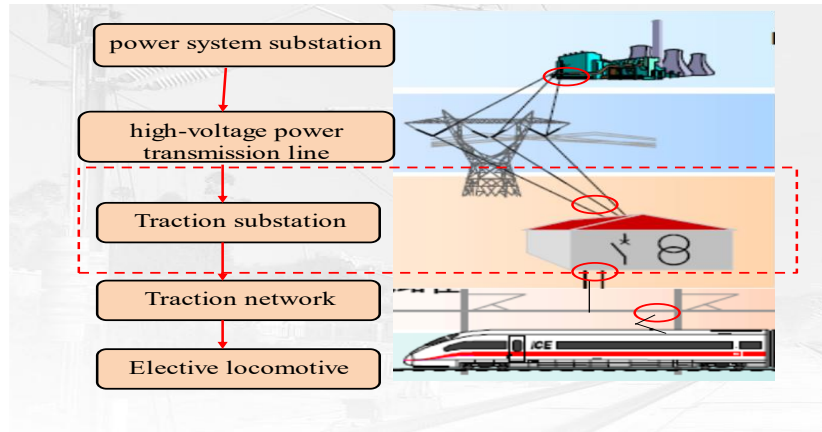


Figure 3.60 Increased output voltage

ii. Adjust the transformer tap-changer to increase the output voltage of the transformer.

Transformer voltage adjustment taps are physical connection points on transformer windings that allow incremental adjustments to the input voltage rating of the transformer to maintain the correct secondary voltage when the primary is higher or lower than expected.

iii. Reduce voltage loss.

Reducing the voltage loss of the traction network can effectively improve the voltage of the traction network. There are many ways to take it.

$$\Delta U_3 = I_2 * Z_q \quad (2.12)$$

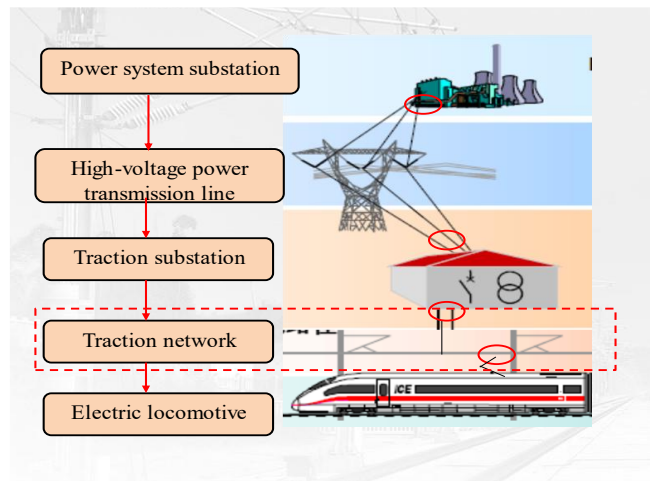


Figure 3.61 Reducing voltage loss

iv. Adopting Series Capacitance Compensation Device.

In the circuit voltage and inductance voltage are reversed and offset each other, Therefore, the capacitor C in series at the beginning of the supply and of traction substation can reduce the voltage loss of the traction and increase the voltage of the traction network.

$$\text{Before } \Delta U_3 = I_2 * Z_q = I(R + (R+jX_L)) \quad (2.13)$$

$$\text{After, } \Delta U_3 = I_2 * Z_q = I(R + j(R-X_c)) \quad (2.14)$$

From the above formula, the compensation voltage is proportional to the traction load current. The larger the traction load current the more the compensation voltage, the smaller the traction load current, and the less the compensation.



Figure 3.62 Capacitance compensation device

v. Improving the current-carrying capacity of the OCS

To reduce the voltage loss of the traction network by reducing the impedance of the traction network, and then improve the voltage of the traction network. Some of the methods are:

- Adopting JTMH-70,95, and 120MG-CU alloy strands as carrier cables
- Adopting double feeder lines etc.

vi. Adopting reasonable power supply mode

The performance of electrified railways depends on the power supply modes and structures of traction power supply mode. For instance, we can adopt parallel power supply mode at the end of the supply arm. This can effectively reduce the voltage loss of the traction network.

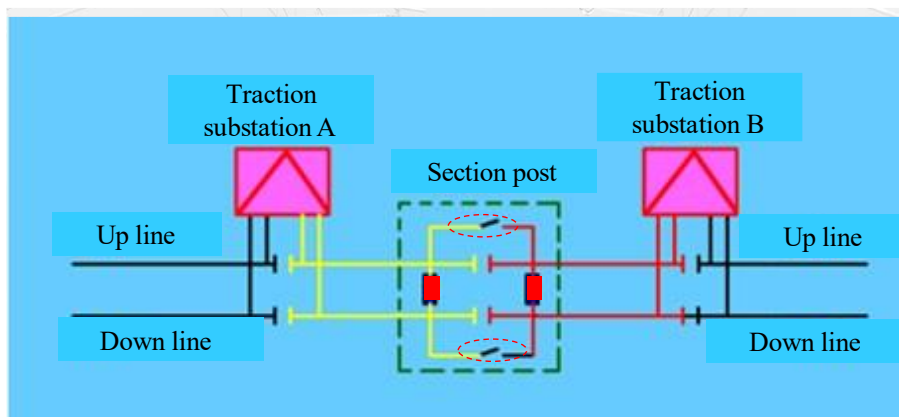


Figure 3.63 End parallel connection

vii. Reasonable length of power supply arm

If the power supply arm is too long, the impedance of the traction network will increase, the voltage loss will be too large, and the voltage at the end of the power supply arm will be too low. Therefore, the minimum voltage at the end of the power supply arm should be considered when setting the length of the power supply arm.

CHAPTER FOUR

STUDY AND ANALYSIS OF SMART GRID INTEGRATION WITH RAILWAY POWER SUPPLY

4.1 Introduction

The integration of smart grid technology with railway power supply is a crucial area of study and analysis in the field of transportation and energy management. The smart grid offers the potential to enhance the efficiency and reliability of railway power systems, leading to reduced operational costs and environmental impact. By optimizing power distribution and consumption, as well as incorporating renewable energy sources, the integration of smart grid technology with railway power supply holds great promise for the future of sustainable and efficient transportation systems. This article will delve into the various aspects of this integration and its potential impact on the railway industry. Artificial Intelligence (AI) plays a crucial role in optimizing the operation and management of smart grid systems (Shaik et al.,2023). By leveraging AI algorithms, smart grids can efficiently predict energy demand, optimize power distribution, and detect and respond to potential faults or outages. AI enables the integration of renewable energy sources and facilitates the implementation of demand response programs, ultimately enhancing the overall efficiency and reliability of the grid. As AI continues to advance, its application in smart grid technology is poised to revolutionize the energy sector, paving the way for more sustainability.

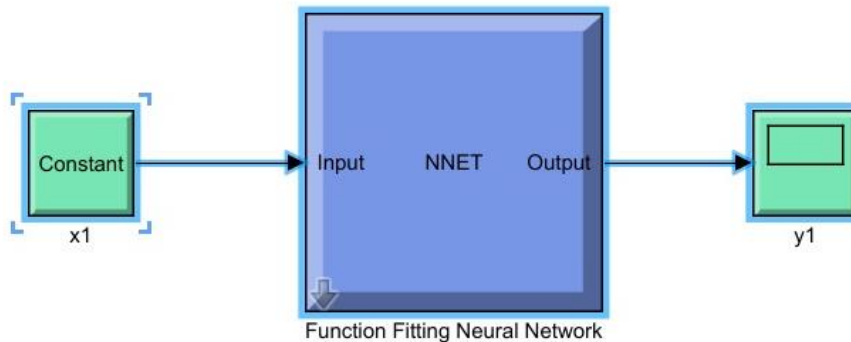


Figure 4.1: ANN model

4.2 Design and Analysis of RBFN Based MPPT controller for wind energy Integrated with Traction power supply System.

4.2.1 Introduction

Achieving a reliable and sustainable power supply system for trains is a major challenge facing the rail industry today. One crucial aspect of this challenge is the integration of renewable energy sources, such as wind power, into the traction power grid. In wind turbine systems connected to the grid, the process of tracking the maximum power point is essential

for optimizing the efficiency and output of the wind energy being generated. The effectiveness of a wind energy conversion system (WECS) relies heavily on how accurately the maximum power point tracking (MPPT) controller can extract the maximum available power from the wind turbine. Utilizing a control system based on a single MPPT approach and a radial basis function network is a crucial component for maximizing the efficiency of these systems.

This dissertation work proposes a dynamic MPPT controller for a permanent magnet synchronous generator (PMSG)-based variable speed autonomous wind power conversion system (WPCS) that leverages artificial neural network technology. The model presents the MPPT algorithm used to extract the maximum possible power output from a PMSG-driven wind turbine. In this study, the researchers implemented a 300kW wind farm to test their approach. A DC-DC boost converter is used to step up the low AC voltage generated directly by the PMSG, which is driven by the wind turbine. The proposed ANN-based controller provides an effective solution for seamlessly integrating wind energy into AC traction power supply systems for rail applications. Extensive MATLAB/Simulink simulations were carried out to validate the performance of the ANN-based control strategy, especially under varying load conditions. This innovative approach represents an important advancement in optimizing the efficiency and sustainability of wind-based power generation for rail transportation. The electric railway system is a significant consumer of energy, making it a prime target for sustainability initiatives aimed at reducing environmental impact and operational costs. One promising approach to enhancing the self-reliance and efficiency of the rail industry is the integration of renewable energy sources, such as wind power, directly into the railway's electrical infrastructure. By hybridizing traditional railway substations with wind turbines, rail operators can harness the abundant and distributed nature of wind energy to power their extensive transportation networks. This innovative integration allows for the direct supply of wind-generated electricity to the railway's power grid, utilizing specialized transformers to ensure the electricity is compatible with the trains' voltage and frequency requirements. The ability to connect multiple wind turbines to different sections of the railway's electrical infrastructure provides a steady and reliable power source, mitigating the intermittency often associated with renewable energy. Furthermore, the system is designed to feed any excess energy generated back into the primary electricity grid, ensuring optimal use of the renewable resource and contributing to the overall energy sustainability of the surrounding community. This hybridization of railway substations with wind energy represents a significant step towards a more sustainable and efficient rail transportation system, reducing the industry's

reliance on traditional, nonrenewable energy sources and paving the way for a greener future in rail operations (Khan et al.,2021, Shu et al.,2023).

The majority of current MPPT algorithms have the flow of being slow tracking, which lowers utilization efficiency. The following are examples of artificial neural networks (ANNs) using back propagation techniques: fuzzy logic controller for intelligent control with DC-DC converter, incremental conductance computation (INC), hill climbing or perturbation and observation (P&O), and particle swarm optimization are some examples of MPPT control techniques that can be used to increase wind energy efficiency (Reddy et al.,2018,M. Lwin et al., 2018, Shahrin et al,2007).A review of the literature on several maximum point tracking system techniques has been conducted and reported in this study.

A straight MPPT method, similar Perturb & Perceive, was proposed by V. T. Vasantha et al., 2022, besides is intended for use in solar energy systems. In addition to designing the RBFN procedure that is utilized in MPPT for renewable energy plants the utilization of wind power systems in grid-tied applications is investigated once it is linked to a hybrid structure. Using a DC/DC converter, a suggested maximum power point tracking, or MPPT, control scheme for wind energy conversion systems (WECS) depends on artificial neural networks (ANNs) in (El-Helw et al.,2017).The outcomes are contrasted using the Back Propagation Network (BPN) method and the conventional P&O (Perturb and Observe) technique. For maximal power extraction, the bidirectional backstepping termination sliding type is presented in (N. Femia et al.,2004).This is confirmed whether the structure is finite-time stability using the Lyapunov coefficient. PV power is supplied to the load via a DC-DC buck-boost converter. A radial basis function neural network produces reference voltages for the suggested controller (RBFNN).

Tiwari R, Babu NR ,2016, proposed the greatest amount of tracking from solar and wind energy is achieved with a controller based on fuzzy logic. However, to create fuzzy rules and maximize power generated from sources of renewable energy, previous information on the weather now is necessary.The benefits of suggested maximum power point tracking (MPPT) regulator include a fast swiftness of tracking the petroleum chamber's operating point, extra elasticity, a great abundance of allowable fluctuations over MPP, besides a reduced reliance taking place fuel stack modelling. This paper Pitchai et al.,2021, uses a variety of MPPT techniques, including Neural network technology built a radial basis-function network (RBFN), gradual conductance, and disruption and observation to determine proper responsibility sequence for gaining the optimal control beginning the solar PV tree. In

comparison to the other two methods, the RBFN-based NN offers superior pursuing competence besides reduced fluctuation, according to simulation and real-time findings. It is necessary to have prior information about current weather conditions to create fuzzy rules that increase the amount of power produced by sources of sustainable energy.

Among all the available Maximum Power Point Tracking (MPPT) methods in the literature, the Perturb and Observe (P&O) and Hill Climbing methods stand out as the most widely used techniques in both photovoltaic (PV) and wind energy systems. This is primarily attributed to their straightforward structure and ease of implementation, making them accessible even for those with limited technical expertise. Both of these methods operate on the fundamental principle of perturbation, which involves sensing the voltage and current parameters from renewable energy sources to optimize power extraction. In the P&O method, the perturbation element is the voltage, which is adjusted to observe the corresponding changes in power output. Conversely, the Hill Climbing method manipulates the duty cycle as its perturbation parameter, systematically varying it while monitoring the resultant power feedback. By continuously altering these perturbation elements, both methods calculate the change in output power and compare it with previous measurements, thereby isolating the maximum power point from the source. However, a notable limitation of these methods is their effectiveness in tracking the maximum power point under rapidly changing weather conditions, such as fluctuations in sunlight or wind speed, which can hinder their performance and slow the tracking response. To address these challenges, the Incremental Conductance method has emerged as a more robust alternative, particularly in handling the non-linear characteristics of renewable energy sources. By analyzing voltage and current data, this method calculates the ratio of instantaneous conductance to incremental conductance, allowing for precise tracking of the maximum power point even in variable environmental conditions. Despite its increased complexity compared to P&O and Hill Climbing methods, the Incremental Conductance method remains relatively less intricate and is still easy to implement, making it a favorable choice in both PV and wind energy applications. As researchers continue to explore and refine these MPPT strategies, the ongoing development aims to enhance efficiency and reliability in harnessing energy from increasingly variable and unpredictable renewable sources. Wind turbines are essential for harnessing wind energy, but their power output varies with wind speed. Variable speed wind turbines offer better control over power output and can track maximum power output for various wind speeds by adjusting rotor speed. Additionally, pitch angle control can be implemented to achieve maximum power

at speeds above rated wind speed. These turbines have higher starting torque, more stable torque curves, and are more efficient in capturing wind energy. With these features, variable speed wind turbines are an asset in maximizing power output from wind energy conversion systems. To improve the performance of MPPT, a new controller designed with the RBFN adaptive strategy is introduced for Wind Energy Conversion Systems (WECS). This RBFN strategy is aimed at optimizing the duty cycle to achieve Maximum Power Point (MPP). The RBFN model is a type of feedforward neural network (NN) that has a more straightforward architecture and offering a reliable and adaptive control mechanism. Furthermore, the duty cycle of the boost converter is regulated by voltage and power signals to the RBFN, eliminating the requirement for wind turbine specific sensor data (such as wind speed with an anemometer) or turbine speed with a tachometer. This eliminates the need for additional sensors, making this MPPT control method significantly more economical. This approach ensures efficient MPPT, reduces fluctuations, minimizes load changes and interruptions, and provides a quick response. Traditional strategies such as P&O, TSR, and OT, among others, struggle with varying wind conditions and need accurate mathematical models to function effectively. These traditional methods face challenges in optimizing their parameters, leading to the adoption of smarter controllers to enhance overall system efficiency. The integration of artificial intelligence (AI) in control strategies addresses several of these challenges and is crucial for achieving maximum power point (MPP). AI techniques do not rely on mathematical models and can effectively approximate nonlinear systems.

RBFN stands for Radial Basis Feed Forward Neural Network, which employs radial basis network as its activation function. The training process involves supervised learning, which mirrors the back propagation algorithm. In this research, an RBFN controller was developed to regulate the turbine within a wind energy conversion system by adjusting the pitch angle based on wind speed. The designed RBFN controller features three layers: an input layer, a hidden layer with a nonlinear radial basis function activation, and a linear output layer. The wind speed and generator speed are input to the RBFN's input neurons, which then calculate the pitch angle as the output. This controller is designed to enhance power output during low wind speeds and optimize power during high wind speeds. The duty cycle is employed to optimize power output, while the reference pitch angle is used to adjust the generator speed, thereby regulating the generator's power output within the rated wind speed range. Radial Basis Function Neural Network (RBFN)-based Maximum Power Point Tracking (MPPT) controllers offer several advantages over conventional P&O, Hill climbing, and Fuzzy Logic

methods for wind energy integration with railway power supply. The primary benefit lies in their ability to handle nonlinear and rapidly changing wind speed conditions effectively. Unlike P&O and Hill climbing methods, which rely on iterative search algorithms, RBFN-based controllers utilize a neural network to estimate the maximum power point (MPP) directly. This eliminates the need for perturbation and observation, resulting in faster and more accurate MPP tracking. Additionally, RBFN controllers are less susceptible to oscillations around the MPP, ensuring a stable power output. The performance of the proposed controller was validated using MATLAB/Simulink software.

Wind power has emerged as the most reliable and significantly advanced renewable energy source over the past several decades, transforming the energy landscape and providing a sustainable alternative to fossil fuels. As the deployment of wind generators has soared, their integration into the power system grid has become increasingly important, emphasizing the need to optimize energy output from wind resources. Wind speed, being highly variable and unpredictable, necessitates the development of systems that can quickly adapt to these fluctuations in order to maximize energy generation. To achieve this, it is crucial to identify and maintain the optimal generator speed that guarantees the highest energy yield from the wind's kinetic energy. An effective approach to manage this variability is through the implementation of sophisticated control mechanisms that can dynamically adjust the turbine's operational parameters. This ensures that the wind turbine (WT) is consistently operating at or near its maximum power point (MPP), regardless of the shifting wind conditions. By employing advanced algorithms and control strategies, the wind energy conversion system (WECS) can track the MPP in real-time, responding to changes in wind speed and direction to capture the maximum available power efficiently. This focus on maximizing the operational efficiency of wind turbines is not only essential for maximizing energy output but also plays a critical role in the overall stability and reliability of the power grid. As the push for cleaner sources of energy continues to grow, the importance of optimizing wind power generation cannot be overstated, as it is not just a matter of meeting current energy demands but also a significant step towards a sustainable future that reduces reliance on carbon-intensive energy sources. Thus, the combination of advanced control systems and efficient energy conversion mechanisms is key to harnessing wind power effectively, ensuring that it remains a cornerstone of modern renewable energy strategies.

The maximum power extraction algorithms researched so far can be classified into four main control methods, namely as

- Tip speed ratio (TSR) control
- Power signal feedback (PSF) control
- Optimal torque (OT) control
- Hill climb search (HCS) control

Tip speed ratio (TSR) control of WECS

The TSR (Tip Speed Ratio) control method is a crucial technique employed in modern wind turbine systems for optimizing energy extraction from the wind. It revolves around maintaining the rotational speed of the generator in such a way that the TSR is kept at an optimal value. This optimum TSR is the ratio of the speed of the blade tips to the speed of the wind and is a critical parameter that determines the efficiency of power extraction. In order to effectively implement this control strategy, it is essential to have real-time data on both the wind speed and the turbine speed; this can involve direct measurements or estimations derived from predictive models and sensor data. The requirement for both wind and turbine speeds is necessary because fluctuations in wind conditions can significantly affect power output, and to adapt the turbine's operation accordingly, precise control mechanisms must be in place. Additionally, knowledge of the specific optimum TSR for the particular turbine model is imperative, as different turbine designs have varying characteristics that influence their performance under different wind conditions. By continuously adjusting the generator's rotational speed to align with the ideal TSR, the TSR control method ensures that the turbine operates efficiently, maximizing the energy harvested from varying wind speeds. This not only enhances the overall efficiency of the wind energy conversion process but also contributes to the stability and reliability of energy supply, making this control technique an invaluable component of modern wind energy systems. Therefore, integrating accurate measurements, advanced control algorithms, and a thorough understanding of turbine performance characteristics is essential to fully harness the potential of wind energy through the TSR control method.

Power signal feedback (PSF) control

In the context of Power System Frequency (PSF) control within wind energy systems, a critical component involves understanding the maximum power curve of each wind turbine and ensuring that the turbine operation aligns with this curve through sophisticated control mechanisms. The maximum power curve represents the optimal performance of a wind turbine at various wind speeds, indicating the highest electrical output the turbine can achieve without risking mechanical damage. This curve must be accurately determined through

simulations or off-line experiments, which are essential for characterizing the individual performance characteristics of each turbine under varying environmental conditions. Once this curve is established, it plays a pivotal role in generating a reference power output that informs the control system. Specifically, this reference power can be derived either from the predefined maximum power curve, which serves as a guide for operational parameters, or through the application of the mechanical power equation, utilizing real-time data such as wind speed or rotor speed as inputs to dynamically calculate the expected power output. By comparing actual turbine output to this reference power, control algorithms can effectively regulate the performance of the turbine, ensuring that it operates on or near its maximum power curve while responding to fluctuations in wind conditions and grid demands. This approach helps to optimize energy production, enhances the stability of the power system, and ensures that wind turbines contribute efficiently to the overall energy mix while maintaining system reliability. Consequently, having a comprehensive understanding of the maximum power curve and the ability to track it through advanced control strategies is paramount for maximizing the performance of wind energy systems and supporting the transition to sustainable energy sources.

Hill – Climb Search (HCS) Control Principle

The HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal to drive the system to the point of maximum power.

The conventional strategy like P&O, TSR, and OT etc. perform poorly during varying wind speeds and require precise mathematical models. These conventional controllers have problems of inefficient tuning of their gains therefore intelligent controllers are used to overcome this problem and for better system performance. The usage of artificial intelligence (AI) based control methods minimizes some of these issues and play a significant role in extracting MPP.

This dissertation primarily seeks to identify the existing gaps in the current state of the art concerning the control and extraction of maximum power points in wind energy systems, particularly in the context of integrating wind energy with railway power supply systems. With the growing emphasis on sustainable and renewable energy sources, wind energy has emerged as a viable option to enhance the energy efficiency of railway operations. However,

the integration of wind energy into the railway power supply, specifically for the Ethio-Djibouti railway line, presents unique challenges and opportunities. Understanding these intricacies is crucial for optimizing energy output and improving the overall functionality of the railway system.

The Ethio-Djibouti railway line, being a critical transportation corridor within the Horn of Africa, offers a unique case study for the integration of renewable energy sources. This dissertation will explore the current methodologies and technologies employed in wind energy extraction and control, highlighting the limitations that hinder a seamless integration with railway power supplies. By dissecting the existing approaches, from maximum power point tracking (MPPT) techniques to energy storage solutions, this work aims to pinpoint specific areas where advancements can be made. Addressing these gaps is essential not just for enhancing the energy efficiency of the railway line but also for setting a precedent in renewable energy integration in other transportation systems.

The research gap in the study of RBFN-based Maximum Power Point Tracking (MPPT) control algorithms for wind energy systems, particularly in the context of integrating with railway power supply systems, lies primarily in their capability to effectively handle nonlinear and rapidly varying wind speed conditions. Traditional methods such as Perturb and Observe (P&O) and Hill Climbing often rely on iterative search algorithms, which can result in slower convergence times and are more susceptible to fluctuations and oscillations around the maximum power point (MPP). This is particularly critical in fluctuating environments like those found in wind energy applications, where rapid changes in wind speed can drastically affect power output.

In contrast, Radial Basis Function Network (RBFN)-based controllers leverage the power of neural networks to predict and estimate the MPP directly, enabling quicker and more precise tracking of the maximum power from the wind turbine. This direct estimation approach not only accelerates the response time of the MPPT control system but also enhances its accuracy in varying wind conditions. The inherent advantage of RBFN controllers lies in their ability to minimize oscillations around the MPP, resulting in a more stable power output. This stability is crucial when integrating wind energy systems with railway power supplies, which demand consistent and reliable energy input for efficient operation.

Despite the promising features of RBFN-based algorithms, there is still limited exploration and optimization of their implementation for real-world scenarios involving fluctuating wind patterns and integration challenges with existing power supply infrastructure. Therefore,

further studies are essential to quantify and enhance the performance of RBFN-based MPPT control algorithms in these specific applications, paving the way for more efficient and robust renewable energy solutions that can effectively meet the demands of modern rail systems. Addressing this research gap could significantly contribute to the advancement of sustainable energy practices in transportation sectors

This dissertation work also aims to identify and study the existing gaps in the modeling and control of smart grid systems specifically tailored for the railway power supply of the Ethio-Djibouti Railway Line. As the demand for efficient and sustainable energy solutions in transportation networks continues to rise, understanding the unique requirements and challenges of integrating smart grid technologies into railway power systems becomes increasingly crucial. While significant advancements have been made in the general application of smart grids in various sectors, there remains a notable lack of focused research on their implementation within the context of railway infrastructure, particularly in developing regions like East Africa. This study seeks to synthesize current literature, assess the state of existing models, and evaluate their applicability to the specific operational conditions and energy demands of the Ethio-Djibouti Railway Line.

Furthermore, this dissertation will explore various methodologies for modeling and controlling smart grids that cater to the reliability, efficiency, and sustainability goals of the railway system. It will highlight the interplay between renewable energy integration, energy storage solutions, and real-time data analytics in optimizing the power supply for railway operations. By addressing the gaps in current research, this work aims to provide valuable insights that can drive the development of more robust and adaptive smart grid frameworks for railway applications. Ultimately, the findings of this dissertation will contribute not only to the theoretical understanding of smart grids within this specific context but also to practical implementations that can enhance the operational efficiency and environmental sustainability of the Ethio-Djibouti Railway Line

The Ethio-Djibouti Railway Line represents a critical infrastructural development aimed at enhancing regional connectivity and economic growth in East Africa. However, there exists a significant research gap in the specific domain of modeling and controlling a smart grid tailored for the railway power supply along this corridor. Despite the advancements in smart grid technologies globally, there is a paucity of localized studies that integrate the unique operational characteristics, power requirements, and environmental contexts of the Ethio-Djibouti Railway. This gap presents an opportunity for researchers to investigate the potential

of smart grid systems in optimizing energy efficiency, enhancing reliability, and reducing operational costs in railway electrification.

Moreover, the integration of renewable energy sources into the railway power supply system remains an underexplored area, especially considering the abundant solar and wind resources available in the region. Research focused on developing hybrid energy solutions that align with smart grid principles could significantly contribute to sustainability goals while ensuring the robust performance of the railway system. Additionally, understanding the interplay between demand response mechanisms and real-time energy management remains a crucial aspect that is yet to be adequately addressed in existing literature. This underscores the necessity for comprehensive models that can simulate various operating conditions and provide actionable insights for effective grid management. Furthermore, the socio-economic implications of implementing a smart grid for the Ethio-Djibouti Railway Line also warrant rigorous investigation. Understanding how such technological advancements can promote socio-economic benefits, such as job creation and improved public transportation services, is essential for stakeholder buy-in and policy formulation. Thus, this research gap not only highlights technological deficiency but also poses an opportunity for interdisciplinary studies that encompass engineering, economics, and social sciences. Addressing these gaps is critical for advancing the operational efficiency and sustainability of railway systems in the region, ultimately contributing to broader regional development goals.

The integration of wind energy into the power supply system of the Ethio-Djibouti Railway line presents a vital opportunity to address the persistent challenge of power outages that disrupt railway operations. Despite the growing interest in renewable energy sources, there remains a significant research gap surrounding the modeling and implementation of wind energy solutions tailored specifically for railway applications in this region. The intermittent nature of wind energy, combined with the reliability required for train operations, necessitates comprehensive studies to explore innovative methods for integrating these two systems effectively.

This research aims to fill the existing gap by focusing on the development of a robust framework that leverages wind energy to sustain uninterrupted power supply for the railway system, particularly during grid power cuts. Frequent power outages not only hamper operational efficiency but can also compromise safety and lead to financial losses. By investigating the potential of wind energy to serve as a supplementary power source during

critical times, this study seeks to enhance the resilience of railway operations along the Ethio-Djibouti line, thereby improving service reliability for passengers and freight transport.

The findings from this research will hold significant implications for the future of railway electrification in developing regions, where energy infrastructure often faces challenges. By modeling various wind energy integration scenarios and assessing their impacts on power supply continuity, this study can provide actionable insights and recommendations. Ultimately, addressing the power supply challenges will contribute to establishing a more sustainable and efficient rail transport system, which is essential for supporting economic growth and connectivity in the Ethio-Djibouti corridor.

4.2.2 Design of Wind Energy Integrated with Traction System

The electrical supply system for a railway line is a critical component that ensures the trains have access to the necessary power to operate effectively. This system takes the high-voltage electricity from the broader power transmission network and transforms it into the specific characteristics required by the trains. Central to this process are the single-phase 230kV/25kV transformers, which act as the interface between the high-voltage three-phase grid and the railway's single-phase traction power supply. These transformers are connected to two of the three phases in the transmission system, allowing them to draw the necessary power. Importantly, a neutral section is used to separate the traction power supply network into independent sections, each supplied from a different traction substation. This helps maintain the integrity and reliability of the overall system (G. Moor, J. Beukes, 2023).

The Ethio-Djibouti railway, for example, has adopted a 25kV, 50Hz single-phase AC power supply to meet the high traction power demands of its high-speed trains. This specialized railway power supply system was specifically designed to handle the unique power quality challenges that can arise, such as negative-phase current and harmonic distortion caused by power imbalances. To mitigate these issues, the railway's power supply is connected to a high voltage point on the national grid that has a high short-circuit capacity, providing a robust and stable source of electricity. The power is then fed into the railway system through a V/V transformer, which converts the 230kV three-phase voltage down to the required 25kV single-phase for injection into the catenary system that powers the trains. This carefully engineered electrical supply system is essential for ensuring the reliable and high-performance operation of the railway network.

The integration of wind energy with traction systems represents an innovative and promising approach to sustainable transportation. By harnessing the power generated from wind turbines

and channeling it to power electric vehicles like trains and buses, this synergetic design aims to reduce our reliance on fossil fuels and mitigate the environmental impact of public transit. The core concept involves seamlessly combining the technology behind wind energy generation with the mechanisms used in electric traction systems. Wind turbines capture the kinetic energy of the wind and convert it into electrical power, which can then be fed directly into the traction systems that propel electric vehicles. This elegant integration allows the renewable, emissions-free energy from wind to be utilized as the primary source for powering public transportation, rather than traditional internal combustion engines that burn gasoline or diesel. However, the successful implementation of this approach requires careful management of the variable and intermittent nature of wind power. Unlike fossil fuels, the amount of electricity generated by wind turbines can fluctuate based on changing wind speeds and weather conditions. To maintain a steady, reliable flow of power to the traction systems, various energy sources need to be strategically combined using advanced power electronic converters. This creates a hybrid system that can draw from multiple renewable inputs, including wind and solar, and balance out the variability to provide a consistent, grid-quality supply of electricity. Additionally, sophisticated maximum power point tracking algorithms are essential for optimizing the efficiency of these hybrid systems, ensuring that the renewable energy sources are leveraged to their full potential. By overcoming the technical challenges through innovative engineering, the integration of wind energy with traction systems holds immense promise as a sustainable solution for powering the public transportation of the future, paving the way for a greener, more environmentally friendly era of mobility.

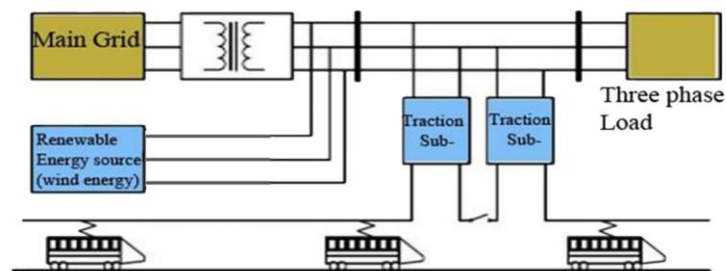


Figure 4.2 Block diagram topology of the hybrid system [127]

It is crucial to track the highest point in the grid-connected turbine architecture to optimize the productivity of solar power. Trains are one of the greatest energy-intensive forms of transportation. Due to the rapid and swift growth of the lighted railroads, tremendous

quantities of electricity are required. Because solar power is variable and uncertain and train load fluctuates quickly, railroad power is vulnerable to unexpected reductions in strength as well as additional reliability issues. These issues affect how the train system operates. To fulfill this country's major electrical requires, the goal in this study is to find a solution for the challenge of acquiring the optimum amount of electricity from intermittent sources of electricity with electrical assets creating low output of emission. This work primarily concerned with the investigation of the optimal power tracking controller approach that uses a direct-current (DC) to direct-current (DC) for wind electricity conversion systems (WECS). A computerized neural web is required for this technique. This approach relies on artificial neural networks. The proposed approach abstracts the selected voltage from wind speed or wave speeds using an artificially intelligent control method based on a Radial Basis Function network. The capability of the suggested MPPT in the absence of wind vitality linked with a mechanical electricity supply system is evaluated by taking into consideration the shifts in information on wind speeds over time (M. Venkatesh et al.,2020, K. Jyotheeswara et al., 2018).A single MPPT controller, which is designed around the Radial Basis Function Network is used in an aerodynamic system with a 300kW wind component rating and a traditional boosting converter topology. The findings from simulations are shown to validate the combination of voltage measuring capability of the proposed MPPT control technique.

The integration of a Radial Basis Function Network (RBFN) based Maximum Power Point Tracking (MPPT) controller into a wind energy system, aimed at supplying traction power, represents a significant advancement in the optimization of renewable energy utilization. This design not only ensures the efficient conversion of wind energy into electrical power but also significantly enhances the capability to extract the maximum possible power from varying wind speeds, through the precise adaptation to the wind's kinetic energy variations. The use of an RBFN-based MPPT controller facilitates the dynamic adjustment of the system's operating points in response to real-time wind conditions, resulting in higher efficiency and reliability in power generation. Furthermore, the design includes provisions for feeding excess energy back into the primary electricity grid, ensuring optimal use of generated power, and contributing to the overall energy sustainability of the surrounding community. Such a system not only amplifies the potential for renewable energy sources in remote areas but also harmonizes with environmental conservation efforts by providing a clean, sustainable power supply solution.

4.3 RBFN -based MPPT control algorithm of wind energy system

Trains are one of the most energy-intensive forms of transportation. Energy use and carbon emissions are related to the global climate. Because wind energy is variable and unpredictable and train load fluctuates quickly, traction power is vulnerable to unexpected dips in voltage and other power quality issues. A stable electricity supply and the achievement of the net zero carbon emission target are the driving forces behind this research project. Additionally, experts and researchers regarding wind power can ascertain the present status of ANN application in wind energy integration with railway traction power supply system. This study may also be helpful in identifying new research directions that could enhance the railway power supply system and produce renewable energy for the railway.

As seen in Figure 4.10, the RBFN-created MPPT controller comprises an input layer, a hidden layer, and an output layer, making it a two-layer network. RBFN is trained using this supervised learning algorithm (MLP). Levenberg-Marquardt (LM) training was used to assess the model in an array of transmitting layers (K. Kumar et al.,2017, M. Lwin et al.,2018). Time-tuning the weights to produce the expected output (duty cycle) when a set of inputs is applied is the training objective of RBFN based on MPPT approaches, as shown in Figure 4.10. To do this, the RBFN must be trained with wind voltage and current values as input variables. The maximum voltage is then provided as output data. The following is a summary of the RBFN implementation methodology.

- Step 1. Input layer to receive voltage and current input data from wind energy sources.
- Step 2. Prepare the training set of data.
- Step 3. Figure an RBFN with a hidden layer.
- Step 4 Modify the parameters of RBFN.
- Step 5. Productivity can be improved by adjusting the weights of the hidden neuron layer by changing the weights of the network.
- Step 6. Complete the RBFN training, validation, and testing.
- Step 7. Create PWM to regulate the switch's duty or work cycle.

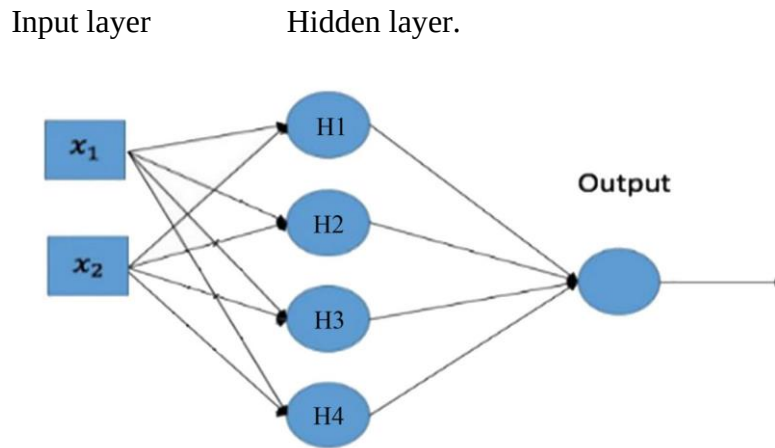


Figure 4.3: RBFN architecture

The RBFN framework for this study was created using MATLAB version R2021, as seen in Figure 4.11. For ANNs to be used for prediction and classification, the statistical features of the test, validation, and training data are crucial. The data set is divided into three subsets: 15% is put aside for testing, 15% for validation, and 70% is used for training. As the training progressed, Levenberg-Marquardt (LM) training algorithms were employed.

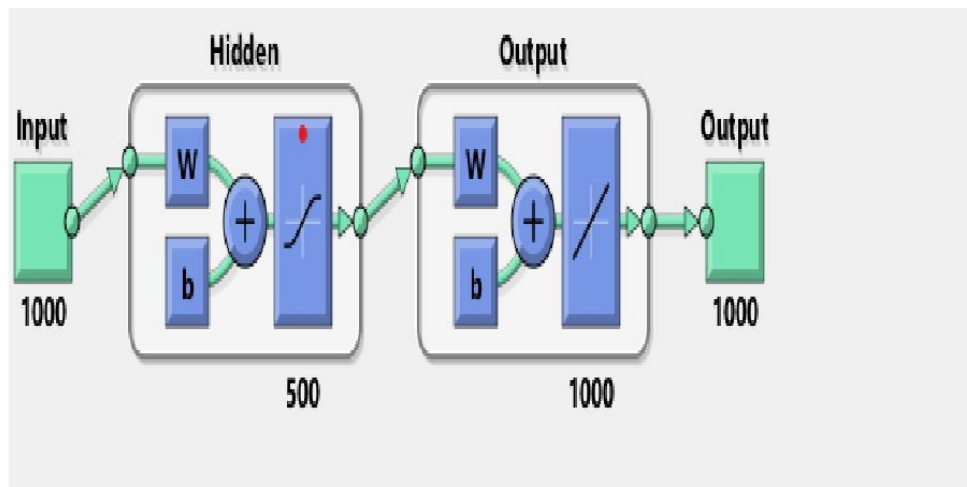


Figure.4.4: RBFN-based single MPPT architecture for the wind energy system.

The WECS operates on a permanent magnet synchronous generator (PMSG). The voltage and power generated by the rectifier are recorded and directed into an RBF-NN controller. The MPPT algorithm manages the power usage of a DC-DC boost converter to optimize power extraction as shown in Figure 4.12. The power from the boost converter is connected to the electrical grid through a voltage source. The generator is linked to the load through a three-phase rectifier and a boost converter. This converter controls the voltage on the generator's side. The use of a diode bridge rectifier guarantees that the actual load on the generator's side

is purely resistive, resulting in a steady DC voltage. Figure 4.12 illustrates a circuit equivalent for each phase on the generator's side, with V_s representing the voltage across the rectifier diode. The grid-side system includes a three-phase variable speed inverter (VSI) that transforms the direct current (DC) voltage into alternating current (AC), which is subsequently linked to the grid. Additionally, a nonlinear load is attached to the point of common coupling (PCC).

The proposed grid-connected system depicted is a comprehensive renewable energy solution that seamlessly integrates multiple components to harness and manage the power generated from wind energy conversion systems (WECs). At the heart of this system are permanent magnet synchronous generators (PMSGs) that convert the kinetic energy of wind into electrical power. To ensure maximum power extraction from these PMSGs, the system employs a maximum power point tracking (MPPT) mechanism. This MPPT controller dynamically adjusts the operation of the connected DC-DC converter, maintaining the optimal electrical parameters to extract the full potential of the wind resource, regardless of fluctuations in wind velocity. To provide energy storage and stability to the overall system, a battery bank has been strategically designed. This battery bank, composed of a series and parallel arrangement batteries, serves as a buffer to store excess power generated by the WECs. This stored energy can then be utilized during periods of high grid demand or when wind speeds are insufficient, ensuring a constant and reliable supply of power to the utility grid. The bidirectional converter plays a crucial role in this system, maintaining a steady DC bus voltage and facilitating the seamless transfer of power between the WECs, battery bank, and the voltage source inverter (VSI).

This study presents a design and optimization method to harness wind energy using PMSG, diode rectifier, boost DC/DC converter and grid-connected VSI DC/AC inverter. The generator is connected to the load using a three-phase rectifier and a boost converter. The boost converter regulates the amount of voltage as referred to the generator side. Usage of diode bridge rectifier ensures that the effective load referred to generator side is purely resistive so that one obtains a constant DC voltage. The grid side system consists of a three phase VSI that converts the DC link voltage to AC which is then connected to the grid. The VSI is responsible for converting the DC power from the WECs and battery bank into high-quality, grid-compatible AC power. Feeding this single-phase AC output through an LC filter ensures that the power delivered to the utility grid is free from any harmful harmonic disturbances, meeting the strict requirements for grid integration. This holistic system design

allows for the extraction of maximum power from the WECs, even in the face of varying wind conditions and grid demands. The stored energy in the battery bank can be strategically deployed to maintain a constant power output, providing a reliable and consistent supply of renewable energy to the utility grid.

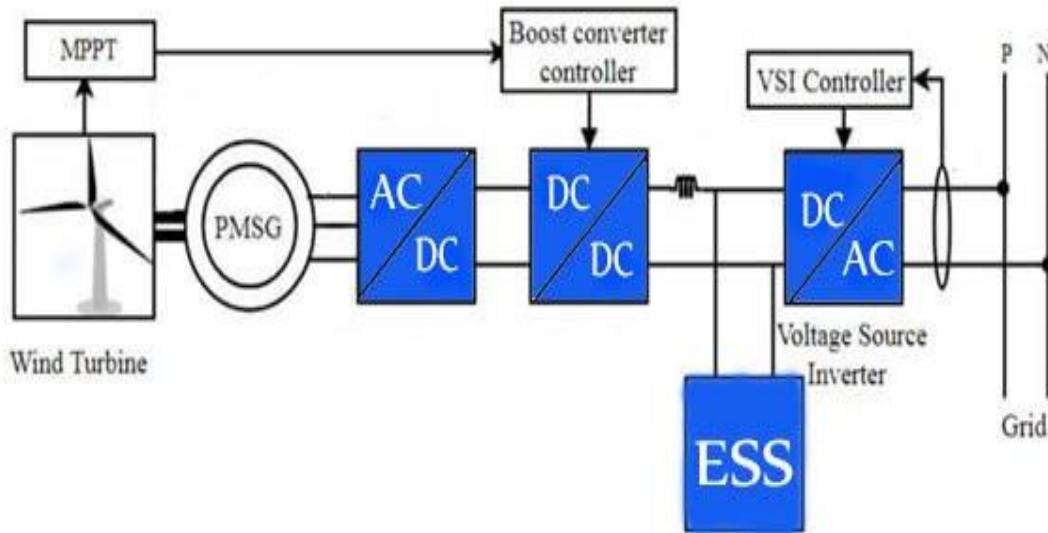


Figure.4.5: Grid tied wind energy system

4.3.1 DC-DC Converter Modeling

Designing a DC-DC converter for wind energy integration with railway power supply system's requires careful consideration of power quality, stability, and reliability. A crucial aspect is ensuring that the wind turbine's output voltage and frequency match the railway's power supply requirements. A well-designed DC-DC converter can achieve this by incorporating Maximum Power Point Tracking (MPPT) techniques to optimize wind energy harvesting. Additionally, the converter must also meet railway standards for power quality, such as IEEE 519, and ensure electromagnetic compatibility with existing railway infrastructure (Altaf et al.,2016, Vazquez et al.,2010). A DC-DC converter with high power density, efficiency, and reliability can enable wind energy to power railway systems efficiently, reducing dependence on fossil fuels and lowering carbon emissions. When designing a boost converter, the selection of inductance and capacitance is crucial, as it directly impacts the output voltage and current delivered to the load. The values of these components are calculated using specific formula, which consider the desired output voltage and current requirements. By precisely determining the inductance and capacitance values, the boost converter can efficiently step up the input voltage to meet the load's needs, ensuring

a stable and reliable power supply. This careful selection is vital to achieving optimal performance, minimizing energy losses, and preventing damage to the load.

The selection of inductance and capacitance is basically based on the output voltage and current required by load of a boost converter. The values of these elements are done by using the following formula:

$$L = \frac{D(1-D)^2 R}{2f} \quad (4.1)$$

Where: D is duty ratio,

f is frequency in hertz, and

R is resistance in Ohm

Optimizing the operation of a DC-DC converter involves striking a balance between the switching period and inductance value. Running the converter at a high duty cycle, near its maximum, is ideal as it reduces switching losses. This is achieved by increasing the switching period, which in turn allows for the use of a larger inductance. However, there's a tradeoff, as a longer switching period requires a larger inductance, affecting the overall design. Calculating the optimal capacitor value, represented by "C", is crucial and can be done using a specific formula, ensuring efficient energy conversion:

$$C = \frac{D}{R \left(\frac{\Delta V_o}{V_o} \right) f} \quad (4.2)$$

4.3.2 Voltage Source Inverters Modeling

A crucial step in harnessing power from a generator is connecting it to a load, which is achieved through a combination of a three-phase rectifier and a boost converter. The boost converter plays a vital role in regulating the voltage on the generator side, ensuring a stable output. By incorporating a diode bridge rectifier, the effective load seen from the generator side becomes purely resistive, ultimately resulting in a constant DC voltage. This design enables the efficient and reliable transfer of power from the generator to the load. In the design of Voltage Source Inverters (VSI), a crucial aspect is the correlation between the DC bus voltage and the generator line voltage. This relationship is fundamental in ensuring the efficient operation of the VSI system. The DC bus voltage, which serves as the input to the inverter, has a direct impact on the generator line voltage, which is the output of the system. A well-designed VSI system should be able to maintain a stable DC bus voltage, despite fluctuations in the generator line voltage, to provide a reliable and efficient power supply. This intricate balance is critical in various industrial applications, including power grids and renewable energy systems (Strasik et al.,2010, S.Wandelt et al.,2011).

The relationship between the DC bus voltage and generator line voltage can be written as

$$V_{dc} = V_{line} \frac{3\sqrt{2}}{\pi} \quad (4.3)$$

so

$$V_{dc} = V_s \frac{3\sqrt{6}}{\pi} \quad (4.4)$$

Which gives,

$$I_s = \frac{\sqrt{6}}{\pi} I_{dc} \quad (4.5)$$

The relation between the voltage v of the PMSG and the rotor speed W_m is as shown as

$$V = k\phi W_m \quad (4.6)$$

Where ϕ is the air gap flux and k is a constant.

The speed of asynchronous generator is shown in

$$W_m = \frac{120f}{p} \quad (4.7)$$

Where f : frequency of the induced voltage in the generator

P : number of poles in the generator

4.3.3 Energy management in wind energy integrated with traction power supply system

Energy management systems have become essential components of modern railway operations, playing a pivotal role in optimizing energy consumption and enhancing the overall efficiency of railway systems and smart railway networks. As the global focus on sustainable transportation solutions continues to intensify, railway operators are increasingly recognizing the need to adopt advanced technologies that can help reduce energy usage, minimize environmental impact, and improve system performance. At the heart of this transition are energy management systems, which provide a comprehensive and integrated approach to monitoring, controlling, and optimizing energy usage across railway networks. These sophisticated systems leverage a range of sensors, data analytics, and automated control mechanisms to continuously monitor and analyze energy consumption patterns, identify areas of inefficiency, and implement targeted strategies to optimize energy usage. This could involve regulating the power supply to trains, managing the operation of supporting infrastructure like stations and maintenance facilities, and coordinating the integration of renewable energy sources into the railway network. By deploying energy management systems, railway operators can achieve significant reductions in energy consumption, leading to substantial cost savings and a smaller environmental footprint. These systems also enable

enhanced operational efficiency, as they allow for real-time adjustments and fine-tuning of energy usage based on factors like passenger demand, weather conditions, and network congestion. This level of dynamic optimization ensures that energy resources are utilized in the most cost-effective and sustainable manner, contributing to the overall competitiveness and long-term viability of railway transportation as a preferred mode of sustainable mobility (Hongzhi et al.,2023, Alzahrani et al., 2022).

The integration of wind energy into railway power supply, while promising for environmental sustainability, presents significant challenges in ensuring stable and reliable energy delivery. Fluctuations in wind speed directly impact power generation, requiring sophisticated control strategies to manage energy storage and smooth out these variations. Artificial neural network (ANN)-based control strategies emerge as a potent solution, offering unparalleled adaptability and learning capabilities for this complex task. ANNs, mimicking the structure and function of the human brain, can learn from historical data and real-time conditions to predict wind energy output and adjust energy storage accordingly. This predictive capability allows for proactive energy management, ensuring optimal utilization of storage capacity and preventing power disruptions. By continuously analyzing data patterns and adapting control parameters, ANNs can automatically adjust energy storage charge and discharge rates to match fluctuating wind energy production. This dynamic approach surpasses traditional control methods, which rely on static parameters and struggle to adapt to unpredictable wind conditions. Consequently, ANN-based control not only enhances the stability and reliability of the railway power supply but also optimizes energy utilization, maximizing the integration of renewable energy sources. Furthermore, ANNs can be deployed for real-time monitoring and fault detection, further enhancing the overall efficiency and resilience of the system.

Flywheel Energy Storage Systems (FESS) offer many benefits compared to other energy storage options. They have a straightforward design that is highly efficient, providing both high power and energy density along with quick response times. Additionally, FESS systems have a longer lifespan and require minimal maintenance. The components of a FESS include a flywheel, electric machine, power conversion system, and bearings as shown in Figure 4.13. A current decoupling network based on ANN is proposed to generate the quadrature stator current component. A multilayer feedforward artificial neural network (ANN) is utilized to estimate a crucial value in real-time, based on the flywheel's rotational speed and the required grid power level. This level is limited by the charging and discharging power limits, which are primarily dependent on the flywheel's instantaneous speed. The ANN controller,

comprising inputs, the hidden layer, and output, uses a hyperbolic tangent and linear activation function in the hidden and output layers, respectively. A Levenberg-Marquardt algorithm and MATLAB's ANN toolbox, the network can accurately generate the desired value within specified ranges of machine speed and grid power.

Integrating wind energy with a railway power supply system offers dual benefits. In standby state, the Energy Storage System (ESS) remains idle, as the substation can supply sufficient power to meet traction demands. However, in operation mode, the substation power demand surges, and the ESS, traction substation, Renewable Energy Source (RES), and Railway Battery Equipment (RBE) work together to provide traction power. Interestingly, even in operation mode, the substation can revert to standby mode if the combined power supply from RES and RBE exceeds traction power demand, allowing excess energy to be stored in the ESS(Braeuer et al.,2019, Killer et al.,2020).

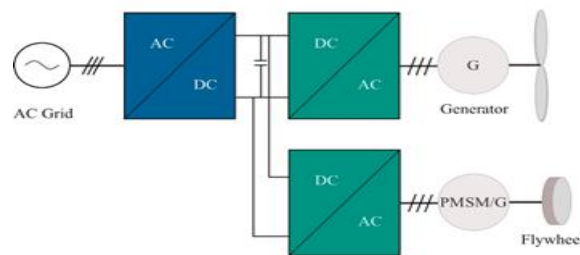


Figure 4.6 Fly wheel Energy Storage System [145]

A smart grid (SG) is a modern electric grid with a two-way flow of electricity and data between power utilities and consumers. Unlike a conventional electric grid, a smart grid is a digital technology-based electricity network driven by automation, communication, and connectivity. The rise of the smart grid is due to its potential to improve grid resilience, energy independence, and reliability, among other factors. Across the world, digital technology-enabled grids are driving smarter resource use and helping consumers, as well as power industry stakeholders reduce costs, save energy, and make better energy usage decisions. The smart grid operates in three main modes. When the substation has available capacity, the traction substation and renewable energy source provide power for trains. The energy storage system remains on standby as the substation has enough power. In this mode, the substation's power demand is met efficiently. The smart grid offers three distinct operating modes to optimize energy management and ensure reliable train operations. In the first mode, when the substation possesses adequate capacity, the traction substation and renewable energy sources

fulfill the traction power requirements for trains, while the energy storage system remains in standby mode as the substation is sufficiently capable of meeting power demands.

In the second mode, when the substation's power demand rises, the traction substation, energy storage system, and renewable energy system collaborate to deliver traction power. The energy storage system transitions into discharging mode to supplement the power supply, and the substation operates in standby mode since the renewable energy source's power output exceeds the traction power demand.

Finally, in the third mode, when the grid experiences peak power demand, the energy storage system assumes the primary role in providing traction power for trains, while the traction substation and renewable energy sources serve as backup power sources. The energy storage system discharges its stored energy, allowing the substation to remain in standby mode to reserve its capacity for critical situations. This flexible operation of the smart grid ensures efficient energy utilization, cost savings, and continuous power supply for train operations, even during periods of high demand as shown in Figure 4.14.

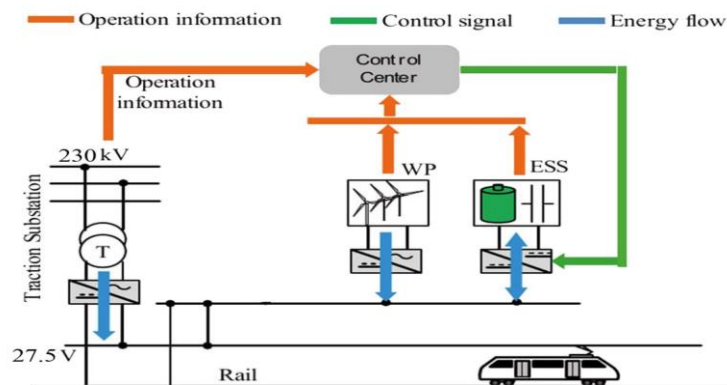


Figure 4.7 Architecture of Energy Management system [145]

In conclusion, ANN-based control strategies represent the most promising approach for efficient management of energy storage in wind energy integrated into railway power supply, offering a future-proof solution for a greener and more sustainable transportation sector.

4.4 Simulation and Result Discussion

As seen in Figure 4:15, in the MATLAB, the MPPT-based wind turbine was modeled. A boost converter and 300kW of wind energy were employed in the proposed model's simulation to increase the voltage step. The RBFN learning algorithm uses 1000 data items to create an output neuron, 500 hidden-layer neurons, and the MPPT algorithm. This study tests the suggested system for wind energy integration with a railway power supply both with and without an MPPT controller. Figure 4:16 shows the best validating results of the RBFN

administrator, which was developed using the Levenberg-Marquardt method. Figure 4.17 presents a validation check and the recommended RBFN-trained network gradients. In Figure 4.18 and Figure 4.19, the optimal regression for training, test, validation, and overall efficacy data is displayed for the proposed and suggested RBFN-based MPPT method.

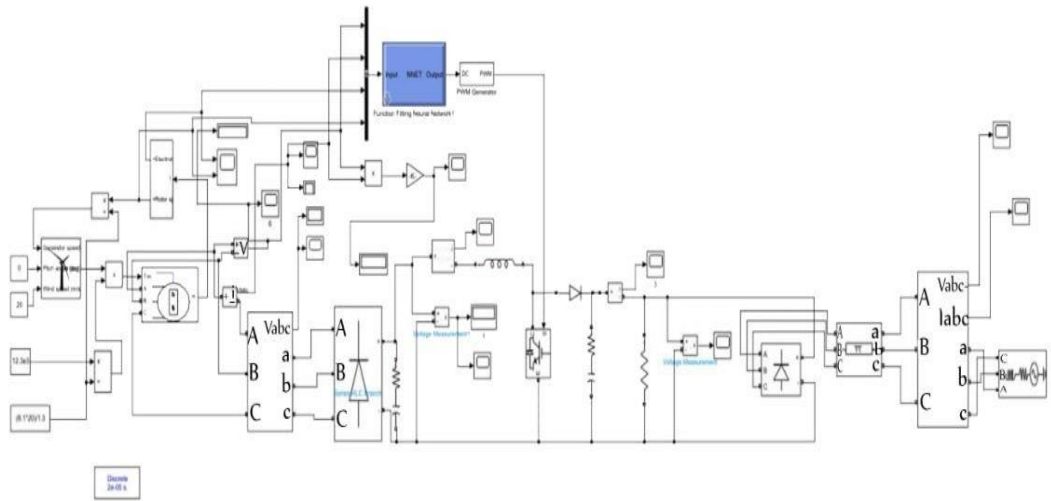


Figure 4.8: Simulation of wind energy system integrated with railway power supply with MPPT.

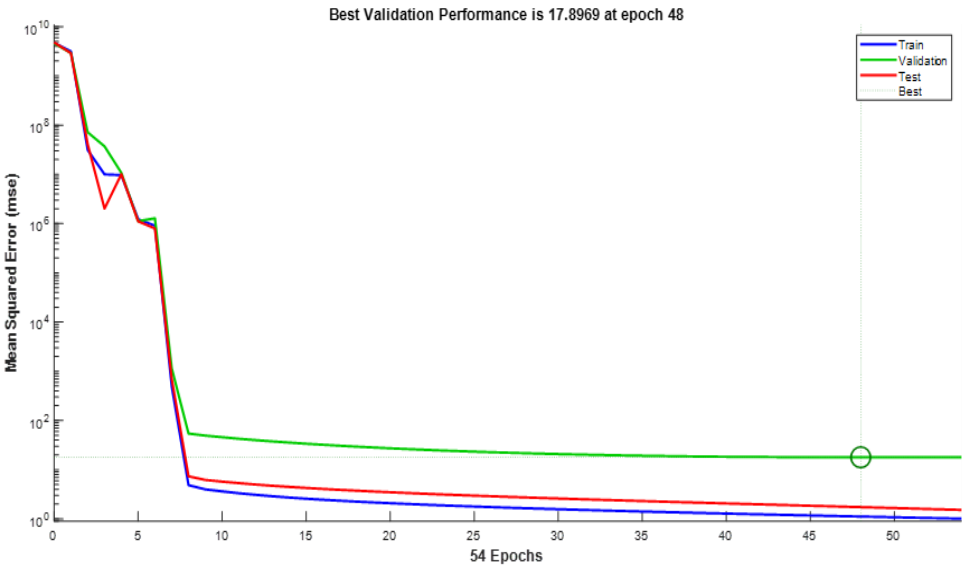


Figure 4.9: Validation performance of RBFN wind with MPPT controller

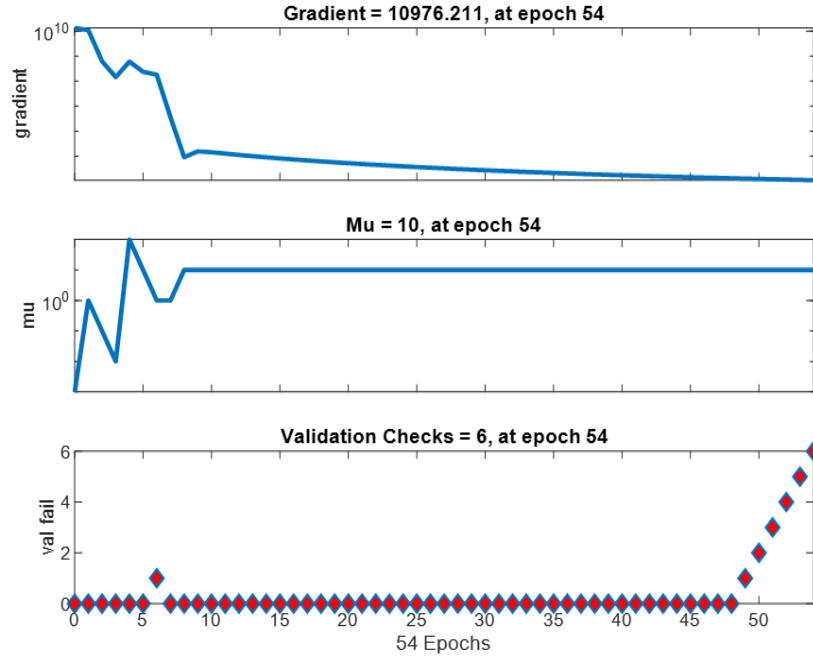


Figure 4.10: Training data of RBFN with MPPT controller

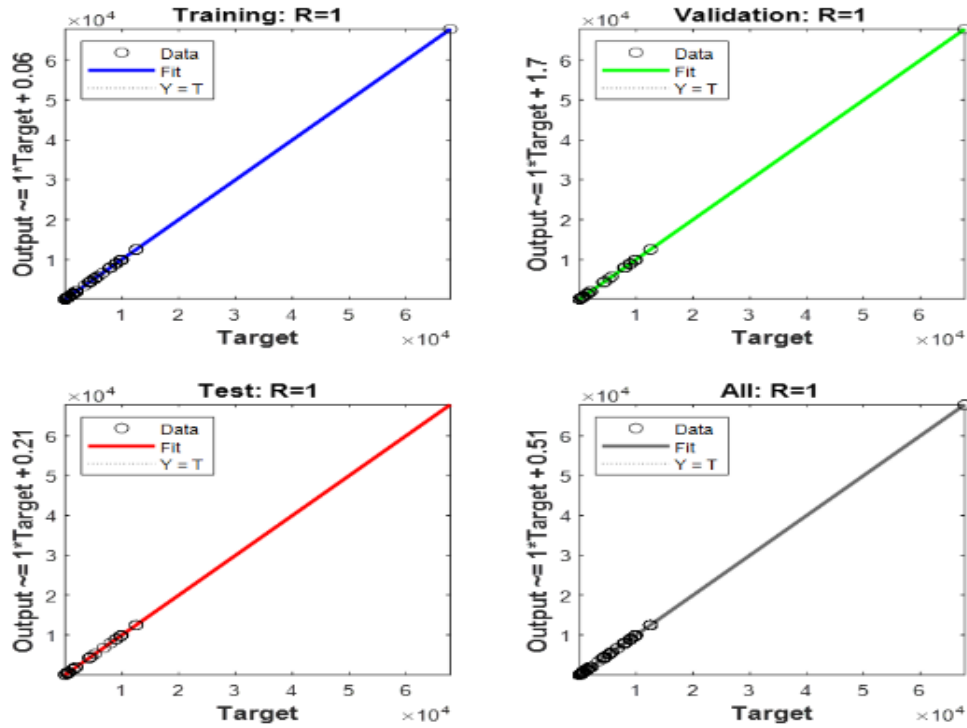


Figure 4.11: Regression plot for training, validation, test of RBFN wind with MPPT controller

The suggested approach is assessed in this study for wind energy integration with a railway power supply using an MPPT controller, and it is also implemented in a MATLAB/Simulink model without an MPPT controller, AC grid rated at 230kV, 50 Hz. For the wind turbine to

monitor its highest output more effectively based on PMSG that is integrated with a railway power supply system, this paper presents artificial neural network techniques based on the RBFN-MPPT controller. The WECS operates on a permanent magnet synchronous generator (PMSG). The voltage and power generated by the rectifier are recorded and directed into an RBF-NN controller. The MPPT algorithm manages the power usage of a DC-DC boost converter to optimize power extraction. The power from the boost converter is connected to the electrical grid through a voltage source. Table 4.1 summarizes the generated power, voltage, and current values both with and without MPPT. This segment gives the outcomes of the imitation done below MATLAB/Simulink.

Table 4.1: Output power in different wind speed

Wind speed(m/sec)	Power without MPPT (kW)	Power with MPPT (kW)
10	240.5	248.8
12	225.7	250.1
14	246,6	254.8
16	252.2	255.7
18	255.2	256.6
20	260.3	289.3

To examine the wind speed variation, a 300kW wind turbine was evaluated using MATLAB and Simulink models in turn. At a wind speed of 18 m/sec with MPPT control, Figure 4.19, Figure 4.20, and Figure 4.21 illustrate the power extracted, the resulting waveforms for the voltage that is generated, output current. Extraction power, output voltage waveform, and output currents are depicted in Figures 4.22, 4.23, and 4.24, without MPPT control. According to the simulation results, there is a small oscillation present, and the average power extracted under MPPT control is 256.6 kW and without MPPT control it is 255.2 kW.

The comprehensive analysis using MATLAB and Simulink modeling provides valuable insights into the wind turbine's dynamic behavior and the critical role of MPPT control in optimizing its performance across varying wind speed conditions. This detailed examination equips the researchers with a deeper understanding of the wind turbine's capabilities, enabling

them to make informed decisions and further refine the system's design and control strategies for improved real-world applications

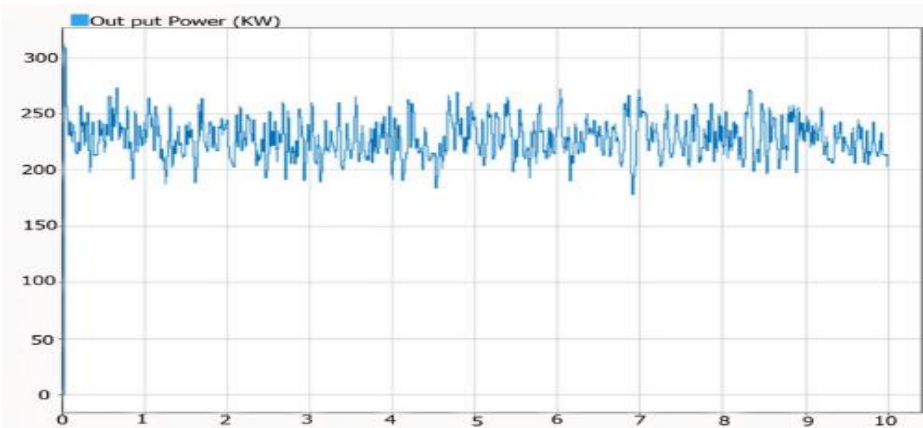


Figure 4.12: Output power with MPPT at 18m/sec

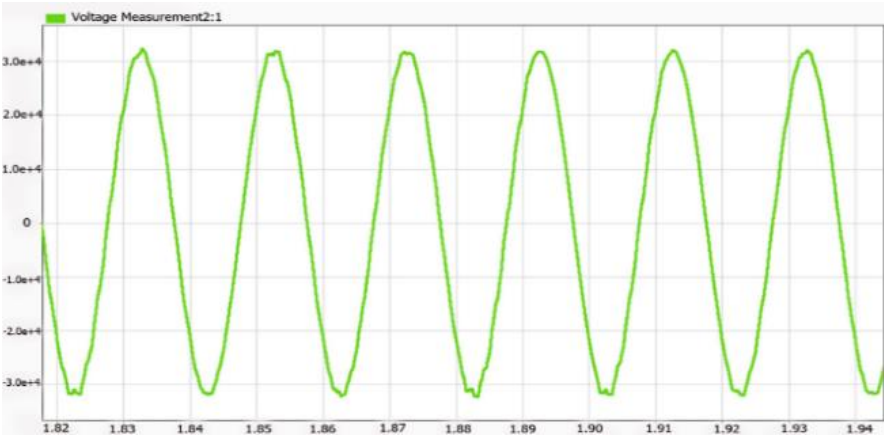


Figure.4.13: Output voltage with MPPT at 18m/sec



Figure. 4.14: Output current with MPPT at 18m/sec

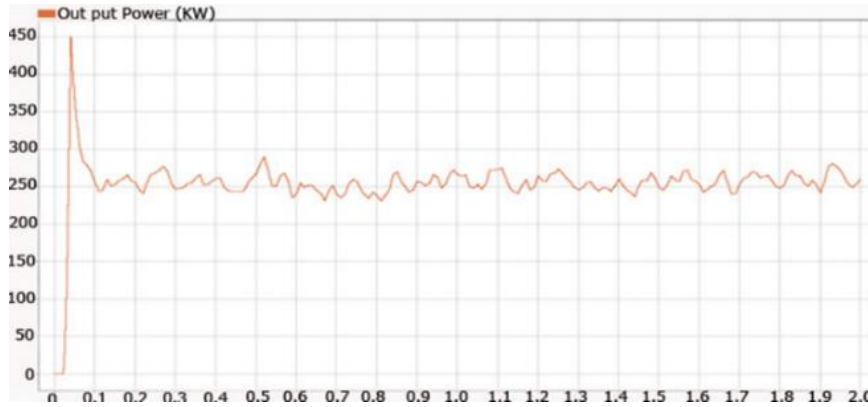


Figure 4.15: Output power without MPPT at 18m/sec

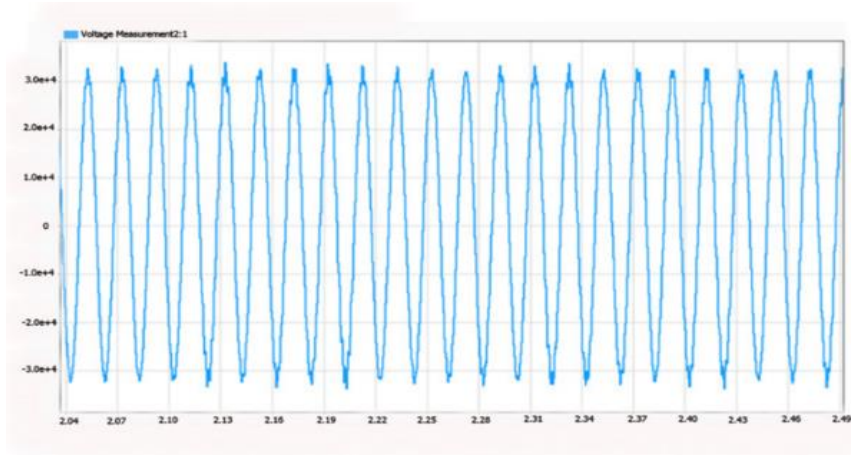


Figure.4.16: Output voltage without MPPT at 18m/sec

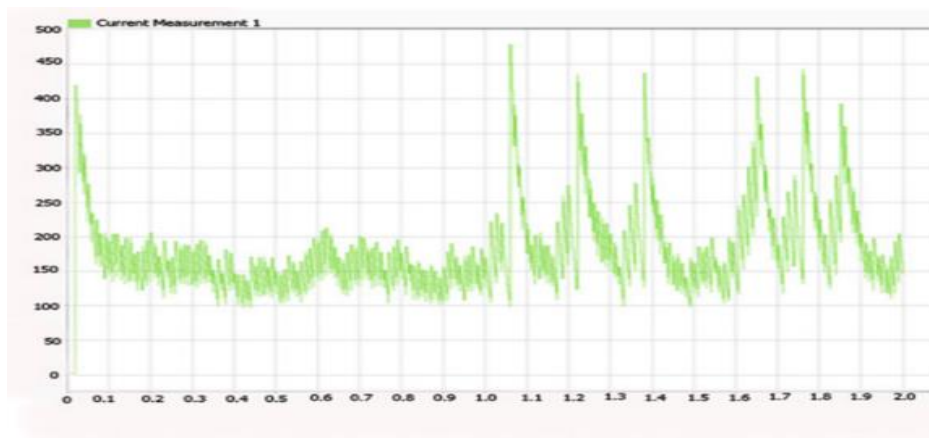


Figure 4.17: Output current without MPPT at 18m/sec

The provided figures offer a detailed look at the power extraction and current waveforms of a wind turbine system operating at a wind speed of 20 m/sec, both with and without Maximum Power Point Tracking (MPPT) control. Figures 4.25 and 4.26 depict the power extracted and current flowing from the system without MPPT control. These waveforms indicate that while

power is being generated, there is a considerable degree of oscillation present, likely due to the lack of optimized control mechanisms. The average power extracted in this uncontrolled scenario is measured at 260.3 kW. In contrast, Figures 4.27, 4.28, and 4.29 show the results when MPPT control is implemented. This advanced control strategy is designed to continuously adjust the system parameters to extract the maximum possible power from the wind. The simulation findings reveal that with MPPT control, the average power extracted increases to 289.3 kW a notable improvement over the uncontrolled case. Furthermore, the waveforms exhibit a smaller number of oscillations, indicating the MPPT control is effectively smoothing out power fluctuations and optimizing the energy capture.

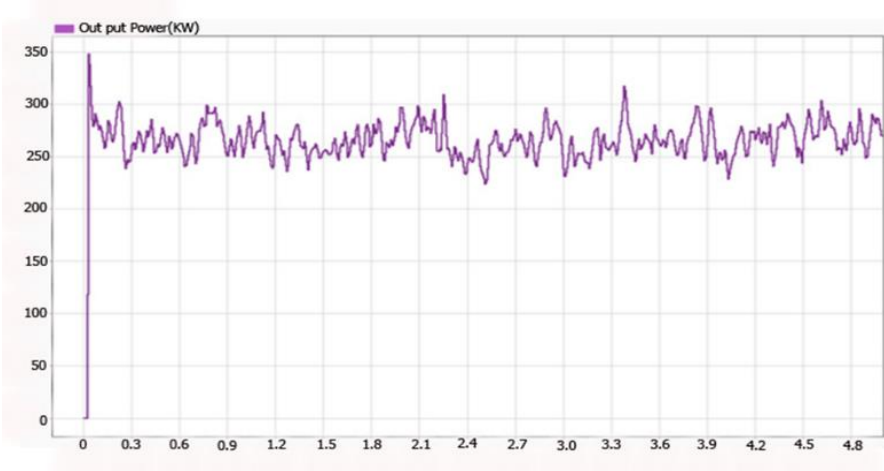


Figure 4.18: Output power without MPPT at 20m/sec

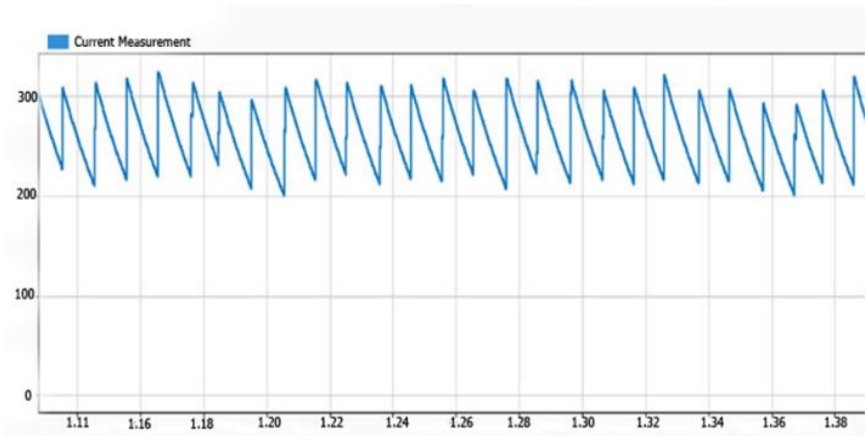


Figure 4.19: Output current wave form without MPPT at 20m/sec

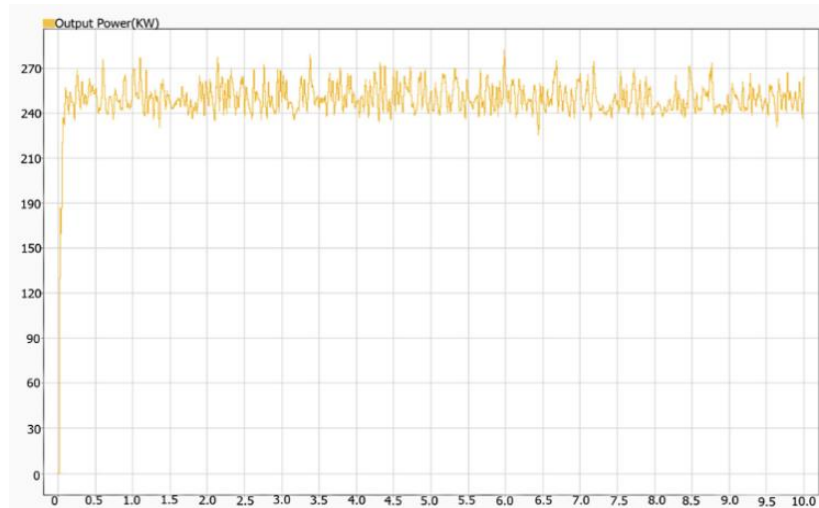


Figure 4.20: Output power with MPPT at 20m/sec

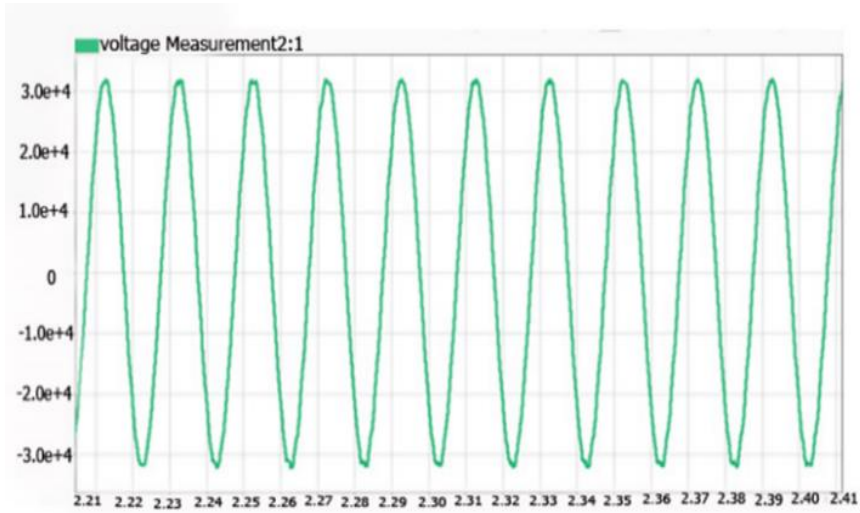


Figure 4.21: Output voltage with MPPT at 20m/sec

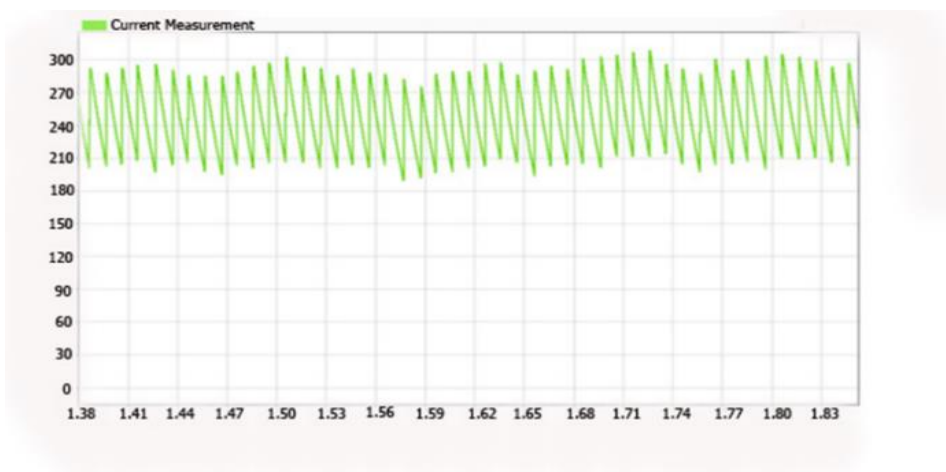


Figure 4.22: Output current with MPPT at 20m/sec

4.5 Analysis of Wind Energy Integration with railway Power supply

The power supply for the Ethiopia-Djibouti Railway is a single-phase, 25 kV, 50 Hz system. The three-phase, 230kV power supply that powers the railway system and is sourced from the national grid via a V/V transformer serves as the main power source in this study. The catenary system is then powered by this 25 kV two-phase voltage, which is created from the 230kV three-phase voltage (Mugisho and Worku, 2021). Figure 4.27 illustrates the basic structure of the suggested arrangement. Three main components make up the suggested system. These include the control system, train locomotive, renewable energy source, and railway traction substation. Wind energy source and the main grid power supply system are integrated into the strategy of a mixture or hybrid scheme. The suggested approach is assessed in this study for wind energy integration with a railway power supply using an MPPT controller, and it is also implemented in a MATLAB/Simulink model, considering a 7200KW load and an AC grid rated at 230kV, 50 Hz.

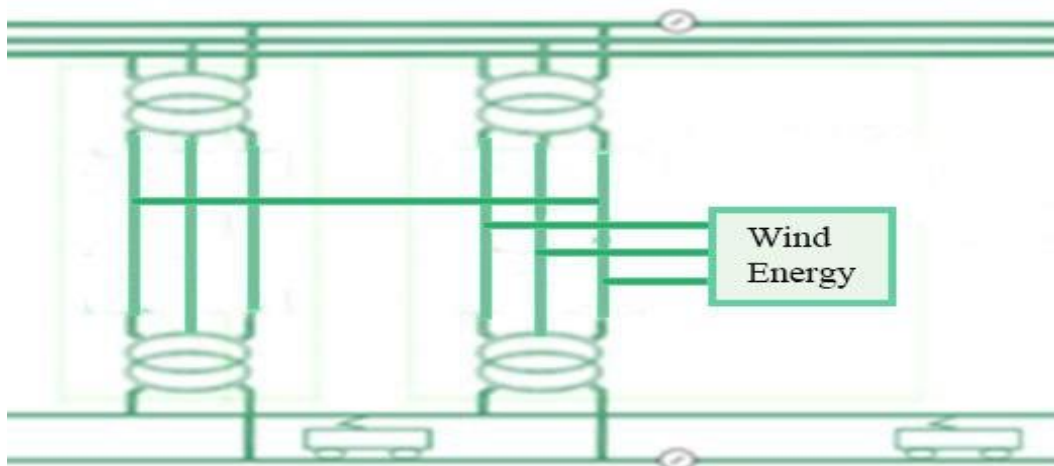


Figure 4.23 Wind energy system integrated with traction power supply.

By using the suggested MPPT control strategy, the AC train electrical power method incorporates wind turbines. AC railway power supply system integrates wind energy through the recommended MPPT control approach. The tracing approach is applied to cutting the greatest control from wind or turbine energy, and it is simulated as a case study. To maximize the electricity generated by the winds, we propose an ANN-based MPPT algorithm to increase the amount of power produced using green energy across a range of weather conditions (H. Elaissaoui et al.,2020, W.M. Lin et al.,2021). This subsection provides an explanation of each of the wind generator, PMSG, and electric power conversion simulators that make up the entire WECS system. This part is the various wind generators, PMSG, and electricity conversion simulators that make up the entire WECS technology.

4.5.1 Grid connected mode

The integration of wind energy into railway power supply systems via grid-connected mode represents a significant advancement in sustainable transportation infrastructure. In this setup, wind turbines generate electricity that is fed directly to railway networks. This seamless integration ensures a steady and reliable power supply, optimizing energy use and minimizing reliance on fossil fuels. The grid-connected mode allows for real-time balancing of supply and demand, leveraging modern grid management technologies. Additionally, this system enhances the resilience of railway operations by diversifying energy sources and reducing carbon footprints. Consequently, it promotes both environmental sustainability and energy efficiency, aligning with global efforts to mitigate climate change and advance green mobility solutions.

In this study, we examine the integration of wind energy into a three-phase 230kV power system sourced from the national grid, with a focus on enhancing the reliability and sustainability of the existing power supply. The system incorporates a Vv transformer, which serves as a crucial interface between the traditional grid and the renewable energy source. A total of five wind turbines, each with a rated capacity of 1.6MW, are connected in series to harness wind energy effectively. This configuration enables the turbines to work in both grid-connected and island modes, providing flexibility in operation and ensuring continuous power delivery under varying conditions.

As illustrated in Figure 4.31 and detailed in Table 4.2, all traction substations connected to the power grid in grid-connected mode are experiencing overload conditions. The recorded bus voltage fluctuates between 239kV and 249.9kV, failing to comply with the IEEE standard, which stipulates an acceptable voltage range of +5% and -5% of the nominal voltage. This deviation indicates a significant issue in voltage regulation and power distribution efficiency, potentially leading to operational inefficiencies and increased wear on electrical infrastructure. Ensuring compliance with IEEE standards is crucial for maintaining system reliability and preventing potential outages or equipment damage, necessitating immediate corrective measures to address the overloading and restore voltage levels within the acceptable range.

the fluctuating nature of wind energy, the island mode can reduce reliance on traditional fossil fuels and decrease overall carbon emissions associated with railway transport. Furthermore, such integration necessitates advanced energy storage solutions and grid management technologies to ensure a stable and reliable power supply, addressing the intermittent and variability of wind energy. This synergy between wind energy and railway systems not only promotes environmental sustainability but also contributes to energy security and operational cost savings (Faria WR, et al. ,2021).

As illustrated in Figure 4.32 and detailed in Table 4.3, all traction substations connected to the power grid supply side operate underloaded when in island mode. The bus voltage at the traction load side ranges from 20.71 kV to 26.3 kV, adhering to European standards EN50163: 2004. According to these standards, the maximum non-permanent voltage permitted for short durations is 29 kV, while the minimum permanent voltage must not fall below 19.0 kV. This compliance ensures that the voltage levels remain within safe and efficient operational limits, thereby maintaining the reliability and stability of the traction power system. The observed voltage range signifies a well-regulated system, meeting the stringent criteria established to ensure safety and performance.

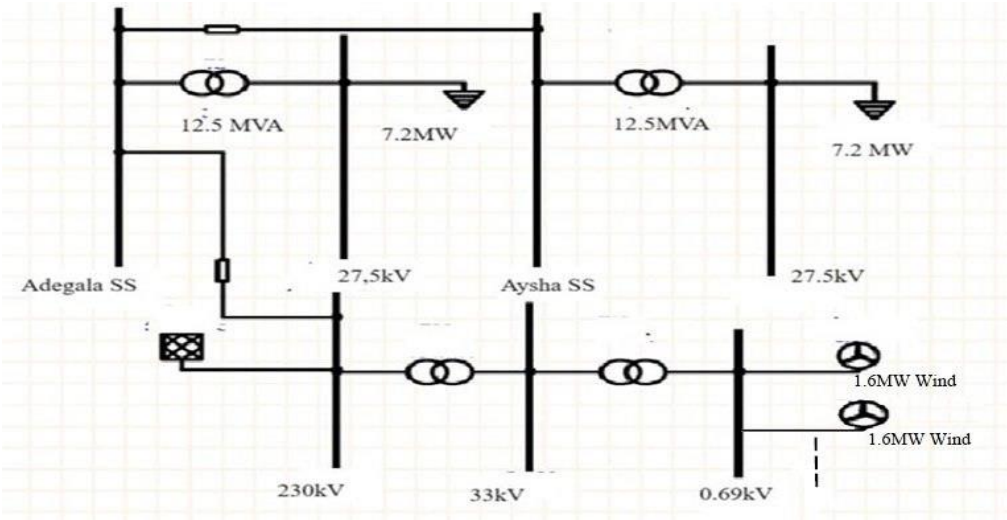


Figure 4.25 Schematic diagram of power flow analysis in Island mode

Table 4.3 Load flow analysis result

Bus Id	Nominal voltage (kV)	Condition	Operating voltage(kV)
Afedem TPS	27.5	Undervoltage	20.71
Hurso TPS	27.5	Undervoltage	21.2
Gota TPS	27.5	Undervoltage	23.2
Adegala TPS	27.5	Undervoltage	24.1
Aysha TPS	27.5	Undervoltage	26.3
Dewanle TPS	27.5	Undervoltage	25.4

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

The following is the conclusion of this research, which is divided into four parts according to the research objective. This section includes a discussion of the overall results gained and the methodology and approach used in the present thesis.

5.1 Conclusion

In conclusion, the research conducted on the Ethio-Djibouti railway route has highlighted the significant challenges presented by single-phase traction loads in terms of power quality management within railway traction systems. The study was structured into three key parts, In the first part power quality analysis of the present railway power system under investigation. Power quality analysis is a critical component of evaluating the efficiency and reliability of modern railway power systems. In the current investigation, SCADA records have revealed that power outages occur for an alarming average of 1368 hours each year. Such disruptions not only impact the operational continuity of railway services but also compromise safety standards and passenger satisfaction. The identification of these outages underscores the necessity for a comprehensive analysis of the existing power infrastructure to determine the underlying causes and potential solutions. Using advanced modeling techniques, the Electrical Transient Analyzer Program (ETAP) has been employed to conduct a detailed analysis of the section under study. This analytical approach has brought to light significant issues regarding power quality, particularly in terms of voltage distortion and unbalance. The findings indicate that the levels of distortion and voltage imbalance exceed accepted industry standards, which can have detrimental effects on the performance of rolling stock and signaling systems. Inadequate power quality can lead to increased wear and tear on electrical components, higher maintenance costs, and, ultimately, reduced train reliability. The results from the ETAP analysis emphasize the urgent need for remedial measures to enhance the power quality of the railway system. Potential strategies may include the installation of power conditioning equipment, reconfiguration of electrical distribution layouts, and the implementation of advanced monitoring systems to enable real-time assessment of power quality metrics.

In the second part, RBFN-ANN based MPPT algorithm used to extract the maximum possible power under various weather conditions simulated in Matlab Simulink. MSE of 0.012 is used to demonstrate the validity using RBFN-based MPPT. The proposed MPPT approach is tested beneath numerous wind hustles using MATLAB/Simulink. The output control graph is displayed in the results section so that the differences in output power with and without MPPT

can be compared. At a wind speed of 20 meter per second, the developed system provides an average maximum power of 289.3 kW with MPPT. The MSE value of 0.012 is comparatively low, making it more appropriate for use in an MPPT controller. According to the simulation's outcomes, monitoring the highest power was effectively accomplished by the RBFN-based MPPT controllers. Further research will be conducted to develop and verify the proposed approach. This will involve using more detailed models and validating the simulation model on a laboratory-scale experimental WECS setup. Additionally, power quality analysis should be conducted to ensure the constancy of the wind energy integrated with the railway power source scheme in the future work.

In the third part, the simulation results indicate that both the wind energy grid-connected system and the island mode configuration effectively operate within acceptable limits, even under conditions of overload and underload. Specifically, all traction substations linked to the power grid in grid-connected mode are facing overload scenarios, leading to fluctuations in recorded bus voltages ranging between 239 kV and 249.9 kV. Unfortunately, these conditions do not comply with the IEEE standard, which mandates that voltage must be maintained within a range of $\pm 5\%$ of the nominal value. This suggests potential concerns regarding system stability and reliability under high demand periods. In contrast, when operating in island mode, the traction substations exhibit an underloaded state, which results in more favorable voltage levels. The bus voltage on the traction load side is reported to range from 20.71 kV to 26.3 kV, aligning with the European standards set forth in EN50163: 2004. These standards are pivotal in ensuring the integrity of power supply, as they dictate that non-permanent voltage peaks must not exceed 29 kV while the minimum permanent voltage should remain above 19.0 kV. Adherence to these criteria is crucial for maintaining both the safety and operational effectiveness of the traction power system.

5.2 Recommendation

The integration of renewable energy sources, particularly wind energy, into railway power supply systems offers a promising solution to address the surging energy demands of modern railway operations. As railway systems strive for greater efficiency and sustainability, the adoption of wind energy through advanced control technologies like the RBFN-based MPPT (Maximum Power Point Tracking) regulator presents a significant opportunity. The proposed system configuration, a Permanent Magnet Synchronous Generator (PMSG), has been proven to enhance energy utilization from wind, making it a practical option for railway traction substations. The successful application and substantial benefits observed in the Aysha wind

farm case study underscore the feasibility and effectiveness of this approach. Given these advantages, it is strongly recommended that railway operators explore this innovative integration of wind energy into their power supply infrastructure, not only to fulfill their increasing energy requirements efficiently but also to contribute to broader environmental goals by minimizing dependency on fossil fuels.

The integration of smart grid technology with railway power supply system's presents a promising avenue for enhancing the efficiency and sustainability of rail transportation. To ensure the reliability and effectiveness of such integration, further research is necessary, particularly in assessing the stability of the grid during the incorporation of wind energy for traction power supply. This research should meticulously examine the dynamic interactions between renewable energy sources and the unique load demands of railway systems. Additionally, investigations into power quality mitigation strategies are imperative to address potential issues such as voltage fluctuations and harmonic distortions that can arise from integrating renewable energy sources with the railway's power supply. By focusing on these research areas, it is possible to develop a robust framework for smart grid integration that not only supports the operational needs of the railway system but also contributes to the broader objectives of sustainable and efficient energy use.

REFERENCES

- [1] Santiyanon, D., Hongesombut, K., & Srisonphan, S. (2016). Simulation of voltage unbalance reduction in railway electrification system by different special transformers, *Procedia Computer Science*, 86, 373–376.
- [2] Sayed Mohammad Mousavi Guzzardi et al. (2015). Power Quality Issues in Railway Electrification: A Comprehensive Perspective. *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 3081-3090.
- [3] Li Xuebin. (2014). Research on power quality compensation system for traction power supply of high-speed railway. *Electric drive*, 44(6):27-30.
- [4] V. N. Olievski (2013). Rail Transport: Framework for Improving Railway Sector Performance in Sub Saharan Africa. SSATP, 2013.
- [5] R.E. Morrison (2000). Power Quality Issues on AC Traction Systems. *Proceedings of Ninth International Conference on Harmonics and Quality of Power*, Orlando, USA, vol. 2, pp. 709-714.
- [6] R. Bullock (2019). Off Track: Sub-Saharan African Railways. The International Bank for Reconstruction and Development, The World Bank
- [7] M.B. Bouraima et al (2020). A study on the development strategy of the railway transportation system in the west African economic and monetary Union (WAEMU) based on the SWOT/AHP technique, *Sci. African*.
- [8] De Bod, A., & Havenga, J. H. (2010). Sub-Saharan Africa's Rail Freight Transport System: Potential Impact of Densification on Cost. *Journal of Transport and Supply Chain Management* 4 (1): 89–101.
- [9] Abbas Alizadeh Boora, Arash, Zare, Firuz, Ghosh, Arindam, Ledwich, Gerard (2007). Applications of Power Electronics in Railway Systems. *Institute of Electrical and Electronics Engineers (IEEE)*.
- [10] Han, Zhengqing, Yuge Zhang, Shuping Liu, and Shibin Gao. (2011). Modeling and Simulation for Traction Power Supply System of High-Speed Railway. *Asia-Pacific Power and Energy Engineering Conference*.
- [11] Jinhao Wang, Huipeng Li, Lei Feng, Long Xu, Xiaohui Lv, Yonghai Xu (2007). Analysis of power quality issues of electrified railway. *8th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*.
- [12] M. Aeberhard, C. Courtois, and P. Ladoux (2010). Railway Traction Power Supply from the State of the Art to Future Trends. *Pisa, Italy*, pp. 1350-1355.

- [13] U. J. Shenoy, K. G. Sheshadri, K. Parthasarathy, H. P. Kincha and D. Thukaram, (2004).Matlab/PSB Based Modeling and simulation of 25 kV AC railway traction system-A particular reference to loading and fault condition, Proc. Of Int. Conf. (IEEE) on TENCON, Vol. C, pp. 508-511.
- [14] Mariscotti, A., & Sandrolini, L. (2021). Detection of harmonic overvoltage and resonance in AC railways using measured pantograph electrical quantities. *Energies*, 14(18)/
- [15] Pei Luo, Mengjie Liu, Qiren Wang, Zhiwei Xiao, Yufeng Yang, Jian Zhang.(2023) .Toughness Analysis and Evaluation of Traction Power Supply System under Extreme Heavy Load.26th International Conference on Electrical Machines and Systems (ICEMS).
- [16] D. Paice (1996). Power Electronic Converter Harmonics - Multipulse Methods for Clean Power,IEEE Press, Second Edition, 1996, ISBN: 078031137.
- [17] Arrillaga, J. & Watson, N.R. (2003). Power quality issues, solutions and standards: A technology review. *Journal of Applied Science and Engineering* 18(4), 371–380.
- [18] Fini Fathima, and S. Prabhakar Karthikeyan (2016). Harmonics Analysis on Various Traction Transformers in Co-Phase Traction System.*Ain Shams Engineering Journal*, vol. 7, no. 2, pp. 627-638.
- [19] Xiaohong Huang, Hanlin Wang, Qun zhan Li, Naiqi Yang, Tao Ren, You Peng, Haoyang Li.(2022).Electrical characteristics of new three-phase traction power supply system for rail transit', *Railway Engineering Science*.
- [20] Lin wei Li, Mingli Wu. (2020).A three-phase symmetric converter in electric railway systems for power quality and energy efficient improvement. *International Transactions on Electrical Energy Systems*
- [21] Sy-Ruen Huang, and Bing-Nan Chen (2002). Harmonic Study of the Le Blanc Transformer for Taiwan Railway's Electrification System. *IEEE Transactions on Power Delivery*, vol. 17, no. 2, pp. 495-499.
- [22] Luo, A., Wu, C.; Shen, J.; Shuai, Z., Ma, F (2011). Railway Static Power Conditioners for High-speed Train Traction Power Supply Systems Using Three-phase V/V Transformers. *IEEE Trans. Power Electron*, 26, 2844–2856.
- [23] Tanta, M.; Barros, L.A.,Pinto, J.G.; Martins, A.P.,Afonso, J.L. (2020).Modular Multilevel Converter in Electrified Railway Systems.Applications of Rail Static Frequency Converters and Rail Power Conditioners,'In *Proceedings of the International Young Engineers Forum (YEF-ECE)*, Costa da Caparica, Portugal,pp. 55–60.

- [24] G.W. Chang, Hsin-Wei Lin, and Shin-Kuan Chen (2004). Modeling Characteristics of Harmonic Currents Generated by High-Speed Railway Traction Drive Converters' Transactions on Power Delivery, vol. 19, no. 2, pp. 766-773
- [25] Alexander Bueno et al. (2010). Harmonic and Balance Compensation Using Instantaneous Active and Reactive Power Control on Electric Railway Systems. Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Palm Springs, USA, pp. 1139-1144.
- [26] R. Lamedica et al. (2020). A Methodology to Analyses Voltage Unbalance Mitigation in 2×25 kV-50 Hz Railway Systems. International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Sorrento, Italy, pp. 600-605.
- [27] Linya Liu, Zifeng Zhong (2024). Introduction to High-Speed Railway. Springer Science and Business Media LLC.
- [28] Yujie Xia, Guosong Lin, Liya Guo, Qiang Li. (2013).Research on Voltage Losses of AT Traction Power Supply System.Energy and Power Engineering.
- [29] M. Aeberhard, C. Courtois, and P. Ladoux (2010).Railway Traction Power Supply from the State of the Art to Future Trends.SPEEDAM 2010, Pisa, Italy, pp. 1350-1355.
- [30] An Luo et al.(2011).Railway Static Power Conditioners for High Speed Train Traction Power Supply Systems Using Three-Phase V/V Transformers.IEEE Transactions on Power Electronics, vol. 26, no. 10, pp. 2844-2856.
- [31] Linwei Li et al. (2019). A Three-Phase to Single-Phase AC-DC-AC Topology Based on Multi-Converter in AC Electric Railway Application.IEEE Access, vol. 7, pp. 111539-111558.
- [32] Qianming Xu et al. (2017). Analysis and Comparison of Modular Railway Power Conditioner for High-Speed Railway Traction System.IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 6031-6048.
- [33] G.W. Chang, Hsin-Wei Lin, and Shin-Kuan Chen (2004). Modeling Characteristics of Harmonic Currents Generated by High-Speed Railway Traction Drive Converters. IEEE Transactions on Power Delivery, vol. 19, no. 2, pp. 766-773.
- [34] M. Goto et al. (1995). Static Negative-Phase-Sequence Current Compensator for Railway Power Supply System. International Conference on Electric Railways in a United Europe, Amsterdam, Netherlands, pp. 78-82.
- [35] Y.E. Zhongming, W.C.L.O. Edward, H. Wenk, P. Tang, S.G. Ye (2000).A study of current harmonics of electrical traction power supply system, 31st Annual IEEE Power Electronics Specialists Conference, pp. 1149-1154.

- [36] Farhad Shahnian, and Rasoul Esmaeilzadeh (2005). Voltage Unbalance Problems and Solutions for Electrified Railway Systems. 7th International Conference Modern Electric Traction in Integrated XXI Century Europe (MET), Warsaw, Poland, pp. 1-5.
- [37] Kaleybar, H.J.; Kojabadi, H.M.; Brenna, M.; Foiadelli, F.; Fazel, S.S. (2017). An active railway power quality compensator for 2×25kV high-speed railway lines. In Proceedings of the IEEE International Conference on Environment & Electrical Engineering & IEEE Industrial & Commercial Power Systems Europe IEEE, Milan, pp. 1–6.
- [38] Michele De Santis, Luca Silvestri, Luca Vallotto, Gino Bella. (2022). Environmental and Power Quality Assessment of Railway Traction Power Substations. 6th International Conference on Green Energy and Applications (ICGEA).
- [39] Hossain, E.; Han, Z.; Poor, H.V. (2012). Smart Grid Communications and Networking, Cambridge University Press: Cambridge, UK.
- [40] Ma, R.; Chen, H.H.; Huang, Y.R.; Meng, W. (2013). Smart grid communication: Its challenges and opportunities' Trans. 4, 36–46
- [41] Kabalci, E.; Kabalci, Y.(2019).Introduction to smart grid architecture. In Smart Grids and their Communication Systems. Springer: Berlin, Germany. 3–45.
- [42] D. Fan, Y. Ren, Q. Feng(2021).Restoration of smart grids: current status, challenges, and opportunities Renewable and Sustainable Energy Reviews. Elsevier, vol. 143.
- [43] C. Feng, Y. Wang, Q. Chen, Y. Ding, (2021). Smart grid encounters edge computing: opportunities and applications Advances in Applied Energy. ScienceDirect, Ç. Iris, J.S.L. Lam.
- [44] W. Wang, Yi Xu, M. Khanna, (2011).A survey on the communication architectures in smart grid. Comput. Network. 55.
- [45] S.R. Salkuti(2021).Challenges, Issues and Opportunities for the Development of Smart Grid. vol. 10, Woosong University, Jayang-dong.
- [46] Zhang, P., et al. (2010). Next-generation monitoring, analysis, and control for the future smart control center.IEEE Transactions on Smart Grid, vol. 1 (2), pp. 186-192.
- [47] Dileep, G. (2020). A survey on smart grid technologies and applications. Renew. Energy, 146, 2589–2625.
- [48] J. R. Anam Malik (2016). A Review of Demand Response Techniques in Smart. IEEE Electrical Power and Energy Conference (EPEC).
- [49] Nico Saputro, Kemal Akkaya, Suleyman Uludag (2012). A survey of routing protocols for smart grid communications. Computer Networks.

- [50] Prashant Gore, Ravishankar Dudhe, Roma Raina. (2023). A review of Renewable Energy & Smart Grid system applications in railways. *Advances in Science and Engineering Technology International Conferences (ASET)*, 2023 Publication.
- [51] Ataul Bari, Jin Jiang, Walid Saad, Arunita Jaekel. (2014). Challenges in the Smart Grid Applications: An Overview. *International Journal of Distributed Sensor Networks*.
- [52] Sun, Zhong Wei, and Tao Jia.(2013).A Proposed Communication System for Field Area Networks of Smart Grid.*Advanced Materials Research*.
- [53] Chen Feng, Zhixuan Gao, Yanying Sun, Peng Chen. (2021). Electric railway smart microgrid system with integration of multiple energy systems and power-quality improvement. *Electric Power Systems Research*.
- [54] K. Sayed, H.A. Gabbar.(2017).SCADA and smart energy grid control automation. Elsevier Publication
- [55] C. C. R. Dehulls, et. al. (2015).Voltage and Frequency Control for Future Power Systems, The Electra IRP Proposal,EDST.
- [56] P. Lopes, et. al.(2015).Defining Control Strategies for Micro Grids Islanded Operation.IEEE Trans. on Power Sys. Vols. 21, NO. 2, pp. 916-924.
- [57] M. Lange and U. Focken (2006). Physical Approach to Short-Term Wind Power Prediction.Springer
- [58] P. Zhang, W. Xiao, and P. Choudhury (2011). Communication systems for grid integration of renewable energy resources,'IEEE Network, vol. 25, no. 5, pp. 22–29.
- [59] Chen, S.-y., et al. (2009). Survey on smart grid technology," *Power System Technology*, vol. 33 (8).
- [60] Zhou, X, Ma, Y.Gao, Z.,Wang,H (2017).Summary of smart metering and smart grid communication.In *Proceedings of IEEE International Conference on Mechatronics and Automation (ICMA)*, Takamatsu, pp. 300–304.
- [61] Ancillotti, E., Bruno, R., and Conti, M. (2013). The Role of Communication Systems in Smart Grids: Architectures, Technical Solutions and Research Challenges. *Comp. Commun.* 36, 1665–1697.
- [62] F. R. Yu, P. Zhang, W. Xiao, and P. Choudhury (2011). Communication systems for grid integration of renewable energy resources,'IEEE Network, vol. 25, no. 5, pp. 22–29.
- [63] B. Heile(2010).Smart grids for green communications [industry perspectives. *IEEE Wireless Communication*, vol. 17, no. 3, pp. 4–6.
- [64] Gapakumar, Bharata Reddy (2016). Stability concerns in smart grid with Emerging Renewable technologies,'Institute of Technology

- [65] F. Camacho, et.al. (2011). Control for Renewable Energy and Smart Grids. The Impact of Control Technology, T. Samad and A.M. Anna swamy.
- [66] Wenyu an, Z. D. Y. L. M. (2013). Development Strategies of Smart Grid in China and Abroad. Proceedings of the Chinese Society of Electrical Engineering, vol. 33 (31), pp. I0001-I0028.
- [67] Sunkara Pradeep, Shreeya Krishna, Muthyala Samhitha Reddy, Datrika Divya Sri, Muni gala Sumana Sri(2023).Analysis and Functioning of Smart Grid for Enhancing Energy Efficiency Using Optimization Techniques with IoT.IEEE 5th International Conference.
- [68] Chren S., Rossi B., Pitner T.(2016).Smart grids deployments within EU projects: The role of smart meters; Proceedings of the 2016 Smart Cities Symposium Prague (SCSP); Prague, Czech Republic, pp. 1–5.
- [69] X. Fang, S. Misra, G. Xue, D. Yang (2011).Smart grid the new and improved power grid: a survey. IEEE Communications Surveys Tutorials, ‘Vol. 14, no.4, pp.944-980.
- [70] Pradeep, Shreeya Krishna, Muthyala Samhitha Reddy, Datrika Divya Sri, Munigala Sumana Sri.(2023).Analysis and Functioning of Smart Grid for Enhancing Energy Efficiency Using Optimization Techniques with IoT.IEEE 5th International Conference on Cybernetics, Cognition and Machine Learning Applications (ICCCMLA).
- [71] Fredrik Ege Abrahamsen, Yun Ai, Michael Cheffena.(2021).Communication Technologies for Smart Grid.A Comprehensive Survey, Sensors.
- [72] Song Tan, Debraj De, Wen-Zhan Song, Junjie Yang, Sajal K. Das.(2017).Survey of Security Advances in Smart Grid: A Data Driven Approach. IEEE Communications Surveys & Tutorials.
- [73] Renbin Feng, Hui Wang, Kui Xie, Chunhua Xu, and Enyong Hu.(2010).The research and design of communication power supply based on the proton exchange membrane fuel cell. IEEE International Conference on Information Theory and Information Security.
- [74] Adel Ab-Belk hair, Javad Rahebi, Abdulbaset Abdulhamed Mohamed Nureddin. (2020). A Study of Deep Neural Network Controller-Based Power Quality Improvement of Hybrid PV/Wind Systems by Using Smart Inverter.International Journal of Photoenergy.
- [75] Shaofeng Xie, Yiming Zhang, and Hui Wang(2021).A Novel Co-Phase Power Supply System for Electrified Railway Based on V Type Connection Traction Transformer.‘Energies, vol. 14, no. 4, pp. 1-21.
- [76] Kai Li, Zhi Zhang, Zhibo Zhanga, Trillion Q. Zheng, Rui Xiang Hao, Xiaojie You, Jingxi Yang.(2021).Analysis and Correction of a Pantograph Location Method Based on Current Information of Traction Network. IEEE Transactions on Transportation Electrification.

- [77] Abbasalizadeh Boora, Arash, Zare, Firuz, Ghosh, Arindam, Ledwich, Gerard. (2007). ‘Applications of Power Electronics in Railway Systems.Institute of Electrical and Electronics Engineers (IEEE).
- [78] P. Mohankumar, R. Vinoth, P. Suresh, J. Ajayan.(2023).The Automated Efficiency Enhancement of Photovoltaic cells using Artificial Intelligence and Internet of Things.9th International Conference on Electrical Energy Systems (ICEES).
- [79] Zhi Zhang, Trillion Q. Zheng, Kai Li, Ruixiang Hao, Xiaojie You, Zhibo Zhang, Jingxi Yang. (2020).Smart Electric Neutral Section Executer Embedded with Automatic Pantograph Location Technique Based on Voltage and Current Signals.IEEE Transactions on Transportation Electrification.
- [80] Hongjun Yang, Xiong Du, Bin Chen, Yuelong Cao, Lianqing Zheng, Heng Wang.(2023). The Influence of Electrified Railway Traction Power Supply System on the Power Quality of Regional Power Grid.IEEE International Conference on Sensors, Electronics and Computer Engineering (ICSECE).
- [81] Linwei Li, Mingli Wu. (2020).A three-phase symmetric converter in electric railway systems for power quality and energy efficient improvement. International Transactions on Electrical Energy Systems.
- [82] Daisuke Kato, Hiroo Horii, Taichiro Kawahara(2014).Next-generation SCADA/EMS Designed for Large Penetration of Renewable Energy.Hitachi Review Vol. 63, No. 4, pp. 151-155.
- [83] Jun Zhu, Haitao Hu, Zhengyou He, Xiaomin Guo ,Weiguo Pan(2021).A power-quality monitoring and assessment system for high-speed railways based on train-network-data center integration. Rail. Eng. Science
- [84] Hu Guozhen; Cai tao; Chen Changsong; Duan Shanxu (2009). Solutions for SCADA system communication reliability in photovoltaic power plants. Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International, pp. 2482 - 2485.
- [85] Sunil Kumar, Kamlesh Dutta. (2016). Intrusion detection in mobile ad hoc networks: techniques, systems, and future challenges. Security and Communication Networks.
- [86] Anantvalee T, Wu J (2006) .A Survey on Intrusion Detection in Mobile Ad Hoc Networks. Wirel/Mobil Netw Secur, Springer:170-196
- [87] Collier, S. E. (2010). Ten steps to a smarter grid. Industry Applications Magazine, IEEE, 16(2), 62-68.

- [88] M. Ismail, W. Zhuang, E. Serpedin, and K. Qaraqe(2015).A survey on green mobile networking: From the perspectives of network operators and mobile users.IEEE Communications Surveys & Tutorials, vol. 17, no. 3, pp. 1535–1556, Third Qu.
- [89] T. Chen, Y. Yang, H. Zhang, H. Kim, and K. Horneman (2011).Network energy saving technologies for green wireless access networks.IEEE Wireless Communications, vol. 18, no. 5, pp. 30–38.
- [90] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, C. X. Wang, T. A. Le, M. R. Nakhai, J. Zhang, and L. Hanzo(2011).Green radio: radio techniques to enable energy efficient wireless networks.IEEE Communications Magazine, vol. 49, no. 6, pp. 46–54.
- [91] J. Wu, Y. Zhang, M. Zukerman, and E. K. N. Yung (2015).Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey.IEEE Communications Surveys & Tutorials, vol. 17, no. 2, pp. 803–826.
- [92] M. Erol-Kantarci and H. Mouftah(2015).Energy-efficient information and communication infrastructures in the smart grid: A survey on interactions and open issues.IEEE Communications Surveys & Tutorials, vol. 17, no. 1, pp. 179–197.
- [93] Niya Chen, Rongrong Yu, Yao Chen, Hailian Xie (2018). Hierarchical method for wind turbine prognosis using SCADA data.IET Renewable Power Generation,Volume 6, Issue 2.
- [94] R. Palma-Behnke, D Ortiz, L. Reyes, G. Jimenez-Estevez, N. Garrido(2011).A social SCADA approach for a renewable based micro-grid .The Huatacondo Project, Power and Energy Society General Meeting.
- [95] Niya Chen, Rongrong Yu, Yao Chen, Hailian Xie (2018). Hierarchical method for wind turbine prognosis using SCADA data.IET Renewable Power Generation,Volume 6, Issue 2.
- [96] Hamidi, V., Robinson F. (2008). Responsive Demand in Networks with High Penetration of Wind Power. 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century.
- [97] B Chen, YN Qiu, Y Feng, PJ Tavner, WW Song(2011).A Wind Turbine SCADA Alarm Pattern Recognition’, IET Digital Library.
- [98] Yang Hu, Jizhen Liu, Taihua Chang, Wei Li, Zhongwei Lin and Hongmin Meng, describes (2014).Effective wind speed estimation and optimized setting strategy for WTGS based on SCADA system,’control conference (AUCC).4th Australian, 43-48.
- [98] Xingzhen Bai, Xiangzhong Meng, Zhaowen Du, Maofa Gong, Zhiguo Hu(2008).Design of Wireless Sensor Network in SCADA System for Wind Power Plant.Automation and Logistics, IEEE International Conference on.

- [99] Michael Wilkinson, Brian Darnell, Thomas Van Delft, Keir Harman(2014).A Comparison of methods for wind turbine condition monitoring with SCADA data.IET Renewable Power Generation 8 (4), 390- 397.
- [100] Linas Gelazanskas, Kelum AA Gamage,(2016).Managing renewable intermittency in smart grid: Use of residential hot water heaters as a form of energy storage.Electrical Apparatus and Technologies (SIELA), 19th International Symposium on, 1-4.
- [101] Shahzad, Mirza Naveed, Saiqa Kanwal, and Abid Hussanan,(2020).A New Hybrid ARAR and Neural Network Model for Multi-Step Ahead Wind Speed Forecasting in Three Regions of Pakistan.IEEE Access .
- [102] Gharavi, H., & Ghafurian, R. (2011). Smart grid: The electric energy system of the future. Proceedings of the IEEE, 99(6), 917-921
- [103] Mellit, A., A. Massi Pavan, and V. Lughi.(2014).Short-term forecasting of power production in a large-scale photovoltaic plant, Solar Energy.
- [104] A. Botterud, J. Wang, V. Miranda, and R. J. Bessa(2010).Wind power forecasting in US electricity markets.The Electricity Journal, vol. 23,no. 3, pp. 71–82.
- [105] Hamed Jafari Kaleybar, Hossein Hafezi, Morris Brenna, Roberto Sebastiano Faranda. (2024). Smart AC-DC Coupled Hybrid Railway Microgrids Integrated with Renewable Energy Sources: Current and Next Generation Architectures. Energies.
- [106] Reisi Ali Reza, Moradi Mohammad Hassan, and Jamasb Shahriar (2013). Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review.” Renewable and sustainable energy reviews.
- [107] Amir, A., Che, H. S., Amir, A., El Khateb, A., and Abd Rahim, N. (2018). Transformerless high gain boost and buck-boost dc-dc converters based on extendable switched capacitor (sc) cell for stand-alone photovoltaic system. Sol. Energy 171, 212–222.
- [108] Babaei, E., Abbasnezhad, A., Sabahi, M., and Hosseini, S. H. (2017). Analysis and design of a softswitching boost dc/dc converter. IET Power Electron. 10 (11).
- [109] E. Koutroulis and K. Kalaitzakis (2006). Design of a Maximum Power Tracking System for Wind-Energy-Conversion Applications’ Transactions on Industrial Electronics, Vol. 53, No. 2, pp. 486-494.
- [110] Petr Žižlavský, Ladislav Mlynařík (2023). Turning of Traction Power Station Converter Output Characteristics. International Conference on Electrical Drives and Power Electronics (EDPE).

- [111] Tsai, Ming-Fa, Chung-Shi Tseng, and Yu Hsiang Hung. (2012). A novel MPPT control design for wind-turbine generation systems using neural network compensatory. IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society.
- [112] Z. Alnasir and M. Kazerani(2016).A Small-Scale Standalone Wind Energy Conversion System Featuring SCIG, CSI and a Novel Storage Integration Scheme.Renewable Energy, vol. 89, pp. 360-370.
- [113] S. Pira (2020).The Importance of Renewable Energies with Emphasize on Wind Power. International Journal of Engineering Research & Technology (IJERT), vol. 9, no. 6.
- [114] Xian(2017).Feasibility Study report of Aysha II wind power project. Northwest Electric Power Design Co.ltd of China power Engineering consulting group.
- [115] A. Tabakhpour and S. Mousavi(2016).Hybrid railway power quality conditioner for high-capacity traction substation with auto-tuned DClank controller,IET Elec. Syst. Transport. Available, vol. 6, n. 3, p. 207-214.
- [116] Mtilde Ornkloo (2016). Compensating Unbalance in Synchronous Railway Traction Systems with Railway Power Conditioners.UPPSALA UNIVERISITY, UTEC ES 16002.
- [117] Shu Zeliang, Xie Shaofeng, Li Qunzhan.(2010).Development and implementation of a prototype for co-phase traction power supply system Proc Asia-Pac Power Energy Eng Conf , pp. 1-4.
- [118] M. Olofsson, E. Thunberg, (1999).Optimal commitment of frequency converter units for railway power supply,Proc IEEE Railroad Conf , pp. 71-77.
- [119] Bharat Bhargava. (1999).Railway electrification systems and configurations, IEEE Power Eng Soc Summer Meet, pp. 445-450.
- [120] Y.E. Zhongming, W.C.L.O. Edward, H. Wenk, P. Tang, S.G. Ye. (2000).A study of current harmonics of electrical traction power supply system 31st Annual IEEE Power Electronics Specialists Conference, pp. 1149-1154.
- [121] Steven Senini, Peter J. Wolfs.(2000).Hybrid active filter for harmonically unbalanced three phase three wire railway traction loads ,IEEE Trans Power Electron, pp. 702-710.
- [122] G. Celli Member, F. Pilo, S.B. Tennakoon. (2000). Voltage regulation on 25 kV AC railway systems by using thyristor switched capacitor,Proc IEEE Harmonics Quality Power, pp. 633-638.
- [123] Omi, M.; Kotegawa, R.; Ando, M.; Masui, T.; Horita, Y.(2014). Introduction and effectiveness of STATCOM to the independent power system of JR East. In Proceedings of the 2014 International Power Electronics Conference, Hiroshima, Japan, 18–21 May 2014; pp. 1317–1321.

- [124] Lee, T.; Hu, S.; Chan, Y. (2013). D-STATCOM With Positive-Sequence Admittance and Negative-Sequence Conductance to Mitigate Voltage Fluctuations in High-Level Penetration of Distributed-Generation Systems. *IEEE Trans. Ind. Electron.* 1417–1428
- [125] Sun, Z.; Jiang, X.J.; Zhu, D.Q.; Zhang, G.X. (2004). A novel active power quality compensator topology for electrified railway. *IEEE Trans. Power Electron.* 19, 1036–1042.
- [125] Luo, A.; Ma, F.; Wu, C.; Ding, S.Q.; Zhong, Q.C.; Shuai, Z.K. (2009). A Dual-Loop Control Strategy of Railway Static Power Regulator Under V/V Electric Traction System. *IEEE Trans. Power Electron.* 2011, 26, 2079–2091.
- [126] Khan ZA, Khan L, Ahmad S, Mumtaz S, Jafar M, Khan Q, (2021). RBF neural network based backstepping terminal sliding mode MPPT control technique for system.
- [127] Shu Cheng, Chang Liu, Tianjin Yu, Chaoqun Xiang, Pengfei Tian, Kaidi Li, Xun Wu. (2023) .Structure Improvement and Control Algorithm Optimization-Based Ground Automatic Neutral-Section Passing Method for Train. *IEEE Journal of Emerging and Selected Topics in Power Electronics*.
- [128] Reddy, K.J.; Sudhakar, N.; Saravanan, S.; Babu, B.C. (2018). High Step-Up Boost Converter with Neural Network Based MPPT Controller for a PEMFC Power Source Used in Vehicular Applications. *Int. J. Emerg. Electr. Power Syst.*
- [129] Toraj Mehrdad Ahmadi Kamarposhti, Mohammad Tayebbifar, Pegah Shaker, Nouri (2013). The Control of Buck Boost DC-DC Converters for DC Motor Drives on variable DC Voltage by Using Neural Network. *Life Science Journal*, volume 10, issue 5, p. 236 - 240.
- [130] Shahrin Azuan Nazeer, Nazaruddin Omar, Khairul Faisal Jumari, Marzuki Khalid, (2007). Face Detecting Using Artificial Neural Network Approach. *First Asia International Conference on Modelling & Simulation (AMS'07)*.
- [131] V. T. Vasantha Kumar, B. Ashok kumar (2022). Design and Analysis of RBFN Based MPPT Controller for Solar Energy System,” *Third International Conference on Intelligent Computing Instrumentation and Control Technologies (ICICICT)*.
- [132] El-Helw Hadi M., Magdy Ahmed, and Marei Mostafa (2017). A hybrid maximum power point tracking technique for partially shaded photovoltaic arrays, *IEEE access* 5.
- [133] N. Femia, G. Petrone, G. Spagnolo and M. Vitelli, (2004),” ‘Optimizing Duty-Cycle Perturbation of P&O MPPT Technique”, *35th Annual IEEE Power Specialists Conference, Aachen, Germany*.
- [134] Tiwari R, Babu NR (2016). Recent developments of control strategies for wind energy conversion systems. *Renew. Sustain. Energy Rev.*, vol. 66, pp. 268-85.

- [135] Pitchai Pandiyan & Subramani Saravanan & Natarajan Prabakaran & Ramji Tiwari & Thangam Chinnadurai & Neelakandan Ramesh Babu & Eklas Hossain (2021). Implementation of Different MPPT Techniques in Solar PV Tree under Partial Shading Conditions. Sustainability, MDPI, vol. 13(13), pages 1-22.
- [136] G. Moor, J. Beukes (2023). Maximum Power Point Tracking methods for small scale Wind Turbines.in Proceedings of Southern African Telecommunication Networks and Applications Conference (SATNAC).
- [137] M. Venkatesh Kumar (2020). DNN control based MPPT techniques for 40 kW wind power. MATLAB Central File Exchange.
- [138] K. Jyotheeswara Reddy, N. Sudhakar. (2018). High Voltage Gain Interleaved Boost Converter with Neural Network Based MPPT Controller for Fuel Cell Based Electric Vehicle Applications. IEEE Access.
- [139] K. Kumar, N. Ramesh Babu, K. R. Prabhu (2017). Design and Analysis of RBFN Based Single MPPT Controller for Hybrid Solar and Wind Energy System.IEEE Access.
- [140] M. Lwin and H. Lin (2018). Neural network based high-performance double boost DC-DC converter in using renewable energy system.Int. Journal of Science, Engineering and Technology Research, vol. 7, pp. 337– 339.
- [141] Altaf Mudho, Dr. Pinto Pius A. J (2016). Design and Implementation of Boost Converter for Photovoltaic Systems.NMAM Institute of Technology, Nitte Vol. 4, Special Issue 2.
- [142] Vazquez, S.; Lukic, S.M.; Galvan, E.; Franquelo, L.G.; Carrasco, J.M. (2010). Energy storage systems for transport and grid applications. *IEEE Trans. Ind. Electron.* 57, 3881–3895.
- [143] Strasik, M.,Hull, J.,Mittleider, J.,Gonder, J., Johnson, P., McCrary, K.,McIver, C.(2010). An overview of Boeing flywheel energy storage systems with high-temperature superconducting bearings. Supercond. Sci. Technol.
- [144] S. Wandelt, Z. Wang, and X. Sun(2011).Worldwide Railway Skeleton Network: Extraction Methodology and Preliminary Analysis.IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 8, pp. 2206-2216.
- [145] Hongzhi Dong, Zhongbei Tian Member, IEEE, Joseph W. Spencer, David Fletcher, Siavash Hajiabady (2023).Coordinated Control Strategy of Railway Multi Source Traction System with Energy Storage and Renewable Energy,IEEE Transactions on Intelligent Transportation Systems.
- [146] Alzahrani, A., Ramu, S.K., Devarajan,G. Vairavasundaram,I., Vairavasundaram, S.(2022), A review on hydrogen-based hybrid microgrid system: Topologies for hydrogen energy storage, integration, and energy management with solar and wind energy,'Energies 15.

- [147] Braeuer, F., Rominger, J, McKenna, R., Fichtner, W. (2019). Battery storage systems: An economic model-based analysis of parallel revenue streams and general implications for industry. *Appl. Energy* .
- [148] Killer, M., Farrokh seresht, M, Paterakis (2020). N.G. Implementation of large-scale Li-ion battery energy storage systems within the EMEA region. *Appl. Energy* .
- [148] Mugisho Mugaruka Josue, and Getachew Biru Worku (2021). Study of Power Reliability and Power Quality Problems of the Ethiopian-Djibouti Railway Distribution Networks. *American Journal of Electrical Power and Energy Systems*, vol. 10, no. 6, pp. 100-108.
- [149] H. Elaissaoui, M. Zerouali, A.E. Ougli, B. Tidhaf. (2020). MPPT algorithm based on fuzzy logic and artificial neural network (ANN) for a hybrid solar/wind power generation system: Proceedings of the Fourth International Conference On Intelligent Computing in Data Sciences (ICDS) (2020), pp. 1-6.
- [150] W.M. Lin, C.M. Hong, C.H. Chen. (2011). Neural-network-based MPPT control of a stand-alone hybrid power generation system: *IEEE Trans. Power Electron.*, pp. 3571-3581.
- [151] Faria WR, et al. (2021). Service restoration in modern distribution systems addressing grid-connected and island operations. *Electr. Power Syst. Res*