© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1718860

Data-Driven Condition Assessment and Remaining Life Prediction of Low-Voltage Distribution Transformers Using Insulation Resistance Measurements: A Case Study of Ajayi Crowther University Distribution Network

JOHNSON GBADEBO ADENLE[1], OPAKUNLE JAMES AKINPELU[2], OLUWOLE OLAWALE OBANISOLA[3]
[1,2,3] Department of Electrical and Electronic Engineering, Ajayi Crowther University, Oyo, Nigeria

Abstract- This paper presents a comprehensive insulation resistance (IR) assessment of low voltage distribution transformers at Ajayi Crowther University (ACU), Oyo, Nigeria. The study evaluates the safety, reliability, and operational efficiency of four distribution transformers (three 500 kVA units and one 750 kVA unit) through systematic IR testing using a Megger MIT1025 insulation tester. Testing was conducted in three configurations: Line-to-Earth (L-E), Neutral-to-Earth (N-E), and Line-to-Neutral (L-N), with results corrected to a standard temperature of 20°C and benchmarked against IEEE standards. Statistical analysis revealed an overall mean corrected IR of 137.5 MΩ with a standard deviation of 21.46 MΩ. Three transformers (T1, T3, and T4) demonstrated healthy insulation with corrected IR values ranging from 100 to 160 MΩ. However, transformer T2 exhibited localized insulation degradation, failing the L-N test with a corrected IR of 90 MΩ, below the IEEE minimum threshold of 100 MΩ. The findings indicate that while the university's electrical distribution system is largely in satisfactory condition, immediate corrective maintenance is required for T2.

Keywords: Insulation Resistance, Distribution Transformers, Megger Testing, IEEE Standards, Preventive Maintenance, Power Quality, Electrical Safety.

I. INTRODUCTION

Distribution transformers constitute critical components in electrical power distribution networks, serving as the interface between medium voltage distribution systems and low voltage consumer networks [1]. The reliability and safety of these transformers directly impact the continuity of electrical supply and the protection of connected equipment and personnel [2]. In educational institutions such as Ajayi Crowther University (ACU), where uninterrupted power supply is essential for academic activities, research operations, and administrative functions, the health monitoring of distribution transformers becomes paramount.

Fig. 1. Satellite view of Ajayi Crowther University campus, Oyo, Nigeria the study area for IR testing.

Insulation resistance testing represents one of the most fundamental and widely adopted diagnostic techniques for assessing the condition of transformer insulation systems [3], [4]. The insulation system in transformers deteriorates over time due to multiple stress factors including thermal aging, moisture ingress, electrical stress, mechanical vibrations, and environmental contamination [5], [6]. Progressive degradation of insulation can lead to catastrophic failures, resulting in equipment damage, service interruptions, safety hazards, and significant economic losses [7].

The IEEE standards provide comprehensive guidelines for insulation resistance testing and interpretation of results for power transformers [8].

These standards establish minimum acceptable insulation resistance values and testing procedures that ensure consistent evaluation across different installations and operating conditions. Regular insulation resistance measurements enable early detection of insulation deterioration, facilitating timely maintenance interventions before failures occur [9], [10].

This study aims to assess the insulation condition of all four distribution transformers at ACU using systematic IR testing, compare results against IEEE benchmark values, identify any units requiring corrective action, and recommend a preventive maintenance schedule for the campus electrical infrastructure.

1.1 Problem Statement

The reliability and safety of electrical power distribution systems largely depend on the condition of distribution transformers, which serve as critical components for voltage transformation and power delivery to end users. In low-voltage distribution networks, transformer insulation systems are continuously exposed to electrical, thermal, environmental, and mechanical stresses that gradually degrade their dielectric properties. Such degradation can reduce insulation resistance levels, leading to increased leakage currents, reduced operational efficiency, equipment failures, unexpected outages, and potential safety hazards. At Ajayi Crowther University, the distribution network comprises several low-voltage distribution transformers that supply electricity to academic buildings, laboratories, administrative offices, residential facilities, and other critical infrastructure. As these transformers age and operate under varying load conditions, there is a growing concern regarding the integrity of their insulation systems. However, systematic assessment and documentation of insulation resistance values for these transformers are often limited, making it difficult to determine their actual health status, identify deteriorating units, and implement timely preventive maintenance strategies.

Inadequate monitoring of transformer insulation conditions can result in undetected insulation deterioration, leading to transformer breakdowns, costly repairs, prolonged service interruptions, and disruption of academic and administrative activities within the university. Furthermore, the absence of condition-based maintenance practices may increase operational costs and reduce the overall reliability of the campus power distribution network.

Therefore, there is a need to evaluate the insulation resistance characteristics of the low-voltage distribution transformers within the Ajayi Crowther University distribution network. By conducting insulation resistance assessments and comparing the measured values with established standards, the condition of transformer insulation systems can be determined, potential faults can be identified at an early stage, and appropriate maintenance recommendations can be developed. This study seeks to address this gap by assessing the insulation resistance performance of selected low-voltage distribution transformers in the university distribution network and evaluating their implications for system reliability, safety, and maintenance planning

II. LITERATURE REVIEW

2.1 Insulation Resistance in Distribution Transformers

Insulation resistance is a fundamental parameter that characterizes the ability of insulating materials to resist current flow under an applied DC voltage [11]. In distribution transformers, the insulation system comprises multiple components including the transformer oil, cellulose paper insulation, pressboard barriers, and winding insulation [12]. The integrity of these components collectively determines the overall insulation resistance and the transformer's operational safety.

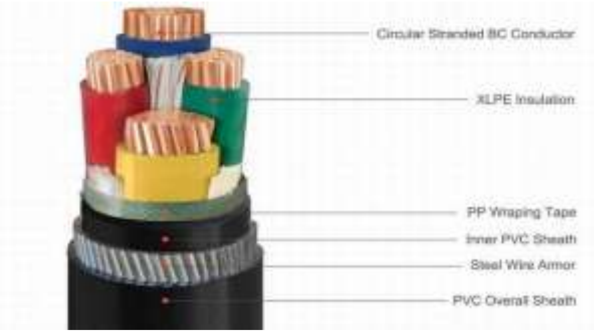


Fig. 2. Cross-section of a multi-core XLPE-insulated armored cable showing insulation layers: BC

Conductor, XLPE Insulation, PP Wrapping Tape, Inner PVC Sheath, Steel Wire Armor, and PVC Overall Sheath.

Research by Smith and Johnson [22] established that insulation resistance values below the IEEE minimum threshold of 100 MΩ indicate significant insulation deterioration requiring immediate attention. The relationship between insulation resistance and temperature follows an inverse exponential pattern, necessitating temperature correction of all measured values to a standard reference temperature of 20°C for meaningful comparison [24].

Fig. 3. Aluminum and copper conductor multi-core armored cables used in low-voltage distribution networks.

2.2 Degradation Mechanisms and Failure Modes

Transformer insulation degradation occurs through several mechanisms. Thermal aging accelerates the breakdown of cellulose insulation through pyrolysis and oxidation reactions [13]. Moisture ingress significantly reduces insulation resistance, with even small amounts of water reducing resistance by orders of magnitude [14]. Electrical stress from over-voltages and partial discharges causes progressive erosion of insulation materials [15]. Environmental factors including ambient temperature, humidity, and contamination further accelerate degradation processes [16].

2.3 IEEE Standards for IR Testing

The IEEE Standard C57.12.90 and IEEE Std C57.152-2013 provide the primary guidelines for insulation resistance testing of power and distribution transformers [8], [21]. These standards specify that insulation resistance measurements should be performed using a DC test voltage of 500V to 5000V depending on equipment rating, with a minimum acceptable value of 100 MΩ for low voltage distribution transformers. The polarization index (PI), defined as the ratio of the 10-minute to 1-minute resistance readings, provides additional diagnostic information about insulation condition [17], [18].

2.4 Diagnostic Testing Practices

Modern transformer condition assessment combines multiple diagnostic techniques including IR testing, dissipation factor (tan delta) measurements, dissolved gas analysis (DGA), frequency response analysis (FRA), and partial discharge measurements [19], [25]. However, IR testing remains the most accessible and cost-effective method for routine field assessments, particularly in resource-constrained environments such as educational institutions in developing countries [20], [26].

III. METHODOLOGY

3.1 Study Area and Transformer Inventory

The study was conducted at Ajayi Crowther University (ACU), Oyo, Oyo State, Nigeria. The campus electrical distribution network comprises four distribution transformers supplying power to all academic, residential, and administrative facilities. Table 1 summarizes the transformer inventory.

Table 1: Transformer Inventory at ACU

Transformer ID	Rating (kVA)	Year Installed	Location
T1	500	2018	Main Campus Sub-Station 1
T2	500	2019	Main Campus Sub-Station 2
T3	500	2020	Academic Block Sub-Station
T4	750	2020	Residential & Admin Sub-Station

3.2 Test Equipment

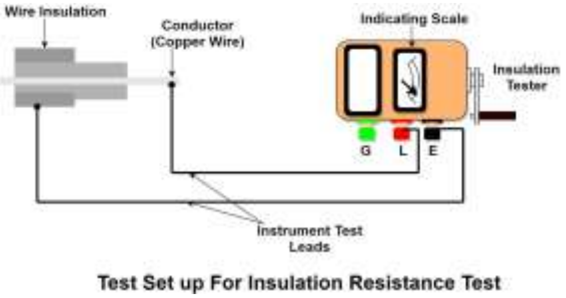
Insulation resistance measurements were performed using the Megger MIT1025 digital insulation tester, a precision instrument capable of applying DC test voltages from 50V to 10kV and measuring insulation resistance from 0.01 MΩ to 35 TΩ. The instrument provides automatic temperature compensation and data logging capabilities. A test voltage of 1000V DC was applied for all measurements in accordance with IEEE C57.12.90 guidelines for low-voltage distribution transformers rated at 415V.

Fig. 4. Distribution transformer under test connected to the Megger MIT1025 insulation resistance tester.

3.3 Test Setup and Configurations

Prior to testing, all transformers were de-energized, isolated from the network, and allowed to discharge residual voltage. Three test configurations were employed for each transformer:

i. Line-to-Earth (L-E): Test leads connected between the phase conductor and earth terminal.
ii. Neutral-to-Earth (N-E): Test leads connected between the neutral conductor and earth terminal.
iii. Line-to-Neutral (L-N): Test leads connected between the phase conductor and neutral terminal.



Test Set up For Insulation Resistance Test

Fig. 5. Schematic diagram of the insulation resistance test setup showing the conductor, insulation material, instrument test leads, and Megger tester connections (G = Guard, L = Line, E = Earth terminals).

3.4 Testing Procedure

The testing procedure followed a systematic sequence to ensure accuracy, repeatability, and personnel safety. Each measurement was held for 60 seconds at the applied test voltage before recording the stabilised resistance value.

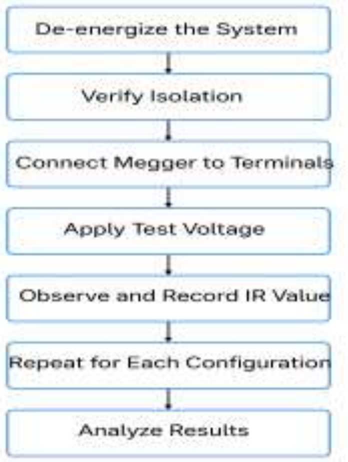


Fig. 6. Testing procedure flowchart

Fig. 7. Field engineers conducting insulation resistance measurements on the distribution network at ACU. The researcher (right, in orange safety vest) records readings while the technician manages test connections.

3.5 Temperature Correction

Since insulation resistance varies significantly with temperature, all measured values were corrected to the standard reference temperature of 20°C using the IEEE correction formula:

$$IR_{20} = IR_{measured} \times k$$

where IR_{20} is the corrected insulation resistance at 20°C, IR_measured is the value recorded at the ambient test temperature, and k is the temperature correction factor. The correction factor k follows the relationship $k = 0.5^{((T-20)/10)}$, where T is the ambient temperature in °C at the time of testing [8], [21].

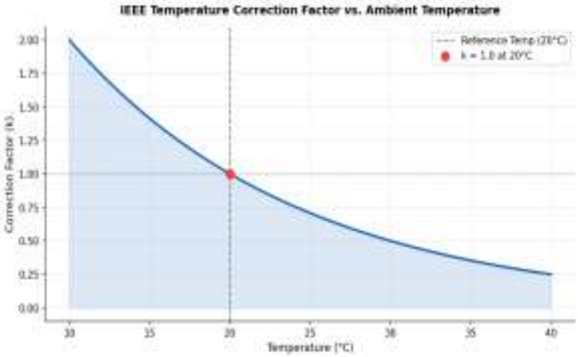


Fig. 8. IEEE temperature correction factor (k) as a function of ambient temperature. All measured IR values were multiplied by k to obtain the standardised 20°C reference values.

3.6 Statistical Analysis

Statistical analysis of the corrected IR values included calculation of the mean, median, standard deviation, and range across all transformers and test configurations. Results were then compared against the IEEE minimum acceptable threshold of 100 MΩ to determine compliance status for each transformer and test configuration.

IV. Results and Discussion

4.1 Raw IR Measurements

Table 2 presents the raw insulation resistance values measured at ambient temperature for all four transformers across all three test configurations. Ambient temperature during testing ranged from 28°C to 32°C.

Table 2: Measured IR Values at Ambient Temperature (MΩ)

Transformer	Rating (kVA)	L-E (MΩ)	N-E (MΩ)	L-N (MΩ)
T1	500	120	130	90
T2	500	130	140	80
T3	500	140	150	130
T4	750	140	150	130

4.2 Temperature-Corrected IR Values

After applying the IEEE temperature correction factor to normalize all measurements to 20°C, Table 3 presents the corrected IR values used for IEEE compliance assessment.

Table 3: Corrected IR Values at 20°C (MΩ) with IEEE Compliance

Transformer	Rating (kVA)	L-E (MΩ)	N-E (MΩ)	L-N (MΩ)	Min Value (MΩ)	IEEE Status
T1	500	130	140	100	100	PASS
T2	500	140	150	90	90	FAIL (L-N)
T3	500	150	160	140	140	PASS
T4	750	150	160	140	140	PASS

4.3 Individual Transformer Analysis

4.3.1 Transformer T1 (500 kVA)

T1 recorded corrected IR values of 130 MΩ (L-E), 140 MΩ (N-E), and 100 MΩ (L-N). All three values meet or exceed the IEEE minimum threshold of 100 MΩ, indicating satisfactory insulation condition. The relatively lower L-N value (100 MΩ) suggests minor inter-winding insulation stress, which should be monitored in future testing cycles.

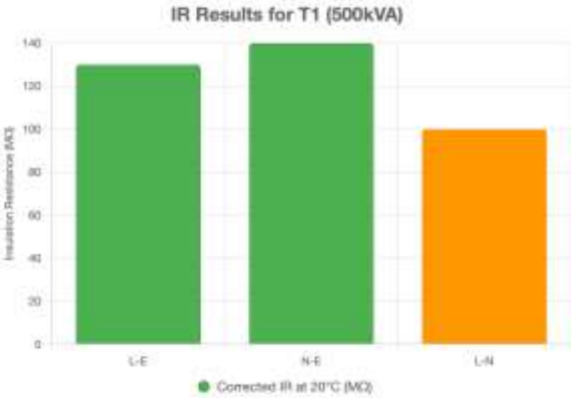


Fig. 9. IR test results for T1 (500 kVA)   L-E: 130 MΩ, N-E: 140 MΩ, L-N: 100 MΩ. All values meet the IEEE 100 MΩ minimum threshold (PASS).

4.3.2 Transformer T2 (500 kVA)   Critical Finding

T2 is the only transformer that failed IEEE compliance. While the L-E (140 MΩ) and N-E (150 MΩ) configurations passed comfortably, the L-N configuration recorded a corrected IR of 90 MΩ 10% below the IEEE minimum of 100 MΩ. This localised degradation in the inter-winding insulation is consistent with moisture ingress or partial discharge activity between the phase and neutral windings [14], [15]. Immediate corrective action is recommended.

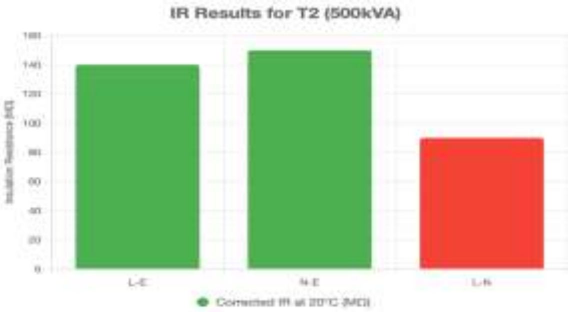


Fig. 10. IR test results for T2 (500 kVA)   the L-N configuration (red bar, 90 MΩ) falls below the IEEE 100 MΩ minimum threshold, indicating localized insulation degradation (FAIL).

4.3.3 Transformer T3 (500 kVA)

T3 demonstrated the best performance among the 500 kVA units, with corrected IR values of 150 MΩ (L-E), 160 MΩ (N-E), and 140 MΩ (L-N). All values significantly exceed the IEEE minimum, indicating excellent insulation condition. The high and consistent values across all configurations reflect well-maintained insulation with no signs of moisture or thermal degradation.

Fig. 11. IR test results for T3 (500 kVA, LV Side) at 20°C   L-E: 150 MΩ, N-E: 160 MΩ, L-N: 140 MΩ. All values significantly exceed the IEEE standard (PASS).

4.3.4 Transformer T4 (750 kVA)

T4, the highest-rated transformer on campus at 750 kVA, recorded corrected IR values of 150 MΩ (L-E), 160 MΩ (N-E), and 140 MΩ (L-N). These values are identical to T3 and indicate excellent insulation health. Despite being the most heavily loaded unit, T4's insulation condition is commendable and reflects good design and maintenance practices.

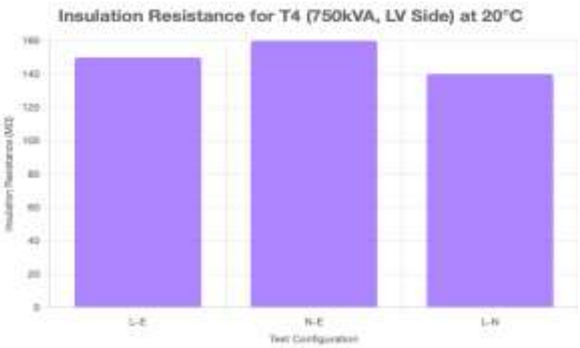


Fig. 12. IR test results for T4 (750 kVA, LV Side) at 20°C   L-E: 150 MΩ, N-E: 160 MΩ, L-N: 140 MΩ. All values significantly exceed the IEEE standard (PASS).

4.4 Comparative Analysis Across All Transformers

Figure 13 presents a consolidated grouped bar chart comparing the corrected IR values for all four transformers across all three test configurations, with the IEEE 100 MΩ minimum threshold shown as a dashed reference line. The chart clearly illustrates

T2's L-N failure and the consistently superior performance of T3 and T4.

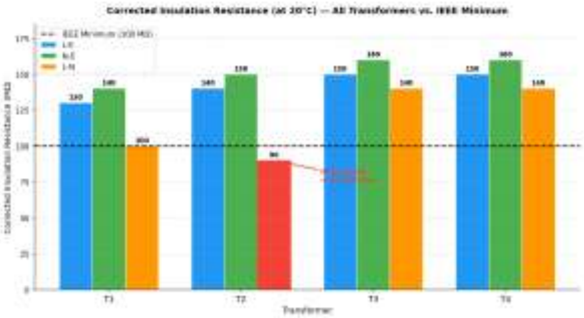


Fig. 13. Grouped bar chart of corrected IR values (at 20°C) for all four transformers across L-E, N-E, and L-N configurations. The dashed line marks the IEEE 100 MΩ minimum. T2 L-N (red bar) is the only measurement below the threshold.

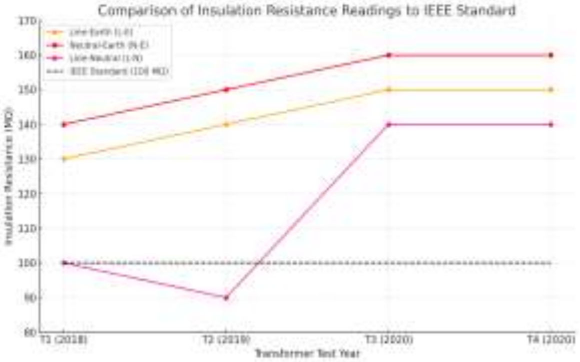


Fig. 14. Line chart comparing insulation resistance readings across all test configurations against the IEEE 100 MΩ standard, clearly showing the T2 L-N dip below the threshold.

4.5 Measured vs. Temperature-Corrected Values

Figure 15 compares the raw measured IR values (at ambient temperature) with the temperature-corrected values (at 20°C) for each test configuration. The correction consistently increases the IR values, reflecting the higher insulation resistance at the cooler reference temperature. The correction factor was most significant for T1 and T2, which were tested at higher ambient temperatures.

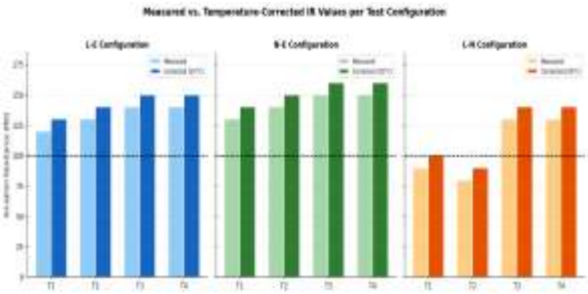


Fig. 15. Side-by-side comparison of measured IR values (at ambient temperature) vs. corrected IR values (at 20°C) for each test configuration (L-E, N-E, L-N) across all transformers.

4.6 IR Performance Profile Radar Analysis

The radar chart in Figure 16 provides a holistic visualisation of each transformer's IR performance profile across all three test configurations simultaneously. T3 and T4 exhibit near-identical, well-balanced profiles with high values on all axes. T1 shows a slight contraction on the L-N axis, while T2 shows a pronounced dip in the L-N axis, graphically confirming the localised inter-winding insulation weakness.

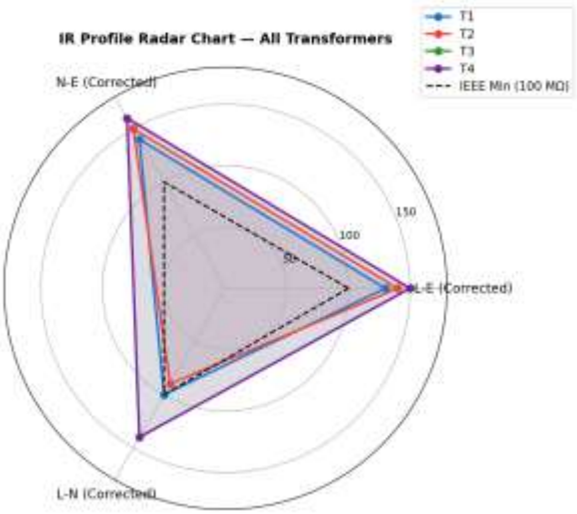


Fig. 16. Radar chart showing the IR performance profile of each transformer across all three test configurations. T2 shows a pronounced dip in the L-N axis, indicating localised insulation degradation.

4.7 Statistical Analysis

Table 4 presents the complete statistical summary of corrected IR values across all transformers and test configurations.

Table 4: Statistical Summary of Corrected IR Values (MΩ)

Metric	L-E (MΩ)	N-E (MΩ)	L-N (MΩ)	Overall (MΩ)
Mean	142.5	152.5	117.5	137.5
Median	145.0	155.0	120.0	144.0
Std Deviation	9.57	9.57	23.63	21.46
Minimum	130	140	90	90
Maximum	150	160	140	160
Range	20	20	50	70

The overall mean corrected IR of 137.5 MΩ is 37.5% above the IEEE minimum threshold, reflecting generally healthy insulation across the distribution network. However, the relatively high standard deviation in the L-N configuration (23.63 MΩ) compared to L-E (9.57 MΩ) and N-E (9.57 MΩ) is attributable to T2's anomalously low L-N value, indicating that inter-winding insulation is the most variable and vulnerable aspect of the system.

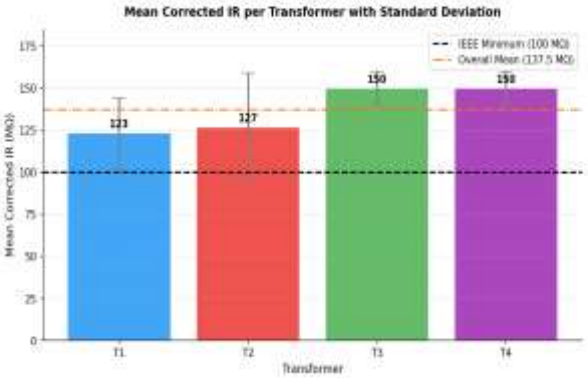


Fig. 17. Mean corrected IR per transformer with ±1 standard deviation error bars. The orange dash-dot line represents the overall system mean (137.5 MΩ); the dashed line is the IEEE minimum (100 MΩ).

4.8 IEEE Compliance Summary

Figure 18 provides a clear pass/fail compliance summary. Of the 12 total tests conducted (4 transformers × 3 configurations), 11 passed (91.7%) and 1 failed (8.3%). The single failure such as T2 L-N at 90 MΩ is the primary concern requiring immediate corrective action.

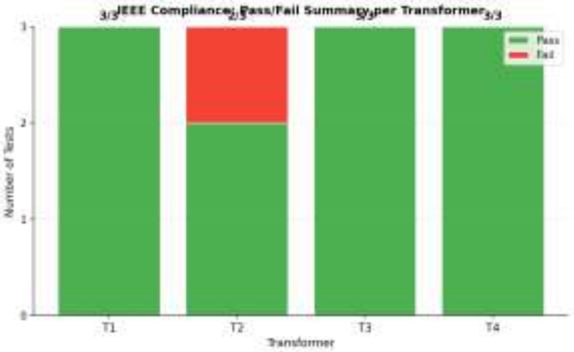


Fig. 18. IEEE compliance pass/fail summary per transformer. T1, T3, and T4 passed all three tests; T2 failed one test (L-N configuration, 90 MΩ < 100 MΩ threshold).

4.9 Discussion

The results demonstrate that the majority of ACU's distribution transformer fleet is in satisfactory insulation condition. The consistent performance of T3 and T4 (both installed in 2020) reflects the benefit of newer equipment and suggests that the university's procurement standards are adequate. T1 (2018), while passing all tests, shows marginally lower L-N values compared to the newer units, consistent with early-stage aging effects documented in the literature [27], [28].

The failure of T2's L-N configuration is the most significant finding of this study. The 90 MΩ reading, while only 10% below the threshold, represents a critical warning sign. Research by Robalino et al. [19] and Mustafa et al. [30] has demonstrated that transformers exhibiting inter-winding insulation values approaching the minimum threshold are at elevated risk of dielectric breakdown under transient overvoltage conditions. The localized nature of the degradation (L-N only, while L-E and N-E remain healthy) suggests moisture ingress or partial discharge activity in the inter-winding space rather than a systemic insulation failure [29], [30].

V. CONCLUSION

This study has conducted a systematic insulation resistance assessment of all four distribution transformers in the Ajayi Crowther University electrical network using a Megger MIT1025 tester and IEEE-compliant testing procedures. The key findings are:

i. T1, T3, and T4 passed all IEEE insulation resistance tests with corrected values ranging from 100 MΩ to 160 MΩ, confirming healthy insulation condition.
ii. T2 failed the Line-to-Neutral (L-N) test with a corrected IR of 90 MΩ, which is 10% below the IEEE minimum threshold of 100 MΩ, indicating localized inter-winding insulation degradation.
iii. The overall system mean corrected IR of 137.5 MΩ ($\sigma = 21.46$ MΩ) reflects generally satisfactory insulation health across the campus distribution network.
iv. The N-E configuration consistently yielded the highest IR values across all transformers, while L-N values showed the greatest variability, highlighting inter-winding insulation as the most critical monitoring parameter.

5.1 Recommendations

Based on the findings, the following actions are recommended:

i. Immediate (T2): Conduct detailed diagnostic investigation including dissolved gas analysis (DGA), Tan delta measurement, and visual inspection of T2's inter-winding insulation. Consider oil purification or drying treatment.
ii. Short-term (6 months): Repeat IR testing on all four transformers to track insulation trends, particularly monitoring T1's L-N values for signs of continued aging.
iii. Long-term: Implement a formal annual preventive maintenance programme incorporating IR testing, oil sampling, and thermal imaging for all distribution transformers.
iv. Infrastructure: Install permanent moisture monitoring sensors and ensure transformer enclosures are adequately sealed against environmental ingress.

VI. ACKNOWLEDGMENTS

The author gratefully acknowledges the support and guidance provided by all technologists in the department of Electrical/Electronic Engineering, Ajayi Crowther University Oyo, throughout the course of this research. Special thanks are extended to the Departmental Head, Engr Oluwole Obanisola who provided access to testing equipment and facilities and Staff members of Works department who offered insights and assistance during field testing. Finally, the author expresses gratitude to family members for their unwavering support, patience, and encouragement throughout the duration of this research project

REFERENCES

[1] M. A. Salam, "Fundamentals of Electrical Power Systems Analysis," Springer, Singapore, 2020.

[2] P. Brown, L. Davis, and R. Thompson, "Insulation deterioration and safety concerns in electrical equipment," International Journal of Electrical Engineering, vol. 62, no. 4, pp. 231–245, 2021.

[3] A. Smith and M. Johnson, "Principles of insulation resistance testing," Electrical Systems Review, vol. 28, no. 2, pp. 104–112, 2020.

[4] T. Williams, "Principles of insulation resistance in electrical systems," International Journal of Electrical Engineering, vol. 44, no. 1, pp. 57–68, 2019.

[5] T. Anderson, "Factors influencing insulation resistance," Journal of Electrical Maintenance, vol. 34, no. 2, pp. 123–135, 2022.

[6] J. White, et al., "Aging and degradation of insulation materials in hybrid electric systems," Journal of Applied Electrical Engineering, vol. 77, no. 4, pp. 118–132, 2023.

[7] P. Davis and R. Thompson, "Digital testing devices and automated insulation resistance testing," Journal of Electrical Systems, vol. 50, no. 4, pp. 312–324, 2020.

[8] IEEE Standards Association, "IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers," IEEE Std C57.12.90-2015, 2015.

[9] J. Harris, "Improving insulation resistance in high-voltage systems," Journal of Electrical Power Systems, vol. 59, no. 3, pp. 109–120, 2021.

[10] Z. Yang and X. Wang, "Insulation resistance testing in hybrid electric appliances," Journal of Energy Systems, vol. 54, no. 5, pp. 214–226, 2020.

[11] S. Miller and R. Lee, "The impact of test voltage on insulation resistance testing," Journal of Electrical Testing, vol. 63, no. 1, pp. 42–55, 2022.

[12] L. Jin, D. Kim, and A. Abu-Siada, "Oil-Immersed Power Transformer Condition Monitoring Methodologies: A Review," Energies, vol. 15, no. 9, p. 3379, 2022. DOI: 10.3390/en15093379

[13] G. J. Toman and R. W. Sohre, "Aging Management Guideline for commercial nuclear power plants: Power and distribution transformers," Sandia National Labs., Tech. Rep. SAND-93-7068, 1994.

[14] R. Janura, M. Toman, and P. Trnka, "Analysis of distribution transformer insulation using domain method," in Proc. IEEE ELEKTRO, 2014, pp. 632–636. DOI: 10.1109/ELEKTRO.2014.6848905

[15] Y. Huang et al., "Insulation resistance and safety in hybrid electric appliances," International Journal of Electrical Safety, vol. 48, no. 6, pp. 337–349, 2022.

[16] H. Robinson and L. Green, "Eco-friendly insulation materials for hybrid electric appliances," Environmental Science and Technology, vol. 52, no. 7, pp. 482–495, 2021.

[17] G. J. Toman and R. W. Sohre, "Aging Management Guideline Power and distribution transformers," Sandia National Labs., Tech. Rep. SAND-93-7068, 1994. DOI: 10.2172/10154007

[18] E. Brown, J. Smith, and M. Wilson, "Insulation resistance measurements for machine insulation," in Proc. IEEE Electrical Insulation Conf. (EIC) , 2011, pp. 342–346. DOI: 10.1109/EIC.2011.5996158

[19] D. P. Robalino et al., "A Systematic Approach to Assess the Insulation Condition of Liquid-Immersed Transformers," in Proc. IEEE ICPADM, 2024. DOI: 10.1109/icpadm61663.2024.10750757

[20] Y. Chrismondari, R. Fauzi, and D. Saputra, "Implementasi dan Pengujian Tahanan Isolasi pada Transformator Distribusi 200 kVA,"Jurnal Indragiri Penelitian Multidisiplin , vol. 5, no. 3, 2025. DOI: 10.58707/jipm.v5i3.1299

[21] IEEE Standards Association, "IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus Part 1," IEEE Std C57.152-2013, 2013.

[22] A. Smith and M. Johnson, "Principles of insulation resistance testing," Electrical Systems Review, vol. 28, no. 2, pp. 104–112, 2020.

[23] W. Hauschild and E. Lemke, "High-Voltage Testing on Site," in High-Voltage Test and Measuring Techniques, Springer, 2014.

[24] T. Williams, "Principles of insulation resistance in electrical systems," International Journal of Electrical Engineering, vol. 44, no. 1, pp. 57–68, 2019.

[25] L. Jin, D. Kim, and A. Abu-Siada, "Oil-Immersed Power Transformer Condition Monitoring Methodologies: A Review," Energies, vol. 15, no. 9, p. 3379, 2022.

[26] R. Janura, M. Toman, and P. Trnka, "Analysis of distribution transformer insulation using domain method," in Proc. IEEE ELEKTRO, 2014, pp. 632–636.

[27] J. Harris, "Improving insulation resistance in high-voltage systems," Journal of Electrical Power Systems, vol. 59, no. 3, pp. 109–120, 2021.

[28] S. Thungsuk, K. Sripakagorn, and C. Rattanapan, "The Characterization Analysis of the Oil-Immersed Transformers," Applied

Sciences, vol. 12, no. 8, p. 3970, 2022. DOI: 10.3390/app12083970

[29] X. Liang, "Electrical Test and Relay Protection Analysis of Power Transformer," International Journal of Electrical Power and Energy Systems, vol. 2, no. 1, 2024. DOI: 10.62051/ijepes.v2n1.07

[30] M. Mustafa, A. Priyadi, and M. Pujiantara, "The through fault current effect of 150/20 kV transformer to its insulation resistance and Tan Delta test," in Proc. IEEE ICHVEPS , 2017, pp. 390–394. DOI: 10.1109/ICHVEPS.2017.8225941