Evaluation of Daily Load Variability and Harmonic Distortion in the Sub-Distribution Network of a Nigerian University

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ORIGINAL RESEARCH

Abstract— In Nigerian universities, power supply and consumption fluctuate due to varying daily activities and demand, with electrical harmonics complicating energy management. Despite their importance, there is limited research on daily harmonic behaviour in university electricity usage, making optimizing energy distribution and improving power quality challenging. This study focused on harmonic analysis in the sub-distribution networks of a Nigerian university, specifically examining 19 units of 11/0.415 kV transformers in the FUTA network. Using NEPLAN software, the study assessed Voltage Total Harmonic Distortion (THDv) at points of common coupling (PCCs) under various load conditions, classifying the PCCs into residential, commercial 1, commercial 2, and special types. The results revealed that residential PCCs had a minimum THD of 4.03 in the morning, with a peak ranging from 14.08 to 20.45 between 1 and 5 am. Commercial 1 PCCs had a minimum THD between 3.01 and 10.09 during the day and a maximum THD from 46.66 to 57.02 at night. Commercial 2 PCCs showed minimum THD between 2.09 and 36.04 during the day, with peaks of 8.48 to 65.14 at night. Special PCCs showed minimum THD between 1.2 and 12.80 during the day, with peaks between 14.41 and 20.34 at night. The study found a strong correlation between load variation and harmonic generation, showing that more diverse, non-linear loads result in lower THDv, and harmonic distortion is higher at night across all PCC types.

Keywords—Daily Load Curve, Demand-Side Management, Harmonic Analysis, Load Variability, Voltage Total Harmonic Distortion,

1 INTRODUCTION

Power quality issues, including harmonic distortion, in electrical power systems is a growing concern, particularly in regions experiencing rapid development and urbanization (Ahmed *et al.,* 2022). Harmonic distortion has been a persistent challenge in the management of electrical systems, particularly in environments like universities where energy demand is highly variable. Universities are dynamic environments with diverse and fluctuating energy demands due to the wide range of activities that take place, including lectures, laboratory work, research, and administrative functions. As major electricity consumers, Nigerian universities are susceptible to the negative impacts of harmonic distortion, which can lead to increased energy costs, equipment damage, and reduced system reliability (Hu, *et al.,* 2023). Power electricity demand varies from time to time based on the consumers routine and non-routine activities that affect consumers' electricity use (Jabian *et al.,* 2020). Different customer categories, such as residential, commercial and industrial consumers exhibit different load consumption patterns (Beck and Machlev, 2019). The load consumption pattern changes from working days to non-working days and from daytime to night-time consumption. The nature of the connected loads, such as the quantity of connected non-linear loads to total connected loads affects the total harmonic current flowing in the distribution network. This changing load pattern and affect the harmonic level present in a distribution network Several authors have conducted studies on load variability and its impacts. (Gunkel *et al.,* 2023) conducted a comprehensive survey on electricity consumption levels to address the problems of future network development and policy design. (Duarte *et al.,* 2024) considered load variation with demand response and time-of-use pricing for electricity consumption. This is essential to address power quality issues to develop a management strategy for the varying harmonic level through demand side management strategy using load shifting technique (Çiçek *et al.,* 2021). It has been shown that load variability in institutional settings can be significant, with peak demand often occurring during specific times of the day or week, such as during class hours or examination periods (Akinyele *et al.,* 2014). Research on energy consumption patterns in Nigerian universities has highlighted the challenges posed by inconsistent power supply and the high energy consumption of non-linear loads, such as computers, laboratory equipment, and air conditioners (Olaleye & Adeyemi, 2019). However, while the temporal variation of load is well-documented, there is a lack of research specifically examining how this variability interacts with harmonic distortion in university settings, particularly in Nigeria (Chandrakasan *et al.,* 2016). Although harmonic distortion has been studied extensively in industrial and commercial settings (Ghosh *et al.,* 2017), research on its occurrence and impact in educational institutions remains limited. Existing studies focus primarily on the

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impact of harmonics on power systems in residential and industrial environments (Ning *et al.*, 2021), but the specific behavior of harmonics in university power distribution networks, especially in regions like Nigeria, has not been adequately explored. While there is a significant body of literature on harmonic analysis, studies that investigate daily load-side harmonic behavior in real-world settings are scarce. Most of the research on harmonic distortion tends to focus on either instantaneous snapshots or broad long-term trends, without considering how daily variations in load affect harmonic generation. A study by Baba *et al.*, (2020) indicated that harmonic levels tend to vary throughout the day, depending on the operational schedules and load profiles, with higher distortion typically observed during periods of high demand or when non-linear loads are more active. These fluctuations in harmonic distortion have important implications for energy management, particularly in environments where load profiles are highly variable, such as universities. Despite the well-documented impacts of harmonic distortion, energy management strategies in universities and similar institutions often overlook this issue. Studies like those by Erdem *et al.*, (2018) have pointed out the failure of traditional energy management systems to incorporate harmonic analysis and control, focusing mainly on load distribution and efficiency rather than power quality. This oversight is especially problematic in settings like universities, where electrical systems are exposed to high demand and complex load types. Furthermore, existing studies do not adequately classify PCCs based on load types or analyze the impact of load-specific harmonics on power quality. This study addressed these gaps by providing a daily load-side harmonic analysis of a Nigerian university's power distribution network. By focusing on 19 units of 11/0.415 kV transformers and evaluating THDv at multiple PCCs categorized into residential, commercial, and special loads, this research provides a more granular understanding of how daily load variability influences harmonic distortion. The findings will contribute to the development of more effective energy management strategies for Nigerian universities, offering insights into energy management, and power quality improvement strategies and the relationship between load variation and harmonic generation.

2. Total Harmonic Distortion

2.1 Evaluation Of Total Harmonic Distortion Indices On FUTA Sub-Distribution Network

The major type of evaluation performed during harmonic analysis is the voltage distortion analysis. Total harmonic distortion considers the contribution of every individual harmonic component to the signal. THD is defined for voltage and current signals as shown in Equations 1 (Peretyatko *et al.*, 2023)

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h{}^2}}{V_1} \quad (1)$$

where V_h is the voltage at h harmonic, and V_1 is the voltage of fundamental harmonic

2.2 Evaluation Of The Daily Power Harmonic Generations On FUTA Sub-Distribution Network

The following steps were carried out in the Evaluation of Power Harmonic Generation on the FUTA Sub-Distribution Network:

i. Obtained and studied the network diagram of the FUTA sub-distribution network.
ii. Identified the points of common coupling of the FUTA sub-distribution network.
iii. Identified and characterized the load connected to each point of common coupling into linear and non-linear loads
iv. Identified the characteristic harmonic spectrum of each type of non-linear load
v. Modelled and simulated hourly representation of the linear and non-linear loads cases to obtain corresponding harmonic responses and total harmonic distortions using NEPLAN software
vi. Computed hourly voltage total harmonic distortion (THDv) of each Point of Common Coupling in the FUTA sub-distribution network.

2.3 Evaluation Of Total Harmonic Distortion Of PCCs Based On Load Type

The 19 transformer substations in the FUTA network considered as Point of Common Coupling (PCCs) are divided into Special, Residential, Commercial 1, and Commercial 2 based on the type of loads associated with the buildings connected, as shown in Table 1

Table 1: Classification of PCCs Based on Load Type

Classification of PCCs Based on Load Type	PCCs	Remark
Residential	Undergraduate Hostel and Aluta	90% of connected buildings are residential.
Commercial 1	Behind Engineering Workshop, Behind LT, 2500, Farm, Front of SMAT, CERAD, Senate	More than 90% of connected buildings are commercial.

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Commercial 2	First Bank, WEMA Bank, GTB, UBA, and Heritage Bank	100% of Connected Buildings are banks
Special	Akindeko, CRET Junction, IDD, and PG Hostel	The buildings connected contain a significant number of Commercial and Residential loads.

2.3 Relationship Between Empirical Daily Load Compositions And Total Harmonic Distortion

To obtain a relationship between the empirical daily load composition and total harmonic distortion on the FUTA sub-distribution network, a case study from the different classifications of PCCs was analyzed based on the daily load compositions and corresponding total harmonic distortion at time (t).

2.4 Correlation Analysis Between Empirical Daily Load Composition And Total Harmonic Distortion (THD) On The Futa Sub-Distribution Network

The correlation analysis between empirical daily load composition and total harmonic distortion was evaluated using Spearman's rank correlation coefficient, Kendall Correlation, and Pearson Correlation. Equations 2 to 5 define Pearson Correlation, Spearman's rank correlation coefficient, and Kendall Correlation.

$$r=\frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(x_i-\bar{x})^2}} \quad (2)$$

where x_i and y_i are the individual data points of the variables X and Y, $\bar{x}$ and $\bar{y}$ are the means(average) of the variable X and Y. r is the Pearson correlation coefficient.

$$\rho=\frac{1-6\sum d_i^2}{n(n^2-1)} \quad (3)$$

Where d_i is the difference between the ranks of the corresponding variables, n is the number of pairs of data, and ρ is Spearman's rank correlation coefficient.

$$\tau=\frac{C-D}{\frac{n(n-1)}{2}} \quad (4)$$

Where C is the number of **concordant pairs**, where for two pairs (x_1, y_1) and (x_2, y_2) , the pairs are concordant if $(x_1 > x_2 \; and \; y_1 > y_2)$ or $(x_1 < x_2 \; and \; y_1 < y_2)$; D is the number of **discordant pairs**, where $(x_1 > x_2 \; and \; y_1 > y_2)$ or $(x_1 < x_2 \; and \; y_1 < y_2)$; n is the number of data points; τ\tauτ is Kendall's Tau correlation coefficient.

3 Result And Discussion

3. 1 Evaluation Of Total Harmonic Distortion Of Pccs On Load Type

Figures 1, 2, 3, and 4 show the daily voltage harmonic distortion of residential, commercial 1, commercial 2, and special PCCs. There is a high correlation in THDv patterns within each classification, suggesting similar types of loads and harmonic distortion sources. Residential PCCs had a minimum THD of 4.03 in the morning, with a peak ranging from 14.08 to 20.45 between 1 and 5 am. This suggests that residential areas typically experience lower harmonic distortion in the morning when the load is relatively light. Residential loads tend to be more linear during this period, as households use appliances that do not generate significant harmonic distortions. The substantial increase in THD during the early hours (1 to 5 am) may be attributed to a few factors. Residential areas may still experience non-linear loads, such as lighting, airconditioners, and fridges, that generate harmonic currents during this period. The lower power demand and absence of large-scale industrial or commercial operations during this time could result in higher THD relative to the overall system. Commercial 1 PCCs had a minimum THD between 3.01 and 10.09 during the day and a maximum THD from 46.66 to 57.02 at night. Commercial 1 area consists of businesses that operate primarily during the day. These areas experience moderate harmonic distortion due to a mix of non-linear loads such as computers, lighting, and office equipment. However, the minimum THD during the day is relatively lower than at night, indicating a more controlled or balanced load environment. The sharp increase in THD at night can be attributed to higher levels of non-linear loads, including air conditioning systems and possibly large lighting systems that are more energy-intensive and prone to generating harmonic distortions. The higher levels of non-linear loads during the night, combined with a possible reduction in overall demand for power from other sources, can result in significantly higher harmonic distortion.

Commercial 2 PCCs showed minimum THD between 2.09 and 36.04 during the day, with peaks of 8.48 to 65.14 at night. This range indicates a highly variable harmonic distortion depending on the specific activities and loads in the commercial 2 areas. This could suggest that while some non-linear loads are present, they are less consistent throughout the day. The wide range of THD values also suggests that some periods within the day might experience higher distortion depending on specific activities or equipment usage. Similar to Commercial 1 areas, Commercial 2 areas show a much higher THD during the night, likely due to increased non-linear loads. The higher THD values at night could reflect the operation of heavier machinery or

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specialized equipment, such as large refrigeration units or lighting systems, that generate significant harmonic currents.

Special PCCs showed minimum THD between 1.2 and 12.80 during the day, with peaks between 14.41 and 20.34 at night. The relatively lower minimum THD during the day for special areas (which might include laboratories, hospitals, or other specialized facilities) could be due to the nature of their equipment, which might operate more smoothly and be designed to minimize harmonic disturbances. These areas may also employ precisely engineered equipment to avoid introducing harmonics into the grid. The increase in THD at night for special PCCs may indicate that, even in specialized facilities, harmonic generation increases with higher load demands.

The findings suggest the need for targeted strategies in managing harmonic distortion across different PCC types. Residential areas might benefit from optimizing non-linear appliances and possibly using harmonic filters. **Commercial and industrial areas** may require more advanced harmonic mitigation strategies, particularly during night-time, when distortion levels are highest. **Specialized areas** could also benefit from more tailored solutions to minimize harmonic generation, ensuring critical equipment remains protected from potential power quality issues.

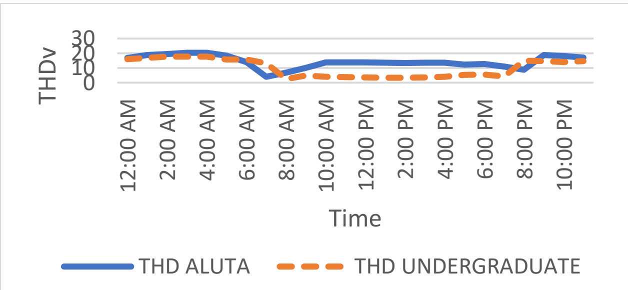

Figure 1: Daily Voltage Total Harmonic Distortion of Residential PCCs

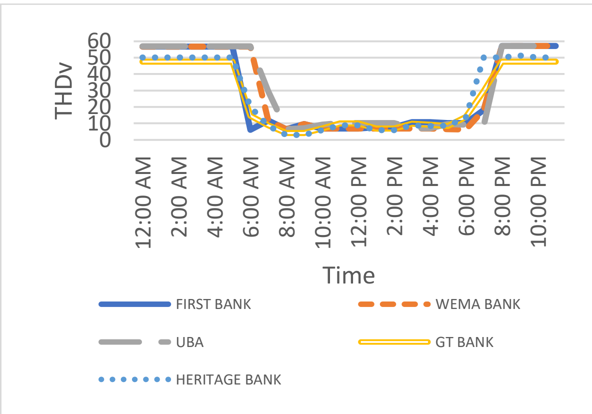

Figure 2: Daily Voltage Total Harmonic Distortion of Commercial 1 PCCs

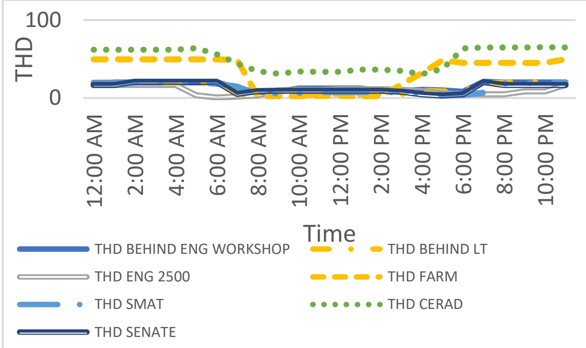

Figure 3: Daily Voltage Total Harmonic Distortion of Commercial 2 PCCs

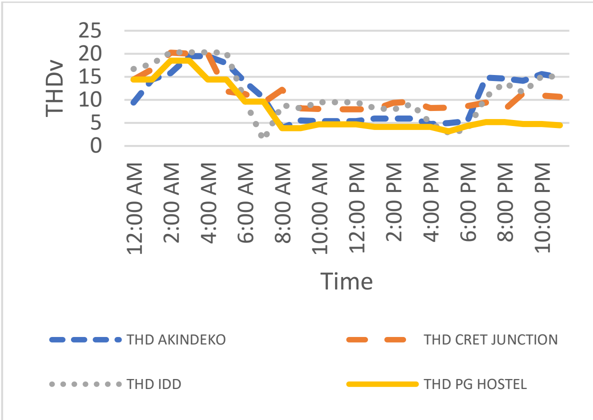

Figure 4: Daily Voltage Total Harmonic Distortion of Special PCCs

3.2 Relationship between Empirical Daily Load Compositions and Voltage Total Harmonic Distortion

Figures 5 to 8 show the relationship between empirical daily load compositions and total harmonic distortion for each case study of the different classifications of PCCs. It can be observed from Figures 5 to 8 that as the **diversity and quantity of non-linear loads** increase, the **voltage total harmonic distortion (THDv)** tends to decrease. This may seem counterintuitive because non-linear loads are known to cause harmonic distortion. However, several factors such as **Load diversity, Harmonic Interference, and Destructive Interference, Variation in Harmonic order, Load Interaction, and Parallel Connection account for the lower total harmonic distortion (THDv) as the diversity and quantity of non-linear goes higher.**

When different types of non-linear loads (with varying harmonic characteristics) operate on the same system, their harmonic emissions often do not align perfectly in phase. When these harmonics are out of phase, they can partially cancel each other, reducing the net harmonic distortion. In an environment with multiple non-linear loads, destructive interference can occur, where the harmonic contributions from different loads counteract each other. This reduces the overall harmonic impact on the voltage and thus results in a lower THDv. Non-linear loads typically generate harmonics at **specific orders.** When these diverse load types operate together, the **overall harmonic distortion is spread** across a broader range of frequencies, reducing the peak levels of any single harmonic component and, thus, the overall THDv. The

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greater the number of different loads with distinct harmonic profiles, the less concentrated the harmonic distortion becomes, leading to lower THD.

Different devices' impedance characteristics can interact in a mixed load environment, so harmonics are partially absorbed or dampened. This happens when one load impedance at a specific harmonic frequency is low. In contrast, another load's impedance is high at the same frequency, reducing harmonic propagation through the system. In systems where loads are connected in parallel, diverse non-linear loads can lead to a scenario where harmonic currents from one load are "absorbed" or "smoothed out" by the load characteristics of another. This results in lower harmonic distortion in the overall voltage waveform. The **total number of loads** (non-linear or otherwise) also impacts the overall harmonic distortion. As more non-linear loads are added to a power system, their harmonic contributions become more statistically averaged. With loads of varying types and harmonic emissions, the **total harmonic current** is distributed across frequencies and phases, leading to a lower harmonic concentration in the overall voltage. This occurs because some devices may contribute harmonics at different times, and some harmonic currents may be canceled out due to phase differences. As a result, the system realizes less pronounced harmonic distortion at specific frequencies, which reduces the overall THDv. With loads of varying types and harmonic emissions, the **total harmonic current** is distributed across frequencies and phases, leading to a lower harmonic concentration in the overall voltage. The more significant number of loads attenuates the effect of any single harmonic source. With more loads, there is a tendency for harmonic currents to become more evenly spread across the system. This occurs because some devices may contribute harmonics at different times, and some harmonic currents may be canceled out due to phase differences. As a result, the system realizes less pronounced harmonic distortion at specific frequencies, which reduces the overall THDv. Load imbalance can exacerbate harmonic distortion, as unbalanced loads tend to generate harmonics more efficiently. As loads increase, mainly if they are well-distributed, this imbalance tends to decrease, leading to lower THDv.

3.4 Correlation Analysis between Empirical Daily Load Composition and Total Harmonic Distortion (THD) on the FUTA Sub-Distribution Network

Table 1 shows the results of the correlation analysis between the empirical daily load composition and Total Harmonic Distortion (THD) on the FUTA sub-distribution network. Table 1: Correlation Analysis between the Empirical Daily Load Composition and Total Harmonic Distortion (THD)

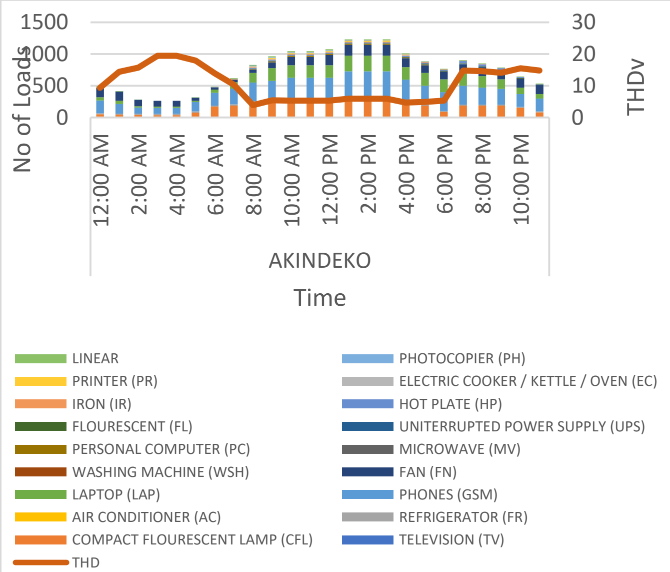

Figure 5: Relationship between Empirical Daily Load Compositions and Voltage Total Harmonic Distortion for Special PCC (Akindeko)

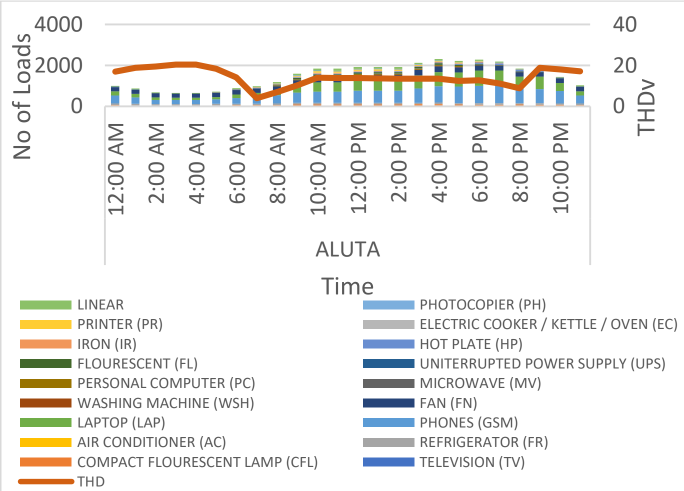

Figure 6: Relationship between Empirical Daily Load Compositions and Voltage Total Harmonic Distortion for Residential PCCs (Aluta)

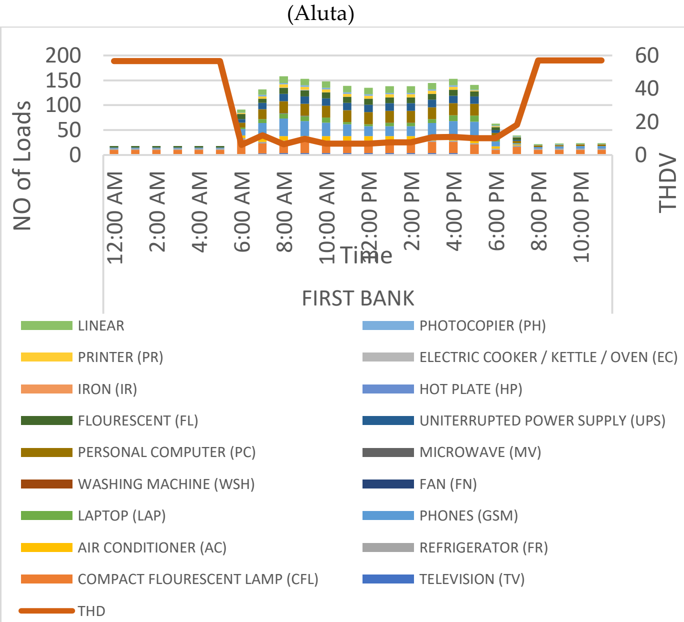

Figure 7: Relationship between Empirical Daily Load Compositions and Voltage Total Harmonic Distortion for Commercial 2 PCC (First Bank)

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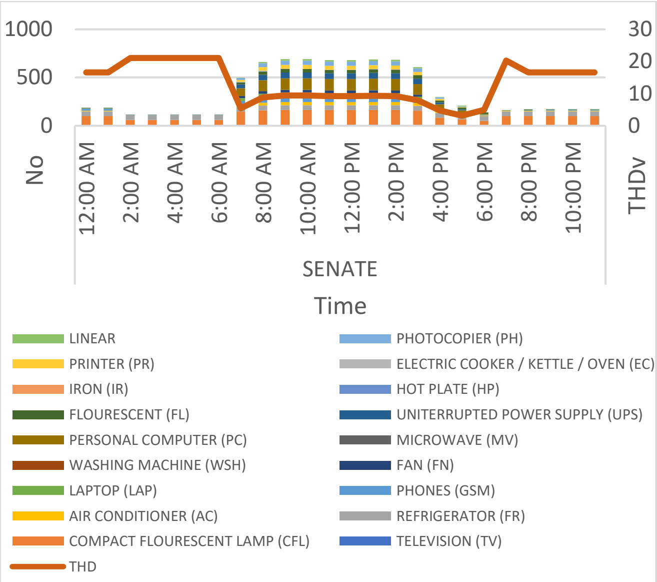

Figure 8: Relationship between Empirical Daily Load Compositions and Voltage Total Harmonic Distortion for Commercial 1 PCC (Senate)

Table 1: Correlation Analysis between the empirical daily load composition and Total Harmonic Distortion (THD) on the FUTA sub-distribution network.

Correlation Models	Result
Pearson Correlation	**-0.7858**
Spearman Correlation	**-0.8276**
Kendall Correlation	**-0.6560**
R-squared	**0.6175**

The **Pearson correlation coefficient** indicates a **strong negative linear relationship** between the empirical daily load composition and THD. A value of **-0.7858** suggests that, in general, as the daily load composition increases, THD tends to decrease in a linear fashion. This is a significant negative but imperfect relationship, implying other factors may also influence THD. The **Spearman rank correlation coefficient** measures the **monotonic** relationship between the variables, i.e., whether the relationship between the variables consistently increases or decreases, without necessarily being linear. A value of **-0.8276** shows a **strong negative monotonic relationship,** indicating that as daily load composition increases, THD consistently decreases, but not necessarily linearly. The **Kendall rank correlation coefficient** also measures the **monotonic** relationship between the two variables, with a value of **-0.6560** showing a **strong negative relationship.** It is slightly weaker than Spearman's result, but still significant, indicating a strong inverse association between the variables. The **R-squared value** represents the proportion of the variation in THD that is explained by the daily load composition. A value of **0.6175** suggests that approximately **61.75%** of the variability in THD can be explained by the daily load composition, highlighting its importance as a factor influencing THD. However, other variables or factors could contribute to the remaining unexplained variation. The analysis revealed a **strong negative relationship** between the empirical daily load composition and THD, as shown by the Pearson, Spearman, and Kendall correlation coefficients. The moderate R-squared value suggests that while daily load composition plays a significant role in explaining THD, other factors may also be influencing the levels of distortion.

4 Conclusions

This study provided a comprehensive daily load-side harmonic analysis of a Nigerian university's power distribution network, focusing on 19 units of 11/0.415 kV transformers and evaluating Voltage Total Harmonic Distortion (THDv) at multiple Points of Common Coupling (PCCs) categorized into residential, commercial, and special loads. The findings highlighted the significant impact of load variation on harmonic generation, with distinct patterns of harmonic distortion observed throughout the day and across different load types. The analysis revealed that residential and commercial loads exhibit higher THDv during night-time, while the presence of more diverse, non-linear loads correlated with lower harmonic distortion levels. The results highlighted the complex relationship between load behavior, time-of-day fluctuations, and harmonic distortion. This research fills an important gap in the existing literature, offering a granular understanding of the daily variation in harmonic behavior in university power distribution networks. It underscores the need for more tailored energy management strategies to improve power quality and optimize energy distribution in Nigerian universities, where fluctuating power demands and harmonics remain significant challenges. Effective energy management strategies that account for these variations are critical for optimizing power quality and minimizing the negative effects of harmonics on the electrical network. Harmonic mitigation, load management, and system monitoring should be prioritized, particularly in areas with high levels of non-linear loads, such as commercial and special zones. Implementing tailored solutions based on PCC characteristics will enhance system efficiency, reduce equipment degradation, and improve overall power quality.

5. Recommendation

Based on the findings of this study on harmonic behavior in the sub-distribution networks of Nigerian universities, particularly within the context of the FUTA network, several key recommendations can be made to improve energy management and optimize power distribution:

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i. **Enhanced Monitoring and Data Collection:** The study highlighted significant variations in Voltage Total Harmonic Distortion (THDv) across different Points of Common Coupling (PCCs) and times of day. It is recommended that universities implement more frequent monitoring systems at PCCs to better capture and analyze harmonic distortions. Advanced metering infrastructure (AMI) could be utilized to facilitate real-time data acquisition, helping to identify specific patterns of harmonic behavior linked to load variations.

ii. **Focused Load Profiling:** Universities should conduct more detailed load profiling at different PCCs to better understand the specific load characteristics and their impact on harmonic distortion. This can aid in designing more effective energy management strategies and ensuring the appropriate allocation of resources.

iii. **PCC-Specific Mitigation Strategies:** Targeted mitigation solutions should be implemented in areas with high non-linear loads (e.g., commercial areas), which contribute significantly to harmonic levels, particularly during the night.

iv. **Load and Energy Management Optimization:** The study indicates that diverse and non-linear loads tend to produce higher harmonic distortions. As such, universities should explore demand-side management strategies to optimize energy consumption, particularly by shifting high-demand non-linear loads to times when the overall demand and harmonic distortion are lower. Energy consumption schedules can be aligned with the natural fluctuation of harmonic levels, helping to balance load and reduce power quality issues. Tailored energy management practices are necessary for each type of load. Residential areas may not require as intensive harmonic management as commercial or industrial zones, which would benefit from more advanced harmonic mitigation measures such as active filters and advanced power management systems. Effective management of daily load composition could help mitigate THD in the FUTA sub-distribution network.

v. **Further Research and Development:** While the study contributes valuable insight into the harmonic behavior of Nigerian universities, there is a need for further research to explore the long-term impacts of harmonic distortions on electrical equipment, system performance, and energy efficiency. Future studies should also consider comparing harmonic behavior across different universities to provide a broader understanding.

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