Journal of Engineering Research Innovation and Scientific Development 3 (1), (2025), 56-71 https://doi.org/10.61448/jerisd31256

Journal of Engineering Research Innovation and Scientific Development
journal homepage: www.jerisddelsu.com
Print ISSN 2971-6594 Online ISSN 2971-6608

Assessment of Total Harmonic Distortion for Power Quality Improvement in Low Voltage Distribution Networks

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ARTICLE HISTORY

Received: 16-02-25
Revised: 09-03-25
Accepted: 15-03-25
Published: 20-03-25

ABSTRACT

Ensuring high power quality in low-voltage distribution networks is crucial for efficient and reliable electricity supply. However, the increasing presence of nonlinear loads introduces harmonics into the power system network (PSN), leading to waveform distortions that degrade power quality. These harmonics, primarily generated by electronic devices, motors, generators, and transformers, contribute to power losses, system instability, and unbalanced load distribution at feeder pillars, ultimately affecting service delivery. This study aims to assess the Total Harmonic Distortion (THD) levels in a distribution network powered by a distribution transformer (DT) from a Nigerian power utility company, with a focus on residential, commercial, and small-scale industrial consumers. A Fluke energy analyzer was deployed at the secondary side of the DT, with all necessary calibrations and presetting completed before data acquisition. The collected harmonic data was subsequently processed and analyzed using spreadsheet software to determine the extent of waveform distortion. The results provide insights into the harmonic levels present in the distribution network and their impact on power quality. Findings from the analysis highlight the severity of harmonic distortions, their potential consequences on equipment performance and network stability, and the need for appropriate mitigation strategies. This assessment serves as a foundation for recommending power quality improvement measures to enhance the reliability and efficiency of low-voltage distribution networks.

Keywords: Distribution transformer; Fluke 435-II; Nonlinear loads; Power quality analyzer; Total harmonic distortion (THD)

1. Introduction

The quality of power systems, particularly at the distribution level due to their proximity to customers, has become a significant concern for electrical power engineers (Rodriguez-Pajaron et al., 2022). Harmonic distortion is a critical factor contributing to poor power quality and increased power losses, often caused by abnormal temperature conditions (Yuan et al., 2023; Wu et al., 2016). For instance, distribution transformers (DTs) failing to reach their expected lifespan due to harmonic effects represent an economic loss. Harmonic intensity increases transformer losses, particularly eddy current losses, which are proportional to the square of the conductor current and frequency (Vlahinic et al., 2009). These losses elevate operating temperatures and adversely affect transformer performance (Adesina et al., 2020; Adesina et al., 2020).

Beyond harmonics, other power quality issues include under-voltage, over-voltage, voltage swells, sags, frequency variations, power interruptions, and voltage fluctuations, which particularly impact sensitive electronic devices such as computers (Adesina, 2017; Grady & Santoso, 2001). Harmonics distort current and voltage waveforms, negatively impacting electrical equipment. Harmonic analysis aims to identify and mitigate these distortions within affected networks (Bompard et al., 2001; Adesina &Fakolujo, 2015). Power quality engineers focus on maintaining harmonic levels within permissible standards, such as those outlined in IEEE 519, which sets harmonic distortion limits for voltage and current (Adesina & Fakolujo, 2015).

Harmonics in DTs arise from factors such as winding configurations, high flux densities, system switching, fault residues, extended feeder faults, and grounding issues (Barros et al., 2020). These harmonics, defined as voltages or currents with frequencies that are integral multiples of the fundamental frequency, can be generated by irregular flux distributions in alternator windings, synchronous generators, and electric motors. Factors like pitch, breadth, and winding configurations in machines further contribute to harmonics.

The impacts of harmonics include:

- Generation of pulsating torque in induction motors due to varying flux strength in the air gap.
- Overheating of equipment such as transformers, motors, and generators, leading to potential damage or reduced lifespan.
- Forced operation of circuit components like breakers and relays, causing outages.
- Poor power factor, which can lead to utility penalties and increased customer expenses.
- Flow of zero-sequence currents, affecting system stability and equipment efficacy.

Harmonics in power systems often lead to overcurrent surges, commonly referred to as resonance, which can damage critical components such as fuses and capacitors. Total Harmonic Distortion (THD) currents in transformers and machines are primarily caused by saturated iron cores (Adesina, 2017), necessitating effective mitigation strategies (Grady & Santoso, 2001). The IEEE 519 standard provides widely accepted guidelines for managing harmonics in electric power networks, setting harmonic limits for nonlinear load conditions. According to this standard, harmonic currents should be managed by consumers, while harmonic voltages are the responsibility of utility companies, with both parties sharing accountability for maintaining acceptable harmonic levels (IEEE, 2014).

To address harmonics effectively, engineers must identify the size and location of nonlinear loads within the distribution network. Nonlinear loads are broadly classified into harmonic current source loads, such as thyristor-controlled DC drives and current source inverters (CSI), and harmonic voltage source loads, such as diode rectifiers with DC-side capacitors (Mazumdar, 2006). Increased harmonic-generating loads have heightened concerns among utility companies, particularly with sources like commutated converters used as inverters or rectifiers. In transmission systems, high-power devices such as Static VAR Compensators (SVCs), Uninterruptible Power Supplies (UPS), constant voltage transformers (CVTs), transformer magnetizing currents, rotary machine excitations under heavy loads, and fluorescent lighting are key contributors to harmonics (IEEE, 1992).

Research has extensively analyzed the effects of harmonics on transformers and machines. For example, Thiyab & Abid (2018) evaluated a low-rated transformer (1 kVA) using harmonic signals generated by a frequency oscillator. Parameters such as K-factor (KF), THD, and crest factor (CF) were measured using a Fluke 435 power analyzer. Findings revealed that higher harmonic orders reduced both KF and CF values, indicating a significant impact on transformer performance. IEEE (2014)further demonstrated methods to mitigate the adverse effects of harmonics, including simulating the first three odd harmonic frequencies on a 1 kVA transformer, showing that harmonic injection altered voltage and current outputs.

Saodah(2018) investigated harmonic distortion effects on distribution transformers (DTs) under non-sinusoidal current loads using simulations and experimental measurements. Parameters like no-load losses (NLL), load losses (LL), winding temperature rise (WTR), and insulation life were analyzed across two case studies. Results indicated that DT lifespan decreases with increasing harmonic loads. For instance, a DT could maintain its expected lifespan only if its load remained below 0.6 per unit (pu). These studies emphasize the need for consumer investment in harmonic mitigation to prevent DT degradation.

Despite extensive research on harmonics in power systems and transformers, limited studies have focused on low-voltage (LV) networks of loaded DTs. To address this gap, this research investigates harmonic distortion in a distribution network powered by a selected DT from a Nigerian power utility company. Key objectives include collecting relevant DT data, measuring THD voltage and current per phase, phase-to-neutral and phase-to-phase RMS voltages, current per phase, and overall peak RMS distorted power for a three-phase system. These measurements are conducted at predetermined intervals, with data analyzed using the Fluke 435-II energy analyzer.

The study identifies harmonic-induced losses in DTs, including $I^2 R$ losses, eddy current losses, and stray losses, as major contributors to power quality degradation in distribution networks. The findings highlight the critical need for harmonic mitigation strategies to enhance power quality and ensure the longevity of distribution transformers, particularly in networks serving domestic and commercial customers.

2. Materials and Methods

To assess Total Harmonic Distortion (THD) in a low-voltage distribution network, this study utilized various measurement instruments and analytical tools. The primary materials used include:

(I) Fluke 435 Series II Power Quality and Energy Analyzer – Used to measure voltage, current, and harmonic distortions at the secondary side of the distribution transformer (DT).

(ii) Current and Voltage Probes – Ensured accurate data acquisition by capturing electrical signals without direct connection to live conductors.

(iii) Personal Computer with Spreadsheet Software (Microsoft Excel) – Used for data processing, analysis, and visualization.

(iv) Distribution Transformer (DT) Network – The case study focused on a DT supplying residential, commercial, and small-scale industrial consumers within a Nigerian power utility network.

2.1 Total Harmonic Distortion (THD)

The THD measures the harmonic distortion which is obtainable in power distribution networks (Adesina et al., 2020). THD can either be harmonic current or harmonic voltage. THD is mathematically expressed as a fraction of total harmonic components and the fundamental frequency as illustrated in Equations 1 and 2 (Adesina & Fakolujo, 2015; Xu et al., 2008)

$$\%THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_1} \times 100$$

$$\%THD_I = \frac{\sqrt{\sum_{k=2}^{n} I_k^2}}{I_1} \times 100 \quad (1)$$

$$\%THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + ... + V_n^2}}{V_1} \times 100$$

$$\%THD_V = \frac{\sqrt{\sum_{k=2}^{n} V_k^2}}{V_1} \times 100 \quad (2)$$

where V_k and I_k represents the RMS k_{th} harmonic voltage and current respectively. V_1 is the fundamental frequency, V_n is the RMS voltage of the n^{th} harmonic, N is the highest harmonic in consideration, HD is the total harmonic distortion, and %THD is the percentage total harmonic distortion.

The %THD expressed in Equations 1 and 2 can be rewritten as shown in Equations 3 and 4 for voltage and current respectively.

$$\%THD_V = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \times 100 \quad (3)$$

$$\%THD_I = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \times 100 \quad (4)$$

While distortion power factor (DPF) and distorted (P_d) are also expressed as shown in Equations 5 and 6 respectively (Adesina & Fakolujo, 2015; Cataliotti et al., 2018):

$$DPF = \frac{1}{\sqrt{1 + THD^2}} \quad (5)$$

The distorted power (*Pd*);

$$Pd = V_{rms} \times I_{rms} \times Cos\,(\theta) \quad (6)$$

where θ is the Phase angle and P_d is the distorted power

2.2 Methodology

A power analyzer device (PAD) is used to investigate harmonics on the low-tension side of a distribution transformer. The PAD measures the overall harmonics of the low-tension networks connected to the distribution transformer over a certain period. The PAD specifically used is the Fluke 435-II, 3-Phase Energy and Power Quality Analyzer shown in Figure 1.

Figure 1: Fluke 435 -II, Three -Phase Energy and Power Quality Analyzer

This device measures and records Power and Energy parameters over a set period. The list of Parameters the analyzer can measure includes reactive power, active power, apparent power, system frequency, voltage, current, power factor, harmonics, etc. Power and Energy loggers are usually applied for conducting 3-phase energy and load studies. With Fluke Energy Analyzer and software, analysis can be carried out and detailed reports that point to the problem areas are created.

2.3 Data Collection

Eko Electricity Distribution Company (EKEDC) is one of the electricity service providers in Nigeria to residential, commercial, and industrial customers. Apart from providing electricity, other services include tracking faults, provision of monthly bills, maintenance, new installation of equipment, and other value-added services. A 500 kVA, 33/0.415 kV DT of EKEDC with the parameters shown in Table 1 were used as case studies.

2.4 Algorithm and Experimental Development

The experiment for the research on "Assessment of Total Harmonic Distortion for Power Quality Improvement in Low Voltage Distribution Networks" utilized the Fluke 435 Energy and Power Analyzer. Readings were captured and stored in the device, then later downloaded to a personal computer (PC) or laptop (LC) via a USB cable. To select the appropriate distribution transformer (DT), either 11/0.415kV or 33/0.415kV, the team first identified transformers with significant losses. Prior to the experiment, the researchers visited the transformer site to discuss electricity supply availability with the power station operators, as a continuous power supply was necessary for the experiment's success.

The process for the experiment involved several key steps. First, the team ensured the availability of electricity supply throughout the experiment. Then, they identified the cables for the red, yellow, and blue phases, along with the neutral, on the transformer's LT side, including the earth point. The "Push Logger" button on the Fluke Power Analyzer was used to log high-resolution readings, with the experiment set to run for 60 minutes, taking measurements every 1 minute. The current probe cables and voltage measuring cables were then properly connected to both the Fluke Power Analyzer and the secondary side of the transformer. The red, yellow, blue, and neutral current probes were attached to the transformer's LT bushing terminal, and the ground was connected accordingly.

Once the connections were verified, the experiment was initiated. Readings were recorded at predetermined time intervals, and the minimum, maximum, and average values for each interval were stored in the device's memory. After the experiment, the data was saved in the device's memory card in Comma-Separated Values (CSV) format, which could be opened in Excel. The storage card was then removed from the analyzer, and Fluke software was installed on the PC or LC to download the results. The data was retrieved as CSV files using Fluke Power Quality Analyzer Power Log software. The nature of the downloaded results, shown in Figure 4, could not be fully presented due to the extensive nature of the data. Finally, the data was used to create charts and graphical interpretations using Microsoft Excel, providing a clear visual analysis of the total harmonic distortion and its impact on power quality in the low voltage distribution network.

This algorithm is further illustrated using the flowchart presented in Figure 3.

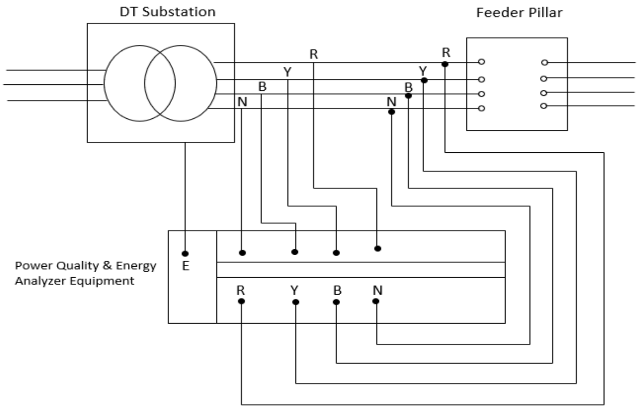

Figure 2: Experimental circuit arrangement case studied substation

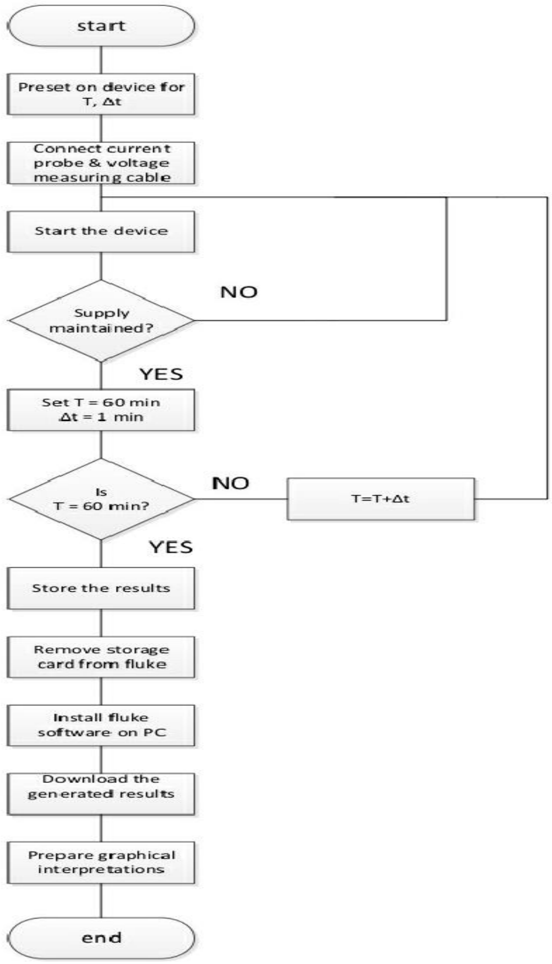

Figure 3: The flow process of DT power analysis using power quality and energy Analyzer

Table 1: Transformer Data

Capacity (kVA)	Voltage Ratio (kV)	Loading (%)	Location
500	33/0.415	80	Lagos

In the flowchart box tagged "Start the Device" in Figure 3, the researchers have automatically set the following on the power analyzer:

1. Name of the DT Substation
2. Total duration of analysis (Time T) (otherwise referred to as setting i.e., 60 Minutes or One hour).
3. Data capturing interval t (measurement time interval).
4. Chosen parameters to be evaluated.

However, when time t is incremented, as long as the power supply is still intact, the system returns to the box (starts the Device) and repeats all the parameter calculations for that time increase. The system continues this process until T = 60 Minutes.

3. Results and Discussion

This section presents the analysis and interpretation of the data collected from the various measurements. It discusses the observed trends, compares results across different parameters (such as voltage, frequency, and current), and identifies any anomalies or patterns that could indicate system inefficiencies or potential issues. The insights gained here are essential for understanding the overall performance of the electrical system and providing recommendations for improvement.

3.1 Case Study Transformer Results and Discussion

The THD voltage at every minute of the 60 minutes (One Hour) duration considered ranges from 0.63- 1.04 v for all three phases, while the corresponding THD voltage of the neutral to ground ranges from 59.48-70.61v.

3.1.1 THD Voltages per Phase (Volts)

Total Harmonic Distortion (THD) in voltage is a crucial parameter in assessing power quality within a distribution network. Table 2 presents the THD voltage measurements for three-phase lines (L1-N, L2-N, and L3-N) and Neutral-to-Ground (N-G) over a 60-minute period. The recorded THD values provide insight into waveform distortion levels and potential power quality concerns.

The measured THD voltages per phase, as presented in Table 2, provide a critical insight into the harmonic distortions affecting the power quality of the case study distribution transformer. The recorded THD voltage values for phases L1-N, L2-N, and L3-N fluctuate within the ranges of 0.63V–0.79V, 0.84V–0.91V, and 0.89V–1.04V, respectively. These values indicate that the harmonic distortions in individual phases are relatively low, suggesting that the phase voltages remain within a reasonably stable limit. However, the THD voltage measured between Neutral and Ground (N-G) exhibits significantly higher values, ranging from 59.48V to 70.61V. The consistently elevated THD voltage at the neutral-ground connection is an indication of inadequate grounding at the substation, which can contribute to power quality issues such as voltage instability, equipment malfunction, and potential safety hazards.

A deeper analysis of the data reveals fluctuations in THD voltage at different timestamps, with no significant phase exhibiting disproportionately higher distortion than the others. The THD voltage of L3-N, which has the highest recorded value of 1.04V, remains within acceptable limits but suggests that this phase experiences slightly higher harmonic distortion compared to L1-N and L2-N. Conversely, the neutral-to-ground voltage is excessively high, indicating the presence of return current in the neutral conductor, likely due to improper load balancing or excessive third harmonic currents in the system.

The implications of these findings highlight the necessity of implementing corrective measures to enhance the grounding and balancing of loads across the three phases. A solid grounding system would mitigate the neutral-ground voltage, reducing associated power quality issues. Additionally, proper harmonic filtering techniques, such as installing passive or active harmonic filters, could help suppress the harmonic voltages at the source. If left unaddressed, the observed high neutral-ground voltage could lead to insulation breakdown, transformer overheating, and increased losses in the system.

In summary, the results from Table 2 indicate that while the phase-to-neutral THD voltages are relatively stable, the excessively high neutral-to-ground THD voltage presents a major concern. This issue suggests poor grounding and potential load imbalance, which could lead to further power quality deterioration if corrective measures are not implemented.

3.1.2 THD Current per Phase (Amperes)

The measured Total Harmonic Distortion (THD) current per phase, as shown in Table 3, provides a comprehensive understanding of harmonic distortions within the distribution system.

The measured Total Harmonic Distortion (THD) current per phase, as shown in Table 3, provides a comprehensive understanding of harmonic distortions within the distribution system. The recorded values for phase L1 fluctuate between 12.82A and 16.68A, L2 ranges from 5.15A to 6.31A, and L3 varies from 8.46A to 10.05A. Meanwhile, the neutral (N) current exhibits significant variations, ranging from 12.89A to 16.76A. These fluctuations indicate that harmonic currents are more prominent in phase L1 and the neutral conductor compared to L2 and L3. The notably higher harmonic current in L1 suggests an imbalance in the phase loads, which can contribute to excessive heating of equipment and increased losses in the system.

The relatively stable and lower THD currents observed in L2 suggest that this phase experiences fewer harmonics, potentially due to more balanced or linear loads. However, the consistent presence of harmonic currents in L3, although slightly lower than in L1, suggests that nonlinear loads are contributing to distortion in this phase as well. The neutral current values are particularly concerning, as they closely match the highest harmonic current in L1, indicating a significant accumulation of triplen harmonics (third-order and multiples). These triplen harmonics are known to sum up in the neutral conductor, leading to excessive neutral currents, which can cause overheating and reduce system efficiency.

Anomalies such as the peaks in L1 THD current at 16.68A (10:06.4) and 16.33A (30:06.4) indicate instances where nonlinear loads may have been operating at higher levels, injecting more harmonic content into the system. Similarly, the neutral current mirrors these fluctuations, confirming that these distortions are predominantly sourced from unbalanced nonlinear loads. If not mitigated, the high neutral current could lead to excessive voltage drops, increased losses in distribution transformers, and potential damage to electrical components.

To improve system performance, it is necessary to employ harmonic mitigation techniques such as active harmonic filters, phase balancing, and load redistribution. Proper system monitoring is essential to detect and correct imbalances before they escalate into severe power quality issues. Additionally, the installation of K-rated transformers or oversized neutral conductors can help handle excessive neutral currents more effectively, reducing potential overheating risks.

In summary, the analysis of Table 3 highlights the presence of significant harmonic currents in L1 and the neutral conductor, with moderate levels in L3 and minimal effects in L2. The results confirm the presence of nonlinear loads contributing to distortions, particularly in L1, leading to high neutral current. Addressing these harmonic distortions through proper mitigation strategies will be crucial in enhancing power quality and ensuring the longevity of distribution components. The subsequent analysis will examine the impact of these harmonic currents on system losses and overall efficiency.

Table 2: Measured THD Voltages per Phase (Volts)

Time	L1 - N	L2 -N	L3 - N	N - G
07:06.4	0.72	0.84	0.99	65.45
08:06.4	0.72	0.85	1	65.25
09:06.4	0.71	0.84	0.99	63.72
10:06.4	0.72	0.85	1	69.69
11:06.4	0.72	0.84	1.01	69.58
12:06.4	0.72	0.85	1.01	67.6
13:06.4	0.71	0.85	1	65.59
14:06.4	0.74	0.86	1.01	61.76
15:06.4	0.74	0.86	1.01	62.72
16:06.4	0.73	0.84	1.01	65.39
17:06.4	0.75	0.85	1.01	65.19
18:06.4	0.75	0.87	1.03	59.64
19:06.4	0.74	0.86	1.04	60.17
20:06.4	0.77	0.89	1.04	63.84
21:06.4	0.79	0.9	1.03	64.59
22:06.4	0.78	0.88	1.02	63.06
23:06.4	0.76	0.86	1	61.64
24:06.4	0.73	0.85	0.99	60.99
25:06.4	0.72	0.85	0.97	61.84
26:06.4	0.76	0.88	0.99	65.6
27:06.4	0.75	0.9	1	66.58
28:06.4	0.74	0.87	1	65.17
29:06.4	0.73	0.87	0.98	64.67
30:06.4	0.71	0.9	0.94	68.14
31:06.4	0.7	0.91	0.92	70.61
32:06.4	0.69	0.9	0.9	70.37
33:06.4	0.68	0.88	0.9	69.04
34:06.4	0.68	0.88	0.89	66.89
35:06.4	0.68	0.89	0.89	68.93
36:06.4	0.68	0.89	0.89	68.51
37:06.4	0.67	0.88	0.89	67.51
38:06.4	0.68	0.88	0.9	63.76
39:06.4	0.67	0.88	0.89	60.79
40:06.4	0.66	0.89	0.89	59.48
41:06.4	0.66	0.89	0.91	60.65
42:06.4	0.65	0.91	0.92	60.26
43:06.4	0.66	0.9	0.93	59.65
44:06.4	0.65	0.9	0.91	62.43
45:06.4	0.65	0.89	0.92	61.7
46:06.4	0.65	0.89	0.91	64.61
47:06.4	0.66	0.9	0.92	63.65
48:06.4	0.68	0.91	0.94	63.37
49:06.4	0.67	0.9	0.92	63.73
50:06.4	0.66	0.9	0.89	64

51:06.4	0.65	0.91	0.9	64.32
52:06.4	0.64	0.9	0.9	65.83
53:06.4	0.66	0.91	0.92	65.12
54:06.4	0.65	0.9	0.91	64.24
55:06.4	0.68	0.9	0.93	63.41
56:06.4	0.65	0.91	0.91	64.81
57:06.4	0.64	0.89	0.92	63.76
58:06.4	0.64	0.89	0.93	64.62
59:06.4	0.64	0.89	0.95	65.53
00:06.4	0.64	0.9	0.96	64.33
01:06.4	0.64	0.89	0.95	64.6
02:06.4	0.65	0.9	0.95	62.73
03:06.4	0.64	0.88	0.96	62.54
04:06.4	0.64	0.88	0.96	64.01
05:06.4	0.63	0.88	0.93	64.24
06:06.4	0.63	0.88	0.96	64.05

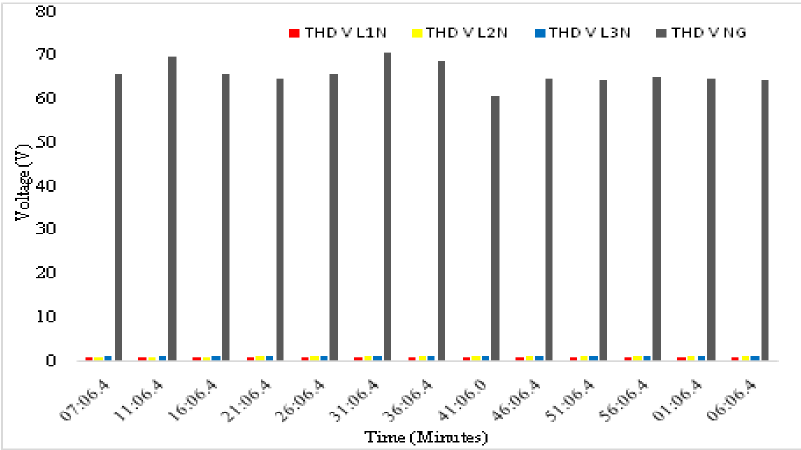

Figure 4: THD voltage against time

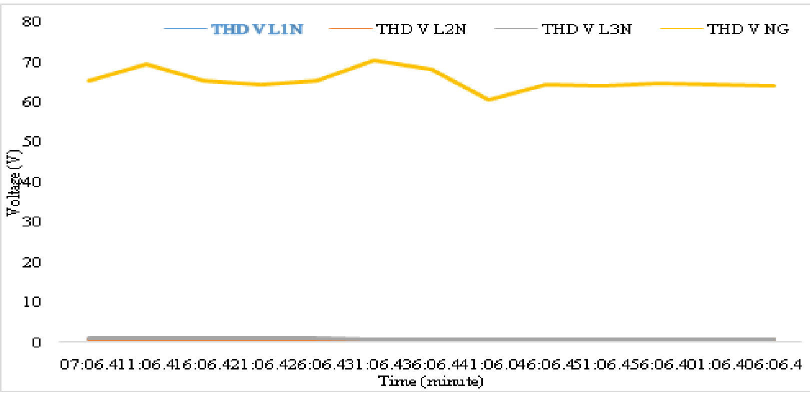

Figure 5 : THD Voltage against Time for Neutral to Ground

3.1.3 Phase-Neutral rms Voltage (Vrms)

This section delves into the phase-neutral RMS voltage measurements, focusing on the stability and variation of voltages in the three phases (L1-N, L2-N, L3-N) and the neutral-ground voltage. This helps assess whether the system maintains balanced voltage levels over time.

The analysis of the phase-to-neutral root mean square (rms) voltage values in Table 4 provides insight into the voltage stability of the system and the potential influence of harmonic distortion on the power quality. The recorded values for L1-N remain relatively stable throughout the observation period, fluctuating minimally between 219.38V and 221.28V, indicating that this phase experiences minimal voltage variation. The L2-N voltage starts around 222.4V and gradually rises to a peak of 225.46V, demonstrating a slight upward trend over time. Similarly, the L3-N voltage remains within a narrow range, increasing from 217.36V to 223.72V, suggesting an overall improvement in voltage levels but with noticeable fluctuations.

The neutral-to-ground (N-G) voltage remains consistently low, ranging from 0.16V to 0.28V. While these values suggest that the grounding system is effective in limiting excessive neutral-ground voltage, the gradual increase from 0.16V to 0.28V towards the end of the recorded period indicates the potential accumulation of neutral current, likely due to the presence of harmonics. This aligns with the previously observed high THD current in the neutral conductor in Table 3, further confirming the presence of triplen harmonics.

From a power quality perspective, the variations in L2 and L3 voltages, particularly the increasing trend in L2, could indicate an imbalance in load distribution or the presence of nonlinear loads affecting voltage regulation. The relatively stable L1-N voltage suggests that this phase is either lightly loaded or experiencing a more balanced power draw compared to the other phases. However, the higher fluctuations in L3-N voltage, especially in the earlier hours, may be attributed to transient load changes or the impact of harmonic distortions causing slight voltage drops.

The steady increase in voltage levels for L2-N and L3-N in the latter part of the observation period suggests that system conditions, such as load variations and harmonic influences, evolve over time. This can lead to increased transformer heating, reduced efficiency, and a higher likelihood of voltage unbalance, which could adversely impact sensitive equipment. The observed rise in neutral-to-ground voltage, although relatively low, highlights the effect of accumulated neutral currents, emphasizing the need for harmonic mitigation measures.

To ensure voltage stability and minimize the effects of harmonic distortions, implementing passive or active harmonic filters could be beneficial. Additionally, improving load balancing across phases and monitoring neutral currents can help maintain consistent voltage levels, preventing excessive voltage drops or increases. Given the observed trends, continued monitoring of voltage variations alongside harmonic analysis is essential to prevent long-term power quality degradation.

Table 3: Measured THD Current per Phase (Amperes)

Time	L1	L2	L3	N
07:06.4	14.56	5.65	9.94	14.64
08:06.4	14.85	5.75	9.8	14.93
09:06.4	14.6	5.78	10.05	14.67
10:06.4	16.68	6.31	9.67	16.76
11:06.4	16.23	6.19	9.58	16.31
12:06.4	15.55	5.98	9.33	15.63
13:06.4	15.47	5.99	9.74	15.54
14:06.4	14.41	5.74	9.89	14.48
15:06.4	14.53	5.67	9.56	14.61
16:06.4	15.18	5.75	9.33	15.25
17:06.4	14.89	5.73	9.11	14.96
18:06.4	13.67	5.53	9.54	13.74
19:06.4	13.72	5.54	9.26	13.79
20:06.4	14.8	5.71	9.55	14.87
21:06.4	14.95	5.61	9.49	15.03
22:06.4	14.57	5.5	9.33	14.64
23:06.4	14.32	5.46	9.21	14.38
24:06.4	13.96	5.41	9.42	14.02
25:06.4	14.54	5.6	9.76	14.6
26:06.4	15.14	5.63	9.52	15.21
27:06.4	15.29	5.61	9.32	15.36
28:06.4	15.29	5.73	9.46	15.36
29:06.4	15.21	5.73	9.54	15.28
30:06.4	16.33	5.91	9.46	16.4
31:06.4	16.12	5.86	9.73	16.2
32:06.4	16.05	5.83	9.41	16.13
33:06.4	15.59	5.73	9.39	15.67
34:06.4	14.9	5.55	9.38	14.97
35:06.4	15.58	5.78	9.39	15.66
36:06.4	15.51	5.81	9.4	15.58
37:06.4	15.43	5.83	8.73	15.5

38:06.4	14.05	5.57	9.03	14.12
39:06.4	13.05	5.3	8.95	13.11
40:06.4	12.82	5.15	8.96	12.89
41:06.4	13.18	5.29	9.01	13.24
42:06.4	13.13	5.37	9.24	13.19
43:06.4	13.18	5.55	9.36	13.24
44:06.4	13.88	5.68	9.2	13.95
45:06.4	13.73	5.6	8.98	13.79
46:06.4	14.41	5.59	8.86	14.48
47:06.4	14.18	5.58	9.21	14.25
48:06.4	13.99	5.52	9.41	14.05
49:06.4	14.24	5.49	9.33	14.31
50:06.4	14.18	5.34	9.11	14.25
51:06.4	14.23	5.38	9.13	14.3
52:06.4	14.36	5.44	9.05	14.43
53:06.4	14.13	5.48	9.31	14.21
54:06.4	13.85	5.31	8.94	13.92
55:06.4	13.66	5.21	8.93	13.73
56:06.4	13.96	5.33	8.98	14.03
57:06.4	13.6	5.28	8.89	13.67
58:06.4	13.7	5.28	8.54	13.78
59:06.4	14.11	5.48	8.46	14.19
00:06.4	13.75	5.47	8.76	13.82
01:06.4	13.75	5.45	8.96	13.82
02:06.4	13.29	5.33	9.08	13.36
03:06.4	13.35	5.35	8.93	13.41
04:06.4	14.03	5.55	8.99	14.09
05:06.4	13.81	5.34	8.64	13.88
06:06.4	14.07	5.5	8.53	14.14

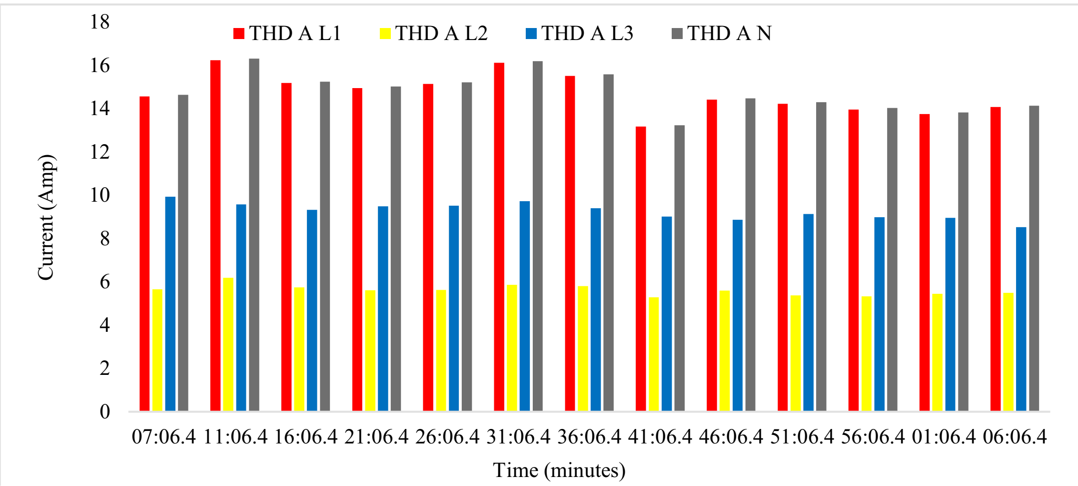

Figure 6: THD Current per phase against Time

3.1.4 Phase - Phase RMS Voltage (V_{rms})

This subsection examines the phase-to-phase RMS voltage measurements (L12, L23, L31), shedding light on the inter-phase voltage balance and identifying potential discrepancies or imbalances that could affect the system's performance.

The phase-to-phase root mean square (rms) voltage measurements reveal important insights into system stability and voltage balance. The L12 voltage fluctuates between 382.14V and 390.02V, L23 ranges from 376.88V to 386.28V, and L31 varies between 380.02V and 390.76V. Over time, there is a noticeable increase in these voltages, with the highest values occurring around the 40th-minute mark. This trend suggests potential overvoltage conditions that may arise due to changes in load demand, system impedance, or reactive power compensation. Voltage unbalance is relatively minor, with differences between L12, L23, and L31 generally within 5V to 10V. However, at certain points, such as the 12th minute, L23 records its lowest value of 376.88V, while the other phases remain above 380V, indicating slight unbalance. Several factors could contribute to the observed voltage variations, including harmonic distortion, which can elevate rms values, and transformer tap changes that regulate voltage dynamically. To mitigate potential issues, continuous voltage monitoring is essential to prevent overvoltage conditions. If harmonic distortion is present, deploying filters or power factor correction techniques could help stabilize the voltages. Additionally, while the system remains relatively balanced, ongoing load management and balancing strategies will further enhance power quality. Overall, while the measured voltages are within operational limits, the increasing trend underscores the importance of proactive regulation to maintain system stability.

3.1.5 Current per Phase (Amperes)

Here, the current measurements for each phase (L1, L2, L3) and neutral (N) are discussed. The current distribution provides insight into the load across the system and identifies any phases that may be overloaded or underutilized.

The measured phase current values exhibit notable variations across the three phases (L1, L2, L3) and the neutral (N) conductor. L1 ranges from 274.2A to 379.0A, L2 fluctuates between 599.7A and 727.2A, while L3 varies from 216.8A to 250.6A. The neutral current follows a similar pattern, spanning 271.7A to 375.9A. These variations indicate an imbalance in the load distribution across the three phases, with L2 consistently carrying the highest current. This suggests that the system is experiencing an unequal phase loading, which could lead to increased losses, heating, and reduced efficiency.

The fluctuations are most pronounced in the second half of the measurement period, where all three phases experience an increasing trend, peaking around the 56th to 60th minute. This rise might be attributed to a higher load demand or transient effects such as motor startups or switching operations in the system. Additionally, the consistently high neutral current (often exceeding 300A) suggests the presence of significant harmonic distortion or an unbalanced load condition, which could strain the transformer and distribution network.

To mitigate these effects, corrective measures such as load balancing, phase reconfiguration, or the application of power factor correction techniques may be necessary. If harmonic distortion is contributing to

Table 4: Phase - Neutral rms Voltage (Vrms)

Time	L1 - N	L2 - N	L3 - N	N - G
1.0	220.96	222.4	218.98	0.16
2.0	220.82	222.32	219.04	0.16
3.0	220.96	222.58	219.18	0.18
4.0	220.88	222.58	219.72	0.18
5.0	220.92	222.52	219.56	0.18
6.0	220.66	222.18	219.16	0.18
7.0	220.3	222.06	218.9	0.18
8.0	220.02	221.76	218.34	0.2
9.0	219.84	221.52	218.16	0.2
10.0	219.5	221.14	217.94	0.2
11.0	219.42	220.98	217.7	0.2
12.0	219.38	221.02	217.36	0.2
13.0	219.78	221.44	217.72	0.22
14.0	220.14	221.88	218.42	0.22
15.0	220.16	221.88	218.5	0.22
16.0	220.18	221.98	218.5	0.22
17.0	220.62	222.42	219.06	0.22
18.0	221.28	222.98	219.64	0.22
19.0	221.28	223.08	219.92	0.24
20.0	221.28	222.74	219.68	0.24
21.0	221.28	222.78	219.74	0.22
22.0	221.28	223.42	220.42	0.24
23.0	221.28	224.18	221.2	0.24
24.0	221.28	224.04	221.72	0.24
25.0	221.28	224.02	222	0.24
26.0	221.28	224.28	222.32	0.24
27.0	221.28	224.42	222.64	0.24
28.0	221.28	224.46	222.7	0.24

29.0	221.28	224.32	222.6	0.24
30.0	221.28	224.02	222.44	0.24
31.0	221.28	223.88	222.36	0.24
32.0	221.28	224	222.06	0.24
33.0	221.28	223.96	221.72	0.24
34.0	221.28	224.48	222.36	0.24
35.0	221.28	225.34	223.18	0.24
36.0	221.28	225.26	223.12	0.26
37.0	221.28	225.36	223.28	0.26
38.0	221.28	225.4	223.6	0.26
39.0	221.28	225.42	223.62	0.26
40.0	221.28	225.46	223.72	0.26
41.0	221.28	225.44	223.4	0.26
42.0	221.28	225.26	223.1	0.26
43.0	221.28	225.32	223.24	0.26
44.0	221.28	225.38	223.46	0.26
45.0	221.28	225.34	223.26	0.26
46.0	221.28	225.18	223.16	0.26
47.0	221.28	225.28	223.2	0.26
48.0	221.28	225.24	222.96	0.26
49.0	221.28	225	222.68	0.26
50.0	221.28	224.42	222.1	0.26
51.0	221.28	224.1	221.78	0.26
52.0	221.28	223.76	221.42	0.26
53.0	221.28	223.34	221.16	0.26
54.0	221.28	223.28	220.92	0.28
55.0	221.28	223.1	220.8	0.28
56.0	221.28	222.98	220.54	0.28
57.0	221.28	223.06	220.68	0.28
58.0	221.28	223.02	220.72	0.28
59.0	221.28	222.62	220.22	0.28
60.0	221.28	222.42	220.2	0.28

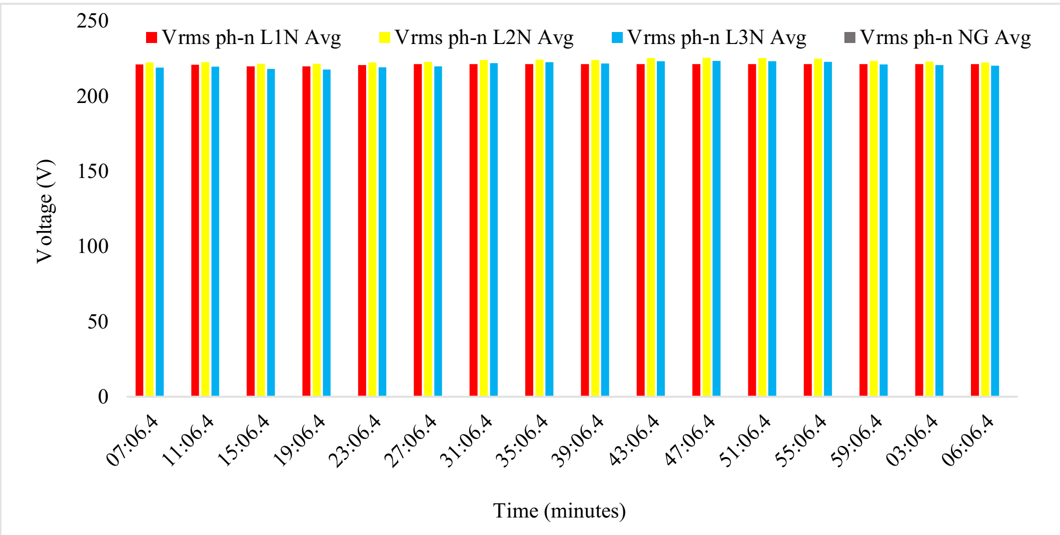

Figure 7: Vrms Ph-N against Time

these high neutral currents, filtering solutions such as active harmonic filters could help reduce power quality issues. Overall, while the system remains operational, the observed imbalances and increasing trends in current highlight the need for continuous monitoring and possible intervention to ensure long-term stability and efficiency.

Table 5: Measured Phase - Phase rms Voltage (Vrms)

Time	L12	L23	L31
1.0	384.62	379.64	382.86
2.0	384.54	379.68	382.66
3.0	384.94	379.98	382.88
4.0	384.88	380.82	382.9
5.0	384.78	380.58	382.92
6.0	384.2	379.84	382.54
7.0	383.98	379.46	381.86
8.0	383.52	378.52	381.32
9.0	383.04	378.22	381
10.0	382.42	377.86	380.4
11.0	382.14	377.46	380.22
12.0	382.28	376.88	380.02
13.0	383	377.54	380.7
14.0	383.74	378.74	381.36
15.0	383.74	378.88	381.4
16.0	383.88	378.92	381.42
17.0	384.62	379.78	382.34
18.0	385.66	380.66	383.56
19.0	385.82	381.06	383.66
20.0	385.36	380.64	383.36
21.0	385.4	380.74	383.46
22.0	386.48	381.9	384.4
23.0	387.9	383.18	385.8
24.0	387.36	383.8	386.18
25.0	387.3	384	386.96
26.0	387.8	384.48	387.58
27.0	387.88	384.88	388.08
28.0	387.94	384.86	388.38
29.0	387.64	384.82	388
30.0	387.14	384.36	387.74
31.0	386.88	384.2	387.54
32.0	387.14	383.76	387.62
33.0	387.14	383.22	387.56
34.0	388.18	384.1	388.82
35.0	389.7	385.54	390.18
36.0	389.54	385.36	390.18
37.0	389.68	385.58	390.3
38.0	389.74	386.08	390.6
39.0	389.82	386.08	390.6

40.0	389.98	386.28	390.76
41.0	390.02	385.86	390.26
42.0	389.68	385.36	389.88
43.0	389.72	385.6	389.96
44.0	389.78	385.9	390.38
45.0	389.7	385.68	390.02
46.0	389.42	385.48	389.96
47.0	389.62	385.52	390.2
48.0	389.5	385.24	389.86
49.0	389.14	384.74	389.4
50.0	388	383.84	388.24
51.0	387.4	383.24	387.8
52.0	386.72	382.7	387.22
53.0	386.04	382.18	386.58
54.0	385.9	381.8	386.34
55.0	385.62	381.54	386.18
56.0	385.48	381.04	386.02
57.0	385.68	381.2	386.18
58.0	385.62	381.36	385.86
59.0	384.82	380.64	385.14
60.0	384.48	380.54	384.76

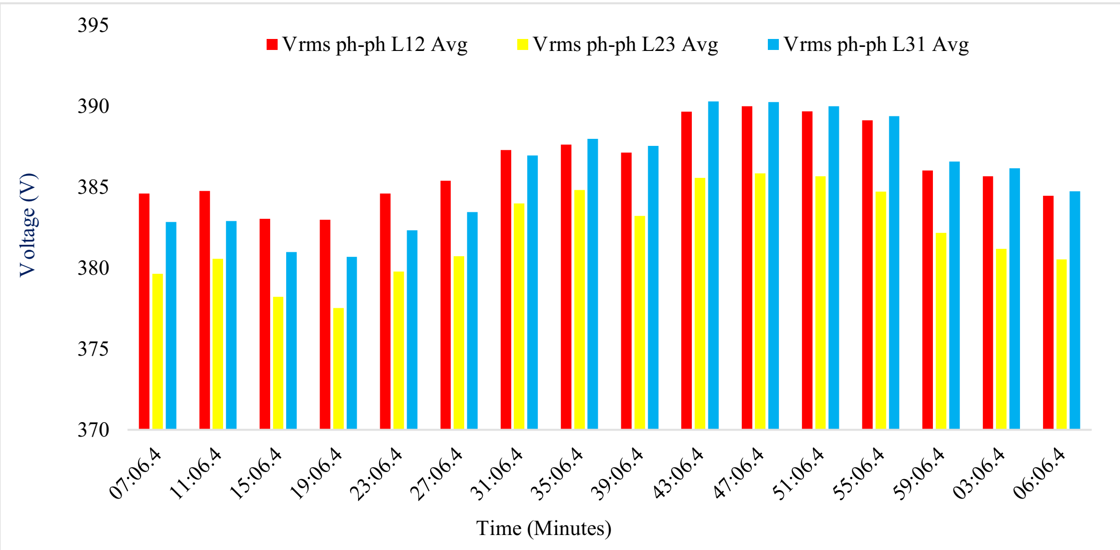

Figure 8: Phase to Phase Voltage Chart against Time

Table 6: Measured Current per Phase (Amperes)

Time	L1	L2	L3	N
1	313	653.3	236.9	310
2	306.3	648.3	238.9	303.4
3	311.3	649.5	232	308.4
4	274.2	599.7	239.8	271.7
5	282	613	241.6	279.4
6	291.6	631.5	247.9	288.9
7	296.1	631.1	238.5	293.4

8	316.5	655.7	234.2	313.6
9	311.6	653.2	242.1	308.7
10	296.5	637.7	247.3	293.7
11	299.6	645.3	250.6	296.7
12	327.5	678.1	239.6	324.4
13	329.5	686.5	245.1	326.3
14	309.2	657	246.2	306.3
15	302.2	648.3	250	299.4
16	307.2	655.6	248.8	304.4
17	308.8	653.3	245.1	306
18	318.5	662.9	238.8	315.7
19	307.1	640.5	231.7	304.4
20	296.4	635.2	239.4	293.7
21	296.7	640.5	246	294
22	295.8	632.7	237	293.2
23	297	633.2	234.3	294.5
24	281.4	616.6	242.8	279
25	284.9	617.6	236.4	282.3
26	284.7	617.1	235.6	282.1
27	291.8	625.8	233.7	289.2
28	303.4	642	231.8	300.7
29	294	630	233.5	291.4
30	296.5	630	231.9	293.9
31	295.3	631.4	237.6	292.7
32	319.5	654	227.5	316.7
33	341.3	684.3	227.5	338.3
34	347.9	695.8	229.9	344.8
35	344.3	694.7	230.7	341.3
36	352.5	702.6	228.5	349.4
37	354.1	692.8	217.8	351.1
38	336.4	671.7	221.6	333.6
39	336.1	675.5	224.5	333.2
40	325.3	668	231.9	322.5
41	333.1	672	221.5	330.3
42	345.7	683.6	216.8	342.9
43	345.1	678.4	217.2	342.4
44	340.8	677.1	221.7	338
45	341.3	675.8	221.1	338.6
46	339.3	675.1	223.6	336.5
47	346.8	679.2	218.3	343.9
48	353.6	697.3	229.3	350.7
49	357.3	706	232	354.3
50	352.7	696.9	230.1	349.8
51	358.9	705.9	230.4	355.9
52	361.3	711.7	238.5	358.2
53	352.8	702	242.6	349.8
54	363.5	711.9	235.7	360.4

55	365.4	709.1	229.4	362.4
56	379	725	227.5	375.9
57	377.3	727.2	229.9	374.2
58	358	702.1	229.7	355
59	359.9	714	240.3	356.9
60	348.9	704.5	242.4	346

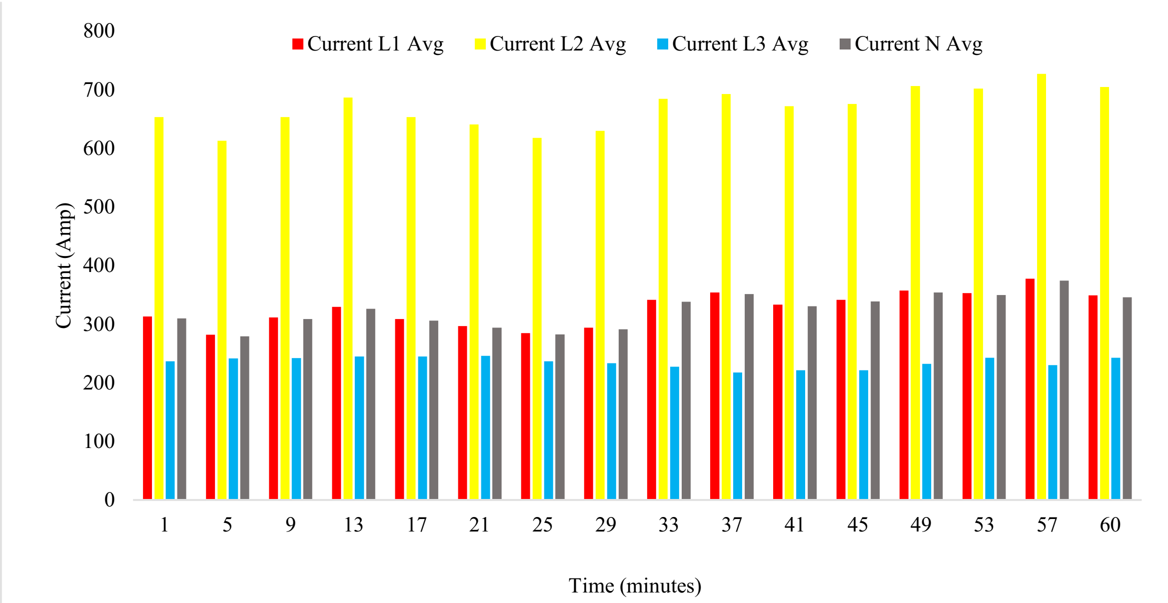

Figure 9: Chart of Current per Phase against Time

Table 7: Recorded Peak RMS 3-Phase Power

Phase description	V_{rms} (V)	I_{rms} (A)	Cos θ
Red Phase	384.62	313	0.94
Yellow Phase	379.64	653.3	0.99
Blue Phase	382.86	236.9	0.98

where,

$415 \leq V_{rms} < 370$ Volts

$696 \leq I_{rms} > 0$ Amperes, and $0 < \text{Cos } \theta < 1$

4. Conclusion

In this study, Total Harmonic Distortion (THD) in the current, voltage, and neutral-ground voltage of a 500 kVA, 11/0.415 kV distribution transformer was assessed using the Fluke 435 experiment. The results from Tables 2 through 7 reveal key observations about the transformer's performance in relation to international standards and existing research on power quality. Notably, the THD voltage observed at the neutral-ground connection suggests that the transformer, along with associated equipment, is not solidly earthed, which is consistent with similar findings in global studies where improper grounding contributes to increased harmonic distortion (Javadian et al., 2021). Additionally, the current THD values for each of the three phases and the neutral line exhibit a significant imbalance, with current values ranging from 5.3A to 16.76A. Such imbalances are commonly observed in low voltage distribution networks, and the results underscore the need for adequate load balancing, as echoed by recent research on harmonics in distribution systems (Singh et al., 2020). When comparing the measured phase-to-neutral voltage to international standards, the Nigerian single-phase voltage of 230V falls within the typical range of 215V to 225V, consistent with the findings from Table 4, which reports voltage values ranging from 217.36V to 224.46V. Similarly, the neutral-ground voltage, ranging from 0.16V to 0.24V, is relatively low, aligning with the expectations of an effectively grounded system (Hassan et al., 2018). In terms of phase-to-phase voltage, Nigeria's standard of 415V aligns well with the results from Table 5, where 97% of readings fall within the typical range of 380V to 390V, further validating the stability of the voltage levels within the expected norms (Bhardwaj & Srivastava, 2020). However, the measured current per phase (Table 6) indicates that the load on the transformer is consistently near 50% of the rated current, but often exceeds the recommended load, hovering in the 600A to 700A range. This suggests a substantial overload on the phases throughout the experimental period, which could lead to an unstable network. Recent studies in power quality have also highlighted similar issues of overload and phase imbalance, emphasizing the detrimental effects on system stability and efficiency (Sharma et al., 2022). Therefore, the findings of this experiment point to a need for immediate corrective actions such as load balancing to reduce neutral current and prevent further harmonic distortion. These actions align with recommendations in existing research, which advocate for harmonic control equipment in instances where THD exceeds acceptable levels (Kumar et al., 2019).

The study's limitations include the reliance on a continuous power supply, where interruptions to the feeder require restarting the experiment. Despite this limitation, the findings underscore the importance of regular maintenance and proactive measures to ensure load balance and minimize harmonic distortion. International standards for THD, which typically set acceptable limits for voltage and current harmonics, should be referenced when making adjustments to power distribution systems to meet established quality benchmarks (IEC 61000-4-7, 2011). This research supports the growing body of knowledge in power quality, reinforcing the need for routine monitoring and corrective actions to ensure stable and efficient operation in low voltage distribution networks.

Competing Interest

The authors declare that we have no competing interests.

Funding

Not applicable

Availability of Data and Materials

The data used are contained in the Transformer network obtained from Eko Electricity Distribution Network, Marina, Lagos, Nigeria.

Authors' Contributions

The research was carried out by the listed authors. The experimental design and data sourcing were handled by LM. However, LM, OO, KDD, and ABO collaborated to arrange the research experiment. LM and ABO also coordinated the collation of the results. The post-experimental report was drafted by OO and KDD, while LM and ABO developed the manuscript for publication as an article in a reputable Journal. In the end, the four authors finally read the manuscript and thus gave consent approval to this manuscript submission to the desired Journal.

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