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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 evaluated the loading conditions and operational performance of selected 11/0.415 kV distribution transformers along the Ile-Oluji 11 kV feeder in Ondo State, Nigeria. Field measurements of phase currents, line voltages, and transformer rated capacities were obtained from ten distribution substations during operational periods. The measured parameters were used to determine transformer apparent power demand, percentage loading, and phase imbalance conditions using standard transformer loading equations and IEEE loading recommendations. The results revealed considerable variation in transformer utilization levels, with percentage loading values ranging from 58.08% to 98.32%. Ajala Junction Substation recorded the highest loading condition of 98.32%, while CAC Primary School Substation recorded the lowest loading level of 58.08%. Three substations, namely Ajala Junction (98.32%), Idiomo Market (87.69%), and Lota Road (85.78%), operated within critical loading conditions, indicating exposure to elevated thermal stress and reduced operational safety margins. Noticeable phase current imbalance was also observed across several substations, contributing to increased copper losses and uneven transformer winding heating. The study concluded that sustained operation near rated transformer capacity adversely affects transformer reliability, insulation lifespan, and voltage performance. Continuous transformer load monitoring, periodic phase balancing, and feeder reconfiguration were recommended to improve operational reliability and distribution network efficiency.
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Keywords: Distribution transformer, transformer loading, thermal stress, phase imbalance, voltage regulation.

1. Introduction

Distribution transformers are essential components of electric power systems because they reduce medium distribution voltages, commonly 11 kV, to utilization voltages suitable for residential, commercial, and small industrial consumers. Their operational performance significantly influences voltage quality, supply reliability, energy efficiency, and continuity of service within power distribution networks (Gonen, 2014; Airoboman *et al.*, 2020). Increasing urbanization, rapid population growth, industrial expansion, and rising electricity demand have imposed substantial stress on existing distribution infrastructures in many developing countries, thereby increasing transformer loading levels and the likelihood of overloading conditions (Amadi & Izuegbunam, 2016; Oliyide & Cipcigan, 2023).
Distribution transformers are generally designed to operate within specified nameplate ratings; however, prolonged operation beyond rated loading conditions cause excessive thermal stress,

accelerated insulation ageing, increased copper losses, poor voltage regulation and higher probabilities of premature transformer failure (IEEE Power and Energy Society, 2012). Thermal degradation of insulation systems remains a major cause of reduced transformer lifespan in distribution networks (IEC, 2018). The IEEE loading guide for oil-immersed transformers further states that continuous operation under excessive loading conditions increases hotspot temperatures and significantly reduces insulation life expectancy (IEEE Power and Energy Society, 2012).

In many developing countries, especially within sub-Saharan Africa, transformer overloading has become a persistent operational challenge due to increasing consumer demand, illegal load extensions, inadequate infrastructure expansion, poor feeder planning and uncoordinated customer connections. These factors contribute significantly to transformer deterioration, technical losses, voltage instability and recurrent supply interruptions in distribution systems (Akinbulire *et al.*, 2014; Esobinenwu and Ulasi, 2018). Similar operational conditions have been reported in Nigerian distribution networks where many 11 kV substations operate close to their installed capacities due to persistent demand growth and aging infrastructure (Airoboman *et al.*, 2020).

Previous studies have shown that transformer hotspot temperature rises nonlinearly with loading level, thereby accelerating cellulose insulation degradation and reducing transformer service life (Swift *et al.*, 2001; IEC, 2018). Sustained thermal stress can also result in winding deformation, dielectric failure, oil deterioration and eventual transformer breakdown if adequate load management measures are not implemented (IEEE Power and Energy Society, 2012). Furthermore, an imbalance in phase loading contributes to uneven winding heating, excessive neutral currents and increased technical losses, thereby worsening transformer operational efficiency and reliability (Akinbulire *et al.*, 2014).

In Nigeria, 11 kV distribution transformers constitute a major part of secondary electricity delivery infrastructure, supplying residential, institutional and commercial consumers. Nevertheless, many of these transformers are subjected to non-ideal operating conditions characterized by heavy loading, voltage drops, phase imbalance and elevated technical losses (Amadi & Izuegbunam, 2016; Esobinenwu & Ulasi, 2018). These operational deficiencies adversely affect power quality, reliability of supply and asset lifespan within the distribution network. Although several studies have investigated transformer ageing, thermal modelling, failure analysis and loss reduction in power distribution systems, many of these studies were based on simulation approaches, generalized network models, or utility-wide assessments rather than field-based measurements at individual distribution substations (Akinbulire et al., 2014; Oliyide and Cipcigan, 2023). Furthermore, limited empirical studies have specifically evaluated transformer loading behaviour and overload-related operational effects within semi-urban Nigerian distribution networks using real operational data obtained under practical loading conditions. Consequently, there remains insufficient localized information regarding the extent of transformer loading imbalance, thermal stress exposure and operational reliability challenges affecting 11 kV distribution substations in rapidly growing semi-urban communities such as Ile-Oluji, Ondo State.

Accurate assessment of transformer loading conditions and associated thermal effects is essential for effective asset management, preventive maintenance, network reinforcement planning and reliability improvement. Monitoring loading profiles, phase current distribution, thermal stress indicators and voltage performance assists utilities in making informed decisions regarding load balancing, transformer upgrading, feeder reconfiguration and condition-based maintenance practices (Gonen, 2014; IEEE Power and Energy Society, 2012). In addition, localized studies provide practical insights into region-specific demand patterns, operational constraints, and infrastructure deficiencies that may not be adequately represented in generalized network studies.

This study, therefore, evaluates the effects of loading conditions on selected 11 kV distribution transformer substations along the Ile-Oluji feeder in Ondo State, Nigeria. The study assesses transformer loading characteristics using field-measured current and voltage data obtained during operational periods and compares the measured load demands with installed transformer capacities. The research further examines the implications of critical loading conditions on transformer efficiency, thermal stress exposure, voltage regulation and operational reliability. The findings of this study are expected to support improved transformer asset management practices, enhanced load planning strategies, and better operational sustainability of distribution networks in developing power systems.

2. Materials and Method

2.1. 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.

2.2. Research Design

This study adopted a quantitative field-based research approach to evaluate the loading conditions and operational performance of selected 11 kV distribution transformers within the Ile-Oluji feeder network. The approach was selected to enable direct assessment of transformer operating conditions using real-time field measurements obtained under actual network loading conditions. Field-based evaluations provide more realistic operational information for transformer performance assessment because they capture practical loading variations, phase imbalance conditions, voltage fluctuations, and operational constraints within distribution networks (Akinbulire *et al.*, 2014; Airoboman *et al.*, 2020).

The study focused on the measurement and analysis of transformer low-voltage phase currents, line voltages and apparent power demand during both peak-load and off-peak operational periods. The measured operational parameters were compared with transformer nameplate ratings to determine loading percentages, loading status, and possible exposure to thermal stress conditions. Similar field-measurement approaches have been widely adopted in transformer loading assessment studies due to their effectiveness in identifying critically loaded substations, transformer utilization levels, and distribution system operational deficiencies (Amadi & Izuegbunam, 2016; Esobinenwu & Ulasi, 2018).

To ensure technical consistency and standardization, transformer loading assessment procedures were carried out in accordance with the recommendations specified in IEEE Std C57.91-2011 and IEC 60076-7 loading guides for oil-immersed transformers. These standards provide internationally accepted procedures for evaluating transformer loading capability, thermal performance, hotspot temperature behaviour and insulation ageing characteristics under varying operational conditions (IEEE Power and Energy Society, 2012; International Electro-technical Commission, 2018).

The adopted research framework also incorporated a comparative assessment of loading characteristics across different substations in order to identify transformers operating under critical loading conditions, uneven phase loading conditions, and possible reliability risks associated with sustained high loading. Descriptive statistical techniques and comparative analytical procedures were employed to evaluate loading patterns, transformer utilization trends, voltage regulation behavior and operational reliability implications within the selected distribution network. Figure 1 presents the workflow adopted for the overall research methodology.

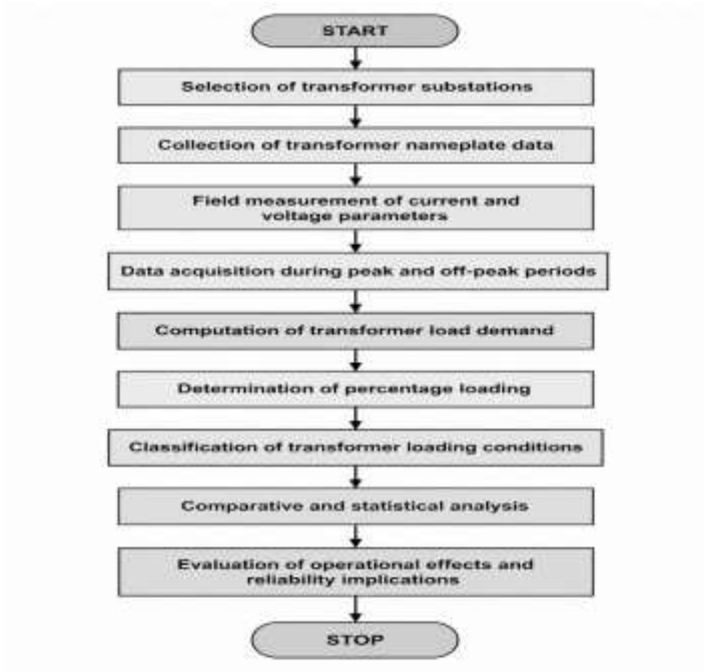

Fig. 1: Research Methodology Workflow

2.3. Transformer Selection Criteria

The transformer substations selected for this study were chosen based on their operational importance, accessibility for field measurements, loading characteristics and representation of typical distribution conditions within the Ile-Oluji 11 kV feeder network. A total of ten distribution transformer substations were investigated in order to obtain a representative evaluation of transformer loading behaviour under varying residential, commercial, and institutional electricity demand conditions.

The selected substations consist of both 300 kVA and 500 kVA oil-immersed distribution transformers supplying mixed categories of consumers, including residential buildings, markets, schools, healthcare facilities, and small commercial establishments. The inclusion of transformers with different rated capacities and consumer density enabled a comparative assessment of transformer utilization levels, loading conditions, voltage regulation performance, and operational stress exposure across different sections of the feeder network. Similar transformer selection approaches have been adopted in previous studies involving distribution transformer loading evaluation and thermal performance assessment within practical utility environments (Airoboman *et al.*, 2020; Wazir *et al.*, 2025).

Transformers located within areas characterized by high electricity demand and observable load growth patterns were intentionally included in the study because such substations are more susceptible to critical loading conditions, overheating, voltage instability, and accelerated insulation degradation. According to Oliyide and Cipcigan (2023), transformer loading characteristics and thermal behaviour are strongly influenced by demand variability, consumer load growth and operational loading patterns within low-voltage distribution networks.

In addition, substations with varying installation ages and customer connection densities were selected to investigate the influence of load distribution and demand variation on transformer operational reliability. Previous studies have shown that uneven loading patterns and sustained heavy loading conditions contribute significantly to transformer degradation, insulation ageing and reduced operational lifespan in distribution systems (Mitra *et al.*, 2022; Zhang *et al.*, 2022).

The selected substations also satisfied practical measurement requirements, including safe accessibility to low-voltage terminals, visibility of transformer nameplate information, and suitability for repeated field measurements during both peak-load and off-peak operational periods. The adopted selection criteria, therefore, ensured that the investigated substations provided reliable operational data suitable for evaluating transformer loading conditions, utilization characteristics, thermal stress exposure and associated operational implications within the selected distribution network.

2.4. Experimental Setup and Measurement Arrangement

Field measurements were conducted directly at the low-voltage terminals of the selected 11/0.415 kV distribution transformers using calibrated digital clamp meters, multimeters, and portable power analyzers. The measurement arrangement was designed to obtain real-time operational parameters required for evaluating transformer loading conditions, voltage performance, and phase current distribution under practical operating conditions.

The experimental setup involved measuring the three-phase load currents (R, Y, and B phases), line voltages, and power factor values at each transformer substation during both peak-load and off-peak operational periods. Transformer nameplate data, including rated capacity, voltage rating, and installation information, were also recorded for subsequent loading analysis. Similar field-based transformer measurement approaches have been adopted in previous studies involving transformer loading assessment and distribution network performance evaluation (Li *et al.*, 2022; Torres-Bermeo *et al.*, 2025).

To ensure measurement reliability and operational safety, all measurements were carried out using insulated measuring tools and appropriate personal protective equipment (PPE) in accordance with standard utility safety procedures (Aklotsoe *et al.*, 2025). Measurements were repeated over multiple operational periods in order to minimize transient loading effects and improve data consistency.

2.5. Data Acquisition

Operational data were acquired through field measurements carried out on the selected transformer substations during peak-load periods (18:00–22:00) and off-peak periods (01:00–05:00). Measurements were conducted over multiple days in order to capture load variations and improve data reliability. The acquired parameters included three-phase load currents, line voltages and transformer rated capacities obtained from transformer nameplates.

Average phase current values were determined from the measured R, Y, and B phase currents for each transformer substation. The measured electrical parameters were subsequently used to compute transformer apparent power demand, percentage loading, and voltage regulation characteristics. Similar data acquisition procedures have been employed in transformer loading and distribution system performance studies because they provide a reliable assessment of practical operating conditions within distribution networks (Hajeforosh *et al.*, 2022; Li *et al.*, 2022).

To ensure accuracy, all measuring instruments were calibrated before field deployment, while repeated measurements were carried out to reduce possible transient measurement errors and operational fluctuations.

2.6. Analytical Equations and Loading Calculations

The electrical parameters measured at each transformer substation were used to determine the apparent load demand and the transformers' percentage loading. For a three-phase distribution transformer, the apparent power demand was calculated using Equation (1):

$$S = \sqrt{3} V_L I_L \tag{1}$$

Where S = apparent power demand (kVA), V_L = line voltage (kV), and I_L= line current (A).
The percentage loading of each transformer was subsequently determined using Equation (2):

$$\% L = \frac{S_{measured}}{S_{rated}} \times 100 \quad (2)$$

Where %L = Percentage transformer loading, $S_{measured}$ = Measured apparent power demand (kVA), and S_{rated} = rated transformer capacity (kVA).
Voltage regulation of the transformers under loading conditions was evaluated using Equation (3):

$$\% VR = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100 \quad (3)$$

Where %VR = Percentage Voltage Regulation, and $V_{no-load}$ and $V_{full-load}$ are transformer terminal voltages under no-load and load conditions respectively.
These analytical equations are widely used in transformer loading and distribution system studies to evaluate transformer utilization, voltage performance, and operational loading conditions (IEEE Power and Energy Society, 2012; Wazir *et al.*, 2025). The computed loading values were further used to classify transformer operating conditions and assess possible thermal stress exposure within the investigated substations.

2.7. Transformer Loading Classification

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

i. Normal loading: %L ≤ 80%
ii. Critical loading: 80% < %L ≤ 100%
iii. Overloading: %L > 100%

Transformers operating close to rated capacity are generally exposed to increased thermal stress, higher copper losses, and accelerated insulation ageing, particularly during prolonged peak demand periods (IEEE Power and Energy Society, 2012; Hajeforosh *et al.*, 2022).
The adopted loading classification framework enabled comparative assessment of transformer utilization levels and identification of substations vulnerable to overheating, voltage instability, and reduced operational reliability. Similar loading classification approaches have been widely adopted in transformer thermal performance studies and distribution network operational assessments (Li *et al.*, 2022; Oliyide & Cipcigan, 2023).

2.8. Data Analysis Techniques

Descriptive and comparative analytical techniques were employed to evaluate transformer loading characteristics, voltage regulation performance and operational reliability across the selected substations. The measured electrical parameters were analyzed to determine transformer utilization levels, loading trends, and phase imbalance conditions under varying operational periods. The computed results were further compared with established transformer loading standards and findings from related distribution network studies to assess the implications of sustained loading on transformer thermal performance, voltage stability and system reliability (Srivastava *et al.*, 2023; Pham *et al.*, 2025; Sadiq *et al.*, 2025; Oliyide & Cipcigan, 2023).

2.9. Measurement Reliability and Safety

To ensure measurement reliability and data consistency, all field instruments used during the study were calibrated before deployment, while measurements were repeated over multiple operational periods to minimize transient errors and load fluctuations. Standard utility safety procedures were strictly observed throughout the field exercise, including the use of insulated measuring equipment and appropriate personal protective equipment (PPE) (Aklotsoe *et al.*, 2025). Similar reliability and safety practices have been recommended in field-based transformer monitoring and distribution system assessment studies to improve measurement accuracy and operational safety during energized system evaluation (IEEE Power and Energy Society, 2012; Li *et al.*, 2022; Wazir *et al.*, 2025).

3. Results and Discussion

This study evaluated the loading conditions and operational performance of ten selected 11/0.415 kV distribution transformer substations within the Ile-Oluji feeder using field-measured electrical parameters obtained during operational periods. Measured phase currents, line voltages and transformer rated capacities were analyzed to determine transformer apparent power demand, percentage loading, loading classification and associated operational implications. The obtained results were further used to assess transformer utilization levels, phase imbalance conditions, voltage regulation characteristics and possible exposure to thermal stress under varying load conditions. Similar field-based performance evaluation approaches have been employed in previous transformer loading and distribution system assessment studies to investigate transformer operational reliability and loading behaviour under practical network conditions (Amadi & Izuegbunam, 2016; Li *et al.*, 2022; Oliyide & Cipcigan, 2023).

Table 1 presents the measured transformer ratings, low-voltage phase currents, and line voltage values obtained from the investigated substations.

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

3.1 Computation of Transformer Load Demand

The measured low-voltage phase currents and transformer rated capacities obtained from the investigated substations were used to determine the apparent load demand and percentage loading of each transformer using Equations (1) and (2), respectively. The computed results presented in Table 2 show considerable variation in transformer loading levels across the studied substations.

The percentage loading values ranged from 58.08% to 98.32%, indicating uneven load distribution within the Ile-Oluji feeder network. Ajala Junction Substation recorded the highest loading level of 98.32%, operating very close to its rated capacity, while CAC Primary School Substation recorded the lowest loading level of 58.08%, indicating relatively low transformer utilization. Similar variations in transformer loading behaviour have been reported in practical distribution network studies where uneven customer demand and unbalanced feeder allocation contributed significantly to disparities in transformer utilization levels (Akinbulire *et al.*, 2014; Amadi & Izuegbunam, 2016).

The results further show that Lota Road (85.78%), Idiomo Market (87.69%), and Ajala Junction (98.32%) substations operated within the critical loading region based on IEEE transformer loading

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

recommendations. Sustained operation near rated transformer capacity increases thermal stress, copper losses, hotspot temperature rise, and insulation ageing rate, thereby reducing transformer operational lifespan and reliability (IEEE Power and Energy Society, 2012; Hajeforosh *et al.*, 2022; Oliyide & Cipcigan, 2023). The observed loading conditions, therefore, suggest the existence of progressive load growth and uneven load allocation within parts of the investigated distribution network.

Figure 2 presents the percentage loading distribution of the investigated transformer substations, highlighting substations operating within normal and critical loading regions.

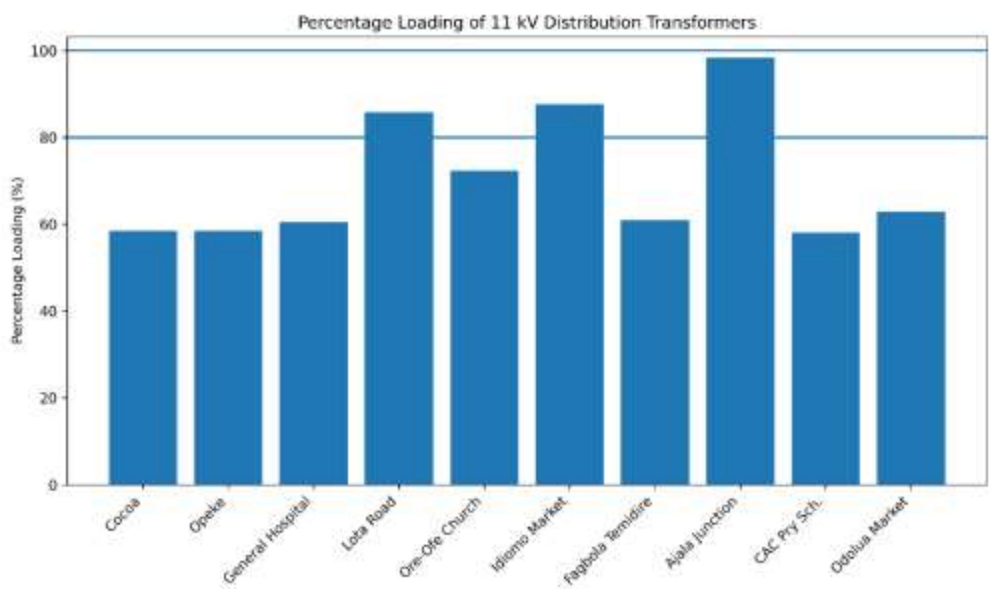

Fig 2: Percentage loading of 11 kV distribution transformers in Ile-Oluji feeder

3.2 Transformer Loading Characteristics

The transformer loading results indicate considerable variation in utilization levels across the investigated substations, reflecting uneven demand distribution within the Ile-Oluji feeder network. Substations such as Lota Road, Idiomo Market and Ajala Junction operated within the critical loading region, indicating exposure to elevated thermal stress conditions during peak demand periods. Similar observations have been reported in recent transformer performance studies where sustained heavy loading and uneven load allocation contributed to increased hotspot temperature rise, accelerated insulation ageing, and reduction in transformer operational lifespan (Diao *et al.*, 2025; Wazir *et al.*, 2025; Ogirimah *et al.*, 2025; Mitra *et al.*, 2022).

Although none of the investigated transformers exceeded their rated capacities during the measurement period, transformers operating close to rated loading conditions remain vulnerable to overheating, increased copper losses, voltage instability and premature insulation deterioration under prolonged loading conditions. According to Diao *et al.* (2025), transformer winding losses and thermal stress increase significantly under unbalanced and high loading conditions, thereby increasing the relative ageing rate of transformer insulation systems. The observed loading conditions, therefore, suggest the need for improved load balancing, feeder reconfiguration, and continuous operational monitoring within the investigated distribution network. Figure 3 compares the measured transformer load demand with installed transformer capacities for the investigated substations.

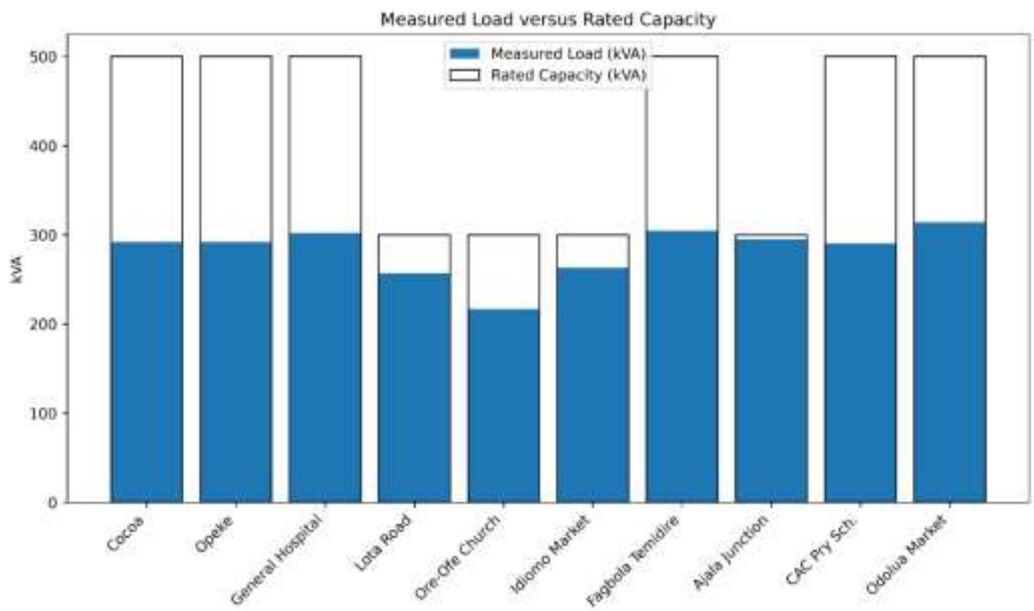

Fig 3: Measured load versus rated transformer capacity

3.3 Phase Current Imbalance Effects

The measured phase currents at the investigated substations revealed a noticeable imbalance among the R, Y, and B phases. At Odolua Market Substation, phase currents of 444A, 416A, and 452A were recorded, respectively, while Cocoa Substation recorded 400A, 430A, and 390A across the three phases. Similarly, Opeke Substation recorded phase currents of 380A, 400A, and 440A, indicating considerable disparity in phase loading conditions. These variations indicate uneven load distribution across the feeder phases, resulting in increased neutral currents, additional copper losses, and unequal thermal stress within transformer windings.

Similar phase-imbalance conditions have been reported in recent distribution transformer studies, in which unequal phase loading contributed significantly to transformer overheating, insulation deterioration, and voltage instability in low-voltage distribution systems (Yang *et al.*, 2024; Diao *et al.*, 2025; Guo *et al.*, 2024; Ogirimah *et al.*, 2025). Transformers operating close to rated capacity under unbalanced loading conditions are particularly vulnerable to hotspot temperature rise and accelerated insulation ageing due to localized winding overheating. The observed imbalance conditions within substations such as Ajala Junction, Idiomo Market, and Odolua Market, therefore, indicate the need for periodic phase load balancing and improved feeder load allocation to minimize technical losses and improve transformer operational reliability. Figure 4 illustrates the measured phase current distribution across the investigated substations, indicating the extent of phase loading imbalance within the feeder network.

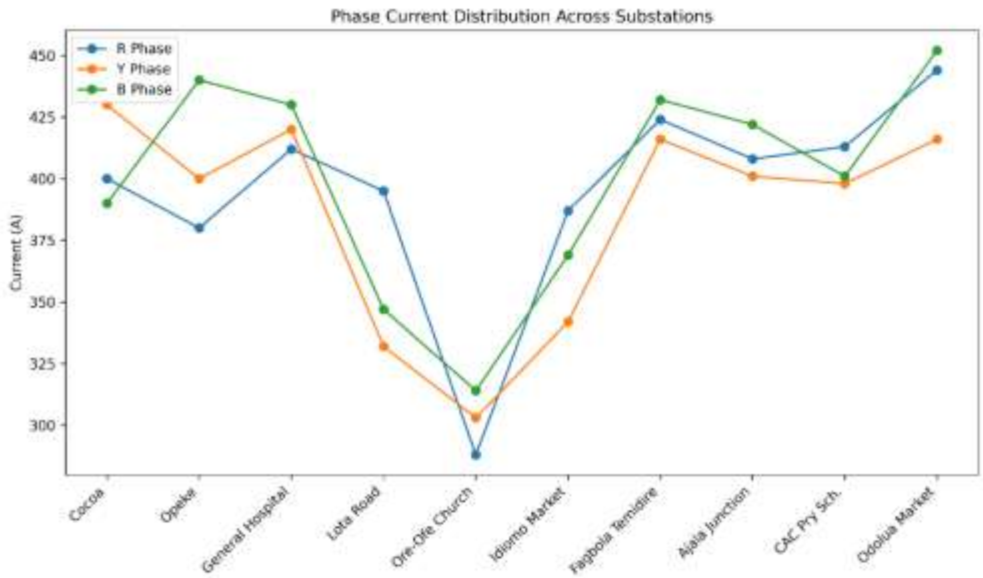

Fig 4: Phase current distribution across substations

3.4 Voltage Regulation and Supply Quality Implications

Transformers operating under high loading conditions are more susceptible to increased voltage drops and reduced supply quality within low-voltage distribution feeders. The investigated substations maintained a nominal line voltage of 415 V; however, substations operating close to rated capacity, particularly Ajala Junction (98.32%), Idiomo Market (87.69%), and Lota Road (85.78%), are more vulnerable to voltage instability during prolonged peak demand periods due to increased internal impedance drop and feeder loading effects. Similar observations have been reported in recent distribution system studies where sustained heavy transformer loading contributed to under voltage conditions, poor power quality, and reduced operational efficiency of consumer equipment (Srivastava *et al.*, 2023; Pham *et al.*, 2025; Zhang *et al.*, 2022).

In practical distribution systems, excessive voltage drop under high loading conditions may result in overheating of electrical appliances, poor motor performance, increased technical losses, and frequent customer complaints. According to Srivastava *et al.* (2023), transformers operating under stressed loading conditions significantly influence voltage stability and feeder regulation performance in low-voltage distribution networks. The observed loading conditions within the investigated substations therefore indicate the need for improved feeder load management and continuous voltage monitoring to maintain acceptable service quality and operational reliability.

3.5 System Level Implications and Load Management Considerations

The obtained results reveal noticeable disparity in transformer utilization levels across the investigated substations, with loading conditions ranging from 58.08% to 98.32%. While substations such as Ajala Junction, Idiomo Market, and Lota Road operated within critical loading conditions, others, including CAC Primary School and Cocoa substations, remained relatively underutilized. Such uneven loading patterns indicate inadequate load redistribution and progressive demand concentration within certain sections of the feeder network. Similar findings have been reported in recent distribution network studies where poor feeder load allocation and increasing urban electricity demand contributed to transformer overutilization, reduced operational efficiency, and increased thermal ageing risks (Khalid *et al.*, 2024; Ramírez *et al.*, 2025; Diao *et al.*, 2025; Torres-Bermeo *et al.*, 2025).

From an asset management perspective, transformers operating close to rated capacity require continuous monitoring, feeder reconfiguration, and possible load transfer to lightly loaded substations to minimize overheating, reduce technical losses, and improve network reliability. According to Khalid *et al.* (2024), intelligent load balancing and dynamic transformer monitoring significantly improve transformer operational lifespan and distribution system reliability under varying load demand conditions. The observed loading conditions, therefore, emphasize the need for proactive transformer loading management strategies within the investigated distribution network.

3.6 Comparative Analysis with Existing Studies

The findings of this study are consistent with previous investigations on transformer loading behaviour and operational reliability within distribution networks. The critical loading conditions observed at Ajala Junction (98.32%), Idiomo Market (87.69%), and Lota Road (85.78%) substations agree with the findings of Khalid *et al.* (2024) and Torres-Bermeo *et al.* (2025), who reported that transformers operating close to rated capacity are more susceptible to increased thermal stress, accelerated insulation ageing, and reduced operational lifespan. Similarly, Mitra *et al.* (2022) observed that sustained heavy loading conditions increase transformer degradation rate and reduce system reliability, particularly within low-voltage urban distribution networks.

The phase imbalance conditions observed in substations such as Odolua Market, Cocoa, and Opeke also correspond with the findings of Diao *et al.* (2025), who reported that uneven phase loading significantly increases winding hotspot temperature and thermal stress in oil-immersed transformers. In addition, the uneven transformer utilization levels recorded within the investigated feeder network support the observations of Zhang *et al.* (2022), where unequal feeder load allocation resulted in operational inefficiencies and increased vulnerability of heavily loaded substations. The present study, therefore, provides practical field-based evidence supporting existing transformer thermal loading theories and demonstrates the operational implications of critical loading conditions within semi-urban Nigerian distribution networks.

4. Conclusion

This study evaluated the loading conditions and operational performance of ten selected 11/0.415 kV distribution transformer substations within the Ile-Oluji 11 kV feeder using field-measured current and voltage parameters obtained during practical operating conditions. The results revealed noticeable variation in transformer utilization levels across the investigated substations, with percentage loading values ranging from 58.08% to 98.32%. Ajala Junction, Idiomo Market, and Lota Road substations were found operating within critical loading conditions, indicating exposure to elevated thermal stress and reduced operational safety margins.

The study further revealed the existence of appreciable phase current imbalance across several substations, contributing to unequal winding heating, increased copper losses, and accelerated insulation ageing. Although none of the investigated transformers exceeded their rated capacities during the measurement period, sustained operation close to rated loading conditions was observed to increase the risk of overheating, voltage instability, reduced transformer lifespan, and deterioration in supply reliability. In addition, the uneven transformer utilization pattern observed across the feeder network indicates inadequate load redistribution and progressive demand concentration within certain sections of the distribution system. The findings of this study therefore emphasize the need for continuous transformer loading monitoring, periodic phase load balancing, feeder reconfiguration, and strategic load redistribution to minimize thermal stress, improve transformer operational reliability, and enhance overall distribution network efficiency. The study also provides practical field-based data that can support effective transformer asset management and distribution system planning within semi-urban power networks in developing countries.

5. Recommendation

Based on the findings obtained from this study, continuous monitoring of transformer loading conditions should be implemented across the investigated substations in order to identify transformers operating within critical loading regions before severe thermal deterioration occurs. Substations such as Ajala Junction, Idiomo Market, and Lota Road should be prioritized for load redistribution, feeder reconfiguration, or transformer capacity upgrading in order to reduce excessive operational stress and improve supply reliability.

Periodic phase load balancing should also be carried out across low-voltage feeders to minimize phase current imbalance, reduce copper losses, and prevent uneven thermal stress within transformer windings. In addition, distribution utilities should adopt proactive transformer asset management practices, including routine operational assessment, thermal condition monitoring, and preventive maintenance strategies to improve transformer lifespan and operational efficiency.
Furthermore, future distribution network expansion within the Ile-Oluji feeder should incorporate proper demand forecasting and coordinated customer load allocation in order to prevent progressive transformer overutilization. The integration of smart monitoring technologies and intelligent load management systems is also recommended to support real-time transformer performance assessment and enhance the reliability of distribution networks operating under increasing electricity demand conditions.

References

1. Amadi, H. and Izuegbunam, F., 2016. Analysis of transformer loadings and failure rate in Onitsha electricity distribution network. *American Journal of Electrical and Electronic Engineering*, 4(6), pp.157-163.
2. Airoboman, A., Inalegwu, A., Andrew, M., Afolayan, I., Godwin, O. and Sanusi, U., 2020. An assessment of distribution transformers performance within Kaduna metropolis, Nigeria. *Journal of Applied Sciences and Environmental Management*, 24(1), pp.27-43.
3. Akinbulire, T.O., Oluseyi, P.O. and Babatunde, O.M., 2014. Evaluation of transformer loading and power losses in secondary distribution networks. *Energy and Power Engineering*, 6(2), pp.41-50.
4. Esobinenwu, C. and Ulasi, J., 2018. Performance analysis of distribution transformer in Nigerian power system. *International Journal of Advanced Academic Research*, 4(3), pp.336-356.
5. Gonen, T., 2014. *Electric power distribution engineering*. 3rd ed. CRC Press.
6. IEEE Power and Energy Society, 2012. *IEEE guide for loading mineral-oil-immersed transformers (IEEE Std C57.91-2011)*. IEEE.
7. International Electrotechnical Commission, 2018. *Loading guide for oil-immersed power transformers (IEC 60076-7)*. IEC.
8. Oliyide, R.O. and Cipcigan, L.M., 2023. Adaptive thermal model for loading of transformers in low carbon electricity distribution networks. *Scientific African*, 20, p.e01683.
9. Swift, G., Molinski, T. and Lehn, W., 2001. A fundamental approach to transformer thermal modeling-Part I: Theory and equivalent circuit. *IEEE Transactions on Power Delivery*, 16(2), pp.171-175.
10. Mitra, B., Singhal, A., Kundu, S. and Ogle, J.P., 2022. Analyzing distribution transformer degradation with increased power electronic loads. *arXiv preprint arXiv:2210.14824*.
11. Mohd Wazir, M. H., Mat Said, D., Md Sapari, N., Mohamed Yunus, M. S., and Mohd Yassin, Z. I., 2025. An electro-thermal modeling of distribution transformer for hottest spot evaluation under photovoltaic-induced harmonics. *International Journal of Renewable Energy Development*, Volume 14(3), pp. 450-462. Available at: https://doi.org/10.61435/ijred.2025.60959
12. Zhang, Y., Qian, T. and Tang, W., 2022. Buildings-to-distribution-network integration considering power transformer loading capability and distribution network reconfiguration. *Energy*, 244, p.123104.
13. Aklotsoe, Y., Edward Antwi, A. and Amartey, E., 2025. A systematic review on the effectiveness of personal protective equipment at the workplace. *International Journal of Creative Research Thoughts*, 13, pp. 44–59.

14. Li, J., Wang, Y., Zhang, H. and Liu, Q., 2022. Distribution transformer loading capability assessment considering dynamic operating conditions. *Frontiers in Energy Research*, 10, pp.1-12.
15. Torres-Bermeo, X., Ponce-Jara, M., Gonzalez, J. and Cardenas, R., 2025. Distribution transformer sizing and loading assessment for technical loss reduction in power networks. *Energies*, 18(7), p.1832.
16. Hajeforosh, S., Arefi, A., Ledwich, G. and Nourbakhsh, G., 2022. Dynamic thermal rating of distribution transformers under varying loading conditions. *International Journal of Electrical Power and Energy Systems*, 137, p.107845.
17. Pham, T.N., Shah, R., Dao, M.N., Sultanova, N. and Islam, S., 2025. Low and medium voltage distribution network planning with distributed energy resources: a survey. *Electrical Engineering*, 107, pp. 1797–1828. Available at: https://doi.org/10.1007/s00202-024-02535-0.
18. Srivastava, P., Haider, R., Nair, V.J., Venkataramanan, V., Annaswamy, A.M. and Srivastava, A.K., 2023. Voltage regulation in distribution grids: A survey. *Annual Reviews in Control*, 55, pp. 165–181. Available at: https://doi.org/10.1016/j.arcontrol.2023.03.008.
19. Sadiq, E.H. and Antar, R.K., 2025. Reliability improvement of distribution networks: A case study of Duhok distribution network. *EMITTER International Journal of Engineering Technology*, 13(1), pp. 73–92. Available at: https://doi.org/10.24003/emitter.v13i1.908
20. Ogirimah, A.A., Onimisi, M.Y., Ali, H. and Owolabi, J.A., 2025. Analysis of thermal ageing effects on transformer oil dielectric properties. *Science World Journal*, 20(2), pp. 774–783. Available at: https://dx.doi.org/10.4314/swj.v20i2.44
21. Diao, G., Ni, H., Si, W., Gu, Y. and Yang, J., 2025. Multi-physics numerical research in oil-immersed three-phase transformer under load unbalance. *Energies*, 18(5), p. 1217. Available at: https://doi.org/10.3390/en18051217
22. Yang, W.C., Lin, W.R., Wu, I.A., Wu, C.Y. and Kuo, T.W., 2024. The impact of multiple single-phase power generation systems on the three-phase voltage imbalance of low-voltage distribution systems. *International Journal of Engineering Research and Technology*, 13(8), pp.1-8.
23. Guo, G., Zhan, X., Wang, J., Liu, Z., Feng, K., Peng, F., Gong, D., Tang, A., Xiang, C. and Wang, Z., 2024. Research on the three-phase load imbalance control of the active distribution network based on the distributed power flow controller. *Frontiers in Energy Research*, 12, Article 1414084. Available at: https://doi.org/10.3389/fenrg.2024.1414084
24. Khalid, M., Ahmed, F. and Ullah, Z., 2024. Intelligent load balancing strategy for improving transformer reliability in smart distribution systems. *Electric Power Systems Research*, 229, p.110118.