



## Performance Evaluation of Insulation and earthing Systems in Distribution Substations for Improved Overvoltage Protection: A Case Study of Distribution Substations on 11kv Ilesa Road Feeder

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### ABSTRACT

Effective insulation and earthing systems are essential for ensuring the safety, reliability, and overvoltage protection of electrical distribution substations. Inadequate performance of these systems often results in equipment damage, power outages, and safety hazards. This project evaluates the performance of insulation and earthing systems in selected distribution substations within the Ilesa Road 11kV feeder with the objective of improving overvoltage protection and operational reliability. Field investigations and measurements were conducted to determine insulation resistance values, earth resistance levels, and the condition of earthing conductors and surge protection devices. The measured parameters were assessed against established IEEE and IEC standards to determine compliance and system adequacy. The results indicate that while some substations operate within acceptable limits, others exhibit elevated earth resistance and reduced insulation integrity, increasing their susceptibility to lightning-induced and switching overvoltages. Based on the findings, the study proposes practical improvement measures, including enhancement of earthing electrode configurations, regular insulation testing, and proper coordination of surge arresters. The outcomes of this project provide useful technical guidance for distribution network operators and contribute to improved substation safety, reduced overvoltage risks, and enhanced system performance in similar distribution environments.

**Keywords:** Distribution Substation, Earthing System, Insulation Performance, Overvoltage Protection, Surge Arrester, Grounding Resistance, Power System Safety.

### 1. INTRODUCTION

Electrical distribution substations play a vital role in the reliable delivery of electric power to end users by stepping down transmission voltages and distributing power to consumers. The operational safety and reliability of these substations largely depend on the effectiveness of their insulation and earthing systems. Insulation systems are designed to withstand electrical stresses under normal and abnormal operating conditions, while earthing systems provide a low-resistance path for fault and surge currents, thereby protecting personnel, equipment, and the environment [2].

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Distribution substations form the backbone of medium-voltage electricity networks, ensuring reliable delivery of power to end-users. Effective overvoltage protection in these substations depends on both the quality of insulation and the integrity of earthing systems [4]. Insulation protects transformer windings from dielectric breakdown, while earthing ensures safe dissipation of fault currents and lightning surges [3].

Overvoltages remain a major challenge in distribution substations and are primarily caused by lightning strikes, switching operations, and system faults. These transient overvoltages, if not adequately controlled, can exceed the insulation strength of equipment, leading to insulation failure, frequent outages, and reduced system lifespan. In addition, poor earthing systems can result in high step and touch potentials, posing serious safety risks to substation personnel and the public [6]. In many developing power systems, including those in Nigeria, the performance of insulation and earthing systems is further compromised by factors such as ageing infrastructure, poor soil resistivity conditions, inadequate maintenance practices, and non-compliance with established standards. Tropical regions with high lightning density are particularly vulnerable, making effective grounding and insulation coordination essential for mitigating lightning-induced overvoltages [1].

Despite these advances, many distribution systems, especially in developing contexts, are still under-analysed in terms of how their protection schemes perform under realistic overvoltage events.

Issues such as inadequate arrester placement, non-ideal earthing, or variations in line and load configurations can degrade protection effectiveness. There is thus a need to conduct detailed studies on typical distribution networks, implementing overvoltage protection schemes, and analysing them to ensure that they meet performance and safety requirements.

However, factors such as moisture ingress, ageing of insulation materials, and high soil resistivity can compromise system performance [5]. To address these challenges, periodic insulation resistance (IR) testing and earthing resistance measurements are critical diagnostic tools. This paper presents an evaluation of insulation and earthing test results from ten substations, compares performance across sites, and recommends corrective measures.

Despite the critical importance of insulation and earthing systems, limited empirical studies have been conducted on their performance in medium-voltage distribution substations in semi-urban Nigerian communities. This study addresses this gap by evaluating the insulation and earthing systems of the selected ten distribution substations on the Ilesa Road 11kV feeder, Akure, Ondo State. Ilesa Road 11kV feeder is one of the feeders that emanate from 60MVA 33/11kV Akure Injection Substation in Ondo State, Nigeria.

## 2. METHODOLOGY

This study employed two diagnostic tests to assess the electrical safety and reliability of distribution substations: the Insulation Resistance (IR) Test and the Earthing Resistance Test. Both procedures were conducted in accordance with IEEE and IEC standards, ensuring accuracy and compliance with best practices.

**Table 1: Insulation Resistance and Earthing Test Results**

S/N	Name of Substations	HV-E (GΩ)	LV-E (GΩ)	HV-LV (GΩ)	Earthing (GΩ)
1	Okuta Erinla 300kVA Substation	10.7	6.5	8.9	1.8
2	Akinrinje 500kVA Substation	4.1	6.2	8.1	4.3
3	Old Lafe 500kVA Substation	8.5	12.1	14.0	6.9
4	New Lafe 500kVA Substation	22.0	17.2	20.8	2.2
5	Abani 1 300kVA Substation	2.6	11.9	7.8	3.1
6	Abani 2 500kVA Substation	10.1	9.9	12.6	1.7
7	Leo 300kVA Substation	4.6	6.7	10.2	9.5
8	Agape 500kVA Substation	28	16	21	4.6
9	Aule 1 500kVA Substation	9.4	8.5	7.9	5.8
10	Aule 2 500kVA Substation	11.4	10.7	9.6	2.7

### 3.1 Insulation Resistance Performance

The HV-E insulation resistance values ranged from 2.6GΩ to 28GΩ, with all substations exceeding the minimum recommended threshold of 1 GΩ for distribution transformers. Substations such as Agape (28GΩ) and New Lafe (22GΩ) recorded exceptionally high values, indicating excellent insulation integrity and minimal moisture ingress or contamination. However, relatively lower values were observed at Abani 1 (2.6 GΩ), Akinrinje (4.1GΩ), and Leo (4.6GΩ) substations, suggesting early-stage insulation ageing or environmental influence, although still within acceptable operational limits.

Similarly, LV-E insulation resistance values ranged from 6.2GΩ to 17.2GΩ, reflecting generally strong low-voltage insulation conditions across all substations. The highest values were obtained at New Lafe (17.2GΩ) and Agape (16GΩ) substations, which demonstrate robust dielectric performance and reduced risk of earth leakage currents.

For HV-LV insulation, values ranged between 7.8GΩ and 21GΩ, confirming effective electrical isolation between transformer

### 2.1 Insulation Resistance Test

Insulation resistance tests were conducted using a 5kV megohmmeter. Measurements were taken across three points: high-voltage to earth (HV-E), low-voltage to earth (LV-E), and high-voltage to low-voltage (HV-LV). IR values were interpreted according to IEEE STD 43-2013, with  $\geq 10$  GΩ considered excellent, 5–10 GΩ moderate, and  $< 5$  GΩ weak.

### 2.2 Earthing Resistance Test

Earthing resistance was measured using the fall-of-potential method with an earth tester. Values  $\leq 3.5$  GΩ were considered good, 3.5–6GΩ moderate, and  $> 6$ GΩ poor, based on IEEE Std 80-2013 guidelines.

### 2.3 Data Analysis

Test results were tabulated and analysed comparatively to assess insulation strength, earthing performance, and their combined effect on substation reliability.

## 3. RESULTS AND ANALYSIS

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

windings. Substations such as Agape (21GΩ), New Lafe (20.8GΩ), and Old Lafe (14 GΩ) exhibited superior inter-winding insulation performance. The absence of critically low HV-LV readings suggests that none of the transformers exhibited internal insulation breakdown or partial discharge-related deterioration at the time of testing.

Overall, the insulation resistance results indicate that the majority of the substations operate under healthy insulation conditions, thereby minimising risks of short circuits, dielectric failures, and insulation-induced outages

### 3.2 Earthing System Performance

The earthing resistance values varied from 1.7Ω to 9.5Ω, with most substations achieving values below the commonly recommended limit of 5Ω for effective grounding in distribution substations. Substations such as Abani 2 (1.7Ω), Okuta Erinla (1.8Ω), and New Lafe (2.2Ω) demonstrated excellent earthing performance, which enhances fault current dissipation and reduces step and touch potential hazards during ground faults and lightning surges.

However, Leo Substation, with an earth resistance of  $9.5\Omega$ , recorded a marginally acceptable value, indicating comparatively poor soil conductivity or insufficient earth electrode configuration. Similarly, Old Lafe ( $6.9\Omega$ ) and Aule 1 ( $5.8\Omega$ ) substations exhibited moderate earthing performance that may limit effective fault clearance during high earth fault currents. These conditions could compromise equipment protection and personnel safety, particularly under transient overvoltage conditions.

### 3.3 Cross-Comparisons

A comparison of the insulation and earthing test results highlights important operational trends, as shown in figure 1. The comparative analysis of insulation and earthing resistances across the ten substations reveals notable variations in performance. Substations such as Agape and New Lafe exhibit consistently high HV-E, LV-E, and HV-LV insulation resistances alongside low earthing resistances, indicating robust dielectric integrity and effective fault current dissipation. In contrast, Leo and Abani 1 substations demonstrate comparatively lower HV-E insulation and elevated earthing resistance, suggesting potential vulnerabilities despite acceptable overall insulation levels. The results highlight that high insulation resistance alone does not guarantee system reliability; substations require both strong insulation and effective earthing to mitigate overvoltage risks and ensure personnel safety. This cross-comparison underscores the need for targeted earthing improvements in substations where grounding performance lags behind insulation quality, thereby enhancing overall operational safety and resilience.

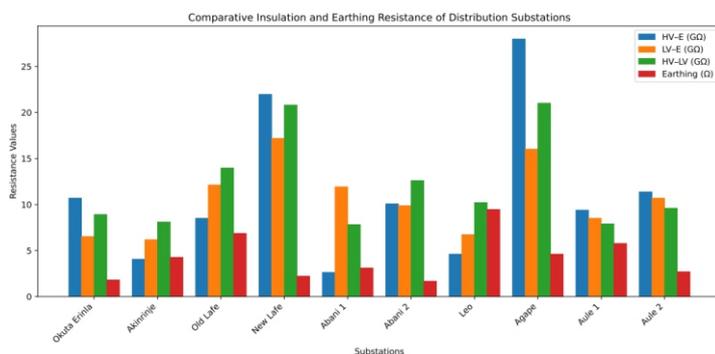


Figure 1. Comparative Bar Chart of Each Insulation Resistance Tests and Earthing Tests Across Substations

## 4.0 CONCLUSION & RECOMMENDATION

### 4.1 Conclusion

This study assessed the insulation resistance and earthing system performance of selected distribution substations to evaluate their effectiveness in enhancing overvoltage protection and overall system reliability. Insulation resistance tests conducted on the high-voltage to earth (HV-E), low-voltage to earth (LV-E), and high-voltage to low-voltage (HV-LV) paths revealed that all substations satisfied the minimum acceptable insulation resistance limits for distribution transformers. The generally high insulation resistance values indicate healthy dielectric conditions of transformer windings, minimal leakage currents, and low probability of insulation-related faults under normal operating conditions.

Substations such as Agape, New Lafe, and Old Lafe exhibited exceptionally high insulation resistance values, reflecting superior insulation integrity and effective maintenance practices.

Although relatively lower insulation resistance values were recorded at Abani 1, Akinrinje, and Leo substations, these values remain within acceptable operational limits and do not indicate imminent insulation failure. However, they suggest the need for closer monitoring to prevent long-term degradation.

The earthing resistance results showed notable variation among the substations. While several substations achieved earth resistance values below  $5\Omega$ , indicating effective fault current dissipation and enhanced personnel safety, others recorded moderately high values. In particular, the Leo substation exhibited a marginally acceptable earth resistance value, which may result in increased ground potential rise during fault or lightning conditions. Such conditions can reduce the effectiveness of surge protection devices and compromise overvoltage mitigation.

Overall, the findings demonstrate that insulation systems across the studied substations are generally in good condition, whereas earthing systems present the primary area requiring improvement to ensure coordinated protection, operational safety, and system resilience against transient overvoltages.

### 4.2 RECOMMENDATION

It is recommended that substations with relatively high earthing resistance values undergo grounding system enhancement through the installation of additional earth electrodes, expansion of earth grids, or application of soil resistivity improvement techniques such as bentonite or conductive compounds. Routine insulation resistance testing should be intensified for substations with comparatively lower readings to enable early detection of moisture ingress, contamination, or insulation ageing. Preventive maintenance practices, including regular inspection and cleaning of bushings, terminals, and earthing connections, should be strengthened to sustain insulation performance and grounding continuity. Soil resistivity surveys should be conducted before grounding system upgrades to ensure optimal design and cost-effective implementation. In addition, grounding systems should be properly coordinated with surge arresters and protective devices to enhance their effectiveness during lightning and switching overvoltage conditions.

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