

Assessing the Impact of Partial Contamination on Overhead Line Insulator Functionality

A Thesis Submitted in Partial Fulfillment for the Degree of Master of Electrical Engineering

By

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This is to certify that the thesis entitled “*Assessing the Impact of Partial Contamination on Overhead Line Insulator Functionality*” is being submitted by **RAJDEEP BARUA** (Registration No. 139688 of 2017-2018), in partial fulfillment of the requirement for the degree of “Master of Electrical Engineering” from Jadavpur University has been carried out by him under our guidance and supervision. The project, in our opinion, is worthy of its acceptance.

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I hereby declare that the thesis contains literature survey and original research work by the undersigned candidate, as part of the Masters of Electrical Engineering studies.

All the information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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1. INTRODUCTION

1.1 Background

Today we are living in an age of electricity. With the increase of industrialization and development of human civilization the power demand is also increasing day by day. So, to maintain it properly we have to rely on High Voltage Transmission and Distribution. So, the usage of High Voltage Insulators is unavoidable. These insulators are exposed to electrical and mechanical stresses as well as various type of environmental effect and pollutions also. For us it is a challenge to monitor its condition and maintain its performance as reliable as a virgin insulator. Now in application the insulators are used in various conditions like hill area, coastal area, coal mine area etc. In each of the cases the type of pollutions is also different we have to consider it also. In the whole transmission system, the insulators are the most sensitive part, failure of which results the failure of whole system. For choosing insulators Porcelain and Glass are by default conventional choice. There is also option of Polymer Insulators. The Porcelain materials are inert, rigid and stable material so the insulators don't experience surface deterioration easily. But they are so much sensitive to moisture, rain, fog and dew. Due to this they are more prone to contamination. Due to the contamination the insulators fail to perform properly. The leakage current increases due to that. The effective operation of power transmission lines is critical to maintaining a regular supply of electricity to communities and enterprises.

Nevertheless, pollution on insulator surfaces—such as dust, salt, and pollutants—can reduce their effectiveness and jeopardize system dependability.

The crucial problem is pinpointing the exact location of partial contamination on polymer insulators and then categorizing the degree of pollution levels. To address this difficult problem, this thesis creatively applies Convolution Neural Network (CNN), is a type of Deep Learning neural network architecture commonly used in Computer Vision. Computer vision is a field of Artificial Intelligence that enables a computer to understand and interpret the image or visual data. CNN is used in this thesis for analysing the data on leakage currents produced by contaminated porcelain insulators. CNN can be used to find trends in the data and categorise insulator behaviour using attributes gleaned from leakage current measurements.

1.2 Literature Review

An insulator serves a crucial role in power systems by isolating live components from each other and from the ground, while also offering mechanical protection. Insulators have been extensively utilized in many networks, such as substations, transmissions, and distributions [1].

Porcelain insulators have long been a prominent feature in the power system and are highly important in both transmission and distribution systems. However, due to their intended outdoor use, these devices are vulnerable to various flaws, especially when exposed to specific environmental conditions such as high humidity, rainfall, or pollution. These conditions can lead to a reduction in their surface resistance. The decrease in surface resistance leads to an increase in the amplitude of the leakage current flowing on the surface [2]. Degradation of the insulator surface may be attributed to the presence of a substantial leakage current (LC) that flows on the surface for an extended length of time [3-5]. Furthermore, since porcelain insulators are heavy in nature, prone to cracking and contamination.

High voltage-tolerant insulators are widely employed in transmission and distribution lines. Their main purpose is to physically isolate two electrical lines and also to isolate electrical conductors from towers. Insulators located in areas susceptible to industrial activity or in close proximity to the shore are more prone to contamination by salt deposits and industrial dust, respectively. Under conditions of elevated humidity and precipitation, the layers will become saturated and capable of conducting electricity, resulting in the passage of leakage current (LC) across the insulator's surface. This will occur because the layers will become conductive after being wet. This progression of LC causes a flash over which short circuits occur between two lines or between line and towers. Because of this, leakage currents are monitored and studied in a lab or out in the field, depending on the circumstances, so that a comparative assessment of the state of the insulator surfaces can be made [6]. Leakage currents may give us with valuable information on the state of the insulator surfaces if we investigate their its pattern [7-8]. In the beginning, the magnitude of the leakage currents is relatively low, and they have a capacitive character. However, as time passes, the magnitude of the leakage currents grows, and it also becomes more resistive; afterwards, the leakage currents' harmonic content also grows [7-11]. The appearance of a dry band on the surface of the insulator is caused by an increase in the LC. A further boost in the harmonic richness may be

achieved by dry band arcing [10]. Therefore, analysis of leakage currents is often performed in both the time and frequency domains [4]. As shown by D. Pylarinas et al, there are quite a few features in both the time domain and the frequency domain that may be employed alone or collectively to analyse LC values [11-12]. These features can be found in both the time domain and the frequency domain. A study that was carried out by I. Ramirez et al. [17] demonstrates the process of measurement of Leakage Current for monitoring the performance of outdoor insulators in polluted environments. An extensive survey on correlation among ESDD, NSDD and leakage current in distribution insulators was done by G. Montoya et al. [20]. The overview of Recurrence Plot is described by N. Marwan [32]. Concepts of CNN architectures, challenges, applications, future directions are described by Alzubaidi et al [38].

Insulator contamination is a critical concern in power transmission systems, as it can lead to electrical breakdown and power outages. Traditional methods for detecting contamination involve visual inspections, which are often subjective and inefficient. The literature highlights the need for advanced techniques that can accurately identify the location and severity of contamination on insulator surfaces.

1.3 Scope of Thesis

The thesis's "Study on Identification of Location and Classification of Partially Contaminated Overhead Porcelain Insulators by Modern Classification Techniques" focus is highly specialized and deals with a crucial component of power system dependability and maintenance. The thesis can be consisting of-

1.3.1 Positioning Issue:

The thesis seeks to solve the difficulty of pinpointing the precise place on a transmission line where a polymer insulator is partially polluted. This is significant because, depending on variables like wind direction, precipitation, and ambient temperatures, various parts of the insulator may become contaminated to differing degrees.

The strategic positioning of sensors along the insulator's length to record leakage current data at various points could be covered in the thesis. These sensors, which measure variations in voltage or current along the surface, could be resistive or capacitive in design.

1.3.2 Contamination Classification:

The thesis can concentrate on categorizing the level or severity of contamination in addition to pinpointing the place. Diverse leakage current patterns may result from varying amounts of pollution.

The thesis may investigate methods for deriving recurrence plot from the gathered leakage current data. After that we have to use a machine learning method CNN for the purpose of Classification.

1.3.3 Data Collection and Analysis:

Detailing the experimental setup for collecting leakage current data from partially contaminated insulators. This could involve creating a controlled environment with varying levels of contamination to generate diverse datasets.

1.3.3.1 Data Preprocessing: Discussing the steps taken to preprocess the collected data, which might include noise reduction, data smoothing, and outlier removal.

1.3.3.2 Data Labelling: Assigning appropriate labels to the collected data, indicating which part of the insulator is partially contaminated each location.

1.3.4 **Development and Validation of Algorithms:**

✓ **Model Development:** Creating and putting into practice algorithms or models that can locate contaminated insulators accurately by using the retrieved features as inputs.

✓ **Training and Validation:** Using one subset of the data to train the generated models and another subset to validate their performance. Assessing accuracy and visualize it with the help of confusion matrix.

1.3.5 **Application and Impact:**

✓ **Utility Application:** Discussing the practical implications of the research. How could the developed techniques be implemented by power utilities to enhance maintenance strategies and reduce downtime.

✓ **Risk Assessment:** Exploring how accurate identification of partially contaminated insulators can mitigate the risk of insulation breakdown and potential power outages.

✓ **Economic Benefits:** Discussing how such technology could potentially result in cost savings through optimized maintenance scheduling and improved asset management.

2. BACKGROUND OF OUTDOOR INSULATORS

2.1 TYPES OF INSULATORS:

Insulators used in transmission lines serve two purposes: mechanical and electrical protection. The insulators provide mechanical support for the cables. They can tolerate the weight of the cables as well as the forces of the wind. Electrically speaking, they maintain the wires at a safe distance from the towers to prevent the formation of an arc between the wire and the metallic components of the tower. The right choice of insulators is crucial for electricity lines to operate successfully. Insulators for overhead lines come in several varieties. The following insulators are most frequently used:

- Pin Type Insulators
- Post Type Insulators
- Suspension Insulators
- String Insulators
- Shackle Insulators
- Stay Insulators.

2.1.1 Pin Type Insulators:

Pin Type Insulators are one of the most commonly used insulators in overhead transmission and distribution lines, especially for voltages up to 33 kV. Pin insulators are typically shaped like a bell or a cone as the Fig.2.1. They are made from materials like porcelain, glass, or composite polymers. The insulator is mounted on a steel or wooden pin that is fastened to the cross arm of the pole. The conductor is tied to the top of the insulator using binding wire. There is a groove at the top of the insulator where the conductor is placed. Although porcelain is typically used to make pin insulators, plastic or glass can also be utilized in certain situations. Since pin insulators are nearly always used outdoors, adequate insulation during rainy conditions is especially crucial. Current may be able to pass through a wet pin insulator and reach the pole. In order to solve this issue, pin insulators—also known as rain sheds or petticoats—are made of two or three pieces of porcelain that are cemented together, depending on the voltage level. When working voltage exceeds 33kV, pin insulators become excessively large and expensive.

A single-piece pin insulator is used at lower voltages. Two or more pieces are bonded together to produce an appropriate creepage distance and thickness for applications needing greater voltage.[3]



Fig.2.1. Pin-Type Insulator

2.1.2 Post Insulator:

While post and pin insulators are essentially the same, post insulators are better suited for higher voltage applications.[2] The post insulator, depicted in Fig. 2.2, is taller and has more petticoats. This kind of insulator can be installed both vertically and horizontally on a supporting structure. Although the insulator is constructed from a single porcelain piece, it features fastening clamp arrangements at both the top and bottom ends. Post insulators are typically used to support isolator switches, bus bars, and other components. [2,5]



Fig. 2.2. Post Insulator

2.1.3 Suspension Insulator:

As pin insulators become excessively large, heavy, and expensive Suspension insulators are therefore employed for voltages greater than 33 kV, as seen in Figure 2.3 a suspension insulator is made up of several porcelain discs that are freely attached to one another in series using metal links that resemble strings [1,5]. The line conductor is fastened to the lower end of the suspension insulator, which is suspended from the supporting structure's cross-arm. Suspension insulator strings are made with each disc intended for a low voltage, approximately 11 kV. The working voltage, the type of insulator being used, and the weather all affect how many discs are in a string. One type of disc insulator called a suspension insulator uses multiple disc

insulators in a cascade [1,5]. Insulator conductors in suspension may be hung from support points [3]. There are two different types of suspension insulators. One is a Hewlett type insulator, while the other is a linked cap type [3].



Fig. 2.3. Disc Insulator

❖ Advantages of Suspension Insulators:

- Each unit of suspension type insulators is designed for low voltage (say 11 kV) and depending upon the working voltage, desired number of discs can be connected in series to form an insulator string suitable for particular voltage
- In case of failure, we have to replace only the damaged unit.
- In case of demand increase we can add extra sufficient discs.
- Suspension type insulators provide more flexibility to the line and mechanical stresses are reduced as the insulator strings can swing freely in any direction and take up a position where it experiences only pure tensile stress

2.1.4 String Insulator:

In a string insulator, several discs are connected in series as shown in the Fig.2.5. It functions as a dead-end insulator most of the time [3]. A transmission line is more likely to experience tensile stress when it ends abruptly, corners, or curves sharply. Strain insulators are utilized at sharp corners or dead ends to maintain this high tension. Shackle insulators can be used for low voltage lines (up to about 11 kV), whereas string insulators, which are made up of a group of suspension insulators, are utilized for high voltage transmission lines. on this instance, the insulator discs are positioned on a vertical plane [3,4] and the suspension string is placed horizontally. It is possible to assemble two or more suspension strings simultaneously for more load.



Fig. 2.4. String Insulator

2.1.5 Shackle Insulator:

In distribution networks it is typically used. It is mainly used in low voltage transmission lines[3.5]. We can use it both horizontally and vertically[3,4]. Here, the conductor is positioned between the clamps of this type of insulator, and the insulator is fastened along the groove[3-5]. They can be directly fixed to a pole with a bolt or to the cross-arms. However, the use of such insulators is decreasing after increasing the use of underground cables for distribution purpose. In the Fig.2.5 a picture of Shackle Insulator is shown.



Fig: 2.5. Shackle Insulator

2.1.6 Stay Insulator:

The stay insulator is also named an egg insulator for its typical structure as Fig.2.6, it is used in the stay wire structure to keep the conductor a height from the ground. Stay insulator is used for low voltage applications. The stay insulator is made of porcelain, They are typically installed between the grounded portion of the guy wire and the portion that may come into contact with live electrical parts, ensuring that the guy wire remains electrically insulated from the ground[3-5].



Fig: 2.6. Stay Insulator

2.2 Insulating Materials

Insulators in the power system network are primarily classified into two groups. Most of them consist of polymers and non-polymers [10]. The predominant materials employed in the production of ceramic insulation are glass and porcelain. Polymer insulators are currently utilized in distribution and transmission networks. The primary materials utilized for outdoor insulation are glazed porcelain, toughened glass, and polymers. The mechanical and electrical properties of each material are directly influenced by its microscopic structure. Below, each of these materials will be detailed.

2.2.1 Porcelain:

Porcelain has been employed as an insulating material since ancient times and continues to be utilized now. Porcelain is commonly composed of ceramic materials [3-5]. Clay, quartz, and feldspar are the primary materials utilized in the production of porcelain insulators. Porcelain insulators are made from inorganic minerals and clays. These materials are heated in a kiln, resulting in the formation of silicate crystals and different oxides within a glassy matrix [3-5]. During the fire process, the material undergoes a full transformation and becomes completely impermeable to moisture [3]. The insulator is typically coated to create a smooth surface that prevents pollutants from sticking to it and facilitates the washing of important things with rainwater [3, 4]. Another vital role of this glazing is to furnish a compressive external layer. It serves the dual purpose of inhibiting the formation of surface fractures and enhancing mechanical strength [3]. The image depicting the porcelain insulator can be observed in Figure, while the characteristics of the porcelain insulator have been organized in Table.2.1.



Fig. 2.7. Porcelain Insulator

Table. 2.1. Parameters of Porcelain Insulator

SL No	Parameters	Value
1	Tensile Strength	4.26-6.00(kgf/mm ²)
2	Dielectric Constant	6.16
3	Puncture Strength	12.5*27.6(kV/mm)

2.2.1.1 Advantages of Porcelain Insulator:

- High heat resistance and strength
- Very stable against UV radiation
- High compressive strength
- Surface discharge and leakage current activity are difficult to damage these insulators.

2.2.1.2 The Disadvantages of Porcelain Insulators:

- Weight is very high
- Easily gets contaminated
- Highly vulnerable to cracking
- Chances of damage by thermal effects
- Low tensile strength as well as low cantilever strength to weight ratio

2.2.2 Glass:

Due to its better dielectric strength compared to porcelain insulators, glass is also used in the production of transmission line insulators. It is mostly used for Extra High Voltage (EHV) Direct Current (DC) and Alternating Current (AC) power networks. Heating glass increases its durability. Although the inner surface of the insulator cools gradually, the surface must cool rapidly during the toughening process [3-5]. In order to inhibit the formation of small cracks on the surface and to slow down the spread of cracks, the solidification process is designed to provide a long-lasting compressive stress on the outer sections [3-5]. The components of silica, limestone, dolomite, feldspar, soda ash, and salt cake (or sodium sulphate) are combined and heated to temperatures reaching 1500 degrees. Subsequently, the liquefied glass is poured into a mold in order to shape the glass disc of the cap-and-pin insulator. Once the disc is extracted from the mold, it undergoes thermal toughening to improve its mechanical characteristics. Following a thorough quality examination, any defective units are discarded, while the metal fittings are affixed. Toughened glass exhibits superior mechanical qualities in comparison to porcelain cap-and-pin insulators.

Glass has a lower melting point compared to porcelain, which makes it more susceptible to surface erosion caused by the heat generated by surface discharges. Issues arise in contaminated environments when the formation of channels on the underside of the glass surface weakens the structural integrity of the unit. Cap-and-pin insulators, made of both porcelain and glass, have the ability to create interconnected structures to bear significant mechanical burdens. Even if the dielectric of a unit is ruptured, they maintain their structural integrity. Nevertheless, ceramic insulators possess a fragility that renders them vulnerable to acts of vandalism or deliberate shooting incidents. In contaminated environments, the ability of ceramic insulators to withstand electrical flashover is greatly diminished, necessitating the use of larger creepage distances. This, in turn, leads to the creation of larger and heavier insulator units. In order to decrease the dimensions of high voltage electrical systems, polymeric insulators have been employed. These insulators are lightweight and possess excellent performance in polluted settings due to their water-repellent qualities [3-5]. The image of the glass insulator is depicted in Fig.2.8, while the characteristics of the glass insulator are presented in Table. 2.2.



Fig. 2.8. Glass Insulator

Table. 2.2. Parameters of Glass Insulator

SL No	Parameters	Value
1	Tensile Strength	5.34-8.35(Kgf/mm ²)
2	Dielectric Constant	6.8
3	Puncture Strength	70-120(kV/mm)

2.2.2.1 Advantages of Glass Insulator

- Very high dielectric strength
- It remains unaffected by UV rays and other environmental effects
- High tensile strength
- Impurities and air bubbles are immediately identifiable.
- Extensive service life
- Glass is less expensive than porcelain.

2.2.2.2 Disadvantages of Glass Insulator

- It absorbs contaminants easily Compared to other insulators, leakage current is higher in glass insulators
- It is easily breakable and prone to vandalism.

2.2.3 Polymer:

Due to their exceptional insulating performance, polymer insulators have become widely favoured in the power industry [5]. Composite insulators, also known as polymer insulators, are shown in Fig.2.8. [5]. As per the definition, a "composite" is an insulator that has a fiberglass core to enhance its mechanical strength [3-5]. The housing functions as a protective barrier against external factors and provides the necessary electrical characteristics for the core. Polymers are commonly utilized for the housing materials of composite insulators. The housing contains a core made of a strong fibrous composite material. The polymer housing is designed to safeguard the core by preventing water, humidity, leakage current, and discharges from causing any damage. Additionally, it ensures proper insulation. The profile must effectively manage the leakage current on its surface by ensuring the appropriate creepage distance and reducing the accumulation of airborne contaminants. These lightweight composite insulators offer a superior strength to weight ratio and a more compact design, allowing for a longer creepage distance within a given axial length when compared to ceramic insulators. In addition, the durable housing safeguards the unit from acts of vandalism. They also come in a more compact size overall has a tendency to decrease leakage current and enhance performance in polluted environments. Polymers with a silicone structure exhibit exceptional contamination performance due to their surfaces' water-repellent properties. Unlike ceramic materials, these polymeric materials have a low surface free energy. As a result, water is unable to settle on the surface in a thin layer. Instead, it is forced to form separate discrete beads [5]. The hydrophobic nature of these polymers offers a notable advantage when compared to ceramic dielectrics. Manufacturing cost of polymeric insulators has been a concern, but there is a growing argument that composite insulators for transmission lines are economically competitive to porcelain and glass insulators. Regrettably, the advantages provided by polymers are not without their share of issues. Unlike ceramic dielectrics, polymers are more susceptible to thermal damage due to their weaker inter-molecular bonds [3-5]. Polymeric insulators can experience degradation over time, which can significantly affect their performance. This degradation is a result of the various stresses they endure during service. The characteristics for polymer insulators are given in the Table. 2.3.



Fig: 2.8. Polymer Insulator

Table. 2.3. Parameters of Polymer Insulator

SL No	Parameters	Value
1	Tensile Strength	5.09858-203.9432 (kgf/mm ²)
2	Dielectric Constant	Less than 3
3	Puncture Strength	300-520(kV/mm)

Polymer Insulator Parameters

2.2.3.1 Advantages of Polymer Insulator

- Lightweight.
- Extremely minimal installation expenses
- Greater tensile strength
- In areas that are contaminated, its efficacy is enhanced.
- The hydrophobic nature necessitates less cleansing.

2.2.3.2 Drawbacks of Polymer Insulation

- Moisture penetrating the core may lead to an electrical failure.
- Deflection in certain applications when subjected to high loads.
- Mechanical failure is also a frequent occurrence.

2.3 Insulator Degradation

During this period, there has been a substantial rise in the demand for electricity [20]. In order to accommodate this substantial demand, power sectors must enhance the efficiency of

transmission lines [1–10]. As a consequence of the electricity sector's liberalization, each consumer must have the freedom to select the appropriate supply network that offers the services they require [15]. The service's development is the primary factor influencing the network's accuracy. It is imperative to prevent faults, as they lead to financial losses for both users and industries [14]. One of the most significant obstacles to maintaining this regularity is the impact of pollution on the transmission line insulator.

The degradation of line insulators is a significant concern for the electricity sector. The quality and dependability of power delivery are significantly influenced by insulator degradation [16, 17]. Insulator degradation is a result of exposure to high-contamination locations, ice accumulation, strong winds, biological pollution, bird droppings, and other factors [19]. Insulators can be damaged by back-flashover caused by overvoltage from a lightning discharge, as indicated by soil resistivity and tower footing resistance [1–5]. Consequently, it is imperative to conduct insulator maintenance on a consistent basis, taking into consideration all potential sources of stress that could potentially lead to insulator failure.

2.3.1 Factors Contributing to Insulator Degradation

Transmission line insulators are susceptible to a variety of environmental factors that may result in their degradation over time. Insulators' electrical performance, reliability, and overall effectiveness in sustaining insulation integrity can be jeopardized by their degradation [19]. Insulator degradation can be influenced by a variety of environmental factors, including:

- **Pollution and Contamination:** Insulators may accumulate dust, industrial emissions, airborne pollutants, and natural detritus. This contamination has the potential to generate conductive paths and elevate the likelihood of flashovers, particularly in humid or damp conditions [19].
- **Moisture and Humidity:** Dew, fog, condensation, and rain can cause water and moisture to accumulate on insulator surfaces. Flashovers can occur as a result of the increased surface conductivity and tracking caused by water droplets [19].
- **The surface of insulators can degenerate over time as a result of ultraviolet UV radiation from sunlight.** Surface fractures, erosion, and modifications in material properties may result from ultraviolet radiation exposure [11].
- **Temperature Fluctuations:** Thermal phenomena may result from substantial temperature fluctuations. Insulator materials undergo expansion and contraction as a result of stress. This has the potential to mechanical stress, fracture, and the degradation of the insulator's electrical and mechanical properties [19].

- **Salt and Coastal Environments:** Insulators situated in proximity to coastal areas or industrial sites with high salt content are susceptible to accelerated corrosion and material degradation as a result of the corrosive effects of salt [19].
- **Chemical Exposure:** Insulator materials may be compromised and their efficacy may be diminished by exposure to chemicals, including industrial contaminants or corrosive agents[13].
- **Wind, ice, and other mechanical forces** can induce physical stress on insulators, which is known as mechanical stress. Cracks, chipping, or even fracturing of the insulator material may result from this stress over time [3-5].
- **Vibrations and Vibrational Fatigue:** Insulators may sustain structural damage and vibrational fatigue as a result of vibrations emanating from transmission lines, apparatus, or machinery in the vicinity [19].
- **Wildlife and Bird Droppings:** The risk of flashovers is elevated by the introduction of detritus and excrement onto insulator surfaces by wildlife activity, such as nesting birds [19].
- **Aging and UV Degradation:** Insulators may naturally age and degrade over time as a result of a variety of environmental factors. A reduction in efficacy and aging can be attributed to temperature fluctuations, moisture exposure, and UV radiation [11,12].

2.3.2 Strategies for Mitigating Insulator Degradation

- Consistent cleansing to eliminate contaminants and debris.
- Repelling water and moisture by applying hydrophobic coatings.
- Material selection that considers environmental resilience.
- Adopting appropriate maintenance procedures.
- Utilizing insulator designs that are resistant to flashover and monitoring.
- Monitoring systems that identify performance changes and degradation.

To guarantee the sustained safety and performance of insulators in high-voltage applications, transmission line operators and engineers must take into account these environmental factors and implement the necessary measures.

2.4 Insulator Aging

Polymeric insulators are more susceptible to aging than porcelain and glass insulators. Over the past few decades, polymer insulators have been extensively employed as high-voltage outdoor insulators [1–5]. The performance of non-ceramic insulators is believed to be preferable to that of porcelain and glass insulators due to their hydrophobic nature [10]. In spite of the numerous advantages of polymeric insulators, their organic composition renders aging an inevitable process. One of the primary causes of aging is the leakage current that flows to the insulator's surface, which leads to dry-band arcing [11,12]. The primary causes of aging are ambient temperature and UV light. Various factors, including UV light, Joule heating due to current flow rain, dry-band arcing, and moist contamination, can also contribute to the aging of polymeric insulators [11].

There are numerous factors that can contribute to the degeneration of transmission line insulators:

- **Environmental Factors:** Insulators are subjected to a diverse array of environmental conditions, such as sunlight, rain, temperature fluctuations, and pollution. The effectiveness of insulating materials can be diminished as a result of the physical and chemical changes that can occur over time [11,12].
- **Ultraviolet (UV) radiation** from sunlight has the potential to degrade the polymer materials that are frequently employed in insulators, resulting in their brittleness and loss of mechanical strength.
- **Pollution:** Surface leakage currents may result from the accumulation of airborne contaminants, including sulphur dioxide and nitrogen oxides, on insulator surfaces, which can form a conductive layer. This may jeopardize the insulation's efficacy.
- **Corona Effects:** A phenomenon known as corona discharge can occur when the electric field surrounding an insulator becomes excessively strong. This can lead to the formation of reactive species, including ozone, which can erode the insulator's surface.
- **Thermal cycling:** The mechanical stress that can result from the expansion and contraction of insulator materials as a result of temperature fluctuations can cause the material to degrade or fracture over time..
- **Mechanical Stress:** Insulators may be subjected to physical stress from mechanical forces such as wind and ice, which may result in structural damage or splitting.

Several measures can be implemented to reduce the deterioration of transmission line insulators:

- Conducting routine visual inspections and testing of insulators can assist in the early detection of evidence of degradation and damage. Insulators that have been damaged or deteriorated should be replaced without delay.
- Cleaning: The removal of accumulated contaminants from insulator surfaces can assist in the preservation of their insulating properties.
- Coatings: The application of specialized coatings to insulator surfaces can extend their lifespan by protecting them from UV radiation and pollution.
- Material Improvement: Researchers are currently engaged in the development of insulating materials that are more resilient to environmental factors and aging, such as advanced polymers or composite materials.
- Design Considerations: In order to mitigate the effect on insulators, transmission line design should consider factors such as wind load, ice load, and mechanical stresses.
- Corona Control: The transmission line can be designed to mitigate corona effects, which can help reduce the formation of harmful surface layers on insulators.

Ultimately, the objective is to guarantee the safety and dependability of power transmission systems by addressing the aging effects of insulators and implementing the necessary measures to preserve their effectiveness over time.

2.5 Characteristics Parameters Determining the Insulator Condition

The state of an insulator is assessed based on many characteristics and criteria that indicate its functionality and condition. Insulators play a vital role in electrical systems by obstructing the passage of electricity between conductive elements. The insulator's state is determined by several essential properties and parameters.

2.5.1 Chemical parameters

Chemical characteristics are crucial in assessing the state of insulators, particularly in outdoor settings where insulators are subjected to diverse pollutants and toxins. The chemical interaction with insulator surfaces can result in surface deterioration, altered conductivity, and other factors that impact the performance of the insulator. The insulator state is influenced by several important chemical factors.

2.5.1.1 ESDD

Equivalent Salt Deposit Density (ESDD) is a widely utilized measure for monitoring the degree

of pollution on insulators [20]. To estimate the ESDD (measured in mg/cm²), NaCl is deposited across the surface regions of an insulator. The conductivity of the insulator is similar to that of the actual deposit diffused in the same amount of water [20].

The ESDD method involves using demineralized water to remove impurities from the surface of an insulator and then analysing the results to determine its conductivity [20].

2.5.1.2. NSDD

Additionally, evaluating the contamination level for insulators is a beneficial technique. The acronym NSDD stands for non-soluble deposit density. The NSDD (Non-Soluble Deposited Dust) model explains the quantity of inactive impurities that accumulate on the insulator's surfaces, measured in square centimetres [20]. Typically, the wash water solution derived from ESDD measurement is utilized to calculate NSDD [20]. A filter paper with a grade of GF/A 1.6 m or a similar grade, which has been cleaned, pre-weighed, and pre-dried, is used to filter the liquid. Subsequently, the filter paper that has been contaminated is weighed and dried.

2.5.2 Electrical Characteristics

Understanding electrical parameters is essential for evaluating the condition of insulators, as they directly impact the insulator's ability to endure electrical stresses and preserve its insulating properties. Monitoring these parameters is crucial for evaluating the condition and efficiency of insulators in electrical systems [3-5]. These are the important electrical parameters that are used to assess the condition of an insulator:

2.5.2.1 Surface Leakage Current

When an accidental electrical connection occurs between the ground and the conductor, surface leakage currents are generated in the equipment [3-5]. Using the earth's surface as a reference for zero voltage is commonly used as the ground in electrical engineering. It is indeed possible for current to escape from the power supply unit and make its way to the installation earth ground through the ground connections [3-5]. Monitoring the condition of the transmission line insulator requires careful attention to surface leakage current.

2.5.2.2 Flashover voltage

Essentially, a flashover refers to an electrical discharge occurring on the surface of an insulator [16]. The flashover voltage is the minimum voltage necessary to induce a flashover across the surface of the insulator. This parameter is crucial in evaluating the insulator's effectiveness in preventing unintended arcing or breakdown. The breakdown of air insulation surrounding the insulator occurs during flashover.

2.5.2.3. Puncture voltage

This voltage is the point at which an insulator loses its ability to conduct electricity, allowing current to flow through its interior [3-5]. This situation leads to a permanently damaged insulator. The puncture voltage exceeds the flashover voltage of the insulator.

Partial Discharge (PD) is the occurrence of localized electrical discharges within the insulator's material, typically caused by defects, voids, or irregularities. Monitoring PD activity can be beneficial in identifying early indications of insulation degradation and potential flashover hazards.

2.6 Impact of Degradation and Ageing on Parameters

Over time, the surfaces of insulators can deteriorate due to a range of impurities. It may have a negative impact on the conductivity of the insulator surface [21]. Moisture and contaminants can result in the formation of a conducting layer that is wet [21–25]. Leakage current is generated as a consequence of this. The heating on the surface of the insulator is not uniform. A dry band zone forms on the surface of the insulator due to localized drying of the contaminated layer [25]. In certain areas, such as a "dry band," the flow of current is significantly restricted due to its high resistance. An applied voltage is present across the dry band region. Arching is a consequence of this phenomenon [25–28]. These arcs have the potential to extend further until they reach the insulator's two metal electrodes, resulting in flashover [25].

2.6.1 The Impact of Contamination

Over time, insulators used in transmission lines and substations can accumulate salt and other impurities due to exposure to pollutants in the open atmosphere. The layer is primarily composed of pollutants such as dust, dirt, industrial toxins, and sea salt [17–19].

In certain environmental conditions, such as rain, mist, or fog, the surface of an insulator can become moistened if it is contaminated. When salt is dissolved in moisture, it enhances the conductivity of surfaces, resulting in an increase in the degree of leakage current [16]. The heat generated by the energy dissipated from this current has the tendency to evaporate moisture [16]. When evaporation happens rapidly in areas with a significant amount of leakage current, dry-band zones are formed [26]. The electrical strains resulting from the almost complete application of power across these dry bands can lead to significant arching. Once arching begins, there is a significant likelihood of a flashover happening [16].

2.6.2 Impact of Ageing

In recent years, there has been a significant increase in the use of polymeric insulators in overhead transmission lines [5]. Throughout the year, various environmental factors such as pollutants, humidity, temperature, and UV rays can significantly affect non-ceramic insulators. Non-ceramic insulators can experience aging due to factors like high temperature and UV exposure. This can weaken their electrical insulation ability and lead to surface deterioration caused by contamination and partial discharges. As materials age, there is a possibility for leakage currents to increase. This can lead to early flashover in a damp and contaminated environment [16].

3. Condition Monitoring Techniques

3.1 Introduction:

The failure of transmission line insulators is responsible for approximately 70% of power outages [15]. Contamination flashover is the main reason behind insulator failure, as indicated by research [16]. Regular assessment of insulator conditions has become increasingly crucial in recent years to prevent any potential failures. Scientists have explored various factors that can be utilized to assess the condition of an insulator. Utilities can potentially anticipate an upcoming insulator failure by utilizing these characteristics. With the availability of monitoring parameters, maintenance tasks such as insulator washing and replacement can be efficiently scheduled, enabling condition-based maintenance. Thus, it is essential to select the appropriate set of criteria that can accurately assess the condition of insulators in use.

The CIGRE Task Force [19] has emphasized the importance of surface conductivity measures, air pollution monitoring, leakage current measurements, and measurement of ESDD in insulator state monitoring. Surface conductivity and leakage current measurement are important methods for monitoring the quality of insulator surfaces. These measurements directly assess the characteristics of in-service insulators, providing valuable information about their performance. Deploying a passive or pilot insulator is necessary to measure NSDD and ESDD, as it represents the state of an in-service insulator under similar conditions [3-5]. Measurements on insulators are unnecessary for the indirect approach to air pollution monitoring.

As stated earlier, the deterioration of the surface condition leads to an increase in insulator failures. There are extensive power transmission wires and insulator structures spanning hundreds of kilometres. The insulators are exposed to different geographic regions with a diverse range of operating and environmental conditions. Various line insulators will be exposed to different levels of environmental stress, resulting in varying probabilities of failure. This is a significant factor in the failure of insulators, leading to a high percentage of line outages [15]. Just because one insulator in a transmission tower is in perfect condition doesn't mean that another insulator in a different tower nearby is also in good shape. If an insulator on a tower fails, it can lead to a complete system failure. Dividing the transmission line into multiple parts based on different stresses is recommended to avoid outages caused by environmental, electrical, and mechanical factors. Ensuring the proper monitoring of insulators in every section of the transmission line is crucial, as any failure in these components can jeopardize the stability of the power system. Evaluating the condition of transmission line insulators is of utmost importance. Factors such as temperature and humidity levels can greatly

affect the performance of transmission line insulators. Nevertheless, there are variations in environmental conditions across different regions. Leakage current analyses for a specific insulator can vary depending on the changing air conditions in different locations. Thus, it is essential to have techniques to assess the levels of contamination in an insulator regardless of the weather conditions. Modern classifiers are especially useful for determining the status of an insulator. In this scenario, the pollution levels of the insulator were estimated using classification methods such as support vector machines.

Condition assessment techniques for transmission line insulators are essential to ensure the reliability and safety of power transmission system. Insulators are used to support and electrically isolate the high-voltage conductors from the transmission towers or poles. Monitoring their condition helps identify potential faults, degradation, or damage that could lead to power outages or unsafe conditions. Here are some common techniques used for assessing the condition of transmission line insulators.

- Visual Inspection Technique
- Infrared Scanning Technique
- Hi-Pot Test Technique
- Leakage Current Measurement Technique

3.2 Visual Inspection Technique

Visual inspections were the initial method used for condition monitoring and remain the most often used. Regular visual inspections are crucial for detecting visible indications of decay, pollution, fractures, or any other tangible harm on insulators (as seen in Figure 3.1).

Inspectors can employ binoculars, drones, or helicopters to closely examine insulators without requiring physical proximity. Although cracks are generally minor, the use of devices such as binoculars or high-powered telescopes is necessary [3-5]. In order to ensure personal safety, it is advisable for the operator to be in close proximity to the insulators, while still maintaining a safe distance. Consequently, the operator is required to perform their duties from either a bucket truck or a helicopter.

The operator must possess expertise in materials design, have a thorough understanding of the specific properties of each type of insulator, and be well-informed about the several types of failures that can potentially occur [1-5]. While the main objective of this approach is to detect surface degeneration, it can also be used to confirm inner issues.

3.2.1 Benefits of This Method:

Detecting a fracture in an exterior component is straightforward.

- Electrical punctures in sheds can be detected.
- Identifying damage caused by a faulty end fitting seal due to moisture is straightforward.
- This approach is user-friendly and does not necessitate any specialized training.

3.2.2 Drawbacks of This Method:

- This approach lacks precision;
- The user's text is a bullet point.
- Detecting tiny cracks might be challenging.
- Utilizing a helicopter or bucket truck incurs significant costs.

3.3 Infrared Scanning Technique

Typically, the heating effect is associated with the damage caused by the application of an electric field on dielectric materials [1–5]. Tests using infrared (IR) scanning, both in the field and in the lab, have yielded satisfactory results in detecting insulator cracks [3-5]. This newly developed infrared camera is incredibly user-friendly and perfect for outdoor use due to its lightweight design. The camera is equipped with a suitable telephoto lens. IR cameras typically have a detection range of just a few meters [5]. There are small regions where the temperature increases by less than 1K, and data can be collected for future analysis. Using an infrared camera that operates between 8 and 14 micro meters is recommended. Images at this wavelength are not as influenced by solar radiation and are extremely sensitive to the potentially harmful temperature ranges [3-5].

Surface discharges can be detected using infrared imaging techniques. This type of discharge is often brief and temporary. As the environment improves, it gradually disappears [3-5]. However, if a discharge of this nature continues in the same location for an extended period, it could potentially impact the overall stability of the housing structure. Thermal imagers are capable of detecting warmer regions even when they are not visible with night vision equipment [3-5]. Warmer areas are heated from within. Fig. 3.1 displays the infrared scanning image of the insulator.

3.3.1 Benefits of using infrared scanning

- Detecting a temperature increase at a specific location is a straightforward task.
- Effortless fault diagnosis is also achievable.
- A novel approach to monitoring the condition of insulators

3.3.2 Drawbacks of Infrared Scanning

- This method can be quite complex.
- There should be precise criteria for the field conditions, such as the absence of wind or solar radiation.

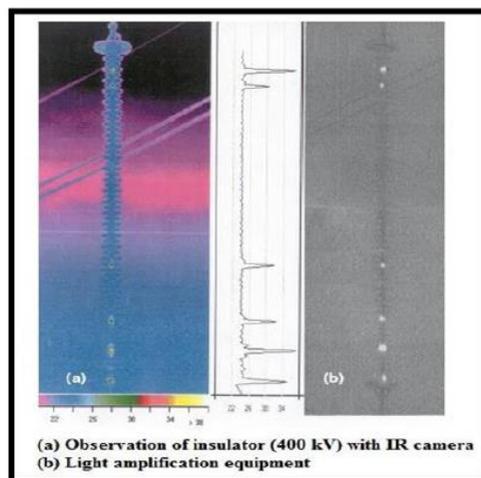


Fig: 3.1. Infrared Scanning

3.4 Hi-Pot Test:

A widely recognized method employed by operators to test porcelain insulators [3-5]. This experiment offers unparalleled precision in situations where the detection of insulator faults is necessary [3-5]. During this experiment [3-5], it is important for the operator to carefully examine each disc in the string for any signs of punctures. If the surface leakage current exceeds the usual capacitive leakage current while the tester is briefly placed on the insulator string, it will trigger a beeping sound to indicate a defective unit. Fig. 3.2 displays a photograph capturing the actual measurement process of the hi-pot test.

3.4.1 Benefits of Hi-Pot Test

- This method is extremely precise.
- This approach is much easier.

3.4.2 Drawbacks of Hi-Pot Test

- The close proximity of the line operator and physical contact with the insulator is essential.



Fig: 3.2. Hi-Pot Test

3.5 Technique for Measuring Leakage Current

Understanding the condition of an insulator can be gained by measuring the leakage current along its surface. If there are higher leakage currents, it could suggest the existence of contaminants or deterioration. Changes in the surface condition of an insulator can impact the flow of leakage current across its surface, as a result of variations in insulator surface resistance [1–12]. The change in resistance may be attributed to the loss of hydrophobicity due to ageing

in silicone rubber insulators and contamination in porcelain and silicon rubber insulators [8–12]. Monitoring the surface conditions of insulators can be effectively done by measuring leakage current. The relationship between leakage currents and insulator surface conditions has been extensively studied [15]. Scientists have devised various techniques centred around leakage current, which has become the main testing measure for evaluating the deterioration of insulator surfaces [23-25]. In the past, various methods have been employed to monitor insulator contamination, including peak value measurements, charge measurements, and pulse counting [31]. Surface leakage current patterns were proposed by Fernando et al. as a means of assessing the level of contamination in insulators,

4. Experimental Procedure

4.1 Overview

Insulators play a vital role in power system networks by isolating transmission lines. Line insulators often become contaminated over time due to the presence of various scattered particles in the air. The insulator's performance is compromised due to the accumulation of contaminants on its surface. Especially in humid situations, the current that leaks on the surface increases progressively as the layer of contamination becomes thicker. If the leakage current is sufficient to maintain the conducting pathway between the live and ground components, surface flashover will eventually occur.

In order to check the quality of transmission line insulators, it is essential to have both a contaminated insulator sample and an experimental setup that can measure leakage current and supply voltage. The insulator becomes naturally contaminated as a result of various pollutants such as salt, dirt, dust, chemicals, and agricultural contaminants. However, acquiring insulators that are naturally contaminated to a specific level of contamination is rather challenging. In order to achieve a specified amount of contamination, it is necessary to artificially contaminate an insulator according to the guidelines provided by IEC 60507 [3] and IEC 60815 [4].

4.2 Sample for Experiment

For experimental purpose three separate disc insulators are used to make a string. Now the specification of the Discs is written in the Table.4.1

Table. 4.1. Specification of Sample Insulator

Parameter	Value
Creepage Distance	332mm
Maximum Diameter	254mm
Axial Height	145mm
Pin Diameter	19mm

4.3 Procedure for Artificial Contamination

Various artificial contamination procedures, including the solid layer method (SLM), salt fog method, and method of ice layer formation, are employed to create samples for experimental work. The Solid Layer Method (SLM) has been selected for intentionally contaminating the line insulators [3-5]. SLM can uniformly coat the insulator surfaces with a layer of contamination that has a somewhat consistent thickness. An on-site investigation revealed that the primary constituent of natural pollution is salt, specifically NaCl, KCl, and other similar compounds. In this study, NaCl is used as a conductive substance and Kaolin [$\text{AlSiO}_2\text{O}_5(\text{OH})_4$] is used as a non-conductive material for the artificial contamination preparation. The specification is given in the Table. 4.2. The order of preparing fake contamination must follow the sequence specified in IEC 60507 and IEC 60815 standards [3, 4].

- **Step 1:** First, distilled water is used to properly clean the insulator.
- **Step 2:** Water, NaCl, and Kaolin [$\text{AlSiO}_2\text{O}_5(\text{OH})_4$] were mixed together to create a solution. To obtain the required amount of contamination, a certain percentage of the mixture's component is used.
- **Step 3:** This mixture is then painted to the insulator's surface and allowed to dry for 24 hours.
- **Step 4:** When the ambient humidity was higher, electric dryer was used for drying purpose.

Table. 4.2. Specification for Artificial Contamination [42]

Types of Pollution	NaCl (gm)	Kaolin (gm)	Distilled Water (ml)	ESDD(mg/cm^2)
Very High	1.7	15	20	0.6277
Very Low	0.05	15	20	0.0562

4.4 Experimental Setup

A laboratory experimental setup has been built to measure the leakage current of insulators. The schematic diagram is given also. A 150 kVA testing transformer is utilized to provide high voltage to the conductors attached to the insulator. The transformer has specifications of 500V/250 kV and operates at a frequency of 50 Hz. A 180 k Ω -rated protective resistor has been employed to transmit the output voltage of the high voltage transformer to the connecting insulator. In this case, a protective resistor is employed to safeguard the insulation of the transformer's winding against excessive current levels that may occur during flashover

situations. To record the applied voltage signal on the oscilloscope, a capacitive potential divider is attached to the high voltage side of the transformer. By employing this potential divider, the magnitude of high voltage is diminished to a level that is compatible with oscillators. The oscilloscope's leakage current is measured by employing a 10 kΩ current shunt. The sampling frequency of the data collecting setup is fixed at 50 kHz to minimize the possibility of losing any important data. This experimental configuration enables the quantification of the current that escapes through each insulator sample that has been deliberately contaminated. The voltage levels tested range from 5 kV with increments of 5 kV.

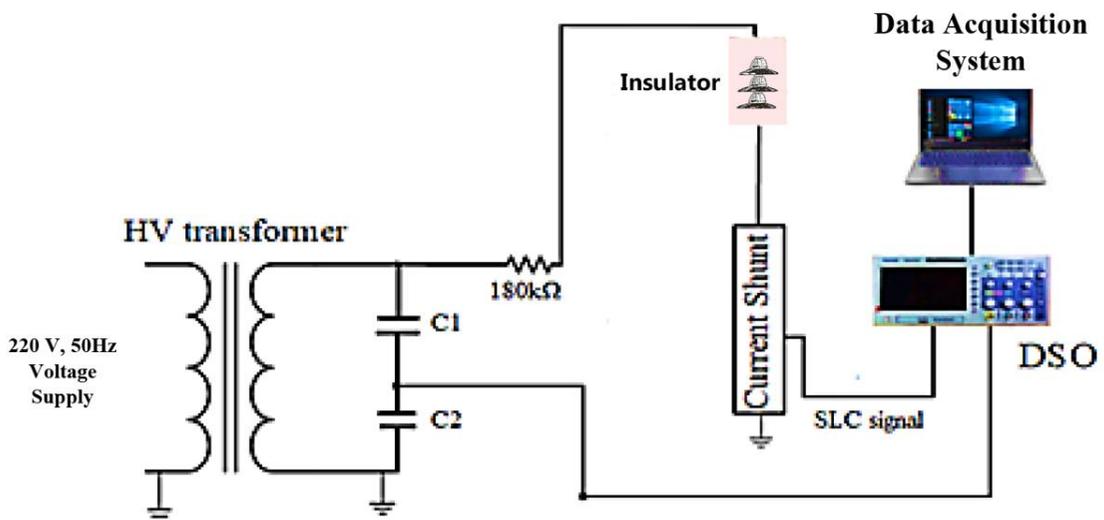


Fig: 4.1. Experimental Setup[41]

4.5 Data Acquisition

Safety Precautions: Safety is paramount when working with high-voltage equipment. Ensure we have the appropriate personal protective equipment (PPE) and follow all safety protocols and guidelines.

Isolation and De-Energization: Before starting, isolate the insulator from the live electrical system and ensure it is de-energized. This may involve temporarily disconnecting it from the power source.

Artificial Contaminated Insulator: An artificial partially contaminated string insulator used for this purpose.

Measuring leakage current: In a partially contaminated insulator requires careful techniques and specialized equipment due to the presence of contaminants. Contaminants on the insulator surface can significantly affect the accuracy of the measurement. Here's a guideline for measuring leakage current in such conditions:

High-Voltage Power Supply: In this experimental setup, the high voltage supply is taken from the output of the transformer (150 kVA, 500 V/ 250 kV, 50 Hz)



(a)



(b)

Fig: 3.2. (a) Photograph of automatic voltage regulator (AVR), (b) Photograph of High Voltage Transformer

Potential Divider: A capacitive potential divider is connected in the high voltage side of the transformer for recording the applied voltage signal in the oscilloscope (as shown in Fig. 3.3). This potential divider is used for the reduction of high voltage to the oscillator compatible voltage.



Fig: 3.3. High voltage potential divider.

Water Resistance: The high voltage supply is applied across the insulator through a series connected $180\text{ k}\Omega$ water resistance (which provides protection from over voltage as well as over current), as shown in Fig. 3.4.



Fig: 3.4. Water Resistance of 180 Ohm

Current Shunt: In electrical engineering, a current shunt is a device used to measure electrical current by diverting it away from the main circuit path. It typically consists of a low-resistance resistor placed in parallel with the load. By measuring the voltage drop across the shunt resistor, you can calculate the current flowing through it using Ohm's law ($I = V/R$). A $10\text{ k}\Omega$ current shunt is used for recording the leakage current in the oscilloscope.



Fig: 3.5. Current Shunt

Digital Storage Oscilloscope: The leakage current signals have been recorded using the digital oscilloscope. The RIGOL digital storage oscilloscope (as shown in Fig .3.6) was used in order to conduct the measurement for leakage current. Through the USB 2.0 host port located on the front panel, it is used to facilitate the rapid and uncomplicated storing of leakage current data inside a flash drive.



Fig: 3.6. DSO

Data Acquisition System: To record and store the leakage current measurements over time:

Connect the Equipment: Connect the high-voltage power supply to the insulator and the current measuring device. Ensure all connections are secure and well-insulated to prevent unintended discharges.

Gradual Voltage Increase: Slowly increase the voltage applied to the insulator while monitoring the leakage current. Start at a lower voltage and gradually increase it until we reach the rated voltage of 11 kV or above the rated voltage (up to 30 kV). This gradual approach helps avoid sudden discharges.

Record Measurements: The leakage current signals have been recorded using the oscilloscope and storage device. Use the data acquisition system to record the leakage current at regular intervals. Consider measuring it continuously for an extended period to capture variations or trends, especially when contaminants are present.



Fig: 3.5. Leakage current recording using digital storage oscilloscope (DSO).

Data Analysis: Analyse the recorded data to assess the insulator's performance. Look for variations or increases in leakage current, which could indicate a problem caused by contaminants insulator. Always prioritize safety and follow safety procedures when working with high-voltage equipment. Consider involving qualified personnel with experience in high-voltage testing to ensure accurate and safe measurements in the presence of contaminants.



Fig: 3.7. Experimental Insulator Image at HV Lab

5. Identification of Location and Classification of Partially Contaminated Overhead Porcelain Insulators

5.1 Introduction:

Overhead line insulators are essential for ensuring continuous and dependable energy delivery. The primary functions of insulators are to offer structural support for overhead lines and to provide electrical insulation between high voltage cables and the ground. Insulator failure accounts for 70% of transmission line outages [21]. The primary causes of insulator failure in polymer insulators are flashover and aging [11,20]. Overhead line insulators are susceptible to several environmental factors such as dust, grime, sea salt, drizzling rain, and humidity [35, 36]. Consequently, insulators rapidly become contaminated by pollutants, salt, chemicals, fertilizers, and various other things. When dust, fog, moisture, rain, drizzle, or similar conditions are present, the leakage current flowing across the surface of insulators steadily rises. Overhead line insulators are essential for maintaining continuous and dependable operation. As the degree of pollution rises, the insulator's surface leakage current also increases. Consequently, the flashover voltage lowers. Flashover in the distribution and transmission systems of the network causes line interruptions. The contamination level of the insulator is of utmost importance.

Several studies have investigated the impact of different contaminants on insulators [41]. Surface resistivity, leakage current, NSDD (Negative Surface Discharge Detector), and ESDD (Electrostatic Surface Discharge Detector) have been employed as the main techniques for monitoring the condition of insulators. Leakage current is an often-utilized factor [36, 41]. Surface leakage current is a very dynamic characteristic that plays a crucial role in obtaining precise information about the condition of a contaminated insulator. It provides more comprehensive results compared to other methods [36, 41]. The thesis focuses on the significant problem of partial contamination of polymer insulators in transmission line systems. The presence of contaminants, such as dust, salt, and pollution, can have a substantial impact on the performance of the insulator. This is because they can modify its electrical characteristics and influence the behaviour of leakage current. Polymer insulators are increasingly used in high-voltage applications because they are lightweight, durable, and easy to install. Nonetheless, the need of researching their behaviour under such conditions is vital for ensuring power system reliability because to their vulnerability to contamination-related concerns. The thesis primarily focuses on the situation of partial contamination. Partial contamination refers to a situation when only a part of the insulator's surface is polluted. This might result in localized distortion of the electric field and modified patterns of leakage current in comparison to insulators that are either wholly polluted or completely pure. Leakage current refers to the

electric current that flows across the surface of an insulator as a result of different circumstances, such as pollution. Examining leakage currents is crucial for comprehending the condition of the insulator, as anomalous currents may result in insulation degradation and eventual malfunction.

A Recurrence Plot (RP) is a visualization tool used in the analysis of dynamical systems and time series data. It is a two-dimensional plot that shows when a state of a dynamical system recurs or repeats itself over time. Essentially, it helps in detecting patterns, regularities, and anomalies within complex systems.

Next, with the recurrence plot here the thesis undergoes the CNN method for classification purpose. Convolutional Neural Network (CNN) is a type of deep learning model primarily used for processing structured grid data, such as images. CNNs are particularly effective in tasks involving image recognition, classification, and processing because they can automatically and adaptively learn spatial hierarchies of features from input data.

5.2 Class Description:

The objective of this work is location identification of contamination

of Porcelain insulator string. Here for project purpose 15 type of contamination Classes are examined. The insulators were just partially contaminated in the projected work. For this purpose, the few specified locations of the insulators have been contaminated with very high level of contamination and remaining part of the insulator have been contaminated with very-light level contamination. In present case, the insulator string has three discs; the discs are named as upper (Uy), middle (My) and lower (Ly). The upper side of any disc can be denoted with suffix '1'(i.e, y= 1) and lower side of any disc can be denoted with suffix '2' (i.e, y=2). using this nomenclature, the lower side of upper-disc can be named as U₂, similarly, U₁M₁L₂ indicates the combination of upper-side of upper-disc, upper-side of middle-disc and lower-side of lower-disc. In this work, 15 of different class (as shown in Table, including without contamination and fully contamination) have been considered for partially contaminated with very-high level of contamination along with reaming portion of the insulator have been contaminated with very-light level of contamination. The description of the different classes have been tabulated in the following Table. 5.1.

Table. 5.1. Description of Different Classes

SL No	Class	Configuration
1	E1	M ₁
2	E2	M ₁ L ₁ L ₂
3	E3	M ₁ M ₂ L ₁ L ₂
4	E4	U ₁
5	E5	U ₁ M ₁ L ₁
6	E6	U ₁ M ₁ L ₂
7	E7	U ₁ M ₁ M ₂ L ₁ L ₂
8	E8	U ₁ M ₂ L ₁
9	E9	U ₁ U ₂
10	E10	U ₁ U ₂ L ₂
11	E11	U ₁ U ₂ M ₁ M ₂
12	E12	U ₁ U ₂ M ₁ M ₂ L ₁ L ₂
13	E13	U ₁ U ₂ M ₂
14	E14	U ₂ M ₂ L ₂
15	E15	Without Contamination or WC

5.3 Preprocessing of Leakage Current Data

Preprocessing leakage current data for location identification of contamination on polymer insulators involves specific steps. The main objective of the work is to identify the contamination locations, the preprocessing steps will focus on preparing the data for subsequent analysis, such as feature extraction, feature selection and classification. Preprocessing steps include noise reduction, outlier removal, and normalization.

The recorded leakage current data are utilized in performing calculations to determine important features of the waveforms. The data obtained is further synthesized into two parts:

- Recorded leakage current data

- Normalized leakage current data

Recorded Leakage Current Data: In application of voltage, leakage current starts to flow over the surface of the insulator. Depending of the contamination severity as well as localized contamination, the magnitude and pattern of the leakage current are also changed. The location of contamination on the insulator may be determined using this data. Therefore, for this purpose the leakage currents have been recorded for specific time instant for different insulator samples. The recorded leakage current signals of the class E15 at 15kV, E14 at 10 kV and E12 at 20kV are shown in the Fig. (5.1- 5.3) respectively. at have been shown in following Figures

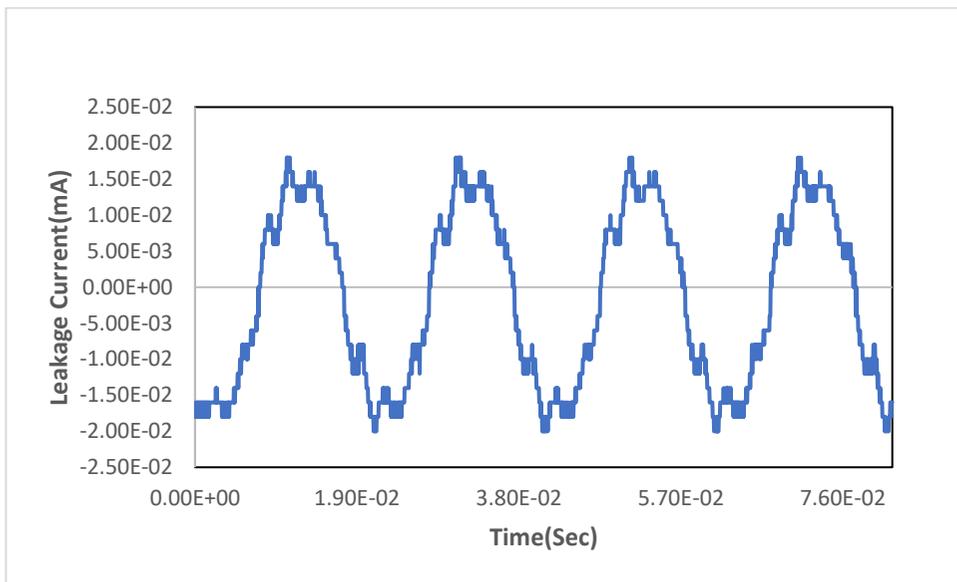


Fig. 5.1. Recorded leakage Current pattern for E15 at 15kV

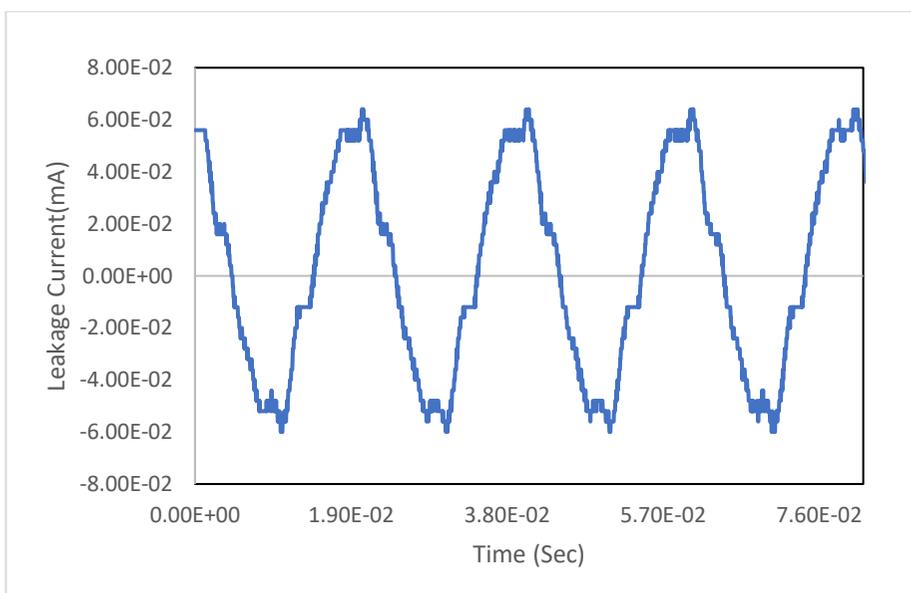


Fig. 5.2. Recorded leakage Current pattern in mA for E14 at 10kV

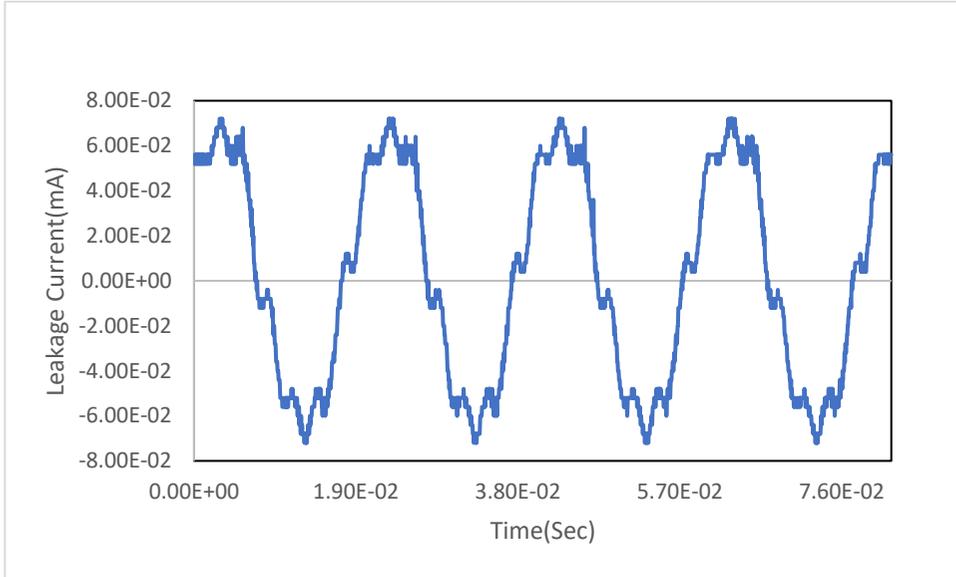


Fig. 5.3. Recorded leakage Current pattern in mA for E12 at 20kV

Normalized Leakage Current Data: Data normalization is a crucial preprocessing step that enhances the performance and convergence of machine learning algorithms. One common method of normalization involves scaling recorded data based on their maximum values. This technique involves dividing each data point by the maximum value. By doing so, all data values are transformed to a range between -1 and 1 as Fig. 5.5, ensuring uniformity and preventing data values with larger scales from dominating the learning process. This normalization technique is particularly useful when the absolute magnitudes of data vary widely, as it helps algorithms converge faster and make fair contributions to the learning process. By bringing all data sets to a common scale, the normalized data ensures that the model can efficiently learn from patterns across all dimensions, promoting more accurate and reliable results in various machine learning tasks.

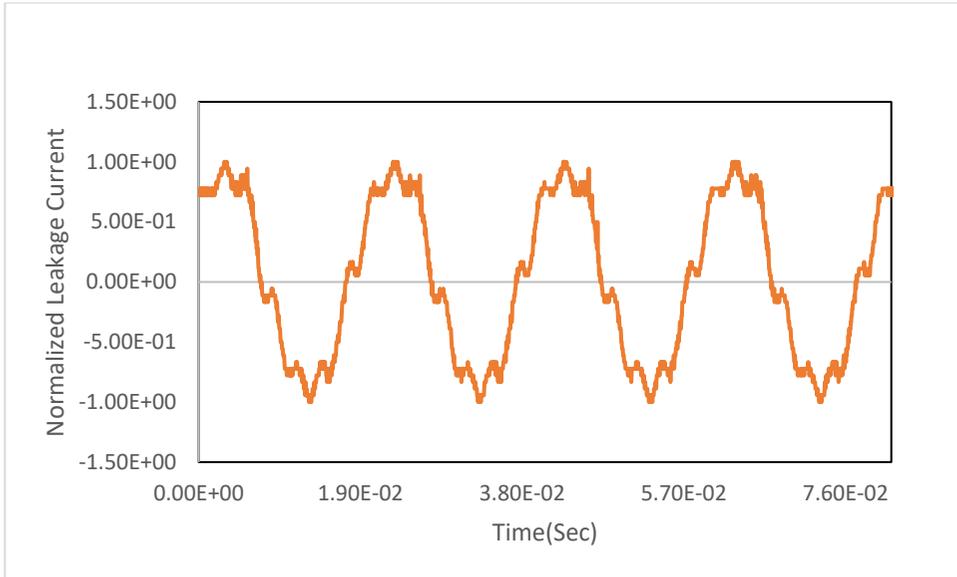


Fig: 5.4. Normalized leakage Current pattern for E12 at 20kV

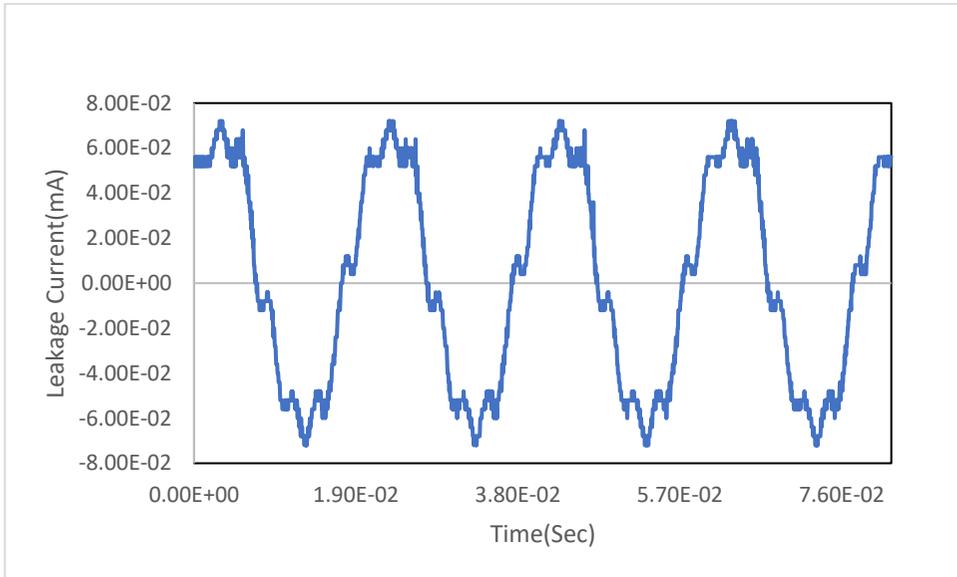


Fig: 5.5. Recorded leakage Current pattern for E12 at 20kV

5.4 Recurrence Plot Determination from Normalized Current:

A Recurrence Plot (RP) is an advanced technique of nonlinear data analysis. It is a visualisation (or a graph) of a square matrix, in which the matrix elements correspond to those times at which a state of a dynamical system recurs (columns and rows correspond then to a certain pair of times). Technically, the RP reveals all the times when the phase space trajectory of the dynamical system visits roughly the same area in the phase space[37].

To Draw Recurrence Plot:

Step 1. Preparation of the Time Series Data:

The time series data that is to be analysed should be obtained. This could be any set of observations recorded over time, such as temperature data, stock prices, or any other sequence of measurements.

Step 2. Reconstruction of the Phase Space (Embedding):

- To analyse the dynamics of the system, the phase space may need to be reconstructed using time-delay embedding. This involves creating a higher-dimensional representation of the time series. Two key parameters are required:
 - Embedding dimension (m): The number of dimensions in the phase space.
 - Time delay (τ): The lag between successive points in the embedding space.

The embedded vectors $x(i)$ in the phase space is given by

$$x(i)=[x(i),x(i+\tau),x(i+2\tau),\dots,x(i+(m-1)\tau)] \quad (5.1)$$

where $x(i)$ represents the original time series data.

Step 3. Construction of the Recurrence Matrix:

- The distance between every pair of points in the reconstructed phase space should be calculated. This is done using a distance metric, such as Euclidean distance.
- Here is your sentence converted to passive voice:
- - A threshold (ϵ) should be defined to determine when two states are considered "recurring". If the distance between two states is less than or equal to the threshold, they are considered to recur, and the corresponding entry in the recurrence matrix is marked with a 1. Otherwise, it is marked with a 0.

The recurrence matrix $R(i,j)$:

$$R(i,j)=\Theta(\epsilon-\|x(i)-x(j)\|) \quad (5.2)$$

where Θ is the Heaviside step function, and $\|\cdot\|$ is the chosen distance metric.

Step 4. Plotting of the Recurrence Matrix:

- Here is your sentence converted to passive voice:
- The recurrence matrix should be visualized as a 2D plot. Points where $R(i,j)=1$ are typically represented as black dots, while $R(i,j)=0$ is left blank (or coloured white).

For this thesis Python is used to determine Recurrence Plot for the time series signals.

Recurrence Plots for E1 at 10kV, E2 at 25kV and E9 at 5kV are shown in the Fig. 5.6, Fig. 5.7 and Fig. 5.8 respectively-

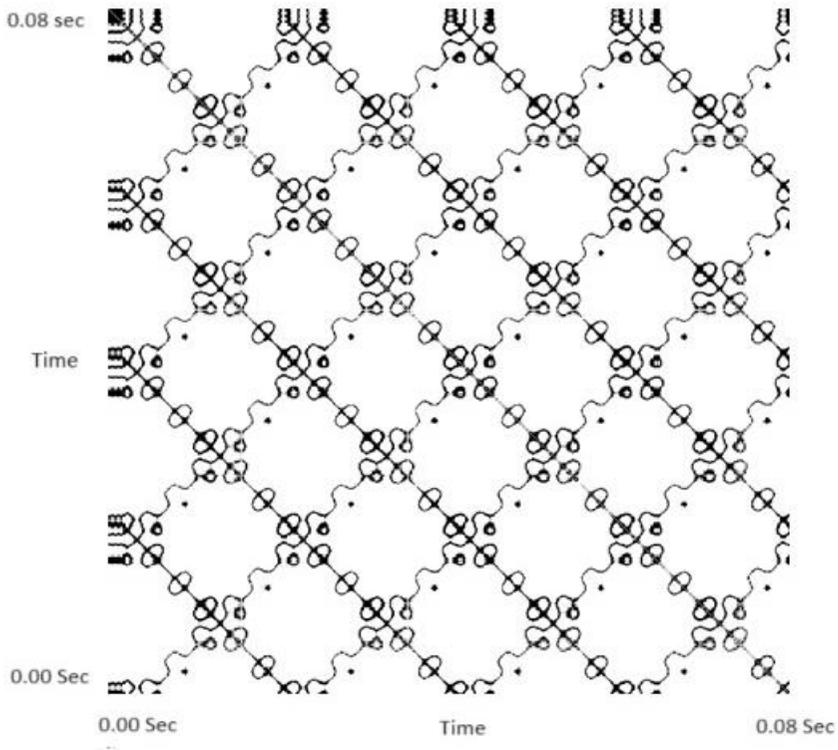


Fig: 5.6. E1-10kV Recurrence Plot

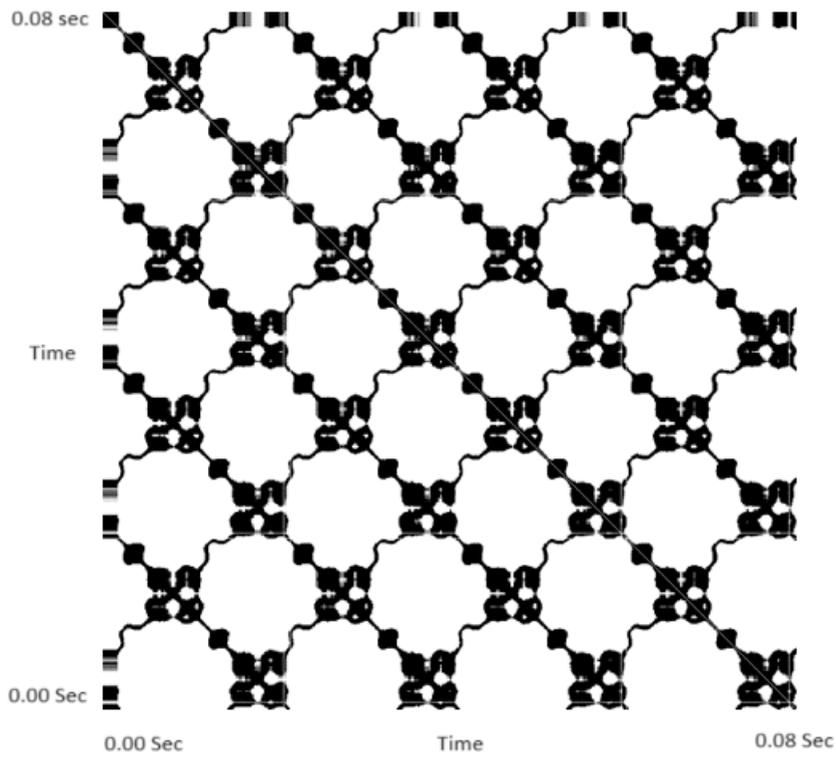


Fig: 5.7. E2-25kV Recurrence Plot

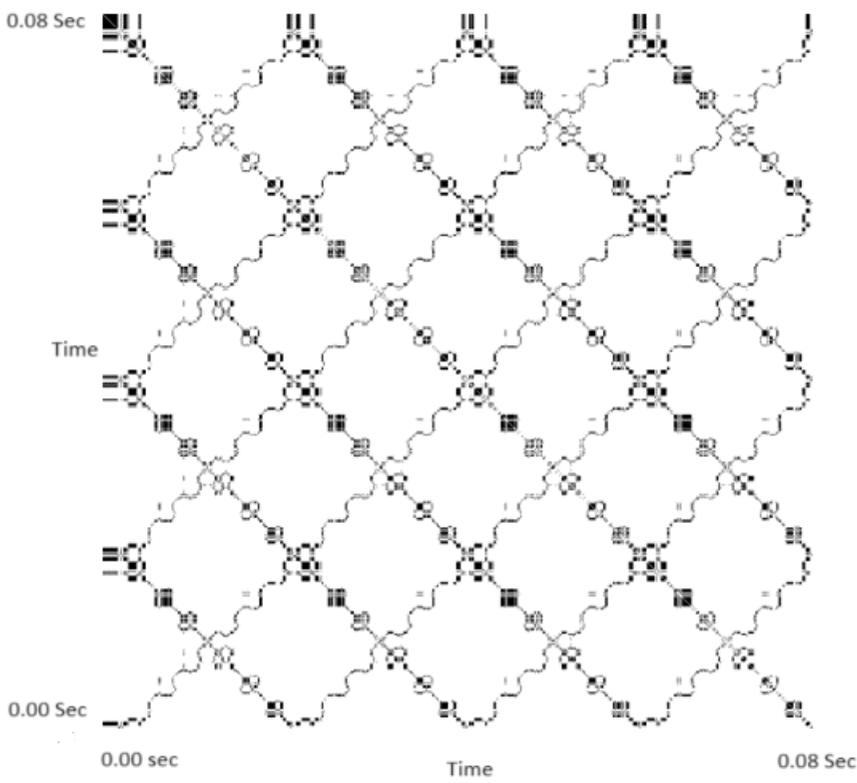


Fig: 5.8. E9-5kV Recurrence Plot

Typical patterns in RPs and their meanings

- (i) Homogeneity: The process is stationary
- (ii) Fading to the upper left and lower right corners: Non-stationary data; the process contains a trend or a drift
- (iii) Disruptions (white bands): Non-stationary data some states are rare or far from the normal; transitions may have occurred
- (iv) Periodic/quasi-periodic patterns: Cyclicities in the process; the time distance between periodic patterns (e.g. lines) corresponds to the period; different distances between long diagonal lines reveal quasi-periodic processes
- (v) Single isolated points Strong fluctuation in the process; if only single isolated points occur; the process may be an uncorrelated random or even anti-correlated process
- (vi) Diagonal lines (parallel to the LOI) The evolution of states is similar at different epochs; the process could be deterministic; if these diagonal lines occur beside single isolated points, the process could be chaotic (if these diagonal lines are periodic, unstable periodic orbits can be observed)
- (vii) Diagonal lines (orthogonal to the LOI) The evolution of states is similar at different times but with reverse time; sometimes this is an indication for an insufficient embedding
- (viii) vertical and horizontal lines/clusters Some states do not change or change slowly for some time; indication for laminar states
- (ix) Long bowed line structures the evolution of states is similar at different epochs but with different velocity; the dynamics of the system could be changing

5.5 Classification Using Convolution Neural Network:

5.5.1 An overview of Convolutional Neural Networks (CNNs)

Convolutional Neural Networks (CNNs) are a type of advanced neural networks that are specifically engineered to handle data with a grid-like structure, typically employed for assessing visual imagery. Convolutional Neural Networks (CNNs) have demonstrated remarkable efficacy in several tasks, including but not limited to image identification, object detection, and image segmentation. The success of CNNs stems from their capacity to

autonomously and hierarchically acquire spatial hierarchies of information from unprocessed pixel inputs [39].

Some key concepts:

- **Convolutional Layers:** The fundamental components of CNNs are convolutional layers, which utilize filters (sometimes referred to as kernels) to process the input data and extract features such as edges, textures, and patterns. Contrary to conventional neural networks, which consider each input pixel separately, CNNs maintain the spatial arrangement of the data, enabling them to identify objects irrespective of their location in the image [40].
- **Activation Functions:** Non-linear activation functions, such as the Rectified Linear Unit (ReLU), are applied after each convolution operation. ReLU introduces non-linearity into the model, enabling it to learn more complex representations of the data [40].
- **Pooling Layers:** To reduce the spatial dimensions of the feature maps while retaining important information, CNNs use pooling layers. Commonly used pooling operations include sum pooling, max pooling (which takes the maximum value from a region) and average pooling (which takes the average value). This down sampling helps reduce the computational complexity and prevents overfitting [40].
- **Fully Connected Layers:** Following a series of convolutional and pooling layers, the extracted high-level features are transformed into a flattened format and then propagated through fully connected layers. The final classification judgments are determined by these layers, which utilize the characteristics extracted by the convolutional layers[40].
- **Dropout:** A regularization technique commonly used in CNNs is dropout, which randomly sets a fraction of the neurons to zero during training. This prevents the network from becoming too reliant on specific neurons and helps reduce over fitting [40].

For this thesis purpose basic CNN architecture are used. The Model is like the following specification-

Table. 5.2. Model Specification

Optimizer	Adam
-----------	------

Batch Size	30
No of Epoh	50
Learning Rate	0.001

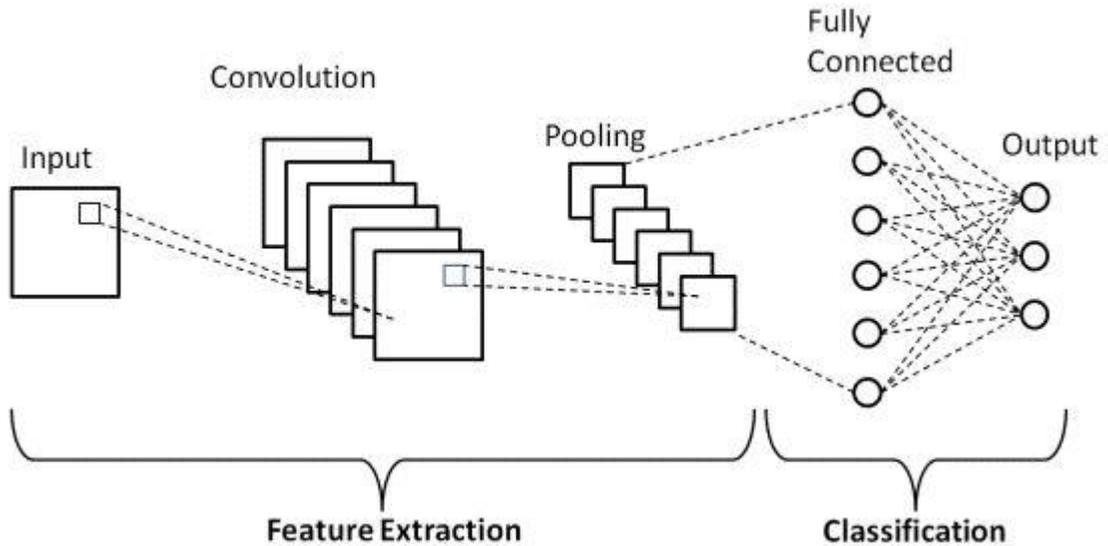


Fig: 5.9. Scheme of CNN

5.5.2 Results:

As a result from our CNN Model we have achieved an accuracy of 85.48% Test accuracy after testing 105 images for 15 No of Classes. We can view the performance of model by using some graphs and through Confusion Matrix.

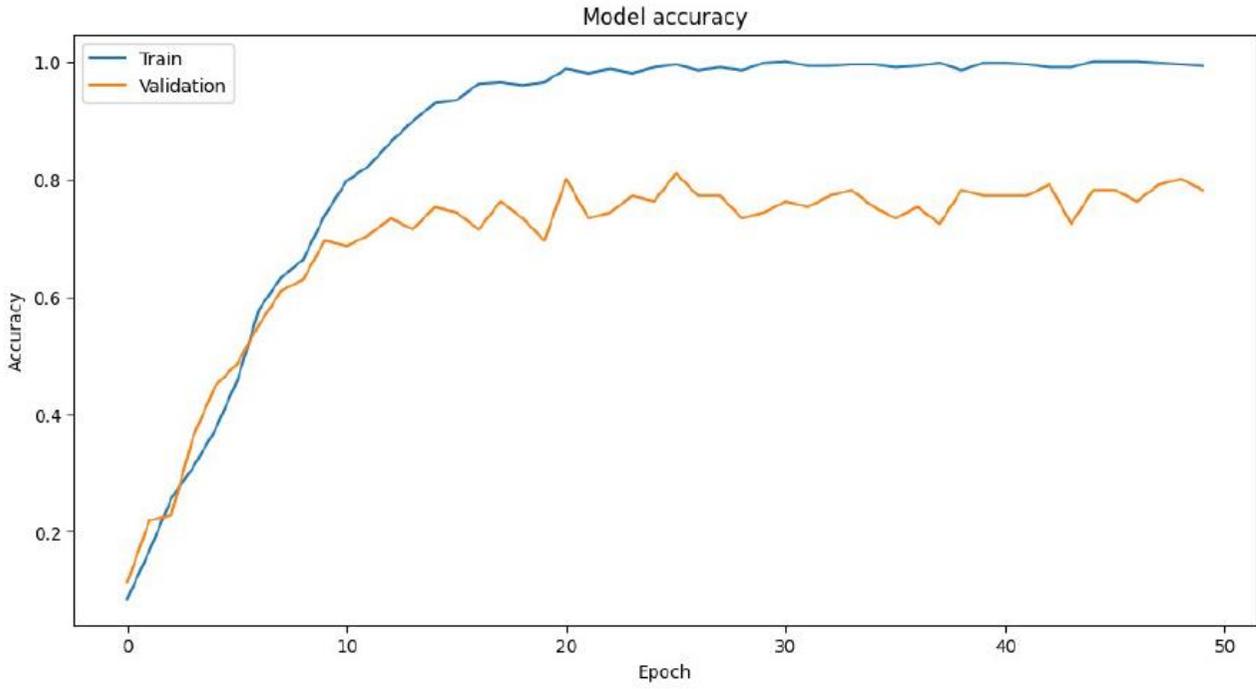


Fig: 5.10. Graph: Train and Validation Accuracy vs Epoch

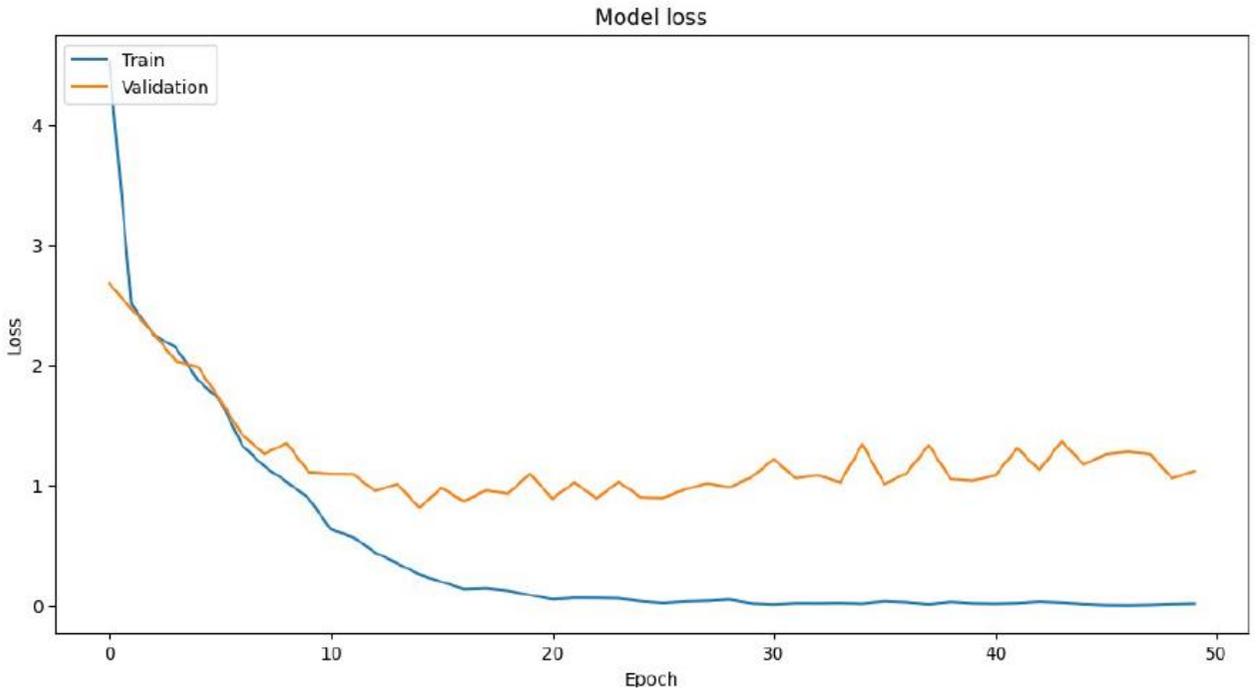


Fig: 5.11. Graph: Train and Validation Loss vs Epoch

5.5.2.1 Confusion Matrix:

This confusion matrix is a tool used to evaluate the performance of your classification model. It shows how many instances of each class your model predicted correctly (the diagonal values) and how many instances it misclassified (the off-diagonal values). Let's break it down:

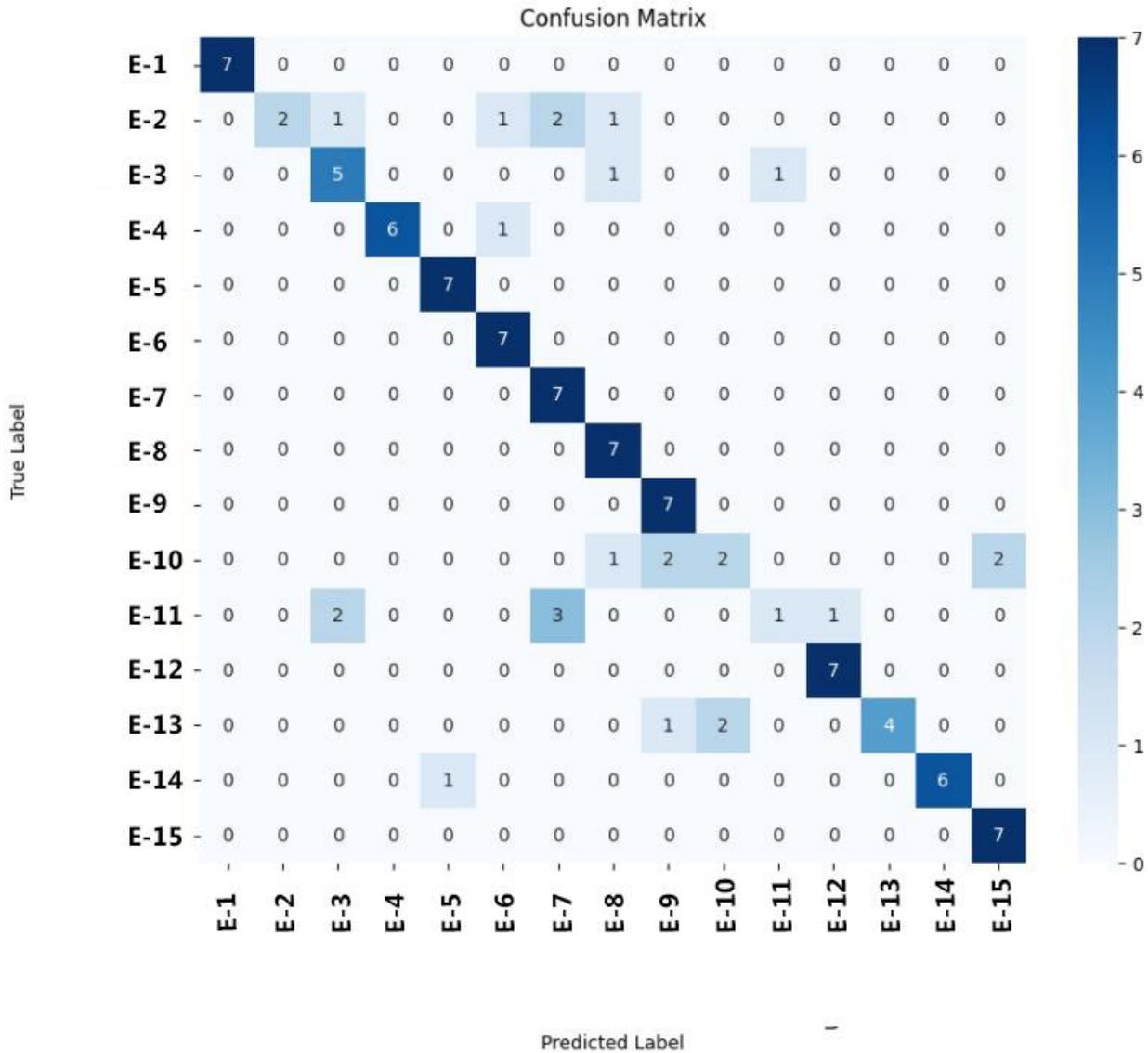


Fig: 5.12. Confusion Matrix

The confusion matrix is a visual representation of the performance of a CNN (Convolutional Neural Network) model, showing how well the model's predicted labels match the true labels. Here's a detailed description of the matrix you provided:

- **Axes:** The vertical axis represents the true labels (E-1 to E-15), and the horizontal axis represents the predicted labels (E-1 to E-15).

- **Diagonal Values:** The diagonal elements (from the top left to the bottom right) represent correct predictions, where the predicted labels match the true labels.
 - E-1, E-5, E-6, E-7, E-8, E-9, E-12 and E-15 have perfect predictions, with all instances correctly classified (7 out of 7).
 - For other classes, like E-4 and E-14, there are some off-diagonal elements indicating misclassifications.
- **Off-Diagonal Values:** These elements show instances where the true label does not match the predicted label. For instance:
 - E-2 has been misclassified as E-3, E-6, and E-7, E-8 indicating that the model confused these classes.
 - Similarly, E-11 was misclassified as E-3, E-7 and E-10 has several misclassifications across other classes.
- **Colour Coding:** Darker colours represent higher values, meaning more instances in those categories. The darkest shades are along the diagonal, indicating strong performance for several classes, while lighter shades indicate fewer instances, often representing misclassifications.

Overall, the CNN model performs well for certain classes (with perfect accuracy), but there are a few classes with notable confusion, indicating areas where the model might need further tuning or training data.

6. Conclusions and Future Scope

6.1 Conclusions:

This thesis examines common challenges associated with preserving the condition of insulators on overhead electricity lines. Transmission line insulators deteriorate over time due to various atmospheric pollutants, including salt, dust, and chemical contaminants. Consequently, it is crucial to monitor the state of overhead insulators in order to enhance the stability of the electrical system. This thesis proposes the use of leakage current signal-based approaches as a means to accomplish so. The methods proposed can provide a nearly accurate prediction of the surface condition of an overhead insulator.

The current study investigated the impact of contamination on the leakage current magnitude of a Porcelain Disc insulator string in the High-Tension Laboratory at Jadavpur University. This experiment was performed on a string of 3-disc Porcelain insulator that was slightly polluted, and it was tested at various voltage levels. An experimental setup has been established to measure the leakage current of an overhead Porcelain insulator. To investigate the impact of surface contamination, an insulator sample was deliberately contaminated using the solid layer approach. The observed leakage current via this arrangement provides valuable information regarding the surface quality of the insulator. Additionally, it was observed that the rate at which leakage current increases is higher in the case of a polluted insulator compared to a clean one.

This thesis introduces a system that combines Recurrence Plot and Convolution Neural Network to accurately categorize leakage current signals for various partially contaminated insulators.

RP Method is used as a method for extracting visual features of the leakage current signal. Mathematical morphology is a useful technique for extracting features from leakage current data. The thesis used the Convolution Neural Network Method for classification purpose and the model achieved 85.48% accuracy. Overall, the combination of RP Plot and CNN classification offers a thorough and strong approach for identifying the location of contamination on silicone rubber insulators using leakage current data.

6.2 Future Scope:

The insights acquired and addressed in this thesis can serve as a foundation for future research in other disciplines. The current thesis focuses on predicting the identification of contamination locations on porcelain insulators. The framework presented in this thesis is highly efficient and may be utilized to monitor the operational status of an overhead insulator. The following list comprises a selection of potential scopes.

1. Only porcelain insulators were utilized in this thesis. This technique has the potential to be expanded to encompass additional types of insulators and other protection equipments.
2. Utilizing contemporary signal processing methods, such as graph signal processing, to enhance the precision of locating contamination on polymer insulators. This has the ability to accurately depict intricate spatial connections between areas of contamination on the surface of the insulator.
3. Location detection of contamination on polymer insulators can be achieved by applying several classification approaches, such as ANN (Artificial Neural Network) and SRC (Sparse Representation Classifier), etc on the data.
4. Acid rain can have an impact on insulators. The potential impact of acid rain on porcelain, polymer, and glass insulators may be a subject of future investigation.
5. Here we have used only two contamination approaches very high and very low. For future works other contamination levels can be also adapted.
6. Researchers must explore the diverse effects that various substances have on insulators in the industrial belt with using Coal dust type material in order to monitor their status.
7. By integrating data from many sources, such as visual pictures, leakage current measurements, and infrared imaging, a more comprehensive assessment of insulator conditions can be achieved, leading to improved accuracy in forecasts.

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