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Environmental Pollution and Influence on Insulator Flashover: A Review

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ABSTRACT

This review delves into various pollutants and their impact on outdoor insulators, exploring strategies to prevent pollution-related flashovers. It delves into protective coatings, suitable insulator choices, and predictive maintenance to mitigate pollution-induced flashovers. These measures are crucial due to the detrimental effects of pollution flashovers on insulators and system reliability. The review also addresses biological pollutants, industrial emissions, and coastal salt pollution's effects on insulation performance, stressing the need for mitigation. Given pollution's direct influence on outdoor insulator performance, the review advocates for tools to gauge pollution levels and regular cleaning programs for contaminated insulators as essential steps.

***Keywords**: Environmental Pollution; Insulator Flashover; Pollution Flashovers; Outdoor Insulator*

Introduction

Environmental pollution has become a pervasive issue globally, with profound implications for various sectors, including power infrastructure. In the context of electrical systems, pollution can significantly affect the performance and reliability of insulators, leading to flashovers and disruptions in power supply (Salem *et al.*, 2022; Gençoğlu & Cebeci, 2008; Abbasi, et al., 2014). Various pollutants, including airborne particles, moisture, sulfur compounds, and industrial emissions, can deposit on insulator surfaces, creating conductive paths that facilitate flashovers. Insulator flashover incidents not only result in downtime and economic losses but also pose safety hazards and environmental risks. Flashovers occur when the insulation properties of an insulator are compromised, leading to the breakdown of electrical resistance and potential interruptions in power supply. With the expansion of industries, growth in urban areas, and the proliferation of transportation networks, there has been a dramatic increase in emissions of pollutants like particulate matter, sulfur compounds, and corrosive gases (Gupta, 2020).

These pollutants settle on insulator surfaces, altering their electrical properties and compromising their ability to withstand voltage stresses. This issue was notably observed in Egypt in 2010 (Abouelsaad *et al.,* 2013), where electricity supply interruptions were attributed to polluted insulators. Insulators play a critical role in power transmission and distribution networks by isolating components with varying electrical potentials. Their purpose is to maintain a specific distance between electrical parts, utilizing air as the insulating medium. This separation is crucial for preventing electrical arcing and ensuring the safe and efficient flow of electricity through the system. The process of environmental pollution affecting insulators continues at the point where conductors or bus-bars are attached and insulated from earthed supporting structures, such as pole structures. Initially, pollution contaminants settle gradually on the insulator surface, which is relatively benign when the insulator remains dry. However, when exposed to humidity, fog, or light rain, these contaminants create a conductive layer that facilitates leakage current flow (Montoya *et al.,* 2004; Rezaei et *al.,* 2005; Siderakis, *et al.,* 2011). This phenomenon is exacerbated when pollutants become dampened due to light rain, dew, or fog, leading to an increase in surface conductivity (Vosloo & Holzhausen, 2003; Shrimathi & Mondal, 2021).

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Studies (Castillo Sierra *et al*., 2015; Velásquez, 2019; Salem, *et al.,* 2022), have shown that the likelihood of faults occurring on insulators is influenced by several factors, including environmental conditions, the material composition of the insulator, working voltage, and the degree of pollution on the insulator surface. Environmental pollution influence on insulator flashover is crucial for mitigating risks, enhancing grid resilience, and ensuring the efficient operation of power systems. By delving into this topic, we aim to contribute to the knowledge base that informs strategies for pollution control, and effective maintenance practices in polluted environments. Through a comprehensive review of existing literature, case studies, and technological advancements, this study seeks to shed light on the complex dynamics of environmental pollution and its implications for insulator flashover, offering insights that can inform policy, engineering practices, and future research endeavours.

Environmental Pollution

There are different types of environmental pollution, each with distinct sources and impacts. These include coastal/marine pollution, biological pollution, industrial pollution, etc., but the most common pollution on insulators are coastal/marine pollution, industrial pollution, and biological pollution. Each form of pollution presents unique challenges and environmental risks, contributing to the complex environmental landscape globally.

Industrial Pollution

Industrial pollution refers to the contamination of the environment, including air, water, and soil, by harmful substances released from industrial activities. These pollutants can have significant impacts on human health, ecosystems, and the quality of natural resources. Industrial pollutants are the result of various industrial activities and processes. Industries such as cement production, fertilizer manufacturing, oil refineries, power generating stations, and metallurgical operations release contaminants into the environment. Industrial pollution that releases particles into the environment can have significant impacts on air quality, human health, and ecosystems (Yousuf *et al.,* 2022; Manisalidis, *et al.,* 2020). These particles, known as particulate matter (PM), can vary in size, composition, and origin, and they are classified based on their diameter. Industrial activities involving combustion, such as power generation, manufacturing processes, and transportation, can emit particulate matter into the air. Also, various industrial operations, such as metal smelting, mining, construction, and processing of raw materials, can generate particulate matter through dust, fumes, and aerosols released during production and handling processes. When contaminants settle on the insulator's surface, they degrade it and create a conductive layer that may cause flashover.

Coastal/Marine Pollution

Coastal pollution refers to the contamination of coastal environments, including oceans, seas, estuaries, and shorelines, by various pollutants. These pollutants can originate from both natural sources and human activities, leading to significant environmental, economic, and social impacts Coastal salt pollution caused by wind-driven processes, such as aerosol transport and salt spray deposition, is a significant environmental concern with wide-ranging impacts on coastal ecosystems, infrastructure, and human health. This type of pollution, commonly known as salt spray or salt drift, can have several environmental and societal impacts, and it is due to strong coastal wind, wave action, and sea salt evaporation. High wind speed near coastal areas can lift salt particles from seawater, especially during storms or windy weather conditions while waves breaking along the coastline can release salt aerosols into the air, which can then be transported inland by strong winds. Power system infrastructure suffers immense pollution problems due to the influence of the sea (Siderakis *et al.,* 2011). Also, in areas with high evaporation rates, such as salt flats or saline coastal marshes, salt particles can become airborne when water evaporates, contributing to sea salt pollution. The severity of coastal salt pollution is determined by the Equivalent Salt Deposit Density (ESDD) in mg/cm^2 as shown in Table 1.

Table 1: Pollution severity with regards to ESDD (IEC TS 60815-1, 2008)

ESDD (g/cm^2	*< 0.01*	*0.01 – 0.04*	*0.04 - 0.15*	*0.15 – 0.40*	*> 0.40*
Site severity on pollution	Very Light	Light	Medium	Heavy	Very Heavy
Leakage distance (inch/kV$_{L-G}$)	0.87	1.09	1.37	1.70	2.11

Biological Pollution

Biological pollution, also known as bio-pollution or biological contamination, refers to the introduction of harmful or invasive organisms into ecosystems where they are not naturally found. This type of pollution can have significant ecological, and health impacts on native species, and habitats. Pollution by lichens and algae on objects, often referred to as biological fouling or bio-fouling, which is a common occurrence in environments where these organisms thrive. Lichens and algae, in particular, produce organic acids such as oxalic acid, which can gradually deteriorate the surface of objects (Scheerer *et al.,* 2009). Lichens are composite organisms consisting of a symbiotic relationship between fungi and algae or cyanobacteria (Morillas *et al.,* 2022). They can grow on various surfaces, including rocks, trees, buildings, and monuments. Lichens are known for their ability to tolerate harsh environmental conditions and can colonize objects in polluted urban areas while Algae are simple, photosynthetic organisms that can grow in aquatic environments, on soil, and on moist surfaces. They are often found in water bodies, on rocks, and on man-made structures such as boats, docks, insulators, and buildings. Algae growth is influenced by factors like light, humidity, temperature, nutrients, and water availability on insulator surfaces. Initially, the presence of biological contaminants may not pose an immediate threat. However, as these contaminants accumulate on various surfaces, a greasy layer is formed.

Insulator Flashovers

Insulator flashovers in high-voltage AC systems happen when the voltage on the insulator's surface reaches a level where the air along the surface breaks down and becomes conductive. This can lead to localized discharges near earthed structures, sometimes escalating into continuous arcs. These flashovers are costly, causing power system downtime and equipment damage. They can be triggered by various factors, with pollution contributing significantly in certain environments. Dry bands of pollution on insulators are known to reduce flashover voltage, leading to frequent flashovers. The resulting arcs can clear pollution or cause severe damage, compromising the insulator's mechanical integrity (Chakraborty, 2017). The mechanical robustness of an insulator dictates its resistance to flashover as a higher flashover voltage can be obtained with greater insulator dimensions. To prevent insulation flashover, it's essential to ensure that the insulator does not exceed the critical disruptive discharge voltage relative to the ambient air, based on a known value of the service voltage. The limiting conditions for insulator voltage and flashover have been realized with a simple but significant experimental tool, the steep front voltage impulse and the switching impulse. The results of impulse tests can be compared to known pollution severity levels to determine the likelihood of a given insulator flashover. The mechanism of flashover on contaminated insulator surfaces has been well discussed in (Gençoğlu & Cebeci, 2008).

Influence of Environmental Pollution on Insulator Flashover

Coastal Pollution on Insulator Flashover

Outdoor insulators located in coastal areas are subject to unique environmental challenges, particularly related to exposure to water droplets or saltwater spray carried by strong winds from the sea. The water droplets, deposit on the surface of the insulator, and as the water evaporates, crystalline salt particles remain on the insulator's surface. Over time, these salt particles accumulate, adhering to the insulator surface and forming a conductive layer. The build-up of salt particles creates a conductive path on the insulator, which can lead to insulator flashover incidents. This conductive layer compromises the insulator's ability to withstand high voltage, increasing the risk of electrical breakdown and flashovers. The presence of salt deposits on the insulator surface not only reduces its insulation effectiveness, but also makes it more susceptible to environmental factors such as humidity and moisture, further exacerbating the risk of flashovers. An instance of sea salt pollution is demonstrated by the measured ESDD at a Rivers State University injection substation in Port Harcourt, Nigeria, recorded at 0.025 mg/cm2. This measurement aligns with the standards set by the International Council on Large Electric Systems, categorizing it as light pollution (Okisak*,* 2019). This level of pollution, if left unchecked, can lead to the accumulation of contaminants on insulators, potentially causing insulator flashovers. While the investigation focused on Port Harcourt, similar pollution challenges are likely present in other coastal states in Nigeria. Figure 1(a) depicts sea salt solution on the insulator while Figure 1(b) represents the discharge of 220 kV Glass coated Insulator due to sea salt pollution.

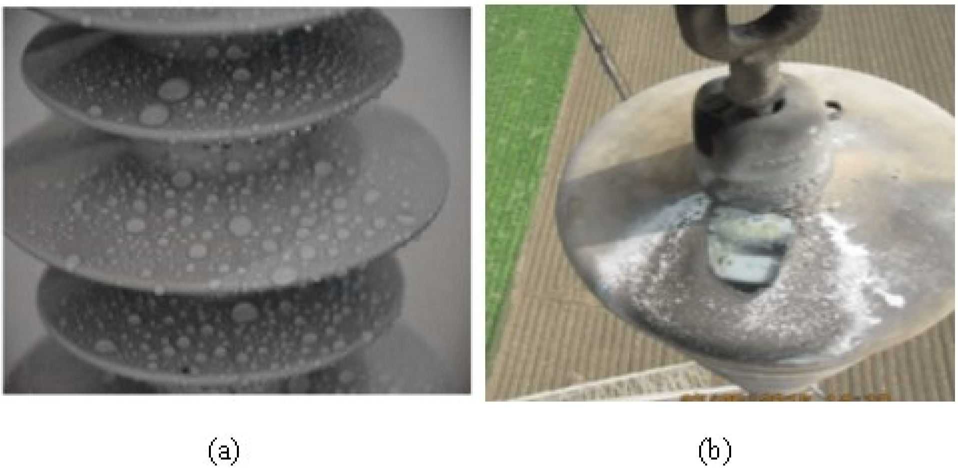

Fig 1: Polluted Insulator: (a) Insulator polluted with sea salt solution (Banik *et al.,* 2015)
(b) Discharge of 220 kV Glass coated Insulator due to sea salt pollution (INMR, 2024)

Industrial Pollution on Insulator Flashover

Once in the atmosphere, industrial particles are attracted to wind, gravity, and electric fields, causing them to land on insulator surfaces. The accumulation of industrial particles creates a conductive layer on the insulator surface, which can lead to insulator flashover events. This conductive layer compromises the insulator's dielectric properties, making it more susceptible to electrical breakdown. The deposition process is gradual, with contaminants continuously settling on the insulator surface over time. If not regularly cleaned or maintained, these contaminants can persist on the insulator surface for months or even years, exacerbating the risk of flashovers (Nitesh & Ketan, 2018) and reducing the insulator's performance and lifespan. Figures 2(a) and 2(b) illustrates an example of an insulator degraded by industrial pollution, showcasing the visible effects of prolonged exposure to industrial contaminants on insulator surfaces. Industrial pollution weakens and reduces the hydrophobicity of insulator surfaces. This loss of hydrophobicity makes the insulator more susceptible to water absorption, leading to increased surface conductivity and a higher risk of flashovers and electrical faults.

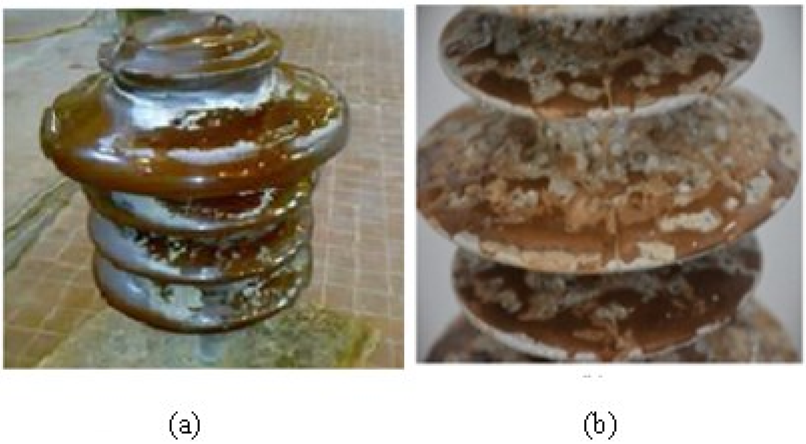

Fig 2: (a) Pollution Degraded Insulator (Hossam-Eldin, *et al.,* 2011)
(b) Insulators given fly ash pollutant (Negara, *et al.,* 2021).

Biological Pollution on Insulator Flashover

Biological contaminants such as bacteria, algae, and lichens contribute to the formation of a conductive layer on the surface of insulators, presenting unique challenges to their performance. Lichens and algae, in particular, produce organic acids such as oxalic acid, which can gradually deteriorate the insulator surface. Initially, the presence of biological contaminants may not pose an immediate threat to the insulator's functionality. However, as these contaminants accumulate and the insulator surface dries, a greasy layer forms, providing a conductive layer environment for the development of a dry band. This dry band, characterized by localized areas of increased conductivity, poses a significant risk of insulator flashovers. Also, the combination of organic acids, moisture, and the formation of a greasy layer creates conditions conducive to electrical breakdown along the insulator surface (Jiang, et al., 2008; Flazi et al., 2007). This build-up can promote the movement of leakage currents, increasing the likelihood of insulator flashovers. The pollution and climatic conditions also contribute significantly to the growth of algae and lichens on outdoor insulators. These organic growths not only compromise the insulators' performance but also serve as potential initiators of pollution-related flashover events. Algae, being hydrophilic and capable of retaining water, significantly influence the hydrophobic characteristics of composite insulating materials (Ouyang *et al.,* 2019). This can accelerate the aging of composite insulation materials due to microbial biodegradation, potentially compromising the integrity of residential and industrial structures. Numerous scholars have looked into how algae affect hydrophobicity (Kumagai, 2007; Li *et al.,* 2022). found that the growth of chlorella vulgaris-induced algae on silicone rubber decreased the material's hydrophobicity and increased leakage current. Moreover, the growth of algae on composite insulators has been shown to affect their hydrophobic properties. Algae has a slow growth rate and requires a long time to cover a wide area. This is especially true of some polymeric insulators. even though there is less of a chance of a biological pollution flashover under natural circumstances (Ramos Hernanz *et al.,* 2006). Figure 3, shows the impact of biological pollution (algae and lichen) on the surface of the insulators.

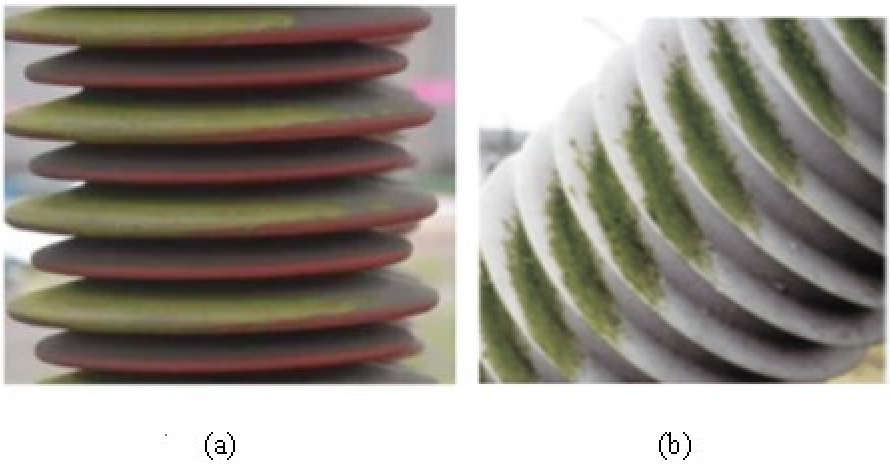

Fig 3: algae growth on ins.ulator (Li, *et al.,* 2022; INMR, 2024)

Mitigation Strategies for Polluted Insulators

Environmental pollution in power systems requires a combination of preventive measures and mitigation strategies. These include the right insulator material used to resist pollution regular cleaning and maintenance of insulators to remove accumulated contaminants, applications of hydrophobic coatings or insulator treatments to enhance pollution resistance, and implementation of environmental monitoring programs to assess pollution levels and predict potential flashover risks.

Choosing the Right Type of Insulator for a Polluted Region

For dielectric materials to function effectively as insulators, they must meet specific criteria: sufficient mechanical strength to endure physical stress, high electric strength to resist punctures, and resilience against adverse environmental factors. Consequently, the choice of insulator material significantly influences the accumulation of pollutants and the occurrence of pollution flashovers.

A. **Porcelain Insulator:** Electro-technical porcelain stands out as a top choice among dielectric materials for insulators, especially in power transmission systems. Its high electric strength enables it to withstand electrical stresses without breakdowns or flashovers. Additionally, porcelain insulators are mechanically robust, enduring wind forces and conductor weight. They resist atmospheric influences like pollution, moisture, and temperature changes, making them reliable outdoors. This stability over time contributes to the long-term reliability of power transmission systems, making porcelain a preferred material for ensuring effective functioning and longevity in electrical infrastructure.

B. **Glass Insulator:** Glass insulators provide a cost-effective option compared to porcelain insulators while maintaining similar electrical and mechanical properties crucial for reliable power transmission. Their characteristics, influenced by alkali content in the glass, affect electrical strength, resistance to arcing, and mechanical resilience against environmental stresses like wind. While porcelain insulators are favoured for their durability, glass insulators offer a balance of affordability and performance, making them a viable choice based on project needs, and the desired cost-performance balance in power transmission projects. The presence of soluble alkalis in glass compositions has a notable effect on insulator performance. Specifically, it increases the hygroscopicity of the insulator surface, meaning it has a greater tendency to absorb moisture from the surrounding environment. This increased moisture content leads to higher surface conductivity, which can affect the insulator's electrical insulation properties (Suflis, et al., 2000; Chrzan & Moro, 2006; Waluyo, et al., 2009).

C. **Polymeric Insulator:** Polymeric insulator materials like silicon rubber and EDPM rubber are hydrophobic, causing water to accumulate on their surfaces instead of spreading out. This hydrophobicity offers two key advantages: it prevents conductive layer buildup, enhancing electrical insulation, and it reduces the insulator's weight compared to ceramics, making handling and installation easier. The choice between silicon rubber and EDPM rubber depends on specific needs; silicon rubber resists UV and ozone, suitable for harsh outdoor environments, while EDPM excels in weathering and heat resistance. Silicone rubbers exhibit exceptional hydrophobic properties. Nevertheless, extended exposure to environmental conditions and electrical discharges can degrade these properties (Boudissa et al., 2005; Gonos, et al., 2002), increasing the likelihood of insulator flashover, especially when surfaces are compromised by pollution.

D. **Ceramic Insulator:** Ceramic insulators are highly valued for their unique properties. They have a hydrophilic nature that allows water to easily flow off their surfaces. Their high dielectric strength enables them to withstand high voltages, preventing electrical arcing and maintaining insulation integrity. These insulators also have low electrical conductivity, reducing current flow and minimizing power losses and electrical accidents. Furthermore, ceramic insulators exhibit high thermal stability, making them suitable for environments with temperature fluctuations, such as outdoor installations. They are resistant to corrosion, extending their lifespan and performance in harsh conditions. Additionally, ceramics are -mechanically strong, providing support to electrical components and withstanding mechanical stresses and environmental factors like wind loads. Ceramic insulators are known for their longevity, reliability, and resistance to tracking, ensuring stable insulation performance even in challenging operating conditions.

E. **Composite Insulator:** Fiberglass reinforced with epoxy resin is layered to create composite insulators, which are frequently covered in silicone rubber for hydrophobicity and weather resistance. This construction results in robust insulators that can handle electrical stress, mechanical loads, and environmental challenges. Their fiberglass core provides excellent electrical insulation even under extreme voltages, crucial for safe power distribution in transmission lines and substations. They also boast exceptional mechanical strength, resisting deformation or fracture from wind, ice, and tension, crucial for overhead lines. These insulators are highly resistant to pollution, UV radiation, salt spray, and corrosion, thanks to the silicone rubber coating, which also prevents surface tracking and ensures long-term performance. Being lightweight, they're easy to handle and install, reducing structural load and costs. Their high pollution resistance and reduced risk of fracture make them ideal for harsh environments like coastal or industrial areas. Overall, composite insulators are versatile and durable, widely used in electrical infrastructure for their reliability in challenging conditions.

Insulator Maintenance Against Environmental Pollution

A. Cleaning of Insulator: When crafting cleaning protocols for insulators, it’s crucial to take into consideration the specific type and extent of pollution they encounter. This tailored approach ensures effective cleaning without causing damage to the insulator surface. Techniques such as dry brushing, water washing, chemical cleaning, and high-pressure water or air cleaning are commonly employed to address different levels and kinds of pollution. Using the appropriate tools and cleaning supplies is paramount in maintaining the integrity of insulators during cleaning processes. For instance, soft brushes or cloths may be used for dry brushing to remove loose debris without scratching the surface. Water washing, on the other hand, may require gentle detergents or environmentally friendly cleaning agents to dissolve and remove stubborn pollutants effectively. The frequency of cleaning should be determined based on pollution levels and environmental conditions. In areas with high pollution levels, such as industrial zones or coastal regions, insulators may accumulate pollutants more rapidly and thus require more frequent cleaning compared to those in cleaner environments. After each cleaning cycle, it’s essential to monitor the performance of the insulators to ensure that pollution has been effectively removed. Parameters such as surface condition, flashover voltage, and leakage current should be carefully examined. Any deviation from normal performance indicators can indicate lingering pollution effects that may require further cleaning or maintenance actions. It is crucial to monitor and regularly clean insulators in coastal areas to remove salt deposits and maintain their dielectric strength, ensuring reliable and safe operation within high wind and marine environments.

B. **Preventive Coating Application:** Preventive coatings play a crucial role in averting the formation of conductive films on power system insulators. Among the common coatings utilized, room temperature vulcanized (RTV) silicone rubber and silicone grease coating stand out (Salem, *et al.,* 2019). These coatings are applied to enhance the hydrophobicity of insulators throughout their operational lifespan, mitigating environmental pollution concerns. They create a water-repellent surface that hinders the formation of conductive layers on the insulator surface. The frequency of re-application of silicone grease depends on pollution severity due to its saturation point. However, the need for periodic re-application and potential on-installation of insulators limits the widespread use of silicone grease. In contrast, RTV silicone rubber is a superior choice for preventive coating as it does not require encapsulation and maintains a hydrophobic surface, effectively inhibiting contaminant buildup.

C. **Predictive Strategies for Curbing Pollution Flashover:** Monitoring and predicting pollution flashovers on insulators in coastal and industrial environments, influenced by pollutants like fertilizer and sea salts, is crucial. This necessity has driven extensive research to understand the parameters leading to flashovers and to develop predictive models for minimizing pollution buildup. A key strategy involves regular inspections of insulators to detect early signs of wear, damage, or pollution accumulation. Researchers have devised various models and techniques for predicting pollution flashovers. In references (Salem, *et al*., 2019; Badachi & Dixit, 2016; Badachi & Dixit, 2015), the authors employed dimensional analysis to establish a mathematical model correlating pollution flashover voltage with Equivalent Salt Deposit Density (ESDD) on insulator surfaces. Additionally, in reference (Gouda, *et al.,* 2014), a dynamic open model was created to forecast flashover voltage and dry band locations on polluted ceramic insulators. This model delves into electric potential and field distribution during flashover and dry band formation. Reference (Khatoon *et al.,* 2022), present four empirical models based on regression analysis to predict flashover voltage due to biological contaminants on insulators, correlating flashover voltage with ESDD to analyse contaminant behaviour. In reference (Salem, *et al.,* 2021), the authors utilized artificial neural networks (ANN) to predict flashover voltage based on contaminant parameters and insulator geometry. ANN demonstrated effective prediction capabilities across varying contamination severities. Utilizing predictive tools enables proactive monitoring and management of contaminant buildup on insulator surfaces, thereby mitigating pollution flashovers.

Conclusion

Harsh environmental conditions, particularly during dusty and stormy weather accompanied by strong winds, intensify the accumulation of contaminants on insulators. Various pollution sources directly affect insulators, including marine/coastal pollutants, industrial emissions, and biological contaminants like algae, lichen, etc. While natural rinsing from rain helps mitigate algae growth to some degree, it may not suffice for thorough cleaning, highlighting the need for early preventive measures. To counter pollution-induced flashovers, techniques such as water washing, applications of silicone grease, and covering insulators with RTV silicone rubber are employed. Assessing environmental pollution severity and its impact on outdoor insulators is crucial for selecting the right materials and methods to effectively prevent or minimize pollution-related flashovers. This proactive approach is vital for ensuring the reliability and optimal performance of electrical systems, especially in challenging environmental conditions.

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