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Research Article

Evaluation of Overloading Effects on Distribution Transformers: A Case Study of Transformer Substations on 11kv Ile-Oluji Feeder

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Abstract

This study evaluates the effects of overloading on the operational performance, efficiency, and lifespan of 11 kV distribution transformers using ten transformer substations in Ile-Oluji, Ondo State, Nigeria, as case study. Field measurements of load currents, voltages, and apparent power were obtained during peak demand periods and compared with transformer rated capacities to determine overload levels and associated thermal stresses. The analysis focused on insulation aging, loss characteristics, voltage regulation, and reliability implications under sustained overload conditions. Results indicate that a significant proportion of the transformers operated beyond recommended loading limits, leading to excessive copper losses, overheating, increased insulation degradation, and increased risk of premature failure. The findings further reveal that overloading contributes to voltage drops and reduced supply quality within the distribution network. The study underscores the necessity for continuous load monitoring, strategic load redistribution, and timely transformer capacity upgrades to mitigate overload impacts. These results provide practical insights for improving asset management, system reliability, and service quality in 11 kV distribution networks, particularly in rapidly growing urban and semi-urban environments.

1. Introduction

Distribution transformers are very important in electric power systems since they step down medium voltages, typically 11 kV, to low voltages needed to serve residential, commercial and small industrial customers. Their performance directly affects the reliability of supply, quality of voltage and efficiency of a system. The high rate of population growth, urbanization, and more electricity demand have placed high demand on the available distribution infrastructure of developing power systems, resulting to transformer overloading [1, 2]. The continued use at above rated capacity, hastens the insulation aging, increases technical losses, reduces voltage regulation, and greatly increases the likelihood of transformer premature failure [3].

In most of the distribution networks in sub-Saharan Africa including Nigeria, overloading of distribution transformers is a significant cause of equipment deterioration and service outages. This is as a result of load increase without corresponding infrastructure development, illegal connections, and uncoordinated load additions [4, 5]. It has been demonstrated, through studies, that the temperature of transformer hotspots increases exponentially with loading, thus increasing the rate of insulation degradation and reducing the anticipated service life [6, 7]. This means that if transformers are subjected to long periods of overloading, there is a higher risk of winding deformation, oil degradation and dielectric breakdown which eventually affects the network reliability and increases maintenance and replacement costs.

In Nigeria's distribution networks, 11 kV transformers form the backbone of secondary power delivery to end users. Nevertheless, many of these transformers operate under non-ideal conditions with frequent overloads, voltage drops, and high technical losses [1, 5]. These are

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the operational problems that compromise the quality of services and add to the persistent energy inefficiency and equipment failure that distribution companies experience. Although there are earlier research works to investigate transformer performance and loss reduction measures, there are few empirical studies that have been conducted to investigate the effects of overloading at the distribution substation level within the semi-urban Nigerian communities.

The real operational effects of transformer overloading must be known for effective asset management, network planning and reliability improvement. The measurement of loading profiles, loss behavior and related thermal stress enables the utilities to make a decision on load balancing, transformer replacement, and system reinforcement [2, 3]. In addition, localized research can be useful in terms of insights into demand characteristics and infrastructure constraints peculiar to certain areas, thus contributing to context-dependent solutions.

This paper, therefore, evaluates the effects of overloading of 11 kV distribution transformers based on ten distribution transformer substations in Ile-Oluji, Ondo State, Nigeria. Through analysis of measured loading conditions and comparing them to transformer ratings, the study aims to measure the degree of overloading and its impact on efficiency, reliability, and asset life. The findings can help in the better management processes of transformers and offer some practical guidance on how the operational sustainability of the distribution networks in the same developing power systems can be improved.

2. Methodology

Study Area and System Description

This study was carried out on ten 11 kV distribution transformer substations within the community of Ile-Oluji, Ondo State, Nigeria. The substations are mostly residential and small commercial load and have radial low-voltage feeders fed through 11/0.415 kV oil-immersed distribution transformers. The selected transformers vary in their rated capacity and installation age, providing a representative evaluation of transformer loading behavior under actual operating conditions in semi-urban distribution systems.

Research Design

Quantitative assessment method was used as the field-based method. Primary operational data were collected through on-site measurements, whereas secondary data, such as transformer ratings and impedance values, were obtained by reading nameplates, utility records, etc. The work was focused on measuring real-time loading conditions and testing the degree and consequences of transformer overloading using traditional loading criteria presented by IEEE and IEC standards.

Data Acquisition

The measurements were performed at peak-load (18:00-22:00) and off-peak (01:00-05:00) periods on several days to record the variations in the loads. Calibrated digital clamp meters and multimeters were used to measure the phase currents and phase-to-neutral voltages at the low-voltage terminals of each transformer. Power factors were measured with portable power analyzers. Transformer rated capacities were recorded directly from nameplates.

For a three-phase transformer, the apparent load demand S (kVA) was computed using:

$$S = \sqrt{3}V_L I_L \tag{i}$$

where
V_L = line voltage (kV),
I_L = line current (A).

The percentage loading of each transformer was then calculated as

$$\%\mathrm{L} = \frac{S_{\text{measured}}}{S_{\text{rated}}} \times 100 \tag{ii}$$

$S_{measured}$ = measured apparent power (kVA),
S_{rated} = rated transformer capacity (kVA).

Overloading Classification Criteria

Based on IEEE Std. C57.91-2011, transformer loading conditions were classified as:

(i) Normal loading: %L $\leq$ 80%
(ii) Critical loading: 80% $<$%L $\leq$ 100%
(iii) Overloading: %L $>$100%

Transformers operating beyond rated capacity were considered thermally overstressed and are prone to accelerated insulation aging.

Voltage Regulation (VR) Assessment

Voltage regulation under load was evaluated using

$$\%\mathrm{VR} = \frac{V_{\text{no-load}} - V_{\text{full-load}}}{V_{\text{full-load}}} \times 100 \quad \text{(iii)}$$

where
$V_{no-load}$ and $V_{full-load}$ are transformer terminal voltages under no-load and load conditions respectively.

Data Analysis Techniques

Descriptive statistics techniques were used to calculate the mean loading, peak loading, and load variation across substations. Transformers that have continuous overloads were identified through comparative analysis. Load profiles were created to test the demand patterns over time whereas the relationships between the level of loading, estimated losses and the acceleration of aging were applied to test the patterns of performance degradation.

Measurement Reliability and Safety

Measurements were repeated over multiple days to minimize time effects and all the instruments were calibrated before being put into use. Field procedures were done based on utility safety standards, such as, using insulated tools and personal protective equipment (PPE), and measurements were taken without supply disconnection.

3. Results and Analysis

This study measured, analyzed and evaluated the insulation resistance and earthing system performance of ten selected distribution substations using standard megger and earth resistance testing procedures. High-voltage to earth (HV–E), low-voltage to earth (LV–E), and high-voltage to low-voltage (HV–LV) paths were all considered for the insulation resistance measurements, while the effectiveness of the earthing system was analyzed through ground resistance values. The obtained results are presented in Table 1.

Table 1: Transformer rating, Measured LV Current and Line Voltages of each substation

S/N	Name of Substations	Transformer Rating (kVA)	Measured LV Current (PER PHASE) (A)			Line Voltage (V)
			R	Y	B	
1	Cocooa Substation	500	400	430	390	415
2	Opeke Substation	500	380	400	440	415
3	General Hospital Substation	500	412	420	430	415
4	Lota Road Substation	300	395	332	347	415
5	Ore-Ofe Church Substation	300	288	303	314	415
6	Idiomo Market Substation	300	387	342	369	415
7	Fagbola Temidire Substation	500	424	416	432	415
8	Ajala Junction Substation	300	408	401	422	415
9	CAC Pry Sch. Substation	500	413	398	401	415
10	Odolua Market Substation	500	444	416	452	415

Computation of Transformer Load Demand

The three-phase apparent load demand and percentage loading on each transformer at various substations was determined using equation i and ii above, respectively. The results are shown in Table 2

Table 2: Computed Loading Results for Ile-Oluji Substations

S/N	Name of Substation	Rating (kVA)	Avg Current (A)	Load (kVA)	% Loading	Status
1	Cocooa Substation	500	406.67	292.31	58.46%	Normal
2	Opeke Substation	500	406.67	292.31	58.46%	Normal
3	General Hospital Substation	500	420.67	302.38	60.48%	Normal
4	Lota Road Substation	300	358.00	257.33	85.78%	Critical
5	Ore-Ofe Church Substation	300	301.67	216.84	72.28%	Normal
6	Idiomo Market Substation	300	366.00	263.08	87.69%	Critical
7	Fagbola Temidire Substation	500	424.00	304.77	60.95%	Normal
8	Ajala Junction Substation	300	410.33	294.95	98.32%	Critical
9	CAC Pry Sch. Substation	500	404.00	290.40	58.08%	Normal
10	Odolua Market Substation	500	437.33	314.36	62.87%	Normal

Transformer Loading Characteristics

Measurement of low-voltage phase currents and certified transformer capacities were used to assess the loading conditions of the ten 11 kV distribution transformers. The three-phase apparent power of each transformer was calculated using (i) and percentage loading was calculated using (ii). The results were summarized in Table 2.

The findings show that the levels of loading on transformers varied widely in the study area between 58.08% and 98.32% which showed a high degree of spatial variation in the load demand. The maximum loading, which is at Ajala Junction Substation, was 98.32% which was close to the rated capacity while CAC Primary School Substation was the lowest with loading of 58.08% implying that it was underutilized. Such a broad distribution of loading reflects an uneven feeder distribution, growth demand disparities, and lack of coordination in customer connection on the substations.

Although no transformers were operating beyond their designated capacities at the time of measurement, three substations, i.e. Lota Road (85.78%), Idiomo Market (87.69%) and Ajala Junction (98.32%) were working in the critical loading zone according to IEEE Std. C57.91. Such operation subjects transformers to high thermal loads, especially when they are operating on peak demand for prolonged periods or when there are contingency conditions like reconfiguration of a feeder or an imbalance of the phases.

Phase Current Imbalance Effects

The phase currents obtained between the substations showed the existence of an appreciable imbalance on the R, Y and B phases. For example, Odolua Market Substation had phase currents of 444 A, 416 A and 452 A respectively and Cocoa Substation had 400 A, 430 A and 390 A. These differences increases neutral currents, worsen copper losses and increase temperatures at the winding ends.

Current imbalance causes uneven heating within the transformer windings accelerating the rate of insulation degradation in the most heavily loaded phase and may lead to asymmetrical aging of the transformer. This phenomenon is critical in transformers that are operating at the range of its rated capacity, like at Ajala Junction and Idiomo Market substations, where a small load addition, or a temporary overload, can cause hotspot temperature to exceed a safe operational level.

Voltage Regulation and Supply Quality Implications

Excessive transformer loading leads to increased voltage drops in low-voltage feeders which have negative impacts on customer's power quality and equipment performance. Transformers that operates near rated capacity have a high internal impedance voltage drop, and this, together with feeder resistance, can cause consumer voltages to be fall outside the statutory limits during peak demand periods.

Substations like Ajala Junction and Idiomo Market that recorded load levels close to rated capacity are more prone to undervoltage conditions especially at the feeder extremities. The condition may also result in decreased efficiency of appliances, overheating of induction motors and customer complaints, further underscoring the operational implications of transformer overloading by distribution systems.

System Level Implications and Load Management Considerations

The findings show that there is a distinct discrepancy between the capacities of the transformers and the spatial demand allocation in the study area. Some of the transformers were overloaded (over 85%) whereas others were underutilized (less than 60%) at loading. Such an imbalance reflects the inefficient feeder arrangement and shows the lack of systematic redistribution of the loads and demand forecasting.

According to asset management, transformers that are heavily loaded should be given priority for immediate intervention by transferring the loads, reconfiguring the network, or increasing the capacity. At the same time, transformers with light loading can be reallocated to locations of high demand or merged to minimize unnecessary fixed losses. These would enhance the efficiency of the system, increase the life span of the transformers and increase the level of reliability of supply.

Comparative Analysis with Existing Studies

The results of this research are in line with the past research on the transformer loading behavior in the Nigerian distribution networks, which reported prevalent critical loading conditions due to demand increase and inadequacy of infrastructure. Studies of a similar nature were done by [1, 4]. Which also discovered that transformers that were loaded more than 80% had a much higher failure rate and lower service life. These findings are furthered by the current study, which presents a field-based empirical data in Ile-Oluji substations, which further substantiates the findings of the applicability of IEEE thermal loading theory to field-based operating conditions in developing power systems.

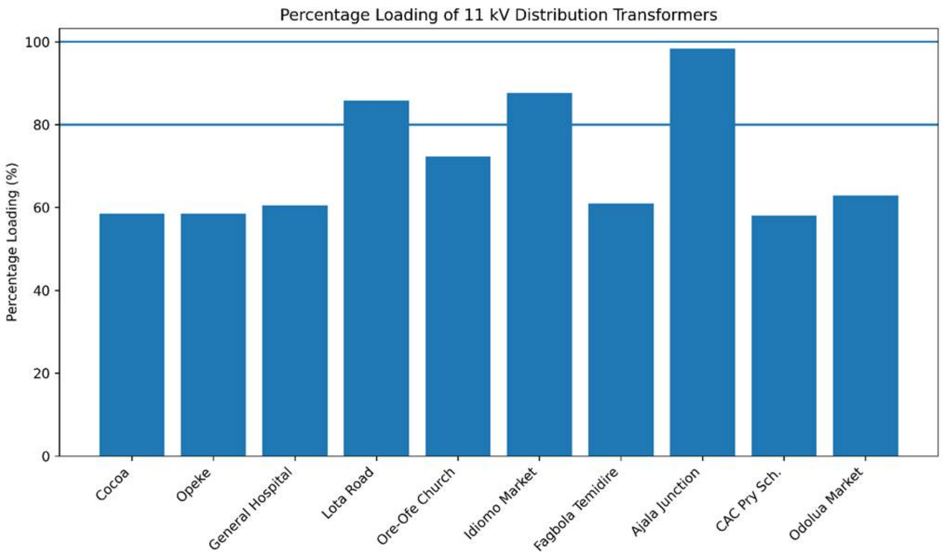

Figure 1: Percentage loading of 11kv distribution transformers in Ile-Oluji feeder

As shown in Figure 1 above, heavy loading conditions is evident in Lota Road and Idiomo Market with operations above 80%, as well as Ajala Junction reaching approximately 98%. Underutilization of transformer is also evident in substations such as CAC Primary School and Cocoa with operations below 70%. The figure demonstrates an uneven load distribution across the network and displays the substations that are at risk of overheating during peak demand times.

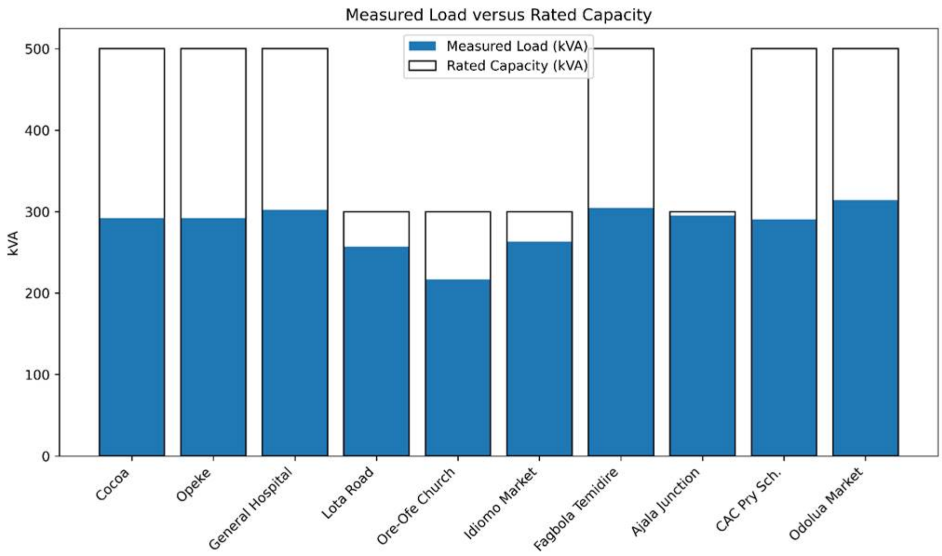

Figure 2: Measured load vs rated capacity of 11kv distribution transformers in Ile-Oluji feeder

Figure 2 above shows that despite the fact that none of the transformer exceeded their rated capacities, some of the units operates very close to their limits. Both Ajala Junction and Idiomo Market substation shows low safety limit, making them vulnerable to overloading in the event of a sudden increase in load. In contrast, different 500 kVA transformers operates at capacity below 65%, showing inefficient usage of asset. The need for load redistribution and network reconfiguration should be considered to solve this imbalance.

As shown in Figure 3, it is observed that there is phase current imbalance at different substations such as Odolua Market, Cocoa, and Opeke substations. Such imbalance results to unequal heat stress on the transformer windings and also causes an increase in copper loss and neutral currents. In heavily loaded substations, phase imbalance causes insulation aging and increases the risk of localized winding failure which underscores periodic phase load balancing importance in distribution networks.

4. Conclusion & Recommendation

4.1. Conclusion

This study analyzed the effects of loading conditions on ten 11 kV distribution transformers in Ile-Oluji, Ondo State, making use of field measured phase currents and transformer rated capacities. The results shows that loading ranges from 58.08% to 98.32% indicating a significant spatial variation in demand across the network. Although none of the transformers exceeded its rated capacity during the period

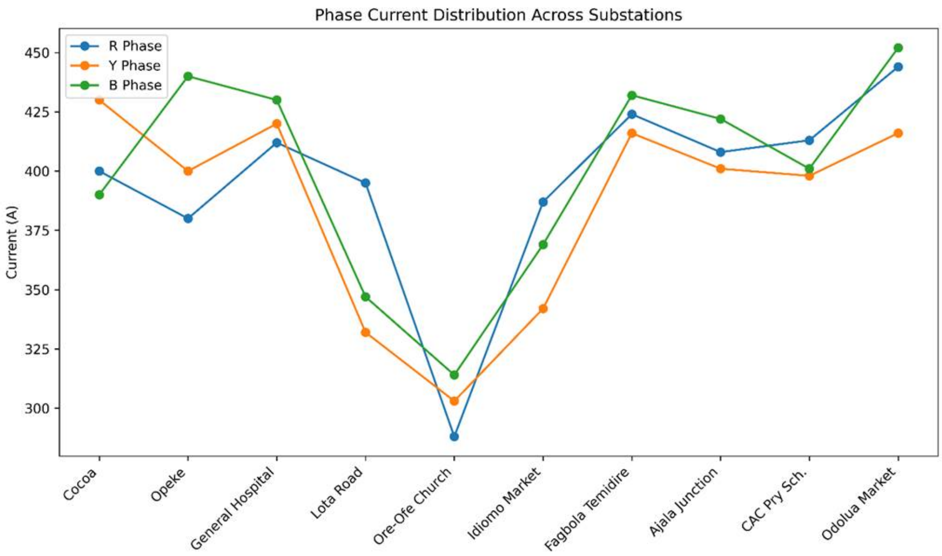

Figure 3: Phase Current distribution across different substations in Ile-Oluji

of measurement, 30% of the substation were operating under heavy loading conditions, with Ajala Junction substation almost at full capacity. These conditions causes overheating, increased copper losses, rapid insulation aging and reduced voltage regulation in transformers, thereby increasing the risk of reduced power supply reliability and early equipment failure.

In addition, phase current imbalance was recorded across different substations, adding to uneven heat stress distribution and high technical loss. Consequently, transformers that are lightly loaded experience underutilization due to persistent core losses without corresponding load benefit. The coexistence of heavily loaded and underutilized transformers within the same network shows suboptimal feeder configuration and inadequate load planning. Overall, the findings confirm that sustained operation close to rated capacity compromises transformer performance and lifespan, leading to the need for load management strategies in 11 kV distribution networks.

Recommendation

To relieve heavily loaded transformers, load redistribution and feeder reconfiguration should be implemented, especially at Ajala Junction, Idiomo Market and Lota Road substations, by transferring loads that are excess to underutilized units within the network. Also, to detect abnormal loading conditions early, routine transformer load monitoring should be carried out through periodic field measurements and smart metering systems. For substations exhibiting sustained load growth, their transformers capacity can be upgraded or replaced with higher rated units to avoid future overloading and improve reliability of supply. Regular phase load balancing across low voltage feeders should be carried out to reduce current imbalance, copper loses and also reduce localized thermal stress on transformer windings. Long term distribution planning frameworks should be incorporated by utilities on transformer loading assessment to ensure that future infrastructural expansion is in line with demand growth patterns. Finally, continuous training of field personnel on transformer loading management and condition based maintenance practices should be prioritized to enhance operational efficiency and ensure transformer lifespan.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

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