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Original Article

Power Quality Analysis of Ethio-Djibouti Railway Power Supply System

Mebratu Delelegn[1], Ravikumar Hiremath[2], Chandra Sekhar Reddy[3]

[1,2,3]*Electrical Power and Control Engineering Department, Adama Science and Technology University, Adama, Ethiopia.*

[1]*Corresponding Author : ethioemebre@gmail.com*

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***Abstract** - Enormous imbalance currents that the single-phase traction loads inject into the transmission systems lead to numerous control quality problems that develop the key challenges in the railway traction system. Power quality parameters have been measured, and a thorough study of influence feature analysis on behalf of the Ethio-Djibouti railway route has been conducted utilizing the 132kV traction substations using MATLAB/Simulink software as a case study. This paper intends to analyze power quality and identify the main harmonic current and voltage harmonics that exceed the recommended limitations in IEEE 519-1992. In the meantime, measurements of power feature at the 132 kV/25 kV level were compared with IEEE 519-1992 to determine the magnitude of energy & current harmonics as thriving as the overall harmonic distortion. The effect of harmonics produced by locomotives on the 132 kV upstream electric grid has been investigated through measurement and simulation. The limits indicated in the IEEE 519-1992 standard are exceeded by the values of individual and total voltage harmonic distortion determined by measurement and modelling at 132 kV and 25 kV, respectively. The voltage imbalance analysis on the 132 kV side is higher than 2%, which is not in compliance with IEEE standard 1159-2009.*

***Keywords** - Harmonic distortion, Negative sequence current, Voltage unbalance, Traction system, Power quality.*

1. Introduction

Electric trains have several advantages, such as large passenger volumes, high efficiency, minimal emissions, and cheap transportation costs. As a result, they are the cornerstone of modern extensive transportation networks. The traction converter transmits the electric vitality to the locomotive through a contact network. After a voltage step down, the traction power supply system transfers energy from the influence grid to the electric railway.

An electric locomotive, a transmission, a substation, and a high-voltage contact line system make up an electrified railway. An electric railway is a box of semiconductors and transformers that transform power from peripheral fonts into electrical power required to initiate an electric motor. The electrified railway's unpredictable loads commonly cause harmonics voltage imbalances, shifts in energy factor, and other power-related issues.

The Vv transformer divides the electricity needed across all three stages to create two individual phases of AC voltages, which are then fed into the traction networks. The electrical supply system of a train track uses one-phase 132kV/25kV generators to supply the cars with high-voltage electrical power, which creates the required characteristics. As seen in Figure 1, the Ethio-Djibouti railway operates on a single-phase power supply with 25 kV and 50 Hz. The neutral section separates the network of traction power supplies into portions, each supplied by a different traction substation [1-4].

The Ethiopia-Djibouti railway electrifies its entire 756 km with 20 tractions, as shown in Figure 2. Each traction substation has two independent power supply sources, one for use and the other reserved for it. It outputs 27.5 kV to the overhead catenary system, with the 27.5 kV side using a single bus-bar segment for connection. The main transformers of the traction substations adopt an operation mode that consists of a master transformer and standby reserve [5].

Every traction substation has a local operation control centre to monitor and manage moving trains and the entire traction substation. Power electronics components used in modern electric drive systems immediately impact the power network's upstream and downstream. Electric locomotives are considered single-phase loads because their speed and load conditions fluctuate over short time periods.

The power transformer of the traction vehicle powers the AC-DC rectifier, which is attached to the DC connector, as shown in Figure 3. A DC-AC converter powers an induction motor with three-phase electricity produced by converting DC voltage. High-power tank engines and various power-driven units of the plug-in rail line use a lot of power electronics converters with an AC-DC traction drive system [6, 7].

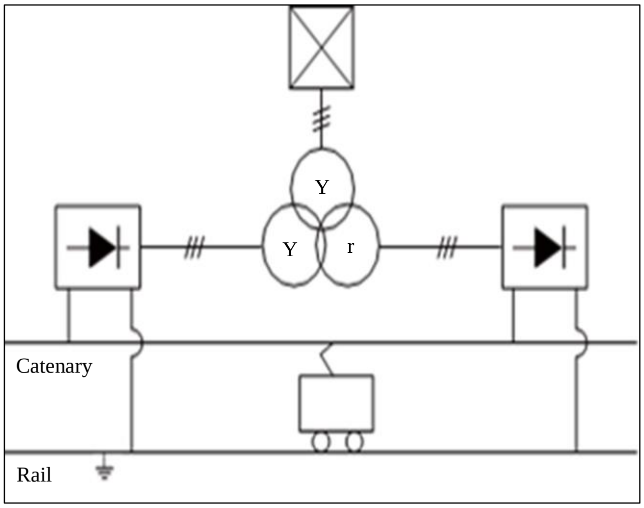

Fig. 1 A 25 kV, 50 Hz electric traction system

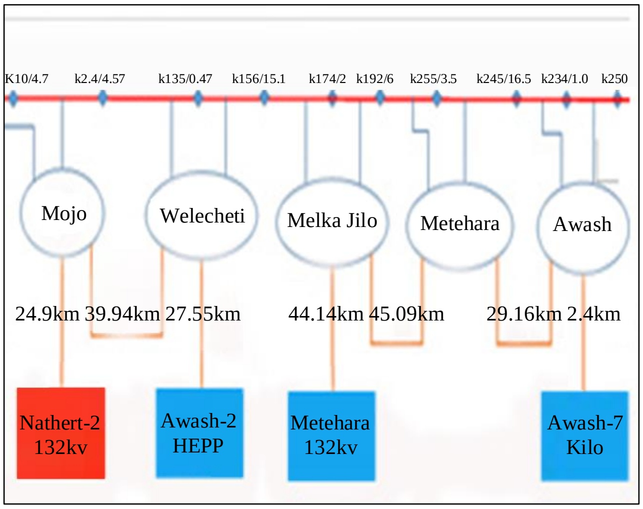

Fig. 2 Ethio-Djibouti traction power supply system

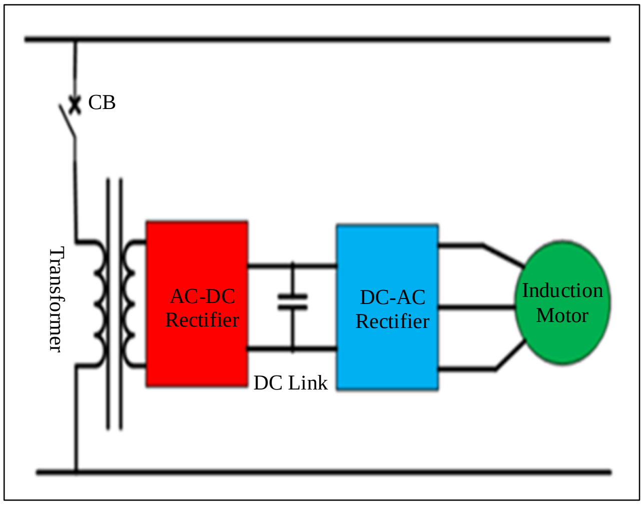

Fig. 3 AC-DC-AC traction locomotive

Nonlinear characteristics and single-phase nature, AC traction loads present several issues with power quality, including high reactive power consumption, low power factor, harmonic injection, and significant negative sequence current, which are becoming more serious problems in the rapid development of railway electrification. These issues negatively impact the electrical grid by increasing feeder line power losses, reducing traction transformer output capabilities, causing protection relays to malfunction, and causing transmission line control systems to operate incorrectly. Subsequently, it helps analyze the electrical output of a railroad line.

To evaluate current systems, determine whether power quality improvement or system enhancement is necessary, and examine new systems or the results of significant system upgrades [8-10]. A lot of research has been done to enhance railway electrification and power quality analysis techniques. Most existing research focuses on power quality analysis using different software simulation methods and is not supported by experiments or measurements to validate the results. The power quality analysis was not well addressed in the Ethio-Djibouti Railway line during the design phase, and it is now in the operation phase. The power supply system faces frequent power cuts due to power quality problems that introduce problems on the local distribution networks. The data taken from the local SCADA system shows frequent power cuts due to overvoltage and power quality problems, leading to a power factor below the national standard of 0.9.

The existing rail system's electrical reliability must be investigated to assess train functionality and determine how the railway system impacts the adjacent supply network. This paper's primary contribution is a comprehensive examination of power quality problems and recommendations for viable solutions to guarantee that the railway operates safely and effectively. The study examines the railway's power quality power systems, now detailing the existing system of the Ethio-Djibouti railway line using MATLAB/Simulink software and validating the simulation results with measured data by a power analyzer device.

To verify the reliability of the simulation, the results are validated against real-time measurements from the traction substations. The study is being conducted on methods for assessing the power quality and potential ways to progress the same. In conclusion, a thorough examination of issues of quality power is covered in detail.

The rest of the paper is organized as follows: The state of the art in power quality analysis is described in Section 2. In Section 3, an electric railway system with different components of traction substations is modelled using Matlab/Simulink to study and simulate the power quality analysis. In Section 4 an analysis of power quality using Matlab /Simulink is performed. In Section 5, measurements were taken using a power analyzer device in the Awash and Methara traction substation at 132000:100VTs and 100CTs for approximately 24 hours to determine the level of individual voltage and current harmonics present, the percentage of total distortion in current and voltage and other power quality parameters. Simulated and measured values were compared to justify the results. Finally, a brief is given regarding the power flow analysis as a conclusion in Section 6.

2. Literature Review

The utility grid may experience issues due to the traction system. The issues are associated with the unbalanced load from a single-phase catenary connection, unbalanced load from the trains that move and change, harmonic current from train rectifiers, reactive power from trains' high-power requirements, voltage flicker from moving loads between sections and so forth. These problems are a major obstacle for the utility as they negatively impact the system.

To identify compensatory solutions, research on a range of power quality concerns has been carried out throughout the previous several decades. Many research articles are being issued on traction, measurement analysis, and the implications and causes of issues with electricity availability in the electrical system. Below is a summary of a few literature evaluations on power quality analysis. In [11, 12, 7], a (RPC) is recommended as a remedy for the issues with power quality. It has undergone thorough analysis and comparison with methods for correcting for harmonic currents and negative sequences.

A DC link and a back-to-back connection are features of an RPC converter. The controller also helps to regulate the reflexive and dynamic authority by supplying a steady DC link voltage. Hence, RPC addresses the issues with power quality instigated by grid traction. By serving the front-end converter, the PWM rectifier transforms the DC conversion of sole-phase electricity onto DC connection battery-powered devices, like active and passive filtration for spectral removal, which may appear utilized to address power quality issues [7, 11, 13-15].

Bozider Filipovic-Grcic, Alan Zupan, and Ana Tomaso Vic Teklic [1] have examined the impact of electric train systems on 110 kV production infrastructure' electrical reliability with EMTP-RV, the battery-powered locomotive line being reconstructed. and the voltages and currents in the 110 kV and 25 kV networks were calculated. In 110/35/25 kV substations, power quality was measured, and the findings were evaluated in compliance with IEC 61000-3-6. Numerous power quality problems in the traction substations are regularly observed because of non-linear load and dynamic loading variation. Voltage imbalances, low power factors and negative sequence power quality issues have garnered increased attention due to their detrimental effects on utility power systems and traction electrical devices. The power electronics used for train control and drive systems in electric railway systems result in voltage and current harmonic distortion at the connection point in addition to voltage and current imbalance [16, 17].

Due to non-linear load and dynamic loading change, several power quality issues are frequently seen in the traction substations. Because they harm utility power systems and traction electrical equipment, voltage imbalances, low power factors, and negative sequence power quality concerns have received more attention. Along with voltage and current imbalance, the functioning of power electronics used in electric railway systems produces distorted harmonics of current and tension at an assertion of interface with railroad regulations and driving structures.

Rasoul Esmaeilzadeh and Farhad Shahnia [18] proposed that traction batteries are frequently linked to minimize variances in voltage to a circuit outside that is at least 100 kV. Nevertheless, this brings a lot dangerously close to utility facilities wiring. which raises worries about excessive negative sequence injection into utility generators. It is advisable to choose the traction substation feeding phases regularly. The grid will remain symmetrical if a comparable load is applied to each electrical source simultaneously. The voltage imbalance is mostly caused by imbalanced currents drawn at the numerous connection regions caused by forces that are not evenly divided. Since the outcome, the energy supply receives a substantial infusion to adverse course cutting-edge, especially thus the electrical network parts encounter unanticipated events such overheating, higher Cable and generator failures, the network of communications disruptions system, etc. [15].

Shaofeng Xie, Hui Wang and Yiming Zhang [19] suggested a unique co-phase electrical supremacy technique for electrifying railways that utilizes a VV-type connected tension transducer. This technique compensates for the reactivity and undesirable course and cancels the empty portion inside the momentum substation's outlet. It is advantageous to increase train operation safety and decrease the negative effects of the rail crossing the neutral section. It can effectively deal with troubles with electricity levels that are mostly triggered by the electrifying railway's unfavourable charge cascade.

Fini Fathima and S. Prabhakar Karthikeyan [20] look at various power quality problems using many traction transformers. The study investigates how the framework behaves while receiving occupied, reacting to, and compensating harmonics using a range of traction transformers. Power quality declines when any multi-phase power line is connected to an electrically powered railway. This causes both voltages and currents in the multi-phase power supply to become distorted and unbalanced, causing increased operating costs and practical and financial challenges. Sy-Ruen Huang and Bing-Nan Chen [21] investigated the harmonic distortion electric locomotives caused in the utility supply network. To ascertain the degree of specific frequencies of the potential and energy that exist together with the percentage of overall harmonic distortion in current and voltage, tests are carried out at 132 kV and 25 kV systems are observed and examined.

3. Modeling and Method

The whole traction power supply system must be modelled to evaluate and analyze a railway system's power quality and how it affects the local distribution network. Power quality analysis is required to assess if system augmentation or power quality enhancement is required and to look at new systems or the outcomes of significant upgrades. Data resources are gathered, examined, and evaluated concerning power quality criteria as part of the power quality evaluation process.

This study focuses on the electrification system of the Ethio-Djibouti railway, specifically on its five traction substations. Each traction substation has a power supply zone of around 40 km long, for a total of 186 km. The constructed model evaluates the effects on a railway system's local distribution network and power quality characteristics. The model has a contact line that provides electric trains with a diode and an electric railway substation rectifier, as shown in Figure 4.

An electric railway substation is a 132kV/25kV transformer with a 20MVA rating connected to the transmission grid. Each traction substation must be linked to two independent, dependable power sources for the locomotive to run constantly. Each traction substation has two sets of Vv wire transformers built in a master-slave arrangement to make sure that if one of these power sources fails. Another transmission line will continue to be able to provide its necessary power. Using MATLAB/Simulink tools, a simulation model for electric traction has been constructed.

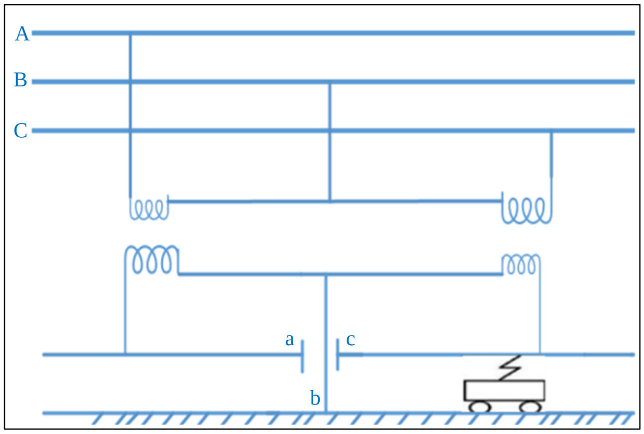

Fig. 4 An illustration showing how an energy source and transportation unit are coupled

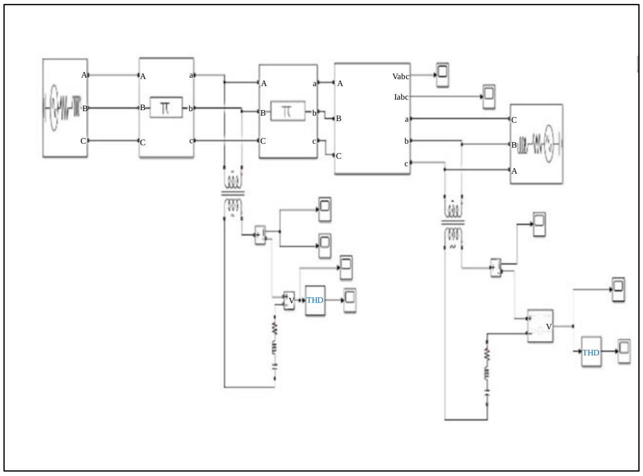

Fig. 5 Schematic diagram for access of traction substation

The Awash 132kV, along with Methera 132kV traction substations, are considered in this study as part of an energized haulage system. Its train outlet receives the motor duty from a 25kV Vv changer, whereas the supply terminal strength is 132kV. The layout schematic of the pertinent entrance module scheme is displayed in Figure 5.

4. Results and Discussion

Electric power systems must fulfil the following power quality indicators and offer consumers a consistent power supply: The three primary fundamental indicators used to assess power quality are frequency, voltage, and harmonic.

Power quality analysis is essential to assess present systems and decide whether power quality correction is required analyzing new systems or the results of significant upgrades to current systems. Figures 6 and 7 show the voltage and current wave patterns at the 132 kV.

Voltage waveform at the 25kV side and current waveform at the 25kV side of the railway substation are shown in Figure 8 and Figure 9.

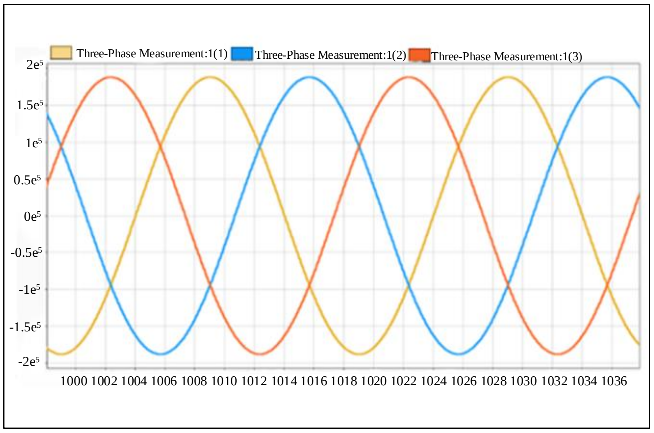

Fig. 6 Shows the voltage waveform

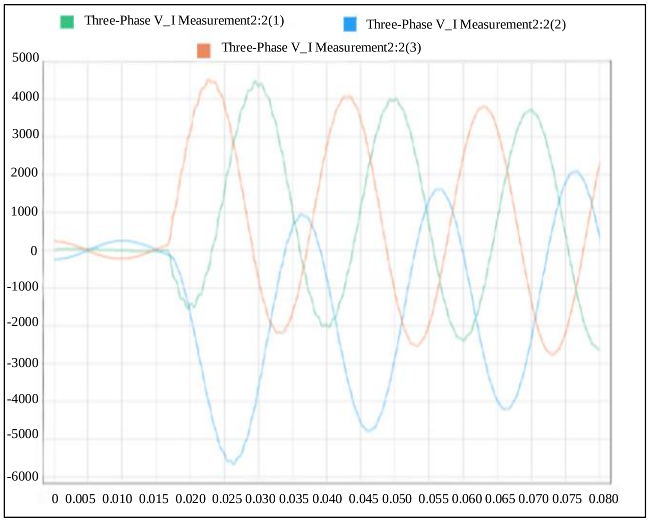

Fig. 7 Shows the current waveform at the 132kV side of the railway substation

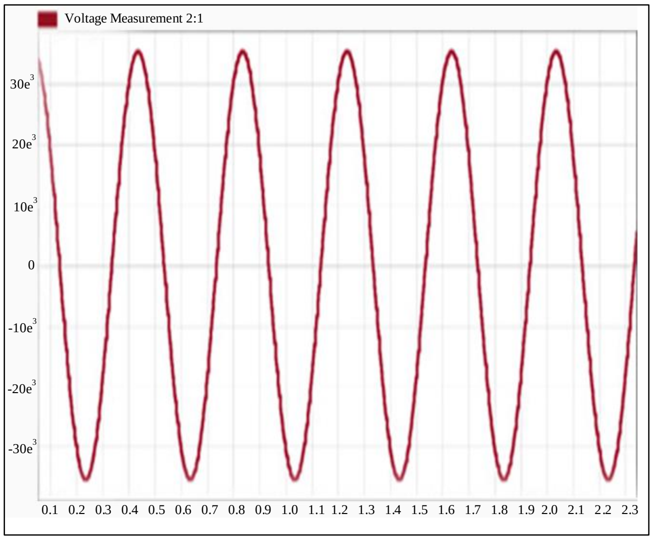

Fig. 8 Voltage waveform at 25kV side

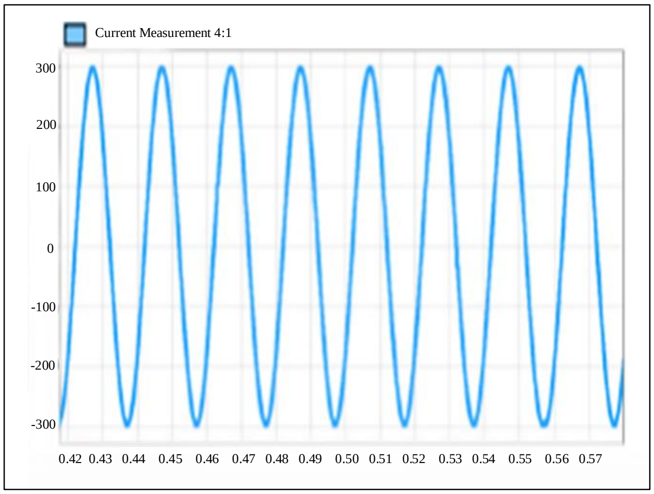

Fig. 9 Current waveform at 25kV side

4.1. Harmonic Analysis

To determine once the power source trainloads' induced sine waves resulted in insufficient amplitude, the level of shared attaching (PCC), periodic present and voltage studies were performed. The area with a normal connection linked to the electricity plant is the evaluation place for harmony computations. The simulation's findings for total voltage and current harmonic distortion are displayed in Figures 10 and 11. MATLAB/Simulink simulations were employed to compute the 132 kV and 25 kV voltage levels. It fully conforms with the IEC specification 61000-3-14 and the IEEE code 519-2014. A MATLAB/Simulink simulation was run to determine the exact amount of unique voltage and current sine waves at 132kV and 25kV traction substations, as shown in Table 1.

Table 1. IEEE harmonic standard 519-2014

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

According to the simulation findings shown in Figure 10, the overall current distortion in Figure 11 is less than the limit given by IEC 610003-4; however, the individual voltage harmonic distortion where the shared relationship is beyond the allowable limitations (1.5%) as per IEEE519-1992.

As per the modelling process yields in Figure 12 and Figure 13, the individual voltage harmonic distortion at the point of common coupling of the 25kV side is within the permissible limits (3%) as per IEEE519-1992, and the total current distortion is lower than the limit specified by IEC610003-4.

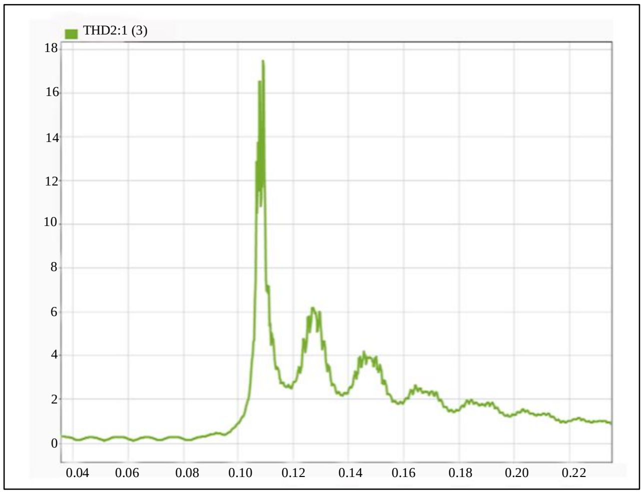

Fig. 10 Voltage harmonic distortion waveform at 132kV side

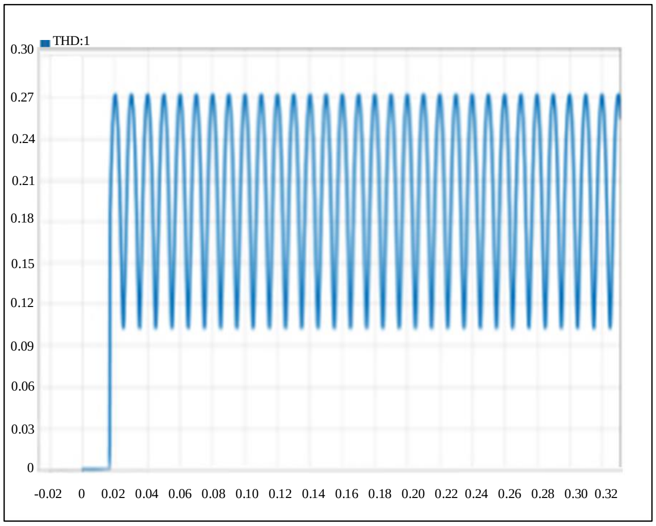

Fig. 11 Current harmonic distortion waveform at 132kV side

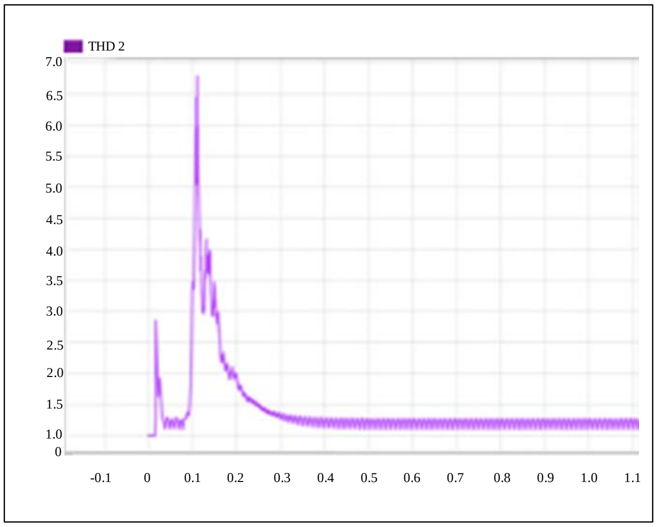

Fig. 12 Voltage harmonic distortion at 25kV

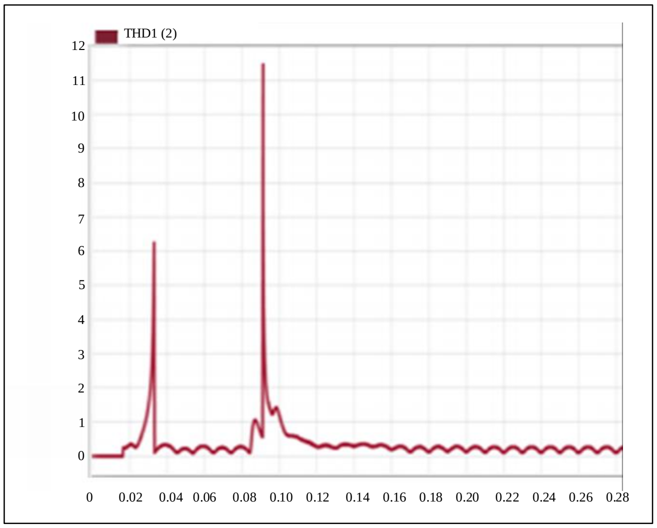

Fig. 13 Current harmonic distortion 25kV

4.2. 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 busses 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 computation shows that in 2015, all traction substation 132kV busses had a short circuit current of 31.5 kA or less, as shown in Table 2.

Table 2. Short circuit analysis results

Name of Substation	Bus Voltage(kV)	Three-Phase Short Circuit(kA)
Melkajilo SS	132	1.273
Methera SS	132	1.273
Awash TS	132	1.184

4.3. Negative-Sequence Analysis

The negative sequence current entering the power supply and endangering electrical equipment are shown in Table 3. IEEE 1159-2009 states that a VUF percentage of more than 2% is not permitted. The voltage imbalance at the 132kV sides of the Methera and Awash substations does not fulfil IEEE standard 1159-2009 because the assessment criterion of negative sequence components is greater than 2%.

Table 3. Negative-sequence results

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

5. Measurement of Power Quality

A span of twenty-four hours is used to assess the voltage characteristics associated with the 132kV/27.5kV electrically powered circuit. A power quality monitoring device was attached to record current and voltage measurements at the Methera and Awash traction substations.

5.1. Voltage Measurement

As shown in Figure 14, all measured voltage values fulfil the IEEE's highest +5% and below -5% requirements.

A power quality analyzer was attached to the 132 kV transformer's primary side through CT and VT metering. The following part provides the findings of voltage and current harmonic measurements at the transformer's 132 kV primary and 25 kV secondary sides.

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 and the proportion of total distortion in current and voltage. The 3rd-order voltage harmonics in Figure 15 have a maximum observed particular voltage harmonic distortion of 12%, above the IEEE 519-1992 standard's 3%.

The maximum measured individual voltage harmonic distortion of the 5th-order voltage harmonics in Figure 16 is 10%, which is above the limit of 3% IEEE 519-1992 standard.

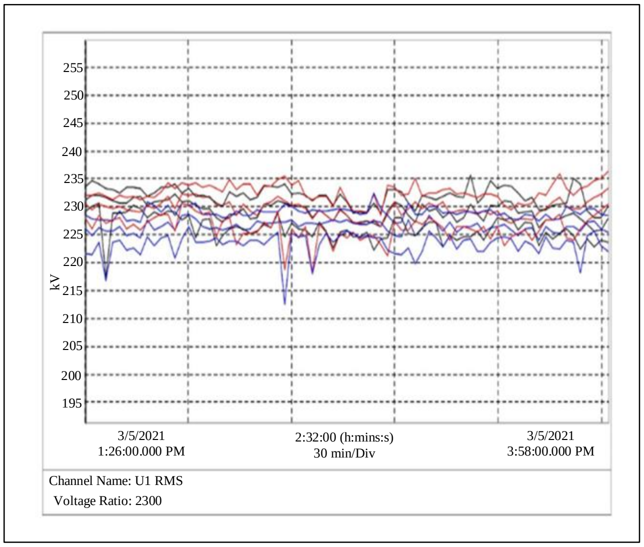

Fig. 14 Voltage measurement

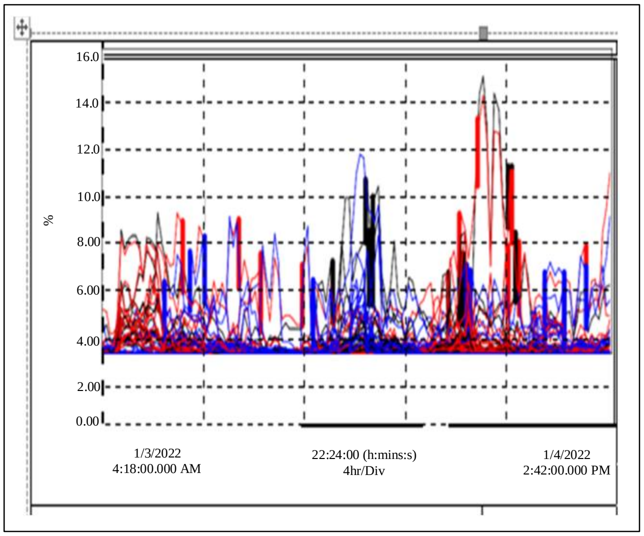

Fig. 15 3rd voltage harmonics at 25kV side of railway substation

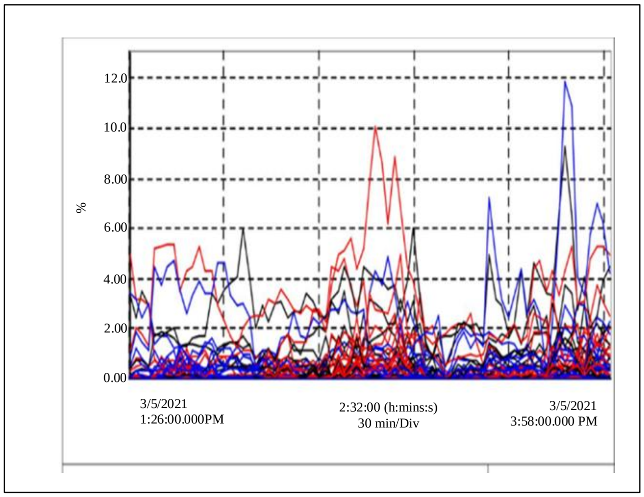

Fig. 16 5th voltage harmonics at 25kV side of railway substation

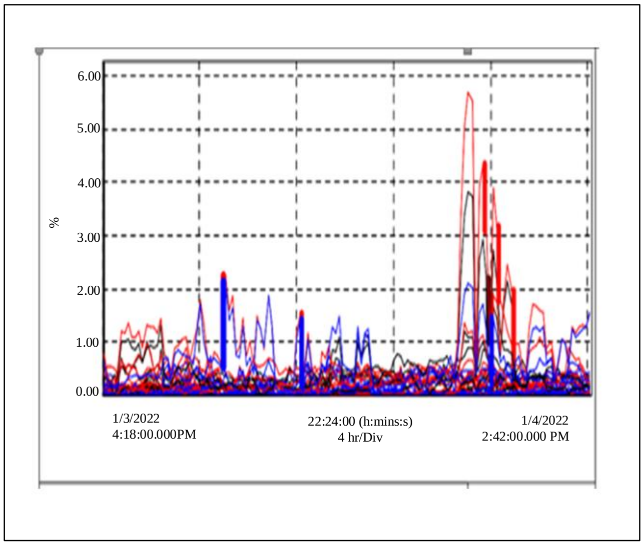

Fig. 17 7th voltage harmonics at 25kV side of railway substation

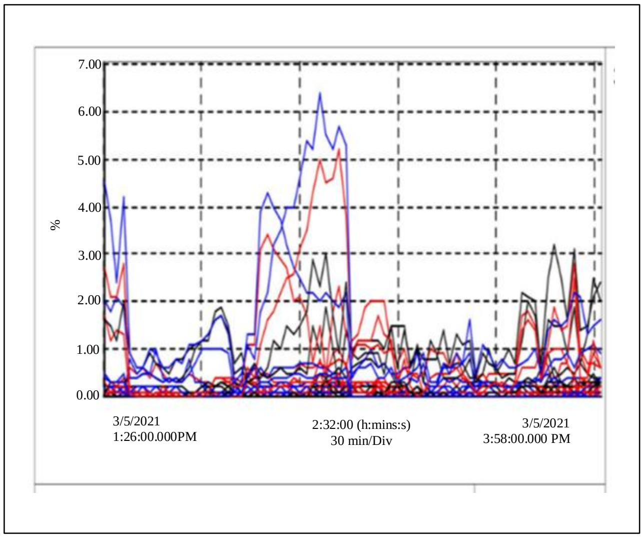

Fig. 18 13th voltage harmonics at 25kV side of railway substation

The maximum measured individual voltage harmonic distortion of the 7th-order voltage harmonics in Figure 17 is 5%, which is above the limit of 3% IEEE 519-1992 standard. The maximum measured individual voltage harmonic distortion of the 13th-order voltage harmonics in Figure 18 is 6%, which is above the limit of 3% IEEE 519-1992 standard. All the measured individual voltage harmonics levels in Figure 19 are less than the 3% level recommended by IEEE 519-1992. The measured individual voltage harmonics levels in Figure 20 are less than the 3% level recommended by IEEE 519-1992.

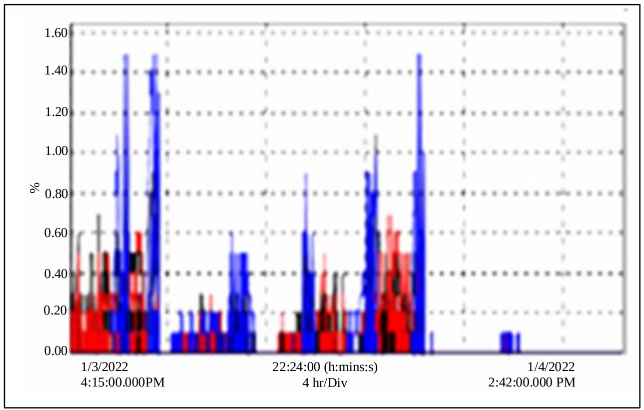

Fig. 19 15th voltage harmonics at 25kV side

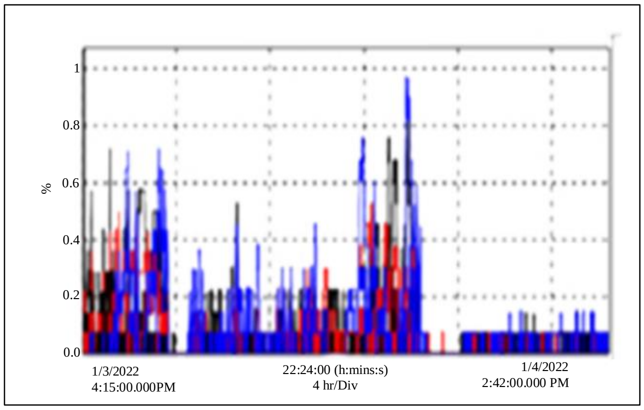

Fig. 20 23th voltage harmonics at 25kV side of railway substation

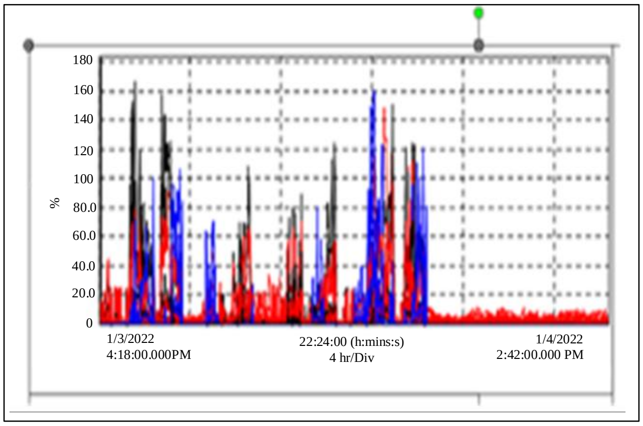

Fig. 21 5th current harmonics at 25kV side of railway substation

The result of the investigation, along with testing from harmonics. in Figure 21 shows that the individual current harmonics exceed the limits recommended by IEEE 519-1992 standard.

The result of the harmonic measurements and analysis for 132kV and 25kV, as in Figure 22 and Figure 23 below, shows that the individual current harmonics exceed the limits recommended by the IEEE 519-1992 standard.

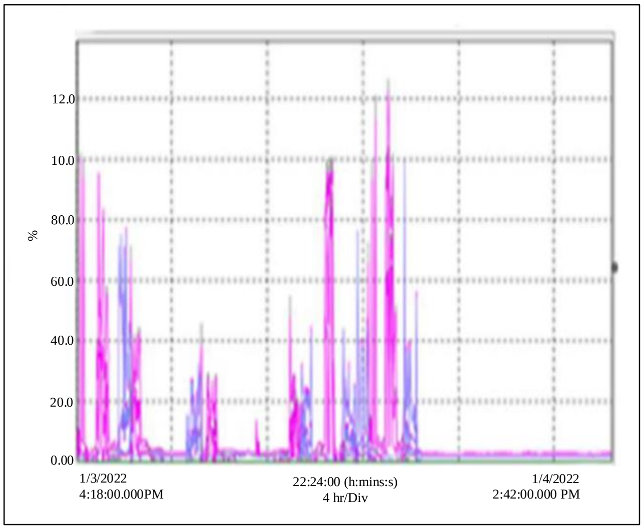

Fig. 22 7th current harmonics at 132kV side of railway substation

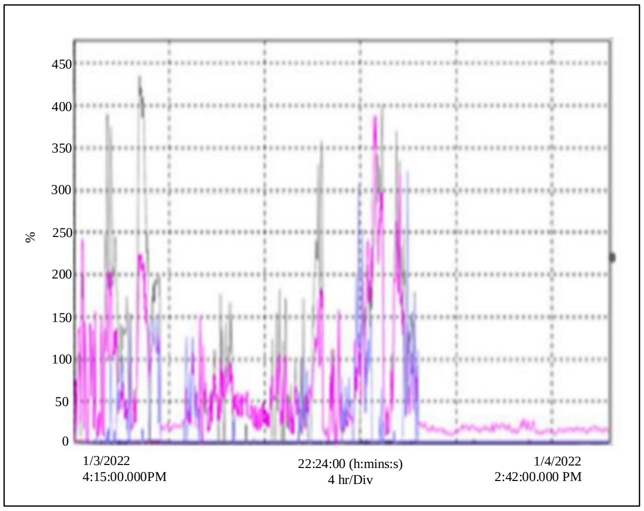

Fig. 23 25th current harmonics at 25kV side of railway substation

5.2. Voltage and Current Unbalance Measurement

The current and voltage imbalance measurements 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 within the acceptable range where the current unbalance is above the limit recommended by IEEE standards, as shown in Figure 24.

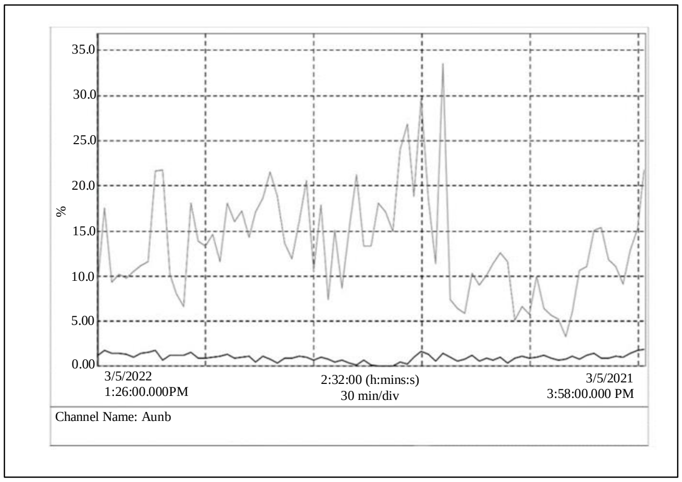

Fig. 24 Voltage and current unbalance measurement

6. Conclusion

This research investigates the power quality phenomena on the Ethiopia-Djibouti railway line. The Awash and Methera 132kV traction substations were used in the power quality investigation of the Ethiopia-Djibouti railway line. At 132 kV and 25 kV, the quantity of each harmonic current plus power and the overall distortion of voltage and current were measured using a power quality analyzer.

The measurement and simulation results for current and voltage harmonics are obtained above IEEE standard 519-1992 limitations. The simulation results of voltage imbalances within the electromagnetic train supply network's connecting spot show that the voltage imbalance on the 132kV side between Awash and Methera is more significant than 2%, which does not meet IEEE standard 1159 -2009. Harmonic currents and unbalanced voltages can have a significant negative influence on the power system's components, which can result in overheating, transmission line losses, communication system interference, malfunctioning protective relays, measuring instrument mistakes, and other issues. Therefore, the modelling and test findings show that harmonics and voltage imbalance should be reduced using the appropriate methodologies, and more research is essential in this area.

Access to Information

The information utilized to support what was found in this research is available from the field investigation upon request.

Acknowledgement

The authors thank the Ethio-Djibouti Railway Company for providing the necessary data to complete this research.

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