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The effect of transformer sizing and load variability on harmonics generated in a Nigerian university

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Abstract

This study investigates the impact of transformer sizing and load variability on the generation of harmonics in the distribution network of the Federal University of Technology, Akure (FUTA), Nigeria. The analysis focuses on Total Harmonic Distortion Voltage (THDv) at various Points of Common Coupling (PCCs) connected to different transformer capacities. Results indicate that PCCs linked to 500 kVA transformers exhibit THDv values ranging from 0.9% to 21.05%, generally falling within acceptable limits, albeit with some outliers. In contrast, PCCs associated with 200 kVA transformers display a broader and more concerning THDv range, from 0.65% to 65%. Additionally, the study reveals a significant increase in THDv at night compared to daytime, attributed to the higher prevalence of non-linear loads during off-peak hours. These findings highlight the critical role of transformer sizing and load patterns in managing harmonic distortion, underscoring the need for effective power quality management strategies within university distribution networks.

Keywords: Harmonic Distortion; Transformer Sizing; Harmonic Analysis; Load Variability

1. Introduction

The increasing demand for electrical power in academic institutions, particularly in developing regions like Nigeria, has necessitated a thorough examination of power quality issues. One significant concern is the generation of harmonics, which can adversely affect the performance and longevity of electrical equipment [1, 2]. This study focuses on the effects of transformer sizing and load variability on harmonic distortion in a Nigerian university setting. Transformers play a crucial role in power distribution, and their sizing directly impacts the harmonic levels produced in electrical systems. Additionally, the dynamic nature of load variability—stemming from diverse academic and administrative activities—introduces further complexities [3]. As universities adopt modern technologies and expand their infrastructure, understanding the interplay between transformer specifications and load patterns becomes essential for maintaining power quality and operational efficiency. This article aims to provide insights into how transformer sizing and fluctuating loads contribute to harmonic generation, offering practical recommendations for improving electrical system design and operation in Nigerian universities. By addressing these factors, this research contributes to the broader goal of enhancing power quality and ensuring the reliability of electrical systems in educational institutions.

2. Methodology

2.1. Case study

FUTA distribution network consists of 1 unit of 33/11 kV 7.5 MVA power transformer, 3 Feeders, and 20 units of 11/0.415 kV distribution transformer.

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Table 1 Data showing FUTA 11/0.415 Substations/ Point of Common Coupling Transformer Sizes and Connected Buildings

	Transformer name / point of common coupling (PCC)	Ratings (KVA)
1	FRONT OF SMAT	500
2	NEW UNDERGRADUATE HOSTELS	500
3	PG HOSTEL	500
4	CERAD	200
5	CRET JUNCTION	500
6	VC LODGE	200
7	BEHIND LT 2	500
8	KACHALA	200
9	ENGINEERING WORKSHOP	500
10	2500	500
11	ALUTA	500
12	SENATE	500
13	IDD	500
14	AKINDEKO	500
15	GTB	200
16	WEMA	200
17	Heritage	200
18	First Bank	200
19	UBA	200

The connected loads to PCC/transformers are classified as linear and non-linear loads for power flow analysis [4]. The network data was obtained from the university's department of work. The load data was obtained through a survey. The load data obtained was used to aggregate the linear and non-linear loads connected to the transformers of the sub-distribution network. The non-linear loads considered in this study are typical residential and commercial loads based on the increasing trend of common non-linear loads penetrating the distribution network in Nigeria such as Television (TV), Compact Fluorescent Lamp (CFL), Fluorescent (FL), Refrigerator (FR), Microwave (MW), air-conditioner (AC), Iron (IR), Laptop (LAP), Phones (GSM), Uninterrupted Power Supply (UPS), Washing Machine (WSM), Hot Plate (HP), Fan (FN), Electric Cooker/Kettle/Oven (EC), Printer (PR), and Photocopier (PH). The non-linear loads were modelled into the distribution network using a bottom approach for harmonic injection modelling for harmonic flow analysis [5]. The PCC/transformers were modelled and simulated separately to determine the harmonic injection from each PCC. The harmonic analysis module of NEPLAN software was used to simulate the modelled networks. The harmonic distortion level at the PCCs of the sub-distribution networks was compared with the recommended level in IEEE Standard 519.

2.2. Harmonic analysis on PCCs/transformer substations

Fourier series was used to determine the spectral components of each non-linear load to obtain the harmonic signal as presented in Equations 1 to 5 [6].

$$f(t) = \frac{a_o}{2} + \sum_{h=1}^{\infty}(a_h \cos(hw_o t) + b_h \sin(hw_o t)) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where w= $\frac{2\pi}{T}$

Equation 1 can be further simplified into Equation 2

$$f(t) = C_o + \sum_{h=1}^{\infty}(C_h \sin(hw_o t) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{ (2)}$$

$$C_h = \frac{a_o}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

$$C_h = \sqrt{{a_h}^2 + {b_h}^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ (4)}$$

$$\emptyset_h = \tan^{-1}\left(\frac{a_h}{b_h}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{ (5)}$$

Where (hw_o) is the h^{th} order harmonic of the periodic function, C_o is the magnitude of the DC component, C_h is the magnitude of the h^{th} harmonic component, and $\emptyset_h$ is the phase angle of the h^{th} harmonic component.

Evaluation of Total Harmonic Distortion Indices on PCCs/Transformer Substations

Total Harmonic Distortion

Total Harmonic Distortion (THDv) is defined for voltage and current signals as shown in Equations 6 and 7 [2, 7]

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} {V_h}^2}}{V_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

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

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I^2}}{I_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

where I_h is the current at h harmonic, and I_1 is the current of the fundamental harmonic

2.3. Evaluation of the daily power harmonic generations on PCCs/transformer substations

Steps in Carrying out the Evaluation of Power Harmonic Generation on PCCs/Transformer Substations

- Obtain and study the network diagram of the FUTA sub-distribution network.
- Identify the points of common coupling and Substations of the FUTA sub-distribution network.
- Identify and characterize the load connected to each point of common coupling and transformer substations into linear and non-linear loads.
- Identify the characteristic harmonic spectrum of each type of non-linear load.
- Model and simulate hourly representation of the linear and non-linear loads cases to obtain corresponding harmonic responses and total harmonic distortions using NEPLAN software.
- Compute hourly voltage total harmonic distortion (THDv) of each Point of Common Coupling/transformer substation.

3. Results and discussions

Figures 1 and 2 show the daily voltage harmonic distortion of the PCCs on the FUTA distribution network. PCCs connected to 500 kVA transformers exhibited THDv ranging from 0.9% to 21.05%. This falls within a generally acceptable range, with some outliers. However, PCCs connected to 200 kVA transformers have a wider range of THDv, from a low of 0.65% to a concerning high of 65%. In addition, it was observed that there was higher THDv (Total Harmonic Distortion Voltage) for PCCs (Point of Common Coupling) at night as against daytime.

The PCCs connected to a 200 kVA transformer experienced higher THDv because of capacity utilization, relative loading, and network resonance**.** A 500 kVA transformer has a higher capacity to handle the total load current, including harmonic currents. This provides more headroom for harmonics without significantly impacting the THDv percentage. In addition, if a 200 kVA transformer operates closer to its capacity, especially at night, it becomes more susceptible to harmonic distortion. Even a small amount of harmonic current can significantly impact the THDv percentage when the transformer is nearing its limits. When a transformer is overloaded, its ability to handle harmonic currents can be compromised. The night load profile on the network feeding the 200 kVA transformers creates conditions for resonance at specific harmonic frequencies. This can amplify existing harmonics, leading to higher THDv readings. The specific harmonic currents injected by nighttime loads can resonate with the impedance of the distribution network feeding the 200 kVA transformers. This resonance can amplify existing harmonics, leading to higher THDv readings than 500 kVA transformers.

Furthermore, harmonic distortion on the PCCs appears higher at night than the actual harmonic current itself. The harmonic distortion percentage is calculated by dividing the harmonic current by the total current, a summation of the fundamental frequency current and harmonic currents. With a lower overall current (due to reduced load), the harmonic current from the remaining non-linear loads becomes a more significant percentage of the total current. This makes the harmonic distortion percentage appear higher at night, even though the actual harmonic current might not increase significantly. During the day, many offices, lecture halls, and businesses are operational, drawing power and contributing to the overall electrical load on the system. This daytime load includes a mix of linear and non-linear loads. At night, many offices, lecture halls, and businesses shut down, reducing the overall load on the system. During nighttime, buildings might have fewer occupants, leading to decreased lighting and appliance usage. At night, the load profile on the network might change. While overall power consumption might decrease, there could be a shift towards an increase in electronic device usage. Laptops, TVs, phone charging, and security lighting might become more prominent at night, contributing to harmonics due to switch-mode power supplies.

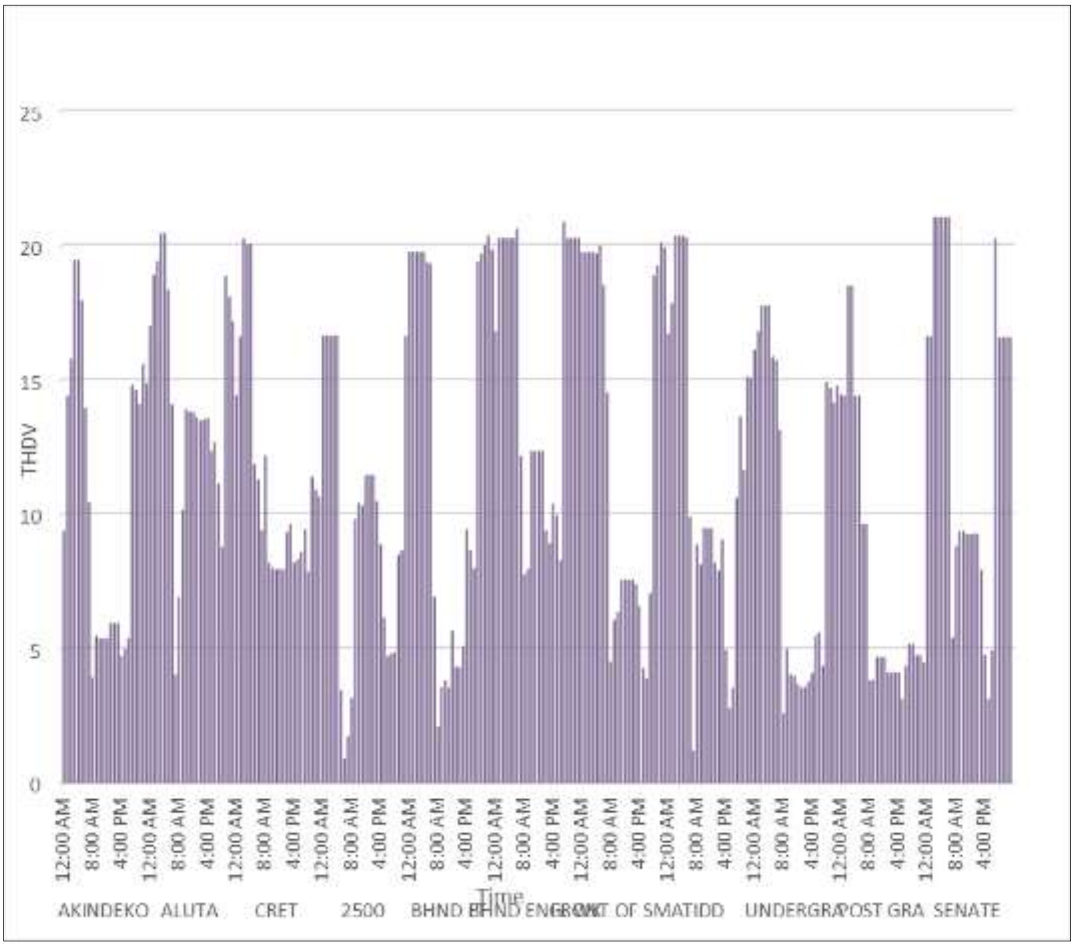

Figure 1 Hourly Voltage Total Harmonic Distortion for PCCs with 500 kVA Transformers in FUTA Distribution Network

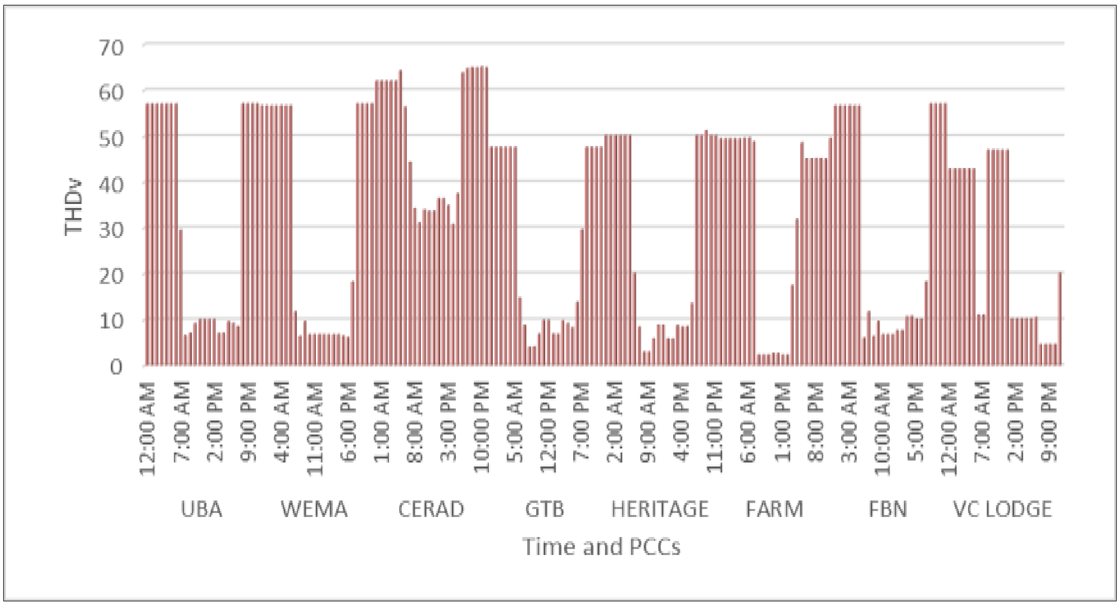

Figure 2 Hourly Voltage Total Harmonic Distortion for PCCs with 200 kVA Transformers in FUTA Distribution Network

4. Conclusion

The study of transformer sizing and load variability on harmonic generation within the Federal University of Technology, Akure (FUTA), reveals significant insights into the institution's power quality challenges. The findings indicate that PCCs connected to 500 kVA transformers generally maintain Total Harmonic Distortion Voltage (THDv) within acceptable limits, ranging from 0.9% to 21.05%. However, the variability in THDv observed in PCCs connected to 200 kVA transformers is concerning, with values spanning from 0.65% to a staggering 65%. This highlights the critical impact of transformer capacity on harmonic distortion levels.

Furthermore, compared to daytime levels, the pronounced increase in THDv at night underscores the influence of load composition and usage patterns. During nighttime, the prevalence of non-linear loads contributes to higher distortion, reflecting a need for careful monitoring and management of power quality, particularly in educational environments that increasingly rely on electronic devices.

The results suggest that appropriate transformer sizing and strategies to manage load variability are essential for minimizing harmonic distortion. Future initiatives should focus on optimizing transformer capacities and implementing harmonic mitigation techniques to enhance the reliability and efficiency of the FUTA distribution network. Addressing these issues will improve power quality and support the university's commitment to sustainable energy practices.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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