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IMPACT OF ENVIRONMENTAL FACTORS ON INSULATOR PERFORMANCE IN NIGERIA'S ELECTRICAL NETWORK

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Abstract
The reliability of insulators in electrical power networks is crucial for ensuring efficient energy transmission and distribution. However, in Nigeria, environmental factors such as industrial pollution, coastal salt deposition, Harmattan dust, high humidity, and temperature variations significantly degrade insulator performance, leading to power outages and increased maintenance costs. This study analyzes the impact of these environmental stressors on the dielectric strength and longevity of insulators in Nigeria's electrical network. Pollution from industrial emissions and vehicular activities contributes to insulator contamination, increasing leakage currents and flashover risks. In coastal regions, salt deposition accelerates dielectric breakdown, while Harmattan dust accumulation in northern and central Nigeria exacerbates dry-band arcing. Additionally, high humidity levels and temperature fluctuations cause material degradation, reducing insulator efficiency over time. Through a review of existing studies and field investigations, this paper highlights key challenges associated with environmental degradation of insulators and explores mitigation strategies such as the use of polymer insulators, hydrophobic coatings, and predictive maintenance techniques. The findings suggest that proactive monitoring and adaptive insulation technologies are essential for improving the reliability of Nigeria's power grid. This research provides recommendations for power utilities, policymakers, and engineers to enhance insulator performance and minimize power disruptions caused by environmental stressors. Future studies should focus on advanced self-cleaning insulators and AI-based monitoring systems to optimize maintenance strategies in Nigeria's unique climatic conditions.
Keywords: Insulator performance, environmental factors, mitigation strategies and predictive maintenance.

Introduction

Insulators play a critical role in the reliability and stability of power transmission and distribution networks by preventing leakage currents, supporting conductors, and ensuring efficient energy delivery. However, their performance is significantly affected by environmental factors such as pollution, humidity, salt deposition, and temperature variations. In Nigeria, where industrial activities, coastal conditions, and seasonal weather variations such as the Harmattan contribute to environmental stressors, insulator degradation has become a major challenge for power system operators (Adebayo et al., 2019). Environmental pollution, particularly in industrialized and urban regions, contributes to insulator contamination, leading to surface conductivity, leakage currents, and eventual flashovers (Okonkwo et al., 2021). Similarly, coastal regions in Nigeria, such as Lagos and Port Harcourt, experience high levels of salt deposition, which accelerates dielectric breakdown, reducing the lifespan of insulators (Balogun et al., 2022). Moreover, Harmattan dust accumulation in northern and central regions increases the risk of dry-band arcing, further degrading insulator efficiency (Adesina and Okeke, 2021), temperature fluctuations and humidity also play a significant role in the aging of insulators.

High humidity levels promote moisture absorption, which reduces dielectric strength, while extreme temperature variations cause expansion and contraction, leading to micro cracks in ceramic insulators (Eze et al., 2019). In response to these challenges, various mitigation strategies such as hydrophobic coatings, composite insulators, and predictive maintenance technologies have been proposed to improve insulator resilience in environmentally stressed regions (Oladipo and Bello, 2023). This study aims to analyze the impact of these environmental factors on insulator performance in Nigeria's electrical network and explore possible solutions to enhance reliability. This research seeks to provide recommendations for improving insulation performance and minimizing power system failures caused by environmental degradation.

Literature Review

Pollution is a major contributor to the deterioration of insulators, leading to surface contamination, leakage currents, and flashovers. According to Adebayo et al. (2019), industrial pollution significantly affects insulator performance in power transmission networks, particularly in urban areas with high levels of carbon deposits from vehicular emissions and factory operations. The accumulation of pollutants such as cement dust, hydrocarbons, and chemical residues forms a conductive layer on insulators, which can lead to increased dielectric losses and insulation failure (Ojo and Eze, 2020).

Studies conducted by Okonkwo et al. (2021) indicate that insulators in industrial areas of Lagos and Port Harcourt exhibit higher rates of flashovers compared to rural locations. The research highlighted that insulator pollution severity increases during the rainy season when contaminants mix with moisture, forming a conductive electrolyte that accelerates breakdown.

Nigeria's coastal regions, particularly in states such as Lagos, Delta, and Rivers, experience high levels of salt deposition due to proximity to the Atlantic Ocean. Balogun et al. (2022) analyzed the impact of coastal pollution on polymer and ceramic insulators, reporting a significant reduction in dielectric strength due to the hygroscopic nature of salt, which increases surface conductivity.

A comparative study by Nnaji and Umeh (2018) found that polymer insulators demonstrated better performance in coastal environments compared to traditional ceramic insulators due to their hydrophobic properties. However, they also emphasized that prolonged exposure leads to surface degradation and loss of hydrophobicity, necessitating periodic maintenance and coating applications The Harmattan season, characterized by dry and dusty conditions, is a significant environmental factor affecting Nigeria's power infrastructure. Research by Adesina and Okeke (2021) found that Harmattan dust increases the rate of dry-band arcing on insulator surfaces, particularly in the northern and central regions of Nigeria. Dust accumulation reduces insulator performance, and without sufficient rainfall to wash off contaminants, prolonged exposure leads to permanent surface degradation. According to Usman et al. (2020), the impact of Harmattan dust is exacerbated when combined with industrial pollutants, forming a thick contamination layer that increases leakage currents and dielectric breakdown. The study recommended frequent cleaning cycles and the application of anti-dust coatings to mitigate these effects. High temperatures and humidity levels in tropical regions like Nigeria accelerate insulator aging and surface deterioration. Eze et al. (2019) reported that extreme temperature fluctuations lead to material expansion and contraction, causing microcracks in ceramic insulators, which reduce mechanical strength and increase vulnerability to pollution ingress.

The combination of high humidity and frequent rainfall exacerbates pollution-induced flashovers. Research by Nnaji et al. (2020) revealed that moisture absorption by insulator surfaces reduces their insulation resistance, making them more prone to leakage currents. Additionally, water droplets act as conductive bridges, enhancing the risk of electrical discharge across insulator surfaces, particularly in humid regions like the Niger Delta (Umeh and Chukwuma, 2021).

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Several mitigation techniques have been proposed to enhance insulator performance in polluted and environmentally challenging regions. Oladipo and Bello (2023) emphasized the importance of routine cleaning schedules and the application of silicone-based hydrophobic coatings to improve contamination resistance. They also highlighted the use of predictive maintenance strategies, such as real-time leakage current monitoring, to identify and address insulation failures before they escalate. Additionally, Adekunle et al. (2022) suggested the adoption of polymer insulators in heavily polluted and coastal environments due to their superior performance in high-contamination areas. The study further recommended integrating artificial intelligence (AI)-based monitoring systems to optimize maintenance schedules and reduce operational costs.

Environmental Factors Affecting Insulator Performance

- **Industrial Pollution and Contaminants**: Industrial pollution is a major environmental factor that significantly affects the performance of high-voltage insulators in Nigeria. Rapid industrialization, particularly in cities such as Lagos, Port Harcourt, Onitsha, and Kano, has led to increased emissions of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon soot, and metallic particles. These pollutants settle on the surface of electrical insulators, creating conductive layers that compromise their insulating properties, leading to leakage currents, flashover, and eventual power failures. The primary effects include:
- **Surface Contamination and Increased Conductivity:** Industrial emissions deposit pollutants on the surfaces of outdoor insulators, forming a conductive layer when combined with moisture as shown in figure 1 below. This significantly increases surface conductivity and leakage currents, reducing the insulating effectiveness of the material (Adoghe et al., 2019). A study conducted in industrial areas of Lagos and Port Harcourt found that insulators in these locations exhibit a 50% higher surface contamination level compared to less industrialized regions (Otaraku and Uwaifo, 2021).



(a) (b)

Figure 1 Contaminated by volcanic ash: (a) Glass insulator
(b)Porcelain Insulators
(https://volcanoes.usgs.gov/volcanic_ash/insulator_flashover.html)

- **Corrosion and Degradation of Insulator Materials:** Acidic pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), react with moisture in the atmosphere to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3), leading to acid rain. These acids accelerate the degradation of insulator materials, particularly porcelain and glass insulators, causing micro-cracks and reducing their mechanical and electrical strength (Nwohu, 2020).

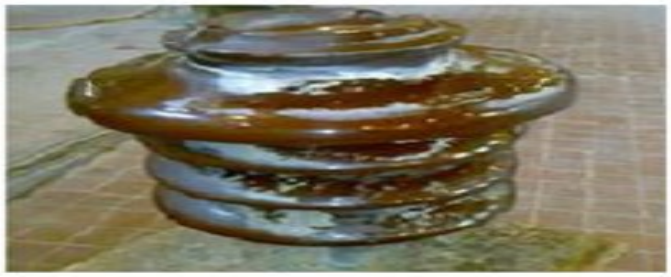


Figure 2: Pollution Degraded Insulator (Priye and Bodie 2024)



Figure 3: Corrosion in Disc Insulator (INMR, 2025)



Figure 4: Discharge on 220 kV coated glass insulator due to high sea salt Contamination (INMR, 2025)

- **Reduction in Flashover Voltage and Increased Power Outages:** The presence of industrial contaminants significantly reduces the flashover voltage of insulators, increasing the risk of electrical breakdown. Research has shown that insulators in heavily polluted industrial zones experience up to a 40% decrease in flashover voltage compared to those in clean environments (Akinyemi et al., 2021). This leads to frequent power outages, particularly in areas close to factories, refineries, and cement plants.



Figure 5: Insulator flashover across a string of 3 glass insulators (https://volcanoes.usgs.gov/volcanic_ash/insulator_flashover.html)

- **Formation of Dry Bands and Arcing:** Industrial contaminants cause non-uniform wetting on the insulator surface, leading to dry band formation. When exposed to high voltage, these dry bands

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generate localized arcing, which gradually erodes the insulator surface and increases the likelihood of flashover (Ogujor and Otasowie, 2018).



Figure 6: Dry Bands and Arcing (Luthando and Riaz, 2005))

- **Increased Energy Losses and Maintenance Costs:** Contaminated insulators increase leakage currents, resulting in significant energy losses. Power utilities in Nigeria, such as the Transmission Company of Nigeria (TCN), have reported higher maintenance costs due to the frequent need to clean or replace insulators exposed to heavy industrial pollution (Adewumi et al., 2022).

Humidity and Rainfall: are significant environmental factors that impact the performance of high-voltage insulators in Nigeria, particularly during the wet season (April to October). These conditions negatively affect insulators by:

- **Increased Surface Conductivity**: High humidity leads to moisture absorption on insulator surfaces, creating a conductive layer that reduces insulation resistance and increases leakage currents (Adoghe et al., 2019).
- **Wet Deposition of Contaminants**: Rainfall washes pollutants onto insulators, forming conductive paths that increase flashover risks, particularly in industrial and urban areas (Ogujor and Otasowie, 2018).
- **Erosion and Aging of Insulator Materials**: Continuous exposure to rain accelerates the wear and degradation of polymeric insulators, reducing their lifespan and performance (Akinyemi et al., 2021).

Harmattan Wind and Dust Storms: is a dry and dusty trade wind that originates from the Sahara Desert and affects West Africa, including Nigeria, typically between November and March. During this period, strong winds carry fine dust and sand particles, which settle on power insulators, significantly degrading their performance. Harmattan-induced dust storms contribute to increased contamination, surface conductivity, insulation breakdown, and power outages in Nigeria's electrical power network. Dust accumulation on insulators results in:

- **Deposition of Dust and Increased Surface Contamination:** Harmattan winds transport large amounts of dust particles that accumulate on the surfaces of insulators, forming a contamination layer. Studies conducted in Northern Nigeria, particularly in states like Kano, Sokoto, and Maiduguri, have shown that dust accumulation on insulators increases during the Harmattan season, leading to higher contamination levels (Ojo et al., 2020)
- **Increased Leakage Current and Partial Discharge:** Dust particles contain salts and other conductive materials that reduce the surface resistivity of insulators. When combined with morning dew or light rain, the dust layer becomes conductive, leading to increased leakage current and partial discharge, which can result in flashover and insulation failure (Adoghe et al., 2019).

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- **Reduction in Flashover Voltage:** Research has shown that the flashover voltage of contaminated insulators can decrease by up to 40% during the Harmattan season due to dust deposition (Akinyemi et al., 2021). This reduction increases the risk of electrical breakdown in transmission and distribution networks, leading to frequent power outages, especially in arid and semi-arid regions of Nigeria.
- **Insulator Surface Erosion and Mechanical Damage:** Strong winds carrying dust and sand particles cause abrasion and surface erosion, particularly on polymer and glass insulators. Over time, this erosion degrades the hydrophobic properties of the insulator, making it more susceptible to contamination and reducing its lifespan (Nwohu, 2020).
- **Increased Frequency of Power Outages:** Power utilities in Nigeria, such as the Transmission Company of Nigeria (TCN) and various Distribution Companies (DisCos), have reported a higher frequency of insulator-related faults during the Harmattan period. This is due to a combination of dust accumulation, increased surface conductivity, and flashover incidents (Oladimeji and Adebayo, 2022).

Biological Growth (Mold, Algae and Bird Dropping): In Nigeria, biological growth is a significant environmental challenge affecting the reliability of outdoor insulators in power transmission and distribution systems. The warm and humid climate, especially in the southern and coastal regions, creates a favorable environment for the growth of fungi, algae, lichen, moss, and bacteria on insulator surfaces as shown in figure 7.



Figure 7: The algae contamination layer distribution on insulator (Yawei et.al. 2022)

These biological contaminants degrade the insulation properties, increase leakage currents, and reduce flashover voltage, leading to power outages and equipment failure (Priye and Bodie 2024), the primary effects include:

- **Surface Contamination and Increased Conductivity:** The high humidity levels in Nigeria, particularly in regions such as Lagos, Port Harcourt, and Calabar, encourage the rapid growth of fungi and algae on insulators. These organisms form a biofilm on the surface, which, when mixed with moisture from rainfall or coastal fog, increases surface conductivity and leakage currents (Adoghe et al., 2020). Studies have shown that insulators in Nigeria's coastal areas exhibit higher contamination rates due to a combination of biological growth and saline deposits from the Atlantic Ocean (Nwohu, 2019).
- **Reduction in Flashover Voltage and Electrical Failures:** Biological contamination significantly reduces the flashover voltage of insulators. Research conducted on power networks in Nigeria indicates that insulators covered with algae and fungi experience up to a 35% reduction in flashover voltage (Ogujor and Otasowie, 2018). This condition increases the risk of partial discharge and eventual insulator failure, particularly during the rainy season when moisture levels are high.

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- **Degradation of Insulator Surface and Mechanical Weakening:** Algae and fungi secrete acidic metabolic byproducts that degrade the surface of polymer and porcelain insulators. This degradation reduces their hydrophobic properties, making them more prone to moisture absorption and further contamination (Otaraku and Uwaifo, 2021). In some cases, lichen growth has been observed to cause micro-cracks on ceramic insulators, weakening their mechanical strength and increasing the risk of structural failure.
- **Attraction of Birds and Additional Contamination:** Birds are attracted to areas where biological growth is prevalent, leading to additional contamination from bird droppings. This is particularly common in Nigeria's power substations located near forests and wetlands. Bird droppings contain salts and organic materials that create conductive paths on insulators, further increasing the risk of flashover and electrical faults (Adewumi et al., 2022).

Temperature Variations: significantly impact the performance of high-voltage insulators in Nigeria, especially due to the country's tropical climate, characterized by extreme heat in the dry season and cooler temperatures during the rainy season. These fluctuations affect the mechanical, electrical, and thermal properties of insulators, leading to performance degradation over time. The primary effects include:

- **Thermal Expansion and Contraction:** Insulators experience repeated expansion and contraction due to daily and seasonal temperature changes. This thermal cycling can cause micro-cracks, reducing mechanical strength and increasing the likelihood of failure (Ogujor and Otasowie, 2018). Prolonged exposure to high temperatures, especially in the northern regions of Nigeria, accelerates material fatigue, particularly in porcelain and composite insulators (Akinyemi et al., 2021).
- **Reduction in Dielectric Strength:** High temperatures cause a reduction in the dielectric strength of insulating materials, making them more prone to electrical breakdown. Studies have shown that for every 10°C increase in temperature, the dielectric strength of some insulating materials decreases by 5–10% (Adoghe et al., 2019). This effect is particularly severe in power stations located in the hot regions of Sokoto, Maiduguri, and Kano.

- **Increased Surface Leakage Currents:** Elevated temperatures, combined with pollution and humidity, lead to the formation of conductive layers on insulators. This increases surface leakage currents, contributing to power losses and eventual flashover events (Nwohu, 2020). Areas with high industrial activities, such as Port Harcourt and Lagos, experience a more significant impact due to additional pollution.
- **Accelerated Aging and Degradation:** Polymeric insulators, commonly used in power networks, are highly susceptible to ultraviolet (UV) radiation from the sun. Prolonged exposure leads to oxidation, surface roughening, and loss of hydrophobicity, reducing their long-term effectiveness (Otaraku and Uwaifo, 2021).

Mitigation Strategies

To ensure the long-term performance of insulators in polluted industrial environments, several maintenance and preventive measures can be adopted:

- **Regular Cleaning and Maintenance:** High-pressure water washing is used to remove industrial pollutants from insulators in high-risk areas (e.g., northern Nigeria) (IEEE, 2017).



Figure 8: High-pressure water washing (INMR, 2025)

- **Dry Cleaning Techniques:** Compressed air or brushes can be used in regions where water is scarce (Akinyemi et al., 2021).
- **Chemical Cleaning:** Special solvents are applied to dissolve stubborn contaminants, such as acidic deposits from cement and petroleum industries (Adoghe et al., 2019).
- **Application of Hydrophobic Coatings:** Silicone rubber coatings prevent moisture absorption, reducing leakage currents (Zhang et al., 2020).



Figure 9: Room temperature vulcanized (RTV) silicone rubber coating (INMR, 2025)

- **Use of Temperature-Resistant Materials:** Insulators with high thermal stability, such as silicon rubber and specially treated glass, are better suited for Nigeria's extreme weather conditions.
- **Use of Anti-Pollution Insulators:** Specially designed insulators with extended creepage distances help mitigate flashover risks in industrial zones (CIGRÉ Report No. 691, 2018).
- **Vegetation and Windbreaks:** Planting trees around substations to reduce dust carried by Harmattan winds.
- **Automated Monitoring Systems:** Implementing real-time insulator monitoring to detect contamination buildup and schedule timely maintenance (Oladimeji and Adebayo, 2022).
- **Proper Insulation Design:** The use of composite insulators with UV-resistant coatings helps mitigate the effects of prolonged sun exposure.
- **Installation of Bird Deterrents:** Prevents birds from nesting on transmission towers, reducing additional contamination (Nwohu, 2019).
- **Stricter Industrial Regulations:** Implementing stricter emission control policies in Nigeria's industrial regions can help reduce the deposition of harmful pollutants on power infrastructure (Nwohu, 2020).

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Conclusion and Recommendations Environmental factors significantly influence insulator performance in Nigeria's electrical network, affecting reliability, maintenance costs, and system efficiency. Pollution, humidity, temperature variations, biological growth, and dust storms contribute to insulation degradation and flashover occurrences. To mitigate these challenges, power utilities should adopt advanced materials, apply protective coatings, implement rigorous maintenance programs, and deploy real-time monitoring technologies. Future research should focus on developing smart insulators with self-cleaning capabilities and enhanced resistance to environmental stressors. Strengthening insulation management practices will play a vital role in ensuring a more reliable and resilient electrical network in Nigeria.

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