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Study of Power Reliability and Power Quality Problems of the Ethiopian-Djibouti Railway Distribution Networks

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Abstract: The structure of railway electrification system is a single-phase line, it uses power electronics devices and has a time varying load characteristic. This is a cause of considerable current unbalance, harmonics and variable reactive power consumption. This usually leads to power quality problems affecting the proper operation of the equipment. Because of the train's unique operation and electrification characteristics, power quality has been a major problem in railway networks. Throughout the history of railway electrification, many research were dedicated to power quality studies. A variety of power conditioning devices have been explored and deployed to traction systems. In this paper, a power quality problem investigation is done by evaluating and measuring major power quality parameters to confirm the mentioned problems on the Ethio-Djibouti railway line. The power quality quantities are measured using Chauvin Arnoux CA 8335 device and relevant data for power quality analysis are extracted using POWER log 5.8 software. Moreover, the power reliability is also evaluated for the same railway network by considering two substations, respectively the Hurso and Adigala substation. The power reliability studies are carried out by considering the recorded outage data due to Overvoltages for a period of one year. The measured data indicates a low power factor which even amounts 0.2, a maximum current unbalance values of 70% and harmonic distortion of 50%. The longest power outage due to over-voltage was 202 hours in January at Adigala substation with a power supply availability of 0.70 p.u in the 2020 years.

Keywords: Harmonic Distortion, Power Factor, Power Quality, Unbalanced System and Railway Networks

1. Introduction

Railway electrification started in the 20th century [1]. Because railway electrical system offers many advantages, several countries adopted It. Lower atmosphere pollution, heavy mass transit ability and high efficiency are few of those advantages. Power quality has been a real issue for proponents of railway electrification since the beginning, and so many research studies have been focused on studying and improving power quality in railway distribution networks. Multiple power supply systems have been employed since the inception of electrified railways. This is owing to the fact that each country has built its own electrified railway system. They all, however, have issues with power quality [2]. System imbalance, reactive power, and harmonics are all main power quality issues in the traction power supply. voltage and current unbalance, grid stability, Voltage fluctuations, harmonics, power reliability, reactive power, and other characteristics all contribute to power quality in railways system [3, 4].

Trains appear like single-phase configuration load in the public grid and create power quality issues in the utility grid, causing disturbances in the network. When the traffic increases the issue becomes larger and solutions to improve power quality are necessary. The unbalances which occur due to the train-load characteristic have also negative impact on transformers, generators and motors connected to the grid, and transmission lines. As a result, the grid might be weaker and more susceptible to voltage drops [1, 4]. Power electronic device in the traction system also increases the harmonic content in the railway supply network. The electric railway loads connected to a three-phase power supply system represents one of the main sources of voltage perturbation in the grid [5, 6]. Power supply configuration system and the time varying traction loads influence the level of the power quality problem.

The Ethiopian-Djibouti railway supply networks are currently working without any power quality mitigation device and actually faces power quality problem such as low and inadmissible power factor, over-voltages, power interruption which affecting the proper operation of the railway supply system and have repercussion on the billing that affects the economical side. Thus, this paper focuses on the analysis of the power quality problems for the Ethiopian-Djibouti railway line and its power reliability due to overvoltage. For the power quality assessment, data are collected and measured using power quality analyzer Chauvin Arnoux CA 8335.

The Figure 1 shows the Ethiopian-Djibouti railway electrification network configuration. All traction substations were connected to two independent and reliable power supplies for continuous locomotive operation; if one power supply fails, the other power line will provide power to the traction substation; and each traction substation was also equipped with two sets of Vv wiring transformer, one for use and one for standby.

Each traction substation is supplied from different substations of Ethiopian Electric Power at 132kV or 230kV level and then the voltage level is stepped down to 25kV by using Vv connected Transformer.

Both passenger locomotive and cargo locomotive for Ethiopian-Djibouti railway adopt single-phase traction power system of 25kV at 50HZ.

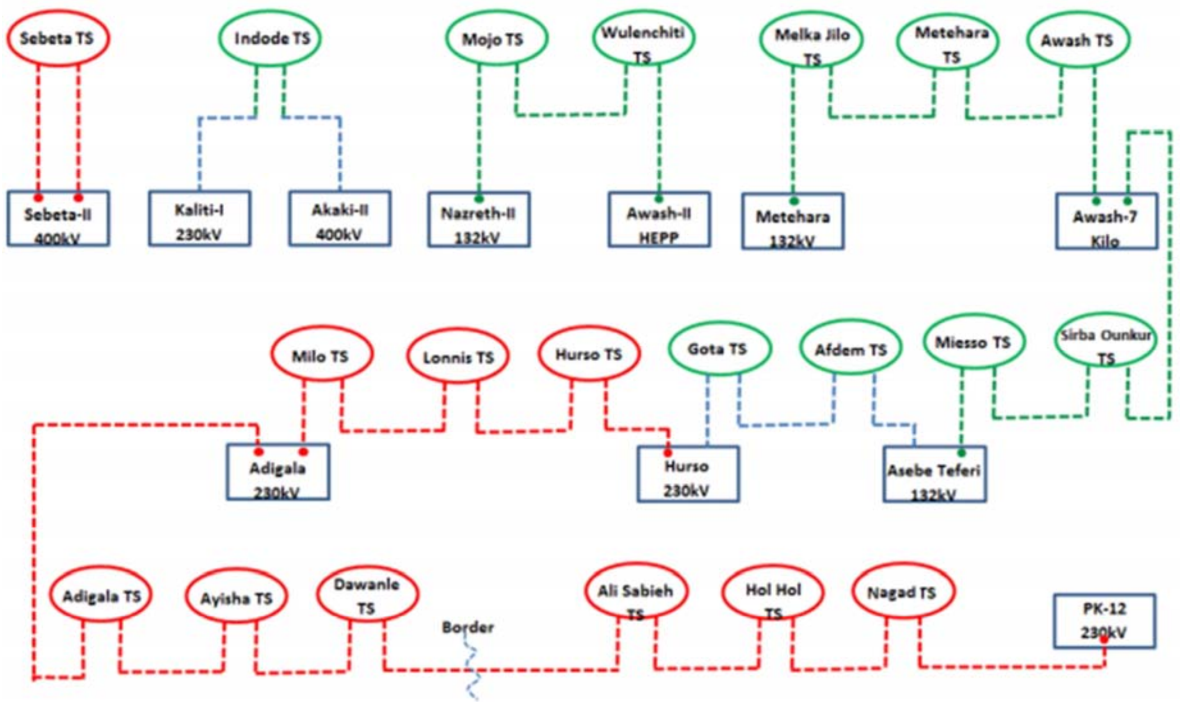

Figure 1. *Structure of external power supply network of Ethiopian-Djibouti Railway line.*

2. Power Quality and Power Reliability

For a long period of time, the fundamental worry of power customers was the supply's continuity or reliability. Consumers nowadays demand not only power reliability, but also power quality. The ability of consumer equipment to work properly determines power quality. The expanding economic implications on network operators (i.e., utilities) as well as their customers are the reason for the present interest in power quality.

The Ethiopian-Djibouti railway electrification network suffers from over-voltages which is one of the power quality problems. Those over-voltages lead to power interruptions. The Figure 2 below shows the relationship between power reliability and power quality.

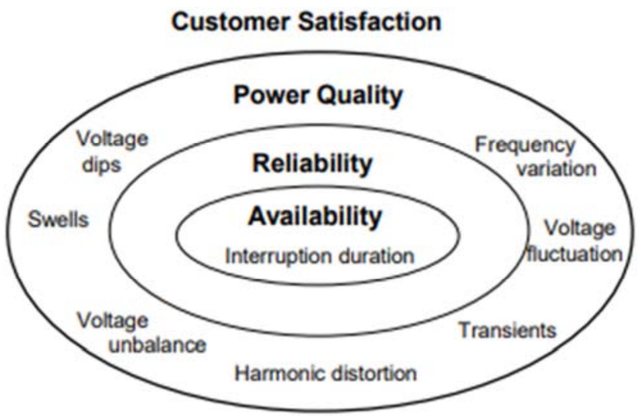

Figure 2. *Power Quality and Reliability Relationship.*

2.1. Main Traction Power Quality Problems

Because traction locomotive loads are showing a dynamic characteristic which is time-varying and non-nonlinear, they could lead to several power quality issues at the same time, as previously stated. Negative Sequence Component with system unbalance, power factor with reactive power and harmonics with nonlinear power electronic devices are all common traction power supply issues.

2.1.1. System Unbalanced

Negative sequence and system unbalance are two key issues with traction power supply. When negative sequence currents exist in power supply systems, unbalance (voltage or current) arises. This could be due to an uneven loading system being connected to the system. Unbalanced train load causes system imbalance in railway power supply [7]. System imbalance is represented in term of percentage ratio of the absolute value of negative and positive voltage/current sequence component by (1).

$$\%\ \text{Voltage Unbalance} = \frac{|V_{neg}|}{|V_{pos}|} \times 100\% \quad (1)$$

In IEEE, there are few published standards for system imbalance, but the National Standard GB/T 15543-2008 [8], states the maximum voltage imbalance permissible at the Point of Common Coupling is 2% for long-term perturbations, whereas for short-term perturbations, it is 4%. This could also be the norm for imbalance tolerance in traction power systems.

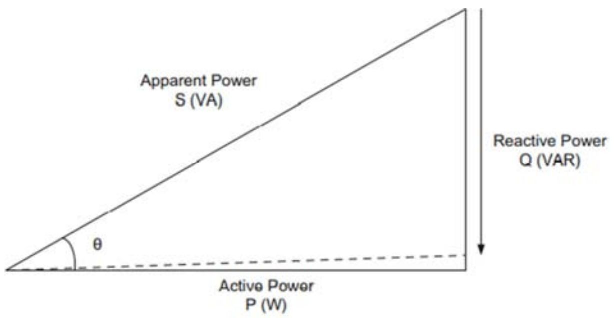

Figure 3. *The classic power triangle scheme.*

2.1.2. Power Factor

In power supply system, reactive power is also a source of concern for power quality. In a harmonic-free electrical network system, the apparent power given by the supplier can be treated as a sum of active and reactive power elements, as per definition [9]. When the load is capacitive or inductive, reactive power is injected or extracted in the power supply. Reactive energy is an important concern in power system when inductive loads such as induction motors are used. The classic power triangle scheme, shown in Figure 3 depicts the combination of active and reactive variables in real power. The real power is expressed in VA, whereas the active and reactive power have W and VAR as units, correspondingly. P, Q, and S have a connection that follows the expression presented in (2). Note that the active power P is the sole true power contribution made by the system load. As a result, it is preferable to have little reactive power as feasible. If the power factor becomes as close to unity as possible, the quantity of reactive power is as near as possible to zero.

$$S^2 = P^2 + Q^2 \quad (2)$$

2.1.3. Harmonics

Oscillatory power and harmonics are also another important issue with electric traction power supply. When a nonlinear load is connected, harmonics are produced. Harmonic problems are growing increasingly as the use of nonlinear electronics in power systems grows. Because locomotives contain significantly nonlinear loads components, this problem also appears in traction power supply. Harmonic level indicating quantity is Total Harmonic Distortion (THD) and is calculated by using (3). Normally, the THD admissible value should not exceed 8% for voltage and 50% for current [10].

$$\text{THD} = \sqrt{\sum_{h=2}^{40}(U_h)^2}\ \% \quad (3)$$

2.2. Power Reliability

Reliability Is the probability that the system will perform its intended function under specified working condition for a specified period of time [11, 12]. Reliability can be described mathematically as a function of time where R(t) is the Chances that the system will continue to work appropriately at time t. Reliability is a real number ranging between zero and one.

Figure 4 below shows the exponential reliability function with time for constant failure rate.

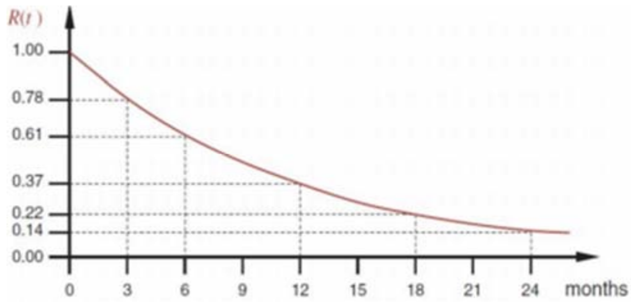

Figure 4. *Typical Reliability Function.*

The standard function that best fits the data in terms of outage duration and frequency of interruption that leads to an outage, i.e., the arbitrary variables are frequency time, and a standard function that best fits is the exponential function because it only contains time as an independent variable. According to [13], it is only a descriptive function as it has only time as the independent variable. The failure rate (λ) is unavoidably one of the important elements for this function that can be employed. According to [14, 15], the density function is defined as follows;

$$f(t) = \lambda \quad (4)$$

The Hazard rate is then given by

$$\lambda(t) = \frac{f(t)}{1-f(t)} = \lambda \quad (5)$$

Failure rate (λ) can be expressed as:

$$\lambda = \frac{\text{Number of times that the failure ocured}}{\text{Number of unit} - \text{hours of operation}}$$

The reliability function is:

$$R(t) = 1 - f(t) = e^{-\lambda t} \quad (6)$$

Mean Time Between Failure (MTBF)

$$\text{MTBF} = \frac{\text{Total system operating hours}}{\text{Number of failures}} \quad (7)$$

Mean Time to Repair (MTTR)

$$MTBR = \frac{\text{Total system operating hours}}{\text{Frequency od outages}} \quad (8)$$

Availability (A)

$$\text{Availability} = \frac{\text{MTBF} - \text{MTTR}}{\text{MTBF}} \quad (9)$$

3.1.1. Reliability at HURSO Power Substation

Table 1. *Reliability parameters 2020 at HURSO substation.*

Month	Frequency	Operation Time [hr]	MTBF [hr]	MTTR [hr]	Failure rate [Event/hr]
January	28	744	26.57143	4.294286	0.838387097
February	29	696	24	3.647241	0.848031609
March	19	744	39.15789	2.556842	0.934704301
April	22	720	32.72727	2.650909	0.919
May	8	744	93	2.39625	0.974233871
June	7	720	102.8571	1.5	0.985416667
July	15	744	49.6	2.372667	0.952163978
August	15	744	49.6	1.86	0.9625
September	20	720	36	1.5235	0.957680556
October	14	744	53.14286	2.302857	0.956666667
November	35	720	20.57143	1.879143	0.908652778
December	36	744	20.66667	2.805833	0.864233871
Total	248	8784	35.41935	1.732056	0.951098588

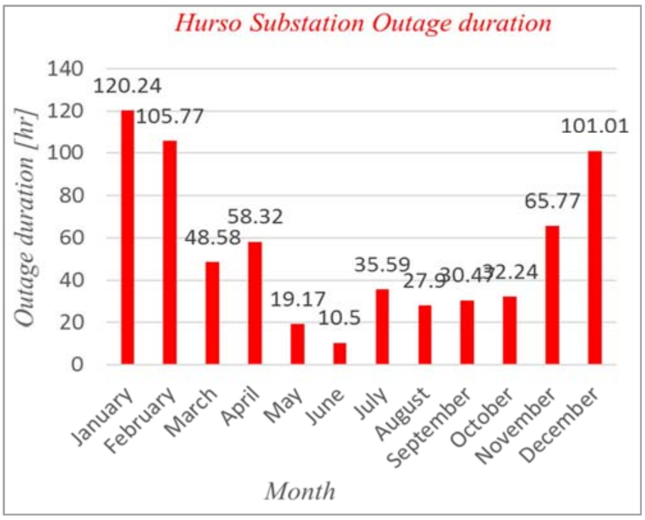

Figure 5. *Hurso substation outage duration 2020 year.*

3.1.2. Reliability at Adigala Power Substation

Tables 1 and 2 show the computed reliability parameters in the year 2020 at both Hurso and Adigala substations, respectively. At Hurso Substation the month of January shows the highest outage duration of 120.24 hours/month (Figure 5) but with the lowest availability of 0.83 (Figure 6). A similar scenario is observed at Adigala substation with outage duration of 178.83 hours in January but February representing the lowest power availability (Figure 8). The lowest outage duration at Adigala substation was recorded in the month of June with a value of 0.0041 /hour (Figure 8). The month of December represented the highest number of outage interruption frequency that was respectively 36 and 42 at Hurso and Adigala substations.

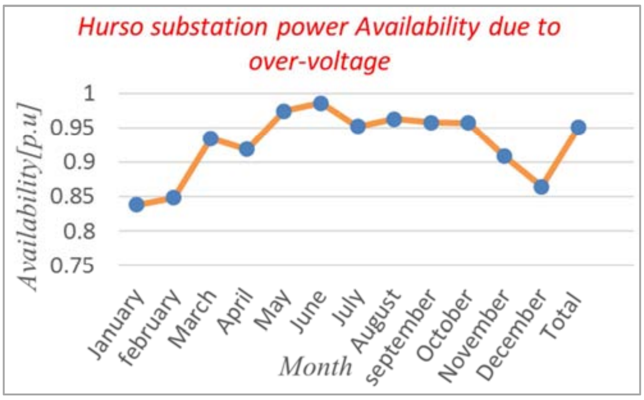

Figure 6. *Hurso substation power availability 2020 year.*

3. Results and Discussion

In this part, the traction system under consideration is investigated considering both AC Ethiopian and Djibouti railway supply system. This study is carried out by collecting and measuring pertinent power quality data. The selected system data for the analysis are obtained from Ethiopian Railway Corporation and measured from different substations using the power quality and energy analyzer Chauvin Arnoux CA 8335.

3.1. Power Reliability Due to Over-voltage Study

The power outage data were collected from two different substations that are severely affected by the over-voltage problem; mainly Adigala and Hurso substation.

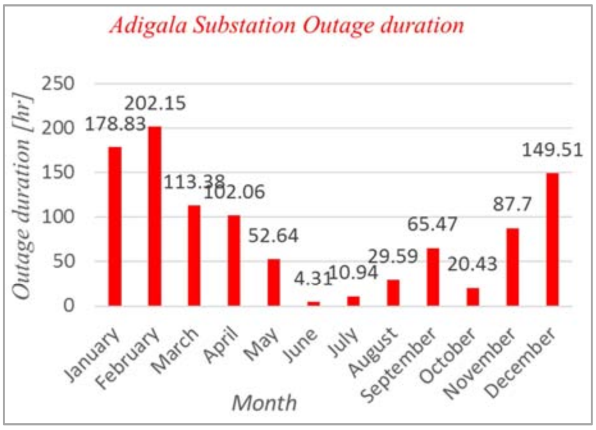

Figure 7. Adigala substation failure rate 2020 year.

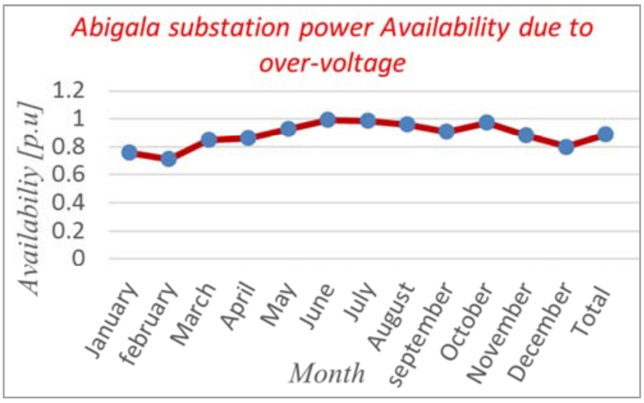

Figure 8. Adigala substation power availability 2020 year.

Table 2. Reliability parameters 2020 at Adigala substation.

Month	Frequency	Operation Time [hr]	MTBF [hr]	MTTR [hr]	Failure rate [Event/hr]
January	33	744	22.54545	0.7596371	0.04435484
February	34	696	20.47059	0.7095546	0.04885057
March	29	744	25.65517	0.84760753	0.03897849
April	23	720	31.30435	0.85825	0.03194444
May	14	744	53.14286	0.92924731	0.0188172
June	3	720	240	0.99401389	0.00416667
July	6	744	124	0.9852957	0.00806452
August	12	744	62	0.96022849	0.01612903
September	21	720	34.28571	0.90906944	0.02916667
October	9	744	82.66667	0.97254032	0.01209677
November	37	720	19.45946	0.87819444	0.05138889
December	42	744	17.71429	0.7990457	0.05645161
Total	263	8784	33.39924	0.88422017	0.0299408

3.2. Main Railway Power Quality Problems Study

Currently, the line under study is evaluated without any compensation device installed and under the condition of power quality problems. The focus is to evaluate the level of the power quality problems by taking into consideration different substation of the line.

Figure 9. Chauvin Arnoux CA 8335 Power Quality Analyzer Installation.

The analysis was carried out using the recorded data. The data used for analysis was measured at Awash railway substation form 8: 50 PM of 06/03/2021 to 9:00 AM of 07/03/2021. Figure 9 shows the Power Quality Analyzer installation at Awash substation.

The device was installed through current and voltage transformers.

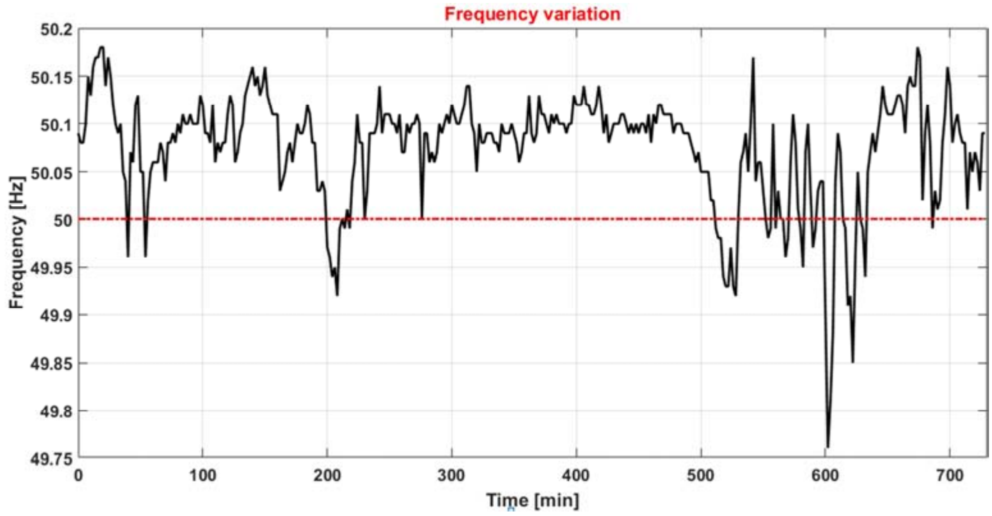

Figure 10. *Traction frequency variation.*

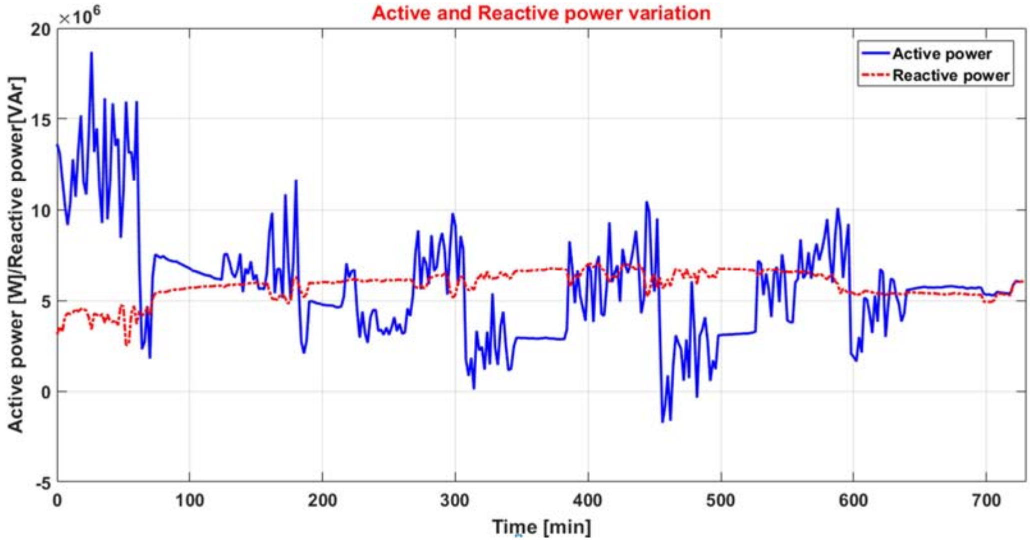

Figure 11. *Traction active and reactive power.*

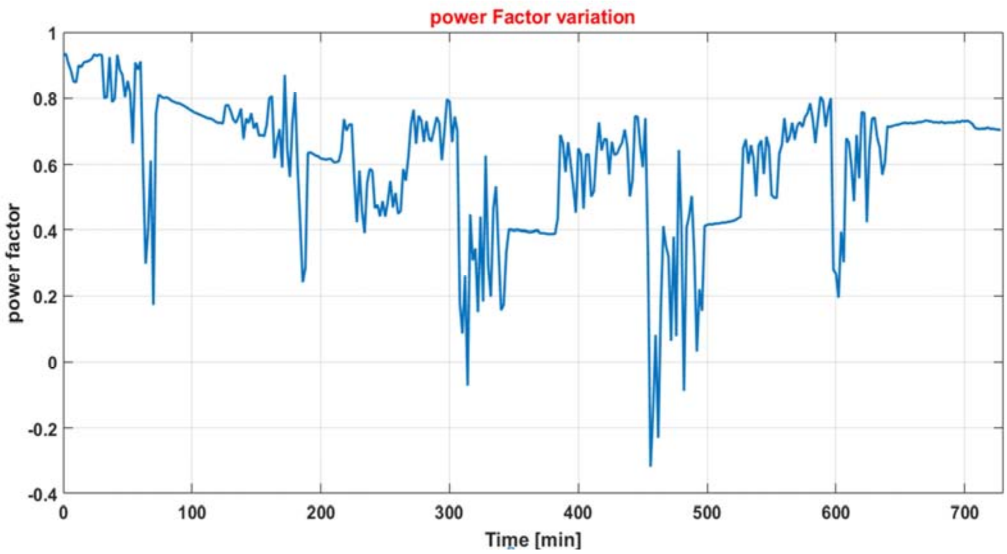

Figure 12. *Traction power factor variation.*

As it can be seen in Figure 10, the frequency variation is within the acceptable range. The reactive power consumption remained almost constant for the measured 728 minutes with a variable active power, which depends on the incoming traffic (Figure 11). The fact that is important to notice here is the relationship between the power factor and the active power, as the two parameters keep variating with the traction load. The decreasing of the active power leads to the decreasing of the power factor at almost constant reactive power consumption. From Figure 12, it can be seen clearly a negative power factor period which is related to a negative active power period as well. This fact is due to the regenerative braking system.

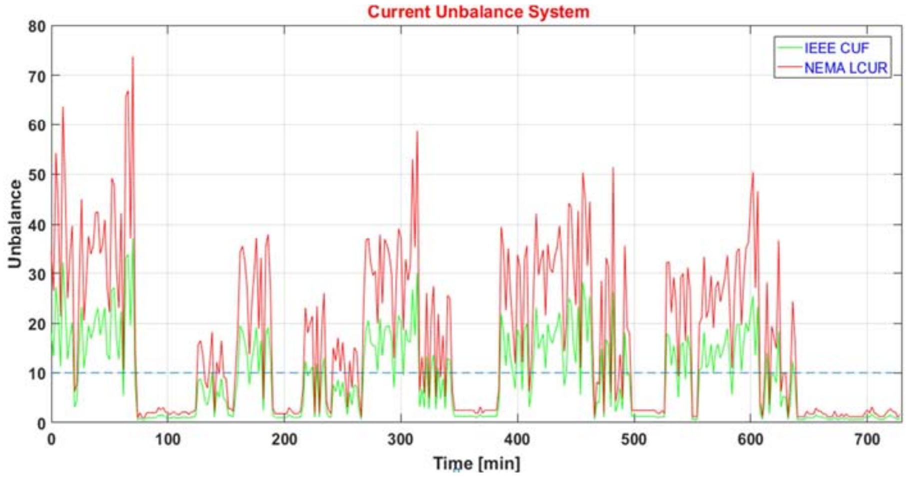

Figure 13. *Unbalance current.*

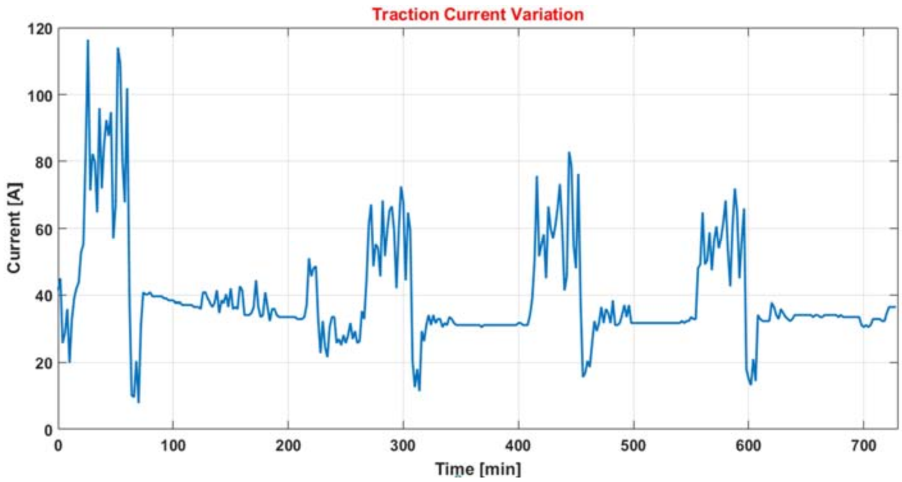

Figure 14. *Traction current profile.*

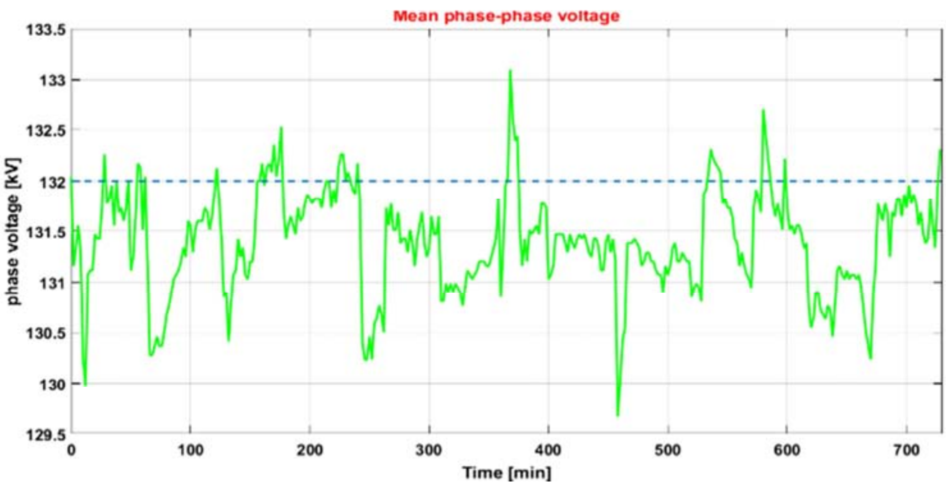

Figure 15. *Traction voltage variation.*

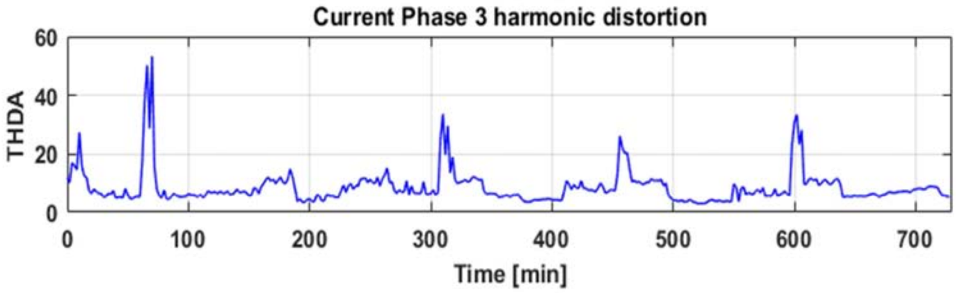

Figure 16. *THD of the current harmonics.*

As observed in Figure 13, the unbalance current computed using the NEMA Line Current Unbalance Rate is higher than the one using the IEEE Current unbalance Factor. Figure 15 shows the traction voltage variation which is within acceptable limit. The line current and the line current harmonics change proportionally within the load traffic of the train in the substation, as it can be clearly seen in Figure 14 and Figure 16 respectively.

4. Conclusion and Future Works

For long and the short system disturbances, the maximum voltage unbalance index acceptable at the point of common coupling is 2% and 4%, respectively, as per GB/T 15543-2008 Standard. According to IEEE Standard 519-1992, the harmonics tolerance is limited to 25% for even harmonics, the maximum acceptable voltage drop is 5%, the maximum frequency deviation is 2% and the minimum power factor allowable is 0.8.

After analysis of collected and measured power quality data, the level of the electrical power quality for the existing Ethiopian-Djibouti railway line is concluded as follow:

1) The frequency fluctuation is between 50.15 Hz and 49.7 Hz, which is within the accepted range.
2) The power factor with the traffic could even drop to 0.2, which shows an inappropriate utilization of the apparent power, thus correction is imperative.
3) The computed unbalance current is found to have a maximum of 70% which is greater than the GB/T 15543-2008 standard at the Point of Common Coupling, thus, taking corrective measure is important.
4) The current harmonics at the Awash substation could reach a magnitude of 50% thus correction measures are important.

The above-mentioned facts indicate that the Ethiopian-Djibouti power supply system networks suffer from power quality problems.

Future works will also address further studies on main railway power quality problems mitigations. An effective mitigation technique will be selected and designed for the specific Ethiopian-Djibouti railway network. The Main railway power quality problems will be designed and mitigation studies will be conducted by modelling the railway system using MATLAB/SIMULINK Software.

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Biography

Mugisho Mugaruka Josue Holds a BSc degree in Electrical Engineering, Power system from the university of Burundi. He also holds a MSc degree in Railway Engineering, Traction and Train Control form Addis Ababa university. His current projects and interests are in the areas of electrical power quality problems and their mitigation, renewable energy integration, efficient power and energy management. He is currently working with the Spinoff Green Community Expertise Office of the Catholic University of Bukavu.

Getachew Biru Worku obtained his M.Sc. and Ph.D. in Electrical Engineering from Dresden Technical University, Germany. He has more than 25 years of academic and research experience in academic institutions and industry. He has given lectures and advised postgraduate students in electrical power in Addis Ababa University, Bahir Dar University, Adama Science Technology University and Jimma University. He has served as Dean, Department head and Academic Program Officer in Bahir Dar University and Chairman of Electrical and Computer Engineering Department in Addis Ababa University. Getachew Biru has also worked in the Aviation Academy in Ethiopian Airlines. His research areas are electrical power and renewable energy applications.