Localization of Contamination on the Surface of the Silicone Rubber Insulator Used in the Overhead Transmission Line

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

by

Surajit Mondal

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Under the guidance of

Prof. Sovan Dalai

DEPARTMENT OF ELECTRICAL ENGINEERING

FACULTY OF ENGINEERING AND TECHNOLOGY

JADAVPUR UNIVERSITY

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JADAVPUR UNIVERSITY

KOLKATA- 700032, INDIA

FACULTY OF ENGINEERING AND TECHNOLOGY

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This is to certify that the thesis entitled "***Localization of Contamination on the Surface of the Silicone Rubber Insulator Used in the Overhead Transmission Line***" is being submitted by **SURAJIT MONDAL** (Registration No. 160169 of 2021- 2022), 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.

Prof. Sovan Dalai
Professor,
Dept. of Electrical Engineering,
Jadavpur University
Kolkata – 700032

Prof. Biswanath Roy
Head, Dept. of Electrical Engineering
Faculty of Engineering and Technology
Jadavpur University
Kolkata – 700032

Prof. Saswati Mazumdar
Dean
Faculty of Engineering and Technology
Jadavpur University
Kolkata – 700032

JADAVPUR UNIVERSITY

KOLKATA- 700032, INDIA

FACULTY OF ENGINEERING AND TECHNOLOGY

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The foregoing thesis is hereby approved as a credible study of Master of Electrical Engineering and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion therein but approve this thesis only for the purpose for which it is submitted.

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

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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Name : **SURAJIT MONDAL**

Class Roll no. : **002110802013**

Exam Roll No. : **M4ELE23013**

Registration no. : **160169 of 2021-2022**

Title of the thesis **:** ***Localization of Contamination on the Surface of the Silicone Rubber Insulator Used in the Overhead Transmission Line***

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Signature with date:

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Contents

1. CHAPTER 1

INTRODUCTION

1.1. Background

High voltage distribution and transmission, as well as the usage of high voltage insulators, particularly in high voltage transmission lines, have become unavoidable due to the rise in power consumption in all industries. These insulators are exposed to electrical and mechanical stressors in addition to the whims of nature like rain, fog, humidity, snow, and pollution depending on their location, whether it be coastal or semi-arid locations. The point being made is that we need to ensure the reliable operation of the insulators and subsequently of the entire transmission system because they are thought to be the weakest link in the high voltage insulation system, failure of which results in the failure of the entire transmission system.

Porcelain and glass, which are conventional ceramic insulators, are inert, stable materials that didn't experience any surface deterioration, but because of their high surface energy, these materials have a high degree of wettability when exposed to moist environments like rain, fog, and dew. Leakage current rises when insulators are dirty and moist, which may cause flashover and system failure. Due to their ability to sustain high tensile strengths and overcome the traditional issues with porcelain and glass insulators, polymeric insulators have begun to gain popularity. On a surface level, they also benefit from being significantly lighter in weight, more affordable to install and maintain, and less vulnerable to vandalism. Technically speaking, compared to ceramic insulators, it has a very high resistance to flashover, puncture, tracking, and erosion. Due to its great hydrophobic feature, or excellent waterrepellency, polymeric insulators perform far better than ceramic insulators when exposed to contamination and pollution.

Due to these factors, at present polymer insulators are most preferred in power sector because of its superior insulation performance. Polymer insulators are also called composite insulator. The term composite mentions to the insulator having fibreglass core that gives mechanical strength. Either high temperature vulcanised (HTV) or room temperature vulcanised (RTV) silicone rubber may be utilised as the bulk material for composite insulators in new installations. (SiR). Two significant classes of housing material are utilized in present time for construction of composite insulator. First one is ethylene propylene diene monomer (EPDM) dependent and the other that are dependent on silicone. EPDM have very tracking resistance and high mechanical strength. The silicone, however, has a higher resistance towards ultraviolet through in extremely contaminated condition. Polymer insulators are thus more favoured to be used in the sectors having significant marine and industrial contamination.

The reliable operation of power transmission systems is of paramount importance for ensuring a consistent supply of electricity to communities and industries. Polymer insulators have gained widespread use due to their lightweight design and durability, contributing to the efficiency and resilience of these systems. However, the presence of contamination, such as dust, salt, and pollutants, on insulator surfaces can undermine their performance and compromise system reliability.
This thesis addresses the critical issue of identifying the precise location of partial contamination on polymer insulators and subsequently classifying the severity of

contamination levels. Our research employs the innovative application of Support Vector Machines (SVM), a powerful machine learning technique, to tackle this complex challenge. SVM is a machine learning method used for regression and classification tasks. SVM is used in this thesis for analysing the data on leakage currents produced by contaminated polymer insulators. SVM can be used to find trends in the data and categorise insulator behaviour using attributes gleaned from leakage current measurements.

1.2. Literature Review

Insulator plays a highly significant function in power systems by separating live components from each other and from ground, as well as by providing mechanical protection. Insulators have seen widespread use across a variety of networks, including substations, transmissions, and distributions [1].

Polymer insulators have had a significant presence in the power system for a very long time and continue to have a significant amount of importance in both the transmission and distribution systems. However, because they are intended to be used outdoors, they are susceptible to a number of flaws, particularly when subjected to particular environmental conditions, such as when the air is humid, when it is raining, or when there is pollution, all of which cause a decrease in their surface resistance. Because of the decrease in surface resistance, the amplitude of the leakage current that flows on the surface is increased [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 polymer insulators are hydrophobic in nature, they not promote the production of continuous water films in the event of humid conditions or during the rainy season.

Insulators that can withstand high voltage are extensively used in transmission and distribution lines. Their primary function is to physically separate two electrical conductors as well as electrical conductors from towers. Insulators that are situated in places that are prone to industrial activity or that are near the shore are more likely to be contaminated by salt deposits and industrial dust, respectively. In conditions of high humidity and rain, the layers will get wet and conductive, which will cause leakage current (LC) to flow over the surface of the insulator. 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 amplitude and 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 M. Amin et al. [13] demonstrates that the use of composite insulators in decreases the leakage current significantly even in the presence of pollution, as well as various LC measuring techniques. An extensive survey on the micro and nano-filler to improve the performance of outdoor silicone rubber insulator was done by G. Momen and M. Farzaneh [14]. The results of this survey showed that aluminium trihydrate (ATH) and Alumina were the most commonly used filler, with Alumina being the reinforcing filler because it increases the tensile strength and ATH being the extending filler because it imparts tracking resistance and also acts as a flame retardant. Additionally, the impacts of different inorganic, metallic, carbonaceous, and organic fillers have been investigated by them as well.

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.

1.2.1. Feature Extraction from Leakage Current Data

In recent years, researchers have turned to data-driven approaches for contamination analysis. Leakage current data collected from insulators can reveal valuable information about their condition. Feature extraction plays a pivotal role in converting raw data into meaningful inputs for classification algorithms. One promising method for feature extraction is mathematical morphology.

1.2.2. Mathematical Morphology for Feature Extraction

Mathematical morphology, a branch of image processing, offers tools to analyze shapes and structures within data. In the context of insulator contamination, mathematical morphology can be employed to extract relevant features from leakage current signals. Morphological operations such as erosion, dilation, opening, and closing can enhance the distinguishability of contamination-related patterns.

1.2.3. mRMR Algorithm for Feature Selection

The mRMR algorithm is a feature selection method that evaluates the relevance and redundancy of individual features in a dataset. It aims to identify the most informative and distinct features while minimizing feature redundancy. The algorithm evaluates the relevance of a feature to the target variable and its mutual information with other features. The mRMR algorithm helps mitigate the curse of dimensionality by selecting a compact set of features that offer maximum discriminative power. Recorded leakage current data is collected from insulators under varying contamination scenarios. Preprocessing steps include noise reduction, outlier removal, and normalization. Mathematical morphology operations (erosion, dilation, etc.) are applied to the raw leakage current signals to extract transformed signals that potentially highlight contamination-related patterns. For each transformed signal, relevant features are extracted. These could include amplitude variations, frequency components, and temporal characteristics. The extracted features are then subjected to the mRMR algorithm. The algorithm assesses the relevance and redundancy of features, ranking them based on their contribution to classification accuracy. A subset of features is selected based on the mRMR rankings. This subset contains the most relevant and non-redundant features, improving the efficiency of subsequent classification.

1.2.4. Support Vector Machines (SVM) for Classification

Support Vector Machines have gained significant popularity for their effectiveness in classification tasks. SVM constructs a hyperplane that best separates data points of different classes. The kernel trick allows SVM to efficiently handle nonlinear relationships in high-dimensional spaces. SVM's ability to generalize well from limited training data makes it a suitable candidate for analyzing leakage current data**.** While existing research has made strides in contamination analysis using SVM, a gap remains in methods that combine mathematical morphology for feature extraction with SVM for both location identification and classification of contamination severity. The proposed thesis aims to bridge this gap by presenting a comprehensive methodology that leverages both techniques for enhanced accuracy and precision in insulator contamination assessment.

1.3. Scope of the Thesis

The scope of the thesis focused on the "Identification of Location and Classification of Partially Contaminated Insulators" is quite specific and addresses a critical aspect of power system maintenance and reliability. Let's delve into the scope and potential components of this thesis:

1.3.1. Location Identification:

Problem Statement: The thesis aims to address the challenge of identifying the specific location on a transmission line where a polymer insulator is partially contaminated. This is important because different sections of the insulator might experience varying levels of contamination due to factors such as wind direction, rain, and environmental conditions.

Sensor Placement: The thesis could discuss the strategic placement of sensors along the insulator's length to capture leakage current data at different points. These sensors could be capacitive or resistive type, capable of measuring current or voltage fluctuations along the surface.

1.3.2. Classification of Contamination:

Problem Statement: Apart from identifying the location, the thesis could also focus on classifying the degree or severity of contamination. Different levels of contamination might lead to varied leakage current patterns.

Feature Extraction: The thesis might explore techniques for extracting meaningful features from the collected leakage current data. These features could capture characteristics such as frequency components, amplitudes, and time-domain behaviour.

Machine Learning Algorithms: In addition to SVM, the thesis could consider other machine learning algorithms suitable for classification tasks. These might include Support Vector Machine methods. The goal would be to create a model capable of accurately identify which part of the insulator partially contaminated based on the extracted features.

1.3.3. Data Collection and Analysis:

Experimental Setup: 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.
Data Preprocessing: Discussing the steps taken to preprocess the collected data, which might include noise reduction, data smoothing, and outlier removal.
Data Labeling: Assigning appropriate labels to the collected data, indicating which part of the insulator is partially contaminated each location.

1.3.4. Algorithm Development and Validation:

- ✓ **Model Development:** Designing and implementing algorithms or models that can take the extracted features as inputs and provide accurate location of the insulator contaminated.
- ✓ **Training and Validation:** Training the developed models on a subset of the data and validating their performance on another subset. Using appropriate metrics to assess accuracy, precision, recall, and F1-score.

1.3.5. Real-world 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.

1.3.6. Limitations and Future Work:

- ✓ **Discussing Challenges:** Addressing any limitations of the proposed methodology, such as the potential impact of environmental factors on measurements.

- ✓ **Future Extensions:** Suggesting avenues for future research, which could include incorporating real-time data streaming, integrating data from multiple sensors, and exploring the potential of emerging technologies like IoT and edge computing.

In summary, the thesis scope revolves around developing a methodology for both identifying the location and classifying the degree of contamination on partially contaminated insulators in power transmission systems. The work has practical implications for maintaining the reliability of power infrastructure, minimizing downtime, and improving the overall efficiency of the power grid.

1.4. Contribution of the Thesis

The contribution of the thesis titled "Leakage Current Analysis of Transmission Line Polymer Insulator under Partial Contamination using Support Vector Machines (SVM)" lies in its exploration of the behavior of polymer insulators in transmission line systems when subjected to partial contamination, with a focus on analyzing leakage currents using Support Vector Machines (SVM).

Transmission line insulator partial contamination is an important problem for the current power grid. When there is moisture present, the leakage current in a partially contaminated insulator increases significantly. In the end, it will result in flashover. Therefore, it is important for analysing the partial contamination of different insulator locations. Therefore, a system that can perfectly classify the data from various partial contaminated insulator locations is necessary. In considering this, a method has been put down in which mathematical morphology is used to extract features from leakage current data and support vector machines (SVM) classification is used to classify the features and identify the various locations of partial contaminated insulator. SVM is a machine learning method used for regression and classification tasks. SVM is used in this thesis for analysing the data on leakage currents produced by contaminated polymer insulators. SVM can be used to find trends in the data and categories insulator behaviour using attributes gleaned from leakage current measurements. The results of this thesis indicate the efficiency of the suggested method for correctly classifying the features and identifying the various Location (which part of the insulator contaminated) of partial contaminated Insulator. Finding the insulators that require repair will be made much easier with the help of this strategy.

1.5. Thesis Organisation

The next chapter that is **Chapter 2** will be deals with the different outdoor insulators that have been in use. Their Degradation, ageing comparative study of the outdoor insulators.

Chapter 3 presents different condition assessment techniques of high voltage insulators.

Chapter 4 deals with the experimental setup and artificial contamination procedure for leakage current measurement.

Chapter 5 presents the experimental results of the leakage current measurement, the leakage current analysis, localization of contamination on the surface of the silicone rubber insulator used in the overhead transmission line..

Chapter 6 provides conclusions from the present study and the future scope of the work.

2. CHAPTER 2

BACKGROUND OF
OUTDOOR INSULATORS

2.1. Introduction

Use of electrical insulators was started a long time ago – around late 1970s.There are numerous books and websites devoted to the subject of electrical insulators which indicate that insulators as we know today originated in the late 1890s with the development of wet process porcelain and glass insulators of adequate quality to withstand the rigors of service. Electrical power is transferred in its entirety via the electrical power distribution and transmission network from generating stations to substations that are close to demand centers [1-14]. The need for electricity has been steadily rising. Electrical utilities want to transmit power at high voltages to offset the demand for power. High-tension overhead lines that lack insulation are still exposed. Aluminium alloys, which are mostly used to make conductors, are manufactured into many strands and may be strengthened with steel strands [1-3]. Sometimes copper is used for overhead transmission, but aluminium is lighter in weight, has just slightly worse performance, and costs significantly less. Recently, 110 kV and higher voltages have been used to carry power through overhead transmission lines [1-5]. As a result, voltages at this level (110 kV and above) are typically referred to as transmission line voltages. On the other hand, lower voltages, like as 33 kV and 66 kV, are occasionally used on long transmission lines with light loads despite being typically regarded as sub transmission voltages [1-5]. The typical voltage used for distribution systems is below 33 kV. Extra high voltage is defined as voltages of 230 kV or more, while ultra-high voltage is defined as voltages of 765 kV or more. Compared to equipment used at lower voltages, ultra-high voltage network demands different design methods [1–5]. Increasing the transmission efficiency is one of the main benefits of power transmission at high voltages. Insulation is one of the most crucial components of any electrical system. The network of the electricity system can be harmed by insulation failure. The main factors that contribute to insulation failure in a power system network include excess voltage, excess current, lightning strikes, and short circuits. Additionally, high heat or cold, vibration, corrosive vapor, and dirt are all causes of mechanical degradation that can result in electrical insulation damage. The weakest insulation location is where there is a high probability of insulation failure. Insulation restricts the flow of current between conductors maintained at various potentials as well as between the ground and the active conductor. Electrical shocks and damage to the entire power system network are both risks that could arise from insulation failure Typically, an insulation system. The majority of insulation systems are made of non-metallic materials. Electrical insulations are often made of materials like paper, rubber, mica, plastic, polyvinyl chloride, etc. Considering an overhead power line, Insulators provide crucial insulation between a line's conductor and its supporting structure, preventing leakage current from flowing from the conductor to the ground [1-12]. Prior to that time, many different materials were used ranging from wood to cement then to glass. In that period from the late 1700s to the late 1800s, application was associated with telegraph lines and thus voltages were low. Gradually with the increase of technical needs, high voltage AC transmission became very mush important and the need for good electrical insulators became a real necessity. It is the low reliability that is purported to have been the driving force behind the development of the modern insulator by Fred M. Locke (1861-1930). While Locke and subsequent early developers patented many unique designs of insulators. Their real contribution was in the development of a material that meets the required mechanical and electrical properties. The history of insulators in the twentieth century can be divided into two distinct eras,

- Ceramic era (porcelain and glass) and
- Non-ceramic (NCI) era.

Ceramic and glass insulators dominated until the early 1970s, when various new types insulators had been used based on organic rather than inorganic insulating materials. Ceramic materials such as porcelain and glass are strong and rigid, under appropriate, controlled loading conditions they are mechanically strong. They are excellent insulating materials electrically.

The materials that are predominantly used for NCIs (silicone rubber or Ethylene Propylene rubber / Ethylene propylene Diene Monomer rubber) are not mechanically strong enough-in fact they are quite weak. Use of these materials required that some other method be found to provide the primary mechanical support. The solution was the use of the fiberglass rod (core) surrounded by the rubber weather sheds which is the common feature of most NCIs in use today. The reason for this change in materials is due to the following advantages:

i. Lighter weight
ii. Higher tensile strength
iii. Easier handling
iv. Greater toughness

Improved surface properties such as hydrophobicity that improves the insulating performance under contaminated conditions.

The search for better insulators – better materials, better designs a, better manufacturing methods continues still now and will continue in future. Ceramic insulators have seen tremendous improvements in quality, consistency of the materials, manufacturing process (both improving quality and reducing costs), the development of designs and materials specifically intended for application in contaminated environments. Though the use of NCIs stared nearly 40 years ago – the development process has been extremely rapid, with current designs, materials and manufacturing methods being generations ahead of the original attempts.

2.2. Types of Insulators

Insulators used in transmission line serve two purposes: one mechanical and the other electrical. Mechanically, the insulators lend support for the wires. They withstand the forces of the weight of the wires and the forces of the wind (also the forces when there is an electrical fault on the line) Electrically, they keep the wires away from the towers and keep them at a safe distance so that an arc will not be established between the wire and the metallic elements of the tower. For the successful operation of power lines, proper selection of insulators is very essential. There are several types of overhead line insulators. Most commonly used insulators are as follows:

- Pin type Insulator

- Post type Insulator
- Suspension type Insulator
- String Insulator
- Shackle Insulator
- Stay Insulator

2.2.1. Pin Insulator:

Pin type insulators or pin insulators (as shown in Fig. 2.1.) are most commonly used for supporting line conductors up to 33 kV voltage level. They are mounted on a pin which in turn is secured to the cross-arm of the pole. There is a groove on the upper end of a pin insulator for housing the conductor. Conductor wire is passed through this groove and tied down with the same wire as that of conductor. A pin insulator is usually made from porcelain, but glass or plastic may also be used in some cases. As pin insulators are almost always employed in open air so proper insulation while raining is also an important consideration. A wet pin insulator may provide a path for current to flow towards the pole. To overcome this problem, pin insulators are designed with two or three (depending on voltage level) pieces of porcelain cemented together which are called rain sheds or petticoats. Beyond operating voltage of 33kV, pin insulators become too bulky and uneconomical.

For lower voltage, a single-piece pin insulator is employed. For applications requiring higher voltage, two or more pieces are bonded together to provide an acceptable creepage distance and thickness [3]. Typically, pin insulators are used for operating voltage up to 33 kV. Disc and suspension insulators are utilised above this voltage.

Fig. 2.1. Pin Insulator

2.2.2. Post Insulator:

Post insulator is more or less similar to pin insulator but former is suitable for higher voltage application [2]. Post insulator (as shown in Fig. 2.2.) has higher numbers of petticoats and has greater height. This type insulator can be mounted on supporting structure horizontally as well as vertically. The insulator is made of one piece of porcelain but has fixing clamp arrangement are in both top and bottom end. In general, post insulators are used to support bus-bars, isolator switches, etc. [2,5].

Fig. 2.2. Post Insulator

2.2.3. Suspension Insulator:

As it is already mentioned above, pin insulators become too bulky, cumbersome and uneconomical beyond 33 kV. So, for voltages higher than 33 kV, suspension insulators (as shown in Fig. 2.3.) are used [1-5]. A suspension insulator consists of a number of porcelain discs flexibly connected in series with each other with metal links in the form of a string. The suspension insulator hangs from the cross-arm of the supporting structure and the line conductor is attached to its lower end. Each disc in a suspension insulator string is designed for a low voltage, say 11 kV. The number of discs in a string depends on the working voltage, the weather condition and the size of insulator used. 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].

❖ **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 the event of failure of an insulator, only the damaged unit is replaced. Replacement of the whole string is not required.
- In case of increased demand on the transmission line, the line voltage can be increased and the additional insulation required for the raised voltage can be easily obtained by adding the desired number of discs to the insulator strings.
- Suspension type insulators provides 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.

Fig.2.3. Disc Insulator

2.2.4. String Insulator:

Multiple discs are joined in series in a string insulator (as shown in Fig. 2.4.). Typically, it serves as a dead-end insulator [3]. Where there is a dead end of a transmission line or at a corner or sharp curve, the transmission line is subjected to greater tensile load. In order to sustain this great tension, strain insulators are used at dead ends or sharp corners. For low voltage lines (say up to 11 kV), shackle insulator can be used but at high voltage transmission lines, strain insulator consisting of an assembly of suspension insulators are used. In this case, the suspension string is arranged horizontally and the insulator discs are in vertical plane [3,4]. Two or more suspension strings can be assembled in parallel to sustain greater tensile load.

Fig. 2.4. String Insulator

2.2.5. Shackle Insulator:

In distribution networks, this kind of insulator (as shown in Fig. 2.5.) is typically utilised [3-5]. It can be used for low voltage transmission lines generally [3]. Both horizontal and vertical application are possible for shackle insulators [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.

Fig. 2.5. Shackle Insulator

2.2.6. Stay Insulator:

The insulator is used in guy wire, where it is necessary to insulate the lower part of the guy wire from the pole for the safety of people and animals on the ground (as shown in Fig. 2.6.). The stay insulator is usually of porcelain and so designed that in case of breakage of the insulator the guy wire will not fall to the ground. The size of the insulator (small or large) depends on the tensile strength [3-5].

Once more, insulators can be divided into hydrophilic and hydrophobic insulators based on their characteristic [3-12]. Glass and porcelain are hydrophilic insulators, which means that a continuous sheet of water accumulates on such surfaces. In general, polymer insulators have a hydrophobic nature. The surface energy of polymers is low. Due to these phenomena, the polymeric material is compelled to prevent the development of continuous water film. It solely results in the creation of solitary water droplets [12].

Fig. 2.6. Stay Insulator

2.3. Insulating Materials

A crucial component of the transmission and distribution networks for power systems is the transmission line insulator [10]. In the power system network, insulators mostly fall into two categories. The majority of those are polymers and non-polymers [10]. Glass or porcelain are the two most common materials used to make ceramic insulation. Currently, distribution and transmission networks also use polymer insulators. The main insulation materials used for outdoor insulation are glazed porcelain, toughened glass and polymers. The microscopic structure of each material affects directly its mechanical and electrical properties. Each of these materials is described below

2.3.1. Porcelain Material

Porcelain has been utilised as an insulator material since the beginning of time and is still in use now. Porcelain is often made of ceramic [3-5]. The fundamental materials used for the manufacturing of porcelain insulators are clay, quartz and feldspar. Inorganic minerals and clays are used to make porcelain insulators (shown in Fig. 2.7.), which, after being burnt in a kiln, are composed of silicate crystals and various oxides in the form of a glassy matrix [3-5]. It becomes completely impermeable to moisture while being completely transformed by the firing procedure [3]. The insulator is usually coated to give it a smoothened surface that prevents contaminants from adhering to it and makes it easier to wash vital items with rainwater [3, 4]. Another crucial function of this glaze is to provide a compressive outer layer. It both prevents the development of surface cracks and boosts mechanical strength [3]. The photograph of the porcelain insulator has been shown in Fig. 2.7. and the parameters of the porcelain insulator have been tabulated in Table 2.1.

Table 2.1. Parameters for 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)

❖ **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.
- 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

Fig. 2.7. Porcelain Insulator

2.3.2. Glass Material

Because glass has a higher dielectric strength than porcelain insulator, it is also utilised to make transmission line insulators. It is primarily utilised for EHV DC and AC power networks, though. Glass is made tougher by heating it. While the inner surface of the insulator cools extremely continuously, the surface must cool very quickly during the toughening process [3-5]. To prevent the development of micro-cracks on the surface and to delay crack propagation, the differential rate for solidification process creates lifelong compressive pre stressing for the outer sections [3-5]. Silica, limestone, dolomite, feldspar, soda ash and salt cake or sodium sulphate are mixed and melted at temperature up to 1500. The molten glass is then poured in a mould to form the glass disc of the cap-and-pin insulator. After removing the disc from the mould, it is thermally toughened to enhance its mechanical properties. After a quality inspection, the flawed units are rejected and the metal fittings are attached. Toughened glass has increased mechanical properties compared with porcelain cap-and-pin insulators.

Glass has a lower melting point than porcelain, making it more vulnerable to surface erosion due to the heat produced by surface discharges. Problems occur in polluted environments where channelling of the glass surface especially at the underside undermines the mechanical strength of the unit .cap-and-pin insulators, both porcelain and glass, can form chains to support large mechanical loads. They retain their structural integrity even if the dielectric of a unit is ruptured. However, ceramic insulators are brittle and thus susceptible to vandalism attacks or shooters. For polluted conditions, the flashover performance of ceramic insulators is significantly reduced and larger creepage is required thus resulting in heavy and bulky insulator units. The need to reduce the size of high voltage electrical systems introduced the use of polymeric insulators that are lightweight and due to their water-repellent properties have superior performance in polluted environments [3-5]. The photograph of the glass insulator has been shown in Fig. 2.8. and the parameters of the glass insulator have been tabulated in Table 2.2.

Table 2.2. Parameters for 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)

❖ **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.

❖ **Disadvantages of Glass Insulator**

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

Fig. 2.8. Glass insulator

2.3.3. Polymer Material

Because of their high insulating performance, polymer insulators are currently the most popular choice in the power industry [5]. Composite insulators are another name for polymer insulators, which is depicted in Fig. 2.9. [5]. According to, the term "composite" refers to an insulator with a fiberglass core that provides mechanical strength [3-5]. The housing serves as both a shield from the elements and a source of the appropriate electrical properties for the core. Polymers are mostly used for housing materials of composite insulators. The housing encases a fibrous composite core of high mechanical strength. The polymer housing should protect the core from any damage deriving from invasion of water and humidity or leakage current and discharges and also provide the insulating profile. The profile should control the leakage current on its surface by providing the necessary creepage distance and minimize the catching of air borne contaminants on its surface. The lightweight composite insulators provide a high strength to weight ratio and are more compact as they provide a longer creepage for a given axial length compared with ceramic insulators. Moreover, the non-brittle housing protects the unit from vandalism attacks. They also have a smaller overall diameter that tends to reduce leakage current and improves its performance in polluted environments.

Polymers consisting of silicone structure show a superior contamination performance that is attributed to the water-repellent properties of their surfaces. Unlike ceramic materials, the surface free energy of these polymeric materials is low and as a result they do not allow water to settle on the surface in a form of thin layer but forces it to form separate discrete beads [5]. The hydrophobic nature of such polymers constitutes a significant advantage compared with ceramic dielectrics. While manufacturing cost of polymeric insulators has been a concern, it has now been argued that composite insulators for transmission lines are economically competitive to porcelain and glass insulators. Unfortunately, all the benefits offered by polymers do not come without problems. While ceramic dielectrics are materials of strong inter-molecular bonds, this is not the case for polymers, hence, making them vulnerable to thermal damage [3-5]. The degradation of polymeric insulators during service has a negative impact on their performance and is caused by the different stresses sustained during service.

Table 2.3. Parameters for Polymer Insulator

Sl. No.	Parameters	Value
1.	Tensile strength	5.09858-203.9432 (kgf/mm^2)
2.	Dielectric constant	<3
3.	Puncture strength	300-520 (kV/mm)

- ❖ **Advantages of Polymer Insulator**
  - Very light weight
  - Very lower installation cost
  - Higher tensile strength
  - Its performance is higher in contaminated areas
  - hydrophobic nature requires less cleaning.

- ❖ **Disadvantages of Polymer Insulator**
  - Electrical failure may result from moisture entering the core.
  - Mechanical failure is also a common occurrence.
  - Deflection in some applications under heavy load.

Fig. 2.9. Polymer Insulator

2.4. Necessary Parameters for Insulator for Evaluation

Some important properties of the insulators on the basis of which their electrical properties performance can be evaluated, some important terms are mentioned below,

2.4.1. Creepage Distance

Creepage distance refers to the shortest distance along the surface of an insulator between two conductive parts. It's a critical parameter in the design and evaluation of insulators used in transmission lines, especially in high-voltage applications. The purpose of creepage distance is to prevent electrical flashover or tracking, which can occur due to surface contamination, humidity, or other environmental factors [10].

Creepage distance is important because it determines the path that a conducting material would need to follow across the insulator's surface to create a short circuit. It helps prevent the formation of electric arcs that could cause damage to the insulator or disrupt the transmission line's operation.

2.4.2. Protected Creepage Distance

The calculation and determination of the protected creepage distance for transmission line insulators involve various factors specific to the application of high-voltage power transmission. The goal is to prevent electrical flashovers and ensure the safe and reliable operation of the transmission lines. If light is directed over the insulators at a 90° angle to their longitudinal axis, it is the section of leakage distances over the lighted part of the insulator that will remain in shadow [10].

2.4.3. Arcing Distance

It is determined by the shortest path through air, outermost part of the insulators, between those portions that generally has the applied voltage between them [3-5]. One of the most important variables is the arcing distances because it significantly impacts the power-frequency and impulsive flashover voltage of the insulator when it is polished [10].

2.4.4. Puncture Distance

It can be explained as the shortest path via insulating materials between those parts that generally have the applied voltage between them.

The diameter of the insulator is another crucial factor. Insulator diameter plays a crucial role. Flashover voltage is influenced by insulator diameter, particularly in areas with snow cover [10]. Insulator's diameter grows if it is covered in snow or ice. Resistance diminishes as diameter rises. Leakage current consequently rises. This in turn increases the probability of flashover condition.

2.5. Degradation of Insulators

The demand for power has significantly increased in this time period [20]. Power sectors must increase the transmission lines' efficiency in order to handle this enormous demand [1–10]. As a result of the electricity sector's liberalisation, each and every customer must have the option of choosing the proper supply network that provides them with the services they need [20]. The network's accuracy is mostly dependent on how the service develops. Faults must be avoided because they result in financial losses for both users and industries [17]. The impact caused by pollution to the transmission line insulator is one of the biggest challenges to maintaining this regularity.

A key worry for the electricity sector is the degradation of line insulators. Insulator degradation has a significant impact on the quality and dependability of power delivery [21, 22]. Insulator degradation is brought on by exposure to high-contamination locations, ice buildup, strong winds, biological pollution, bird droppings, etc. [24]. According to soil resistivity and tower footing resistance, back-flashover caused by overvoltage from a lightning surge can damage insulators [1–5]. Because of this, insulator maintenance must be performed on a regular basis while accounting for all potential sources of stress that could cause insulator breakdown.

2.5.1. Different Factors of Insulator Degradation

Transmission line insulators are exposed to a wide range of environmental factors that can lead to their degradation over time. The degradation of insulators can compromise their electrical performance, reliability, and overall effectiveness in maintaining insulation integrity [24]. Some of the key environmental factors that can contribute to insulator degradation include:

- **Pollution and Contamination:** Airborne pollutants, dust, industrial emissions, and natural debris can accumulate on the surface of insulators. This contamination can create conductive paths and increase the risk of flashovers, especially during wet or humid conditions [24].
- **Moisture and Humidity:** Water and moisture can accumulate on insulator surfaces due to rain, dew, fog, and condensation. Water droplets can increase the surface conductivity and promote tracking, leading to flashovers [24].
- **UV Radiation and Sunlight:** Ultraviolet (UV) radiation from sunlight can cause the surface of insulators to deteriorate over time. UV exposure can lead to surface cracks, erosion, and changes in material properties [11].
- **Temperature Fluctuations:** Wide temperature variations can cause thermal

stress on insulator materials, leading to expansion and contraction. This can result in mechanical stress, cracking, and degradation of the insulator's mechanical and electrical properties [24].

- **Salt and Coastal Environments:** Insulators located near coastal areas or industrial sites with high salt content are prone to accelerated corrosion and material degradation due to the corrosive effects of salt [24].
- **Chemical Exposure:** Exposure to chemicals, such as industrial pollutants or corrosive agents, can deteriorate insulator materials and reduce their effectiveness [14].
- **Mechanical Stress:** Wind, ice, and other mechanical forces can cause physical stress on insulators. Over time, this stress can lead to cracks, chipping, or even breakage of the insulator material [3-5].
- **Vibrations and Vibrational Fatigue:** Vibrations from nearby machinery, equipment, or the transmission lines themselves can lead to vibrational fatigue and structural damage to insulators [24].
- **Wildlife and Bird Droppings:** Wildlife activity, such as nesting birds, can introduce debris and excrement onto insulator surfaces, increasing the risk of flashovers [24].
- **Aging and UV Degradation:** Over time, insulators can naturally age and degrade due to a combination of environmental factors. UV radiation, temperature variations, and moisture exposure can all contribute to aging and reduced performance [11,12].

2.5.2. Mitigation Strategies to Counteract Insulator Degradation

- Regular cleaning to remove contaminants and debris.
- Applying hydrophobic coatings to repel water and moisture.
- Material selection that accounts for environmental resilience.
- Implementing proper maintenance practices.
- Using insulator designs that resist tracking and flashover.
- Monitoring systems that detect degradation and performance changes.

Transmission line operators and engineers must consider these environmental factors and take appropriate steps to ensure the continued performance and safety of insulators in high-voltage applications.

2.6. Ageing of Insulator

In comparison to porcelain and glass insulators, polymeric insulators are more susceptible to ageing. Polymer insulators have seen significant use as high voltage outdoor insulators during the past few decades [1–5]. Because non-ceramic insulators are hydrophobic, their performances are thought to be superior to those of porcelain and glass insulators [10]. Despite the fact that polymeric insulators have several benefits, ageing is inevitable due to their organic makeup. Leakage current flowing to the insulator's surface that results in dry-band arcing is one of the main reasons of ageing [11,12]. UV light and ambient temperature are the fundamental causes of ageing. Numerous factors, such as wet contamination, UV light, Joule heating due to current flow rain, and dry-band arcing, can also contribute to polymeric insulator ageing [11].

There are several factors that can contribute to the aging of transmission line insulators:

- **Environmental Factors:** Insulators are exposed to a wide range of environmental conditions, including sunlight, rain, temperature variations, and pollution. Over time, these factors can lead to physical and chemical changes in the insulating materials, reducing their effectiveness [11,12].
- **UV Radiation:** Ultraviolet (UV) radiation from sunlight can degrade the polymer materials commonly used in insulators, causing them to become brittle and lose their mechanical strength.
- **Pollution:** Airborne pollutants, such as sulfur dioxide and nitrogen oxides, can accumulate on insulator surfaces, forming a conductive layer that can lead to surface leakage currents. This can compromise the insulator's ability to insulate effectively.
- **Corona Effects:** When the electric field around an insulator becomes intense, it can lead to a phenomenon called corona discharge. This can result in the formation of ozone and other reactive species that can deteriorate the surface of the insulator.
- **Thermal Cycling:** The expansion and contraction of insulator materials due to temperature changes can cause mechanical stress and lead to cracking or degradation of the material over time.
- **Mechanical Stress:** Wind, ice, and other mechanical forces can cause physical stress on insulators, potentially leading to cracking or structural damage.

To mitigate the aging of transmission line insulators, several measures can be taken:

- **Regular Inspection and Maintenance:** Regular visual inspections and testing of insulators can help identify signs of degradation and damage early on. Any deteriorated or damaged insulators should be replaced promptly.
- **Cleaning:** Cleaning insulator surfaces to remove accumulated pollutants can help maintain their insulating properties.
- **Coatings:** Applying specialized coatings to insulator surfaces can provide protection against UV radiation and pollution, extending their lifespan.
- **Material Improvement:** Researchers continue to work on developing insulating materials that are more resistant to aging and environmental factors, such as advanced polymers or composite materials.
- **Design Considerations:** Transmission line design should take into account factors like wind load, ice load, and mechanical stresses to minimize the impact on insulators.
- **Corona Control:** Designing the transmission line to minimize corona effects can help reduce the formation of harmful surface layers on insulators.

Ultimately, the goal is to ensure the reliability and safety of power transmission systems by addressing the aging effects of insulators and taking appropriate measures to maintain their effectiveness over time.

2.7. Characteristics Parameters Determining the Insulator Condition

The condition of an insulator is determined by several characteristics and parameters that reflect its performance and health. Insulators are crucial components in electrical systems as they prevent the flow of electricity between conductive parts. Here are some key characteristics and parameters that determine the insulator's condition:

2.7.1. Chemical Parameters

Chemical parameters play a significant role in determining the condition of insulators, especially in outdoor environments where insulators are exposed to various pollutants and contaminants. The interaction between insulator surfaces and chemicals can lead to surface degradation, conductivity, and other issues that affect the insulator's performance. Here are some key chemical parameters that impact the insulator condition.

2.7.1.1. ESDD

Equivalent Salt Deposit Density (ESDD) is one of the methods used the most commonly to track the pollution level of insulators [25]. The corresponding quantity of NaCl is deposited over the surface areas of an insulator, which may have conductivity comparable to that of the actual deposit diffused in the equivalent quantity of water, to determine the ESDD (measured in mg/cm2) [25].

The ESDD method calls for cleaning contaminants from an insulator's surface with demineralized water and determining the conductivity from the results [25].

2.7.1.2. NSDD

It is also useful technique to evaluate the contamination level for insulators. The full form of NSDD is non soluble deposit density. The amount of inert, non-soluble impurities deposited per square centimeter to the surfaces of the insulator is explained by the NSDD [25]. In most cases, wash water solution obtained from the measurement of ESDD is used to calculate NSDD [25]. A clean, pre-weighed, and pre-dried filter paper with a grade of GF/A 1.6 m or comparable is used to filter the liquid, and the contaminated filter paper is then weighed and dried.

2.7.2. Electrical Parameters

Electrical parameters are crucial indicators of the condition of insulators, as they directly relate to the insulator's ability to withstand electrical stresses and maintain its insulating properties. Monitoring these parameters helps assess the health and performance of insulators in electrical systems [3-5]. Here are some key electrical parameters used to determine the insulator condition:

2.7.2.1. Surface Leakage Current

While an unintended electrical contact forms between ground and the conductor, surface leakage currents flow in an equipment [3-5]. Reference zero voltage or the earth's surface should serve as the ground. Actually, it's possible for current to leak from the power supply unit and travel to the installation earth ground via the ground connections [3-5]. For the purpose of monitoring the condition of the transmission line insulator, surface leakage current is crucial.

2.7.2.2. Flashover Voltage

Fundamentally, a flashover is an electrical discharge over an insulator's surface [21]. Flashover voltage is the minimum voltage required to cause a flashover across the insulator's surface. This parameter is critical for assessing the insulator's ability to prevent unintended arcing or breakdown. Air insulation around the surface of the insulator breaks down during flashover.

2.7.2.3. Puncture Voltage

It is the voltage at which an insulator loses its ability to conduct electricity and current passes through its interior [3-5]. A permanently damaged insulator results from this situation. Puncture voltage is greater than insulator's flashover voltage.

Partial Discharge (PD): Partial discharge refers to localized electrical discharges within the insulator's material due to defects, voids, or irregularities. Monitoring PD activity can help detect early signs of insulation degradation and potential flashover risks.

2.8. Effect of Degradation and Ageing on Parameters

During long-term use, insulator surfaces degrade due to various impurities. It can weaken the insulator surface's ability to conduct electricity [28]. Moisture and contaminants lead to the creation of a wet conducting layer [28–32]. Leakage current starts to flow as a result of this. Insulator surface heating from leakage current is not homogeneous. Dry band zone develops over the surface of the insulator as a result of partially localised drying of the contaminated layer [32]. A extremely highly resistive zone known as a "dry band" is where no current really flows. A total applied voltage is shown throughout the dry band region. Arching results from this [32–35]. Such arcs can grow longer until they span the insulator's two metal electrodes, at which point flashover occurs [35–40].

2.8.1. Effect of Contamination

Insulators for transmission lines and substations that are exposed to pollutants in an open atmosphere gradually become covered in salt and other impurities.

Pollutants, dust, dirt, industrial toxins, and sea salt are the principal sources of the pollutants that make up this layer [22–24].

The contaminated surface of an insulator might become moistened by unfavourable environmental conditions (such rain, mist, or fog) [21]. The conductivity of surfaces is increased by salt that has been dissolved in moisture, which raises the degree of leakage current [21, 35]. The heat produced by the energy lost due to this current has the tendency to evaporate moisture [21].

Dry-band zones are created when evaporation occurs quickly in locations with a high density of leakage current [33]. The electrical strains produced by the nearly complete application of power across these dry bands are then substantial enough to cause arching [32–35]. Once arching is started, there is a very high chance that a flashover will occur [21].

2.8.2. Effect of Ageing

In recent years, polymeric insulators have been widely used in overhead transmission lines [5]. All year long, extreme weather conditions such different pollutants, high humidity, temperature, and UV rays have an impact on non-ceramic insulators [26]. Non-ceramic insulators are also subject to ageing which is caused by the high temperature and UV and furthers the collapse of the material's electrical insulation ability, in addition to surface deterioration by partial discharges as a result of contamination. Ageing older can cause leakage currents to increase, which might cause early flashover under the influence of a damp and contaminated environment [21, 26].

3. CHAPTER 3

CONDITION ASSESSMENT TECHNIQUES

3.1. Introduction:

Transmission line insulator failure is the cause of about 70% of power outages [20]. The primary cause of insulator failure is contamination flashover [21, 35]. Regular insulator condition assessment has emerged as one of the most important areas for study in recent years in order to prevent any failure. Researchers have investigated a number of variables that can be used to determine an insulator's state of service. Utilities may be able to foresee an impending failure in an insulator with the use of these characteristics. When monitoring parameters are available, condition-based maintenance is made possible through the efficient scheduling of maintenance tasks like insulator washing and replacement. Therefore, it's crucial to choose the right set of criteria that can reveal the state of in-service insulators.

The application of surface conductivity measures, air pollution monitoring, leakage current measurements, and measurement of ESDD in insulator state monitoring has been highlighted by the CIGRE Task Force [24]. Surface conductivity and leakage current measurement directly monitor characteristics connected to the in-service insulators among the several measurements used to monitor insulator surface quality. The deployment of a passive or pilot insulator, which can be presumed to represent the state of an in-service insulator deployed under conditions comparable to those for the pilot insulator, is necessary for the measurement of NSDD and ESDD, however [3-5]. Measurements on insulators are not required for the indirect measuring approach of air pollution monitoring.

As previously mentioned, degradation in the surface condition increases insulator failures. Hundreds of km' worth of power transmission wires and insulator structure are involved. The insulators are consequently exposed to various geographic regions with a wide range of operating and environmental conditions. Different line insulators will therefore be exposed to various levels of environmental stress and will have varying probabilities of failure. This is one of the main causes of the failure of insulators, which is responsible for up to 70% of all line outages [20]. A perfectly healthy insulator in one transmission tower does not necessarily imply that a similarly healthy insulator in a different tower some distance away. Any tower's failure of an insulator will result in a total system failure. It has been suggested that the transmission line be divided into numerous parts based on various environmental, electrical, and mechanical stresses in order to prevent such outages. Monitoring insulators from each of the separated sections of the transmission line is essential as failure in any insulator puts the stability of the power system in danger. Assessments of the transmission line insulators' conditions therefore become crucial. Temperature and humidity levels, for example, have a significant impact on transmission line insulators. However, there are regional differences in environmental conditions. Even leakage current analyses for a specific insulator can differ from place to place due to shifting air conditions. Therefore, there must be some methods for determining the contamination levels of an insulator independent of the weather. In this sense, modern classifiers are particularly beneficial for determining an insulator's status. In this situation, the pollution levels of the insulator were predicted using classification approaches as support vector machines classification approaches.

Condition assessment techniques for transmission line insulators are crucial 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 first condition monitoring technique utilised and continue to be the most popular. Regular visual inspections are essential for identifying visible signs of deterioration, contamination, cracks, or other physical damage on insulators (as shown in Fig. 3.1.). Inspectors may use binoculars, drones, or helicopters to get a closer look at insulators without the need for physical access. Despite the fact that cracks are typically very small in size, aids for seeing like binoculars or high-powered telescopes must be used [3-5]. By protecting his or her personal safety, the operator should ideally be as close to the insulators as is safe. Therefore, the operator must operate from a bucket truck or a helicopter.

The operator needs to be knowledgeable about materials design, the characteristics of each type of insulator, as well as be aware of the various forms of failures that can occur [1-5]. Although the primary goal of this technique is to find surface degradation, interior problems can also be verified.

Fig. 3.1. Visual Inspection of Insulator

❖ **Advantages of This Technique:**

- It is simple to spot a crack in an external part.
- It is possible to identify electrical punctures in sheds;
- It is simple to locate destruction produced on by a damp end fitting seal.

- This method is simple to use and requires no special training.

❖ **Disadvantages of This Technique:**

- This method is not accurate;
- It is difficult to detect minor cracks;
- When a helicopter or bucket truck is used, it is expensive.

3.3. Infrared Scanning Technique

Most of the time, the heating impact is connected with the degradation produced on by the operation of an electric field over dielectric materials [1–5]. Infrared (IR) scanning tests conducted in the field and in the lab to find insulator cracks have produced satisfactory results [3-5]. A newly built infrared camera that is not cooled is simple to use and lightweight for outdoor applications. It has an appropriate telephoto lens mounted on it. IR cameras have a detection range of a few meters [5]. Little areas with temperature rise less than 1K can be found, and information can be gathered for further analysis. It is suggested to use an infrared camera that operates between 8 and 14 micro meters. Images at this wavelength are less affected by solar radiation and are overly sensitive to the dangerous temperature ranges [3-5].

Surface discharges can be found using IR method. Such discharge is frequently isolated and transient. As the environment gets better, it goes away [3-5]. However, if a discharge like this occurs at the same place for a long time, it may affect the structural integrity of housing. Thermal imagers can identify the warmer regions if no such discharge is visible with night vision equipment [3-5]. Areas that are warmer are heated internally. The photograph of infrared scanning of the insulator has been shown in Fig. 3.2.

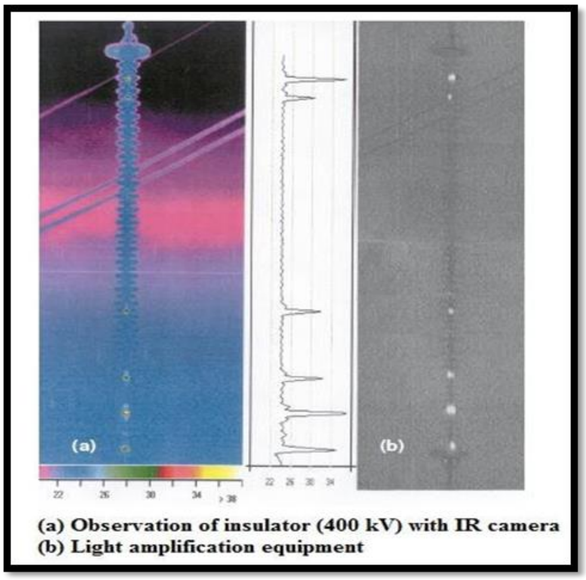

Fig. 3.2. Infrared Scanning

❖ **Advantages of Infrared Scanning**

- It is simple to detect a temperature increase at a specific location.
- Easy fault diagnosis is also possible.
- A new method for insulator condition monitoring

❖ **Disadvantages of Infrared Scanning**

- This method is complicated.
- There should be very specific requirements for the field conditions, such as no wind or solar radiation flux.

3.4. Hi-Pot Test Technique

A method that has become widely known and is used by operators to test porcelain insulators [3-5]. This experiment provides extremely high levels of accuracy in situations requiring the identification of insulator faults [3-5]. The operator should physically inspect each disc in the string for punctures during this experiment [3-5]. Any flow of surface leakage current that is greater than the typical capacitive leakage current magnitude while the tester is placed on the insulator string for a short period of time causes the tester to beep, indicating a defective unit. The photograph of the real-life measurement process of hi-pot test has been shown in Fig. 3.3.

Fig. 3.3. Hi-Pot Test

❖ **Advantages of Hi-Pot Test**

- This method has a very high level of accuracy.
- This method requires less effort.

❖ **Disadvantages of Hi-Pot Test**

- The necessity for close proximity of the line operator and physical contact with the insulator.

3.5. Leakage Current Measurement Technique

Measuring the leakage current along the insulator surface can provide insights into its condition. Higher leakage currents may indicate the presence of contaminants or deterioration. Due to variations in insulator surface resistance, leakage current that flows across an insulator's surface is affected by changes in its surface condition [1–12]. The loss of hydrophobicity caused on by ageing in silicone rubber insulators and contamination in porcelain and silicon rubber insulators may be responsible for this change in resistance [8–18]. Leakage current is a useful measure for monitoring the surface conditions of insulators because of the link between leakage currents and insulator surface conditions [19–23]. Researchers have developed a number of methods based on leakage current, which has developed over time into the primary understood testing measure to assess the degradation of the surface of insulators [30-42]. Peak value measurements, charge measurements, and pulse counting have all been used in the past to monitor insulator contamination [48]. Surface leakage current patterns were suggested by Fernando et al. to be used to evaluate the contamination in insulators.

4. CHAPTER 4

EXPERIMENTAL SETUP AND ARTIFICIAL CONTAMINATION PROCEDURE

4.1. Introduction

Insulators for transmission lines are crucial components of power system networks. Due to the presence of numerous dispersed particles in the air over their service life, line insulators frequently become polluted. Because of the contamination that accumulates on its surface, the insulator's performance suffers. In particular in moist conditions, the surface leakage current gradually rises as the contaminated layer thickens. If the leakage current is adequate to keep the conducting path between the live and ground component open, surface flashover will eventually happen.

For monitoring the quality of transmission line insulators, a sample of a contaminated insulator and an experimental setup for measuring leakage current along with supply voltage are both necessary. Due to many pollutants including salt, dirt, dust, chemicals, agricultural contaminants, etc., the insulator becomes naturally contaminated. However, obtaining naturally contaminated insulators for testing at a certain amount of contamination is quite difficult. For to this reason, an insulator should be contaminated artificially for a specific level as per IEC 60507 [3] and IEC 60815 [4].

4.2. Sample for Experiment

For experimental purpose a polymer 11 kV insulator has been used. The detailed dimensions of insulator sample have been presented in the Table 4.1.

Table 4.1. Parameters of Insulator

Parameter	**Value**
Nominal Voltage	11 kV
Creepage Distance	331 mm
Height (Axial)	146 mm
Pin Diameter	22 mm
Maximum Diameter	256 mm

Fig. 4.1. 11kV polymer Insulator

4.3. Process of Artificial Contamination

For the purpose of creating samples for experimental work, a variety of artificial contamination techniques, such as the solid layer method (SLM), salt fog method, and method of ice layer development, are used. Solid Layer Method (SLM) is been chosen for artificial pollution of the line insulators [3-5]. SLM has the ability to cover the surfaces of the insulator with a contaminated layer that is fairly consistent in thickness. A field investigation showed that the predominant component of natural pollution is salt, such as NaCl, KCl, etc. For the preparation of artificial contamination in this particular work, NaCl is employed as a conductive substance and Kaolin [$AlSiO_2O_5(OH)_4$] as a non-conductive material. According to IEC 60507 and IEC 60815 standards [3, 4], the preparation of artificial contamination must be done in the order listed below.

- **Step 1:** First, distilled water is used to properly clean the insulator.
- **Step 2:** Water, NaCl, and Kaolin [$AlSiO_2O_5(OH)_4$] 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.

The picture of artificially polluted insulator has been shown in Fig. 4.1. This procedure is carried out each and every time prior to experimental process.

4.4. Experimental Set-up

For the purpose of measuring the leakage current of insulators, a laboratory experimental setup has been prepared. The pictures of the experimental setup are shown in Fig. 4.2 and the schematic diagram is shown in Fig. 4.3. Here, a testing transformer with the specifications of 150 kVA, 500V/250 kV, 50 Hz is used to supply high voltage to the conductors connected to the insulator. A protection resistor with a 180 kΩ rating has been used to deliver the high voltage transformer's output voltage to the connected insulator. Here, a protective resistor is used to protect the transformer's winding insulation from larger current values during flashover conditions. For recording the applied voltage signal in the oscilloscope, a capacitive potential divider is connected to the high voltage side of the transformer. Using this potential divider, high voltage is reduced to a value that is suitable with oscillators. The leakage current in the oscilloscope is recorded using a 10 kΩ current shunt. It is essential to keep in mind the data obtaining setup's sample frequency is fixed at 50 kHz to reduce the risk of losing any significant data. This experimental setup allows for the measurement of leakage current for each artificially contaminated insulator sample at voltage levels ranging from 5 kV to 30 kV in steps of 5 kV.

Fig. 4.2. Photograph of Experimental Setup

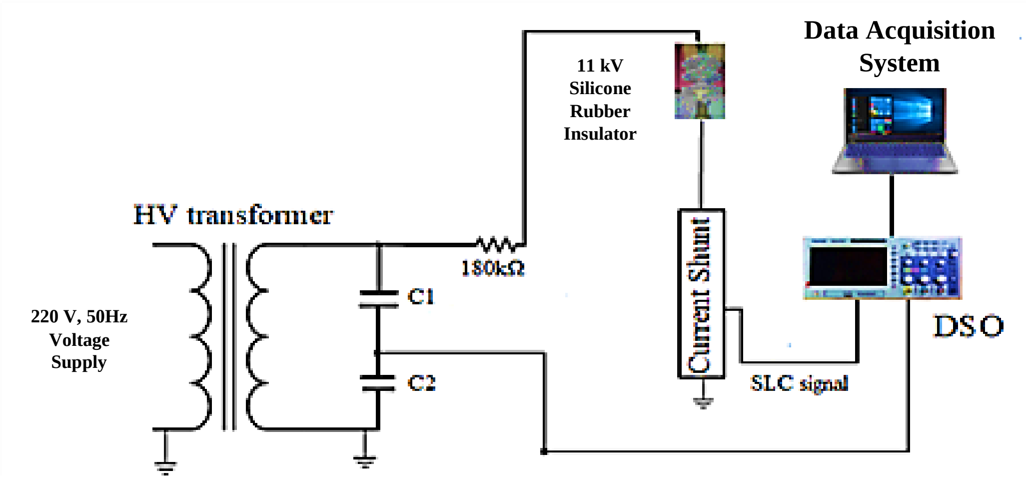

Fig. 4.3. Schematic of Experimental Setup

4.5. Data Acquisition

Measuring leakage current in an 11 kV partially contaminated polymer 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:

4.5.1. 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.

4.5.2. 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.

4.5.3. Artificial Contaminated Insulator: An 11 kV artificial partially contaminated Polymer insulator used for this purpose (as shown in Fig. 4.4).

Fig. 4.4. 11 kV artificial partially contaminated Polymer Insulator

4.5.4. Leakage Current Measurement Device: We shall need a specialized leakage current measurement device designed for high-voltage applications. The equipment should include:

4.5.4.1. 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) (as shown in Fig. 4.5).

(a) (b)

Fig. 4.5. (a) Photograph of automatic voltage regulator (AVR), (b) Photograph of High Voltage Transformer

4.5.4.2. 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. 4.6). This potential divider is used for the reduction of high voltage to the oscillator compatible voltage.

Fig. 4.6. Photograph of high voltage potential divider.

4.5.4.3. **Water Resistance:** The high voltage supply is applied across the insulator through a series connected 180 kΩ water resistance (which provides protection from over voltage as well as over current), as shown in Fig. 4.7.

Fig. 4.7. Photograph 180 kΩ water resistance.

4.5.4.4. **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 kΩ current shunt is used for recording the leakage current in the oscilloscope (as shown in Fig. 4.8).

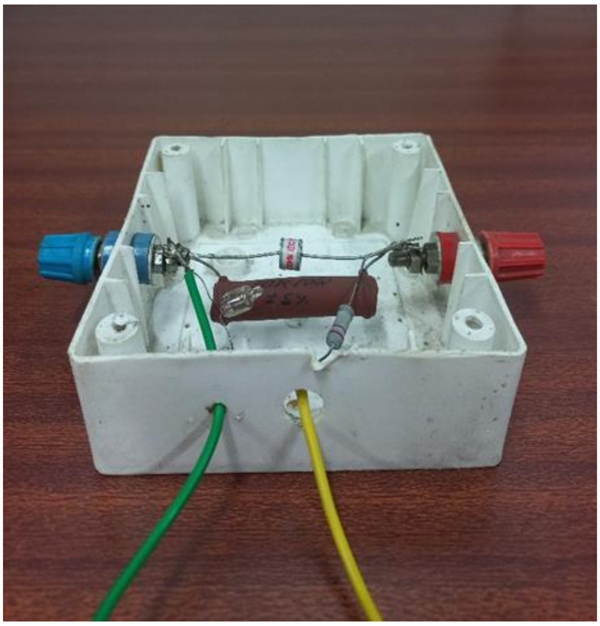

Fig. 4.8. Photograph of current shunt.

4.5.4.5. Digital Storage Oscilloscope: The leakage current signals have been recorded using the digital oscilloscope. The RIGOL digital storage oscilloscope (as shown in Fig. 4.9) 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. 4.9. Photograph of digital storage oscilloscope (DSO).

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

4.5.5.1. 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.

4.5.5.2. 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.

4.5.5.3. 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 (as shown in Figs. 4.10 and 4.11). Consider measuring it continuously for an extended period to capture variations or trends, especially when contaminants are present.

Fig. 4.10. Leakage current recording using digital storage oscilloscope (DSO).

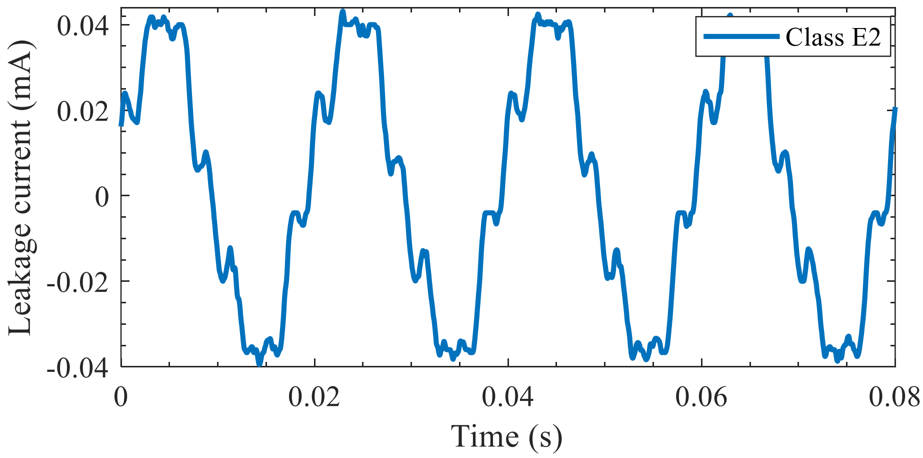

Fig. 4.11. Recorded leakage current waveform.

4.5.6. 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.

5. CHAPTER 5

LOCATION IDENTIFICATION OF CONTAMINATION ON PARTIALLY CONTAMINATED SILICONE RUBBER INSULATOR

5.1. Introduction

To provide uninterrupted and reliable electricity transmission, overhead line insulators are crucial. Insulators' functions include providing mechanical support for overhead lines and electrical insulation between high voltage conductors and the earth. Insulator failure is responsible for 70% of transmission line outages [21]. Flashover or ageing, in the case of polymer insulators, are the two main causes of insulator failure [11,20]. Dust, dirt, sea salt, drizzling, rain and humidity are just a few of the environmental elements that overhead line insulators are affected by [35, 36]. As a result, insulators are quickly polluted by contaminants, salt, chemicals, fertilizers, and other substances [40–51]. In the presence of dust, fog, moisture, rain, drizzle, etc., the leakage current that runs through the surface of insulators gradually increases. To ensure uninterrupted and reliable operation, overhead line insulators are crucial. As the level of contamination increases, the insulator's surface leakage current increases. As a result, flashover voltage decreases. Line interruptions are caused on by flashover in the network's distribution and transmission systems. As a result, the insulator's contamination level is crucial.

Many research efforts have researched into how various pollutants affect insulators [40–51]. Surface resistivity, leakage current, NSDD, and ESDD have been used as the primary methods for insulator state monitoring. Leakage current is one of these that is most frequently used [36, 41]. Surface leakage current is considered one of the most dynamic characteristics because it is essential to produce accurate results regarding the condition of a polluted insulator in a more thorough manner than other methods [36, 41]. The thesis addresses the important issue of partial contamination of polymer insulators in transmission line systems. Contamination, such as dust, salt, and pollution, can significantly impact the insulator's performance by altering its electrical properties and affecting leakage current behavior. Polymer insulators have gained popularity in high-voltage applications due to their lightweight, durability, and ease of installation. However, their susceptibility to contamination-related issues makes studying their behavior under such conditions crucial for maintaining power system reliability. The thesis specifically considers the scenario of partial contamination. Partial contamination occurs when only a portion of the insulator's surface is contaminated. This can lead to localized electric field distortion and altered leakage current patterns compared to fully contaminated or clean insulators. Leakage current is the current flowing along the insulator's surface due to various factors, including contamination. Analyzing leakage currents is essential for understanding the insulator's health, as abnormal currents could lead to insulation breakdown and eventual failure.

Mathematical morphology, a branch of image processing, offers tools to analyze shapes and structures within data. In the context of insulator contamination, mathematical morphology can be employed to extract relevant features from leakage current signals. Morphological operations such as erosion, dilation, opening, and closing can enhance the distinguishability of contamination-related patterns [53-56].

The extracted features are then subjected to the mRMR algorithm. The algorithm assesses the relevance and redundancy of features, ranking them based on their contribution to classification accuracy [59-62].

Support vector machines offer a robust framework for tackling classification problems in high-dimensional spaces. In our study, we leverage the SVM algorithm to analyze leakage current data collected from polymer insulators. Leakage currents, influenced by surface contamination, exhibit distinct patterns that can be harnessed for location identification of which part of the insulator is contaminated [66-71].

5.2. Scheme of Location Identification of Contamination along Polymer Insulator

Mathematical Morphology is used for feature extraction purpose because it is able to enhance the local characteristic of surface leakage current. Mathematical Morphology is also capable to differentiate between similar kinds of data. Moreover, Mathematical Morphology provides slope-based characteristic of surface leakage current in a suitable manner. In this proposed work Mathematical Morphology is applied on leakage current of insulator for extracting necessary features which are helpful to predict the surface condition of overhead line insulator [56-57]. This technique previously used to detect heart sound pattern, to separate various types of noise from leakage current waveforms portraying necessary electrical activity. For selecting a suitable set of extracted features mRMR algorithm is utilized in this work. The mRMR algorithm is a feature selection method that evaluates the relevance and redundancy of individual features in a dataset. It aims to identify the most informative and distinct features while minimizing feature redundancy. The algorithm evaluates the relevance of a feature to the target variable and its mutual information with other features. The mRMR algorithm helps mitigate the curse of dimensionality by selecting a compact set of features that offer maximum discriminative power [62-64]. SVM is a machine learning technique used for classification and regression tasks. In this thesis, SVM is applied to analyze the leakage current data generated from the contaminated polymer insulators. SVM can help in identifying patterns in the data and classifying the behaviour of the insulators based on the features extracted from leakage current measurements [69-71]. The flow chart of the proposed scheme has been shown in Fig. 5.1.

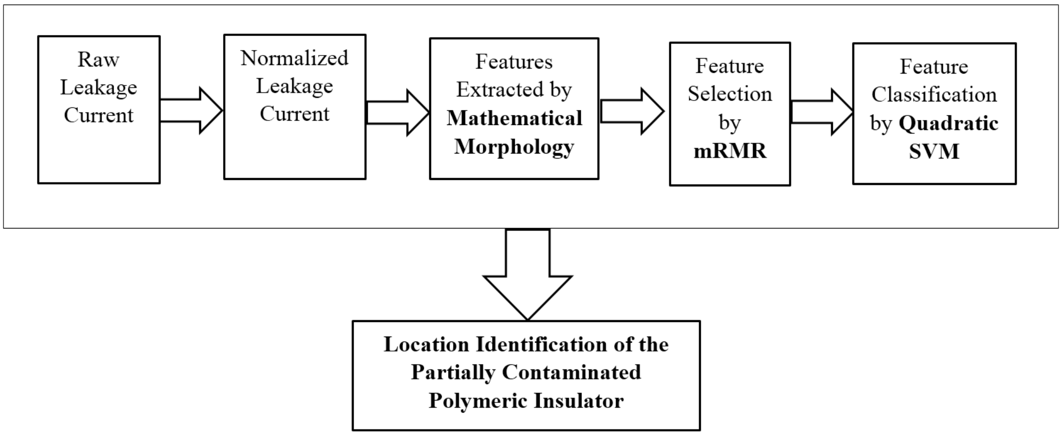

Fig. 5.1. Work flow of the proposed scheme.

Class Description: The objective of this work is location identification of contamination of Polymer insulator. Total 1225 leakage current signals, 35 for each class (E1-E35), are recorded for this analysis. The following Table represented the 35

Class. The SiR insulators were just partially contaminated in the projected work. For this purpose, the few specified locations of the SiR insulator 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 11 kV SiR insulator 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, U2M1L2 indicates the combination of lower-side of upper-disc, upper-side of middle-disc and lower-side of lower-disc. In this work, 35 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 Table 5.1.

Table 5.1. Description of Different Class

Sl. No.	No of Class	Class Name
1.	E1	No-Contamination
2.	E2	U_1
3.	E3	U_2
4.	E4	M_1
5.	E5	M_2
6.	E6	L_1
7.	E7	L_2
8.	E8	U_1M_1
9.	E9	U_2M_2
10.	E10	U_1L_1
11.	E11	M_1L_1
12.	E12	U_1M_2
13.	E13	U_2M_1
14.	E14	U_1L_2
15.	E15	M_2L_1
16.	E16	M_2L_2
17.	E17	U_1U_2
18.	E18	M_1M_2
19.	E19	L_1L_2
20.	E20	$M_1M_2L_1$
21.	E21	$U_1U_2L_2$
22.	E22	$U_1M_1L_1$
23.	E23	$L_1L_2U_1$
24.	E24	$L_1M_1U_2$
25.	E25	$U_1U_2L_1$
26.	E26	$U_1U_2M_2$
27.	E27	$L_1L_2U_2$
28.	E28	$U_1U_2M_1$

29.	E29	$U_1M_2L_2$
30.	E30	$L_1L_2M_1$
31.	E31	$M_1M_2L_2$
32.	E32	$M_1M_2U_1$
33.	E33	$M_1M_2U_2$
34.	E34	$L_1L_2M_2$
35.	E35	Full-Contamination

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

5.3.1. 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 different classes have been shown in Figs. 5.2-5.10.

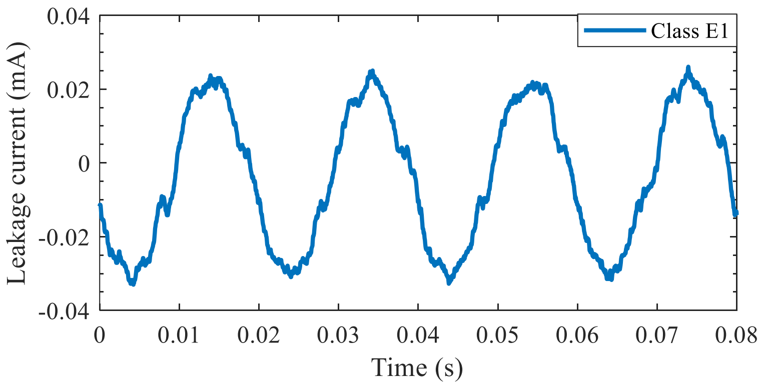

Fig. 5.2. Recorded leakage current signal of the Class E1 at 11kV.

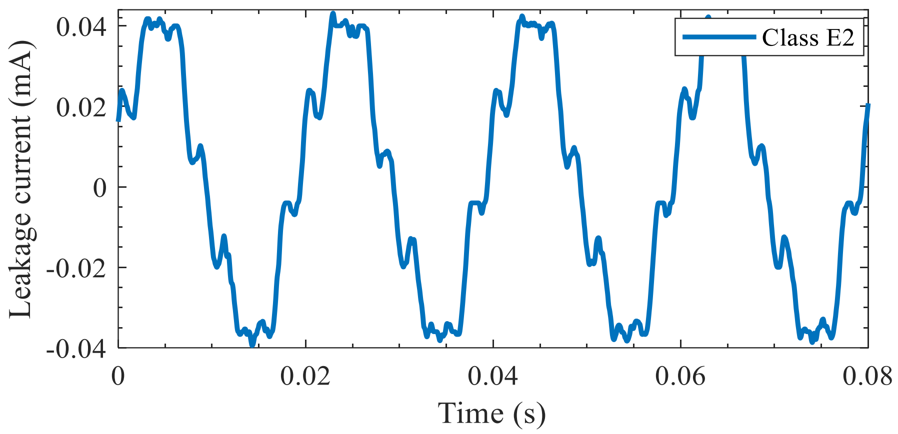

Fig. 5.3. Recorded leakage current signal of the Class E2 at 11kV.

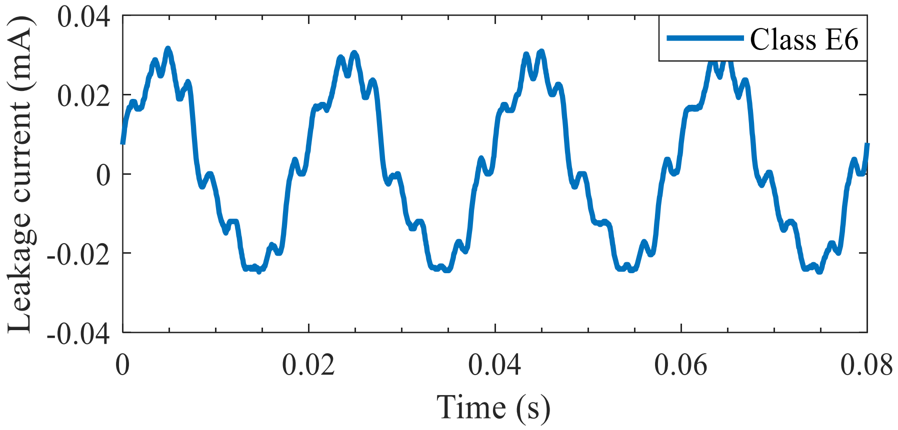

Fig. 5.4. Recorded leakage current signal of the Class E6 at 11kV.

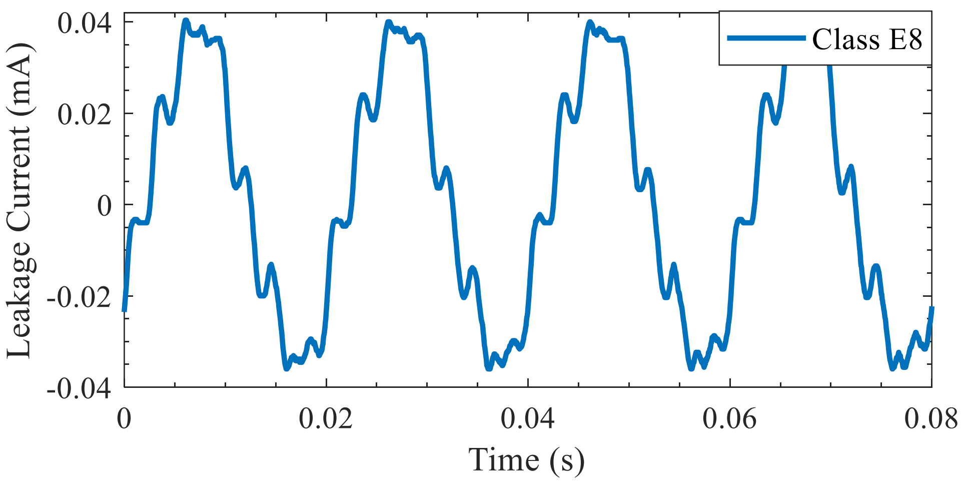

Fig. 5.5. Recorded leakage current signal of the Class E8 at 5kV.

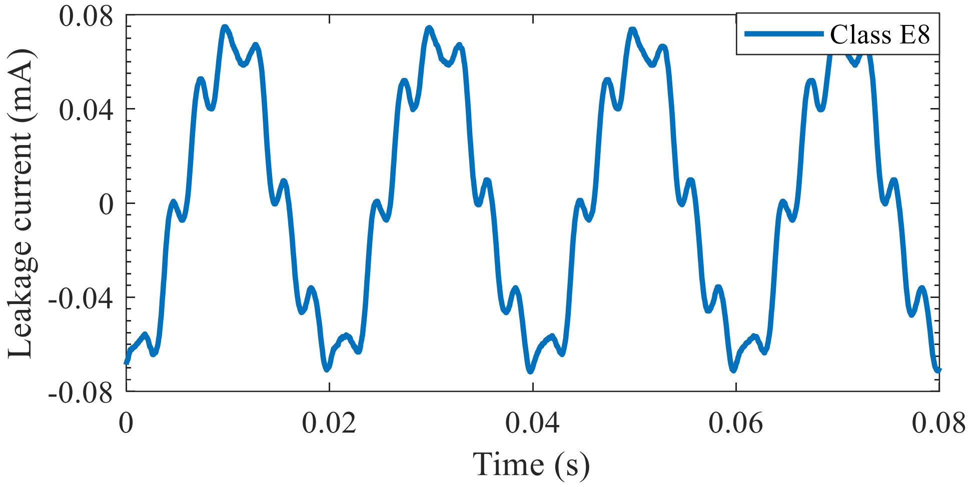

Fig. 5.6. Recorded leakage current signal of the Class E8 at 11kV.

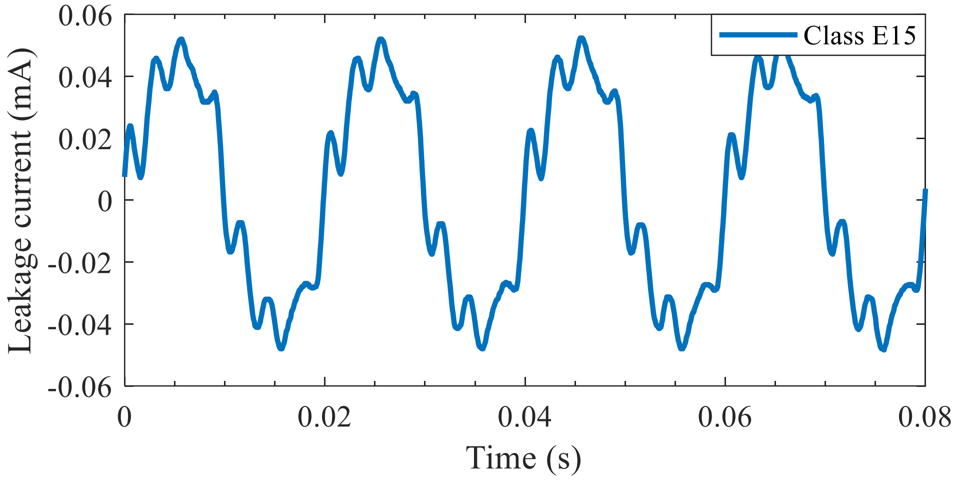

Fig. 5.7. Recorded leakage current signal of the Class E15 at 11kV.

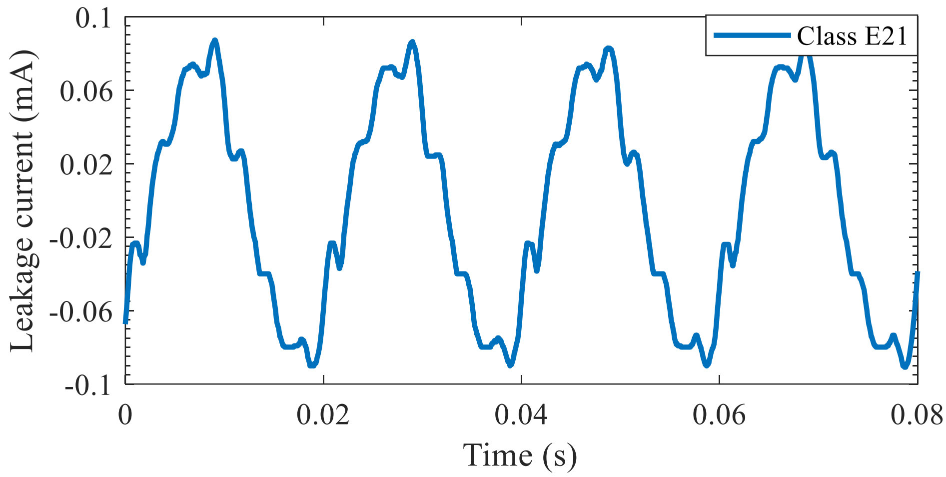

Fig. 5.8. Recorded leakage current signal of the Class E21 at 11kV.

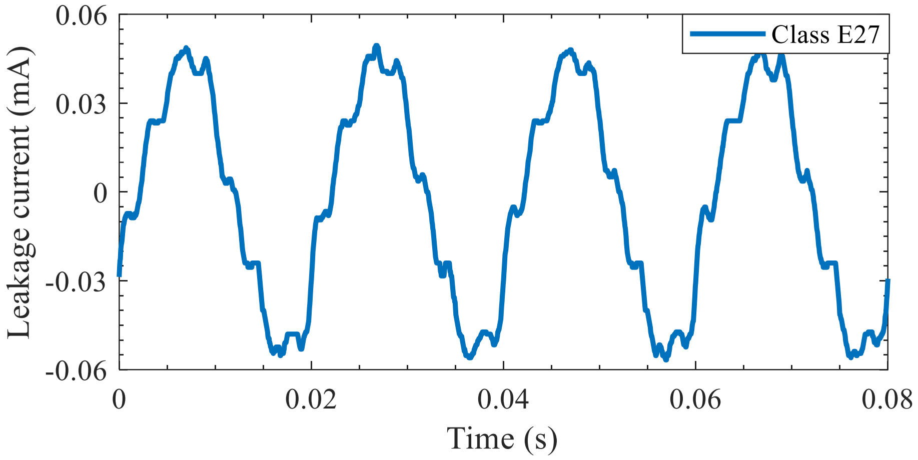

Fig. 5.9. Recorded leakage current signal of the Class E27 at 11kV.

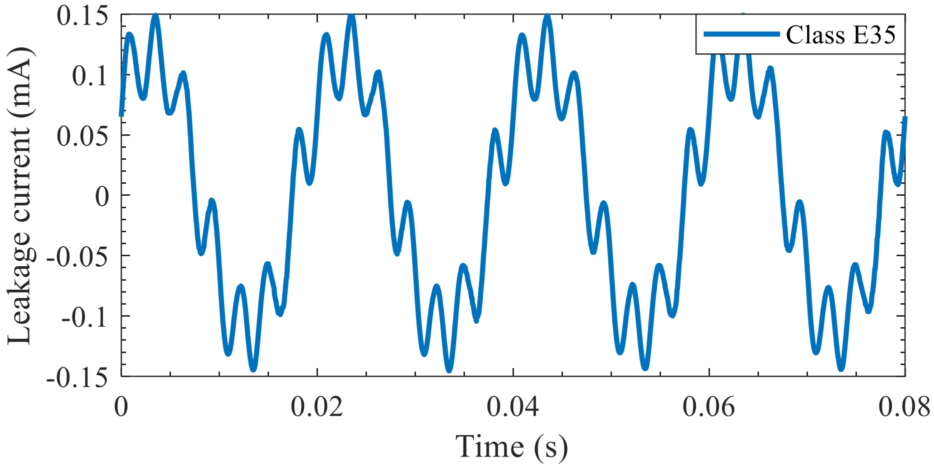

Fig. 5.10. Recorded leakage current signal of the Class E35 at 11kV.

5.3.2. 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 0 and 1, 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 fairer 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.

The actual and normalized leakage current signals of the class E27 have been shown in Fig. 5.11 and Fig. 5.12, respectively.

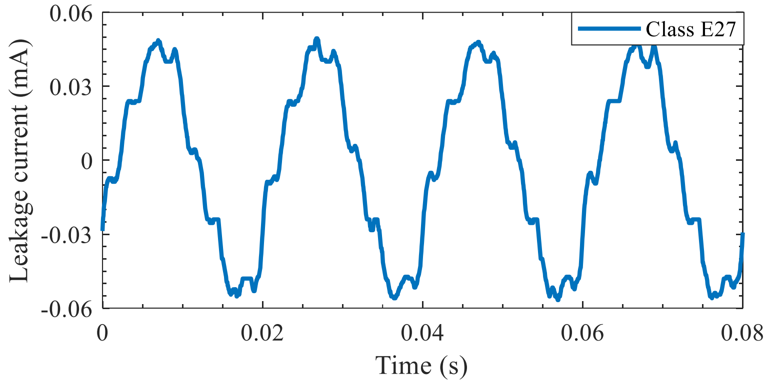

Fig. 5.11. Recorded leakage current signal of the Class E27 at 11kV.

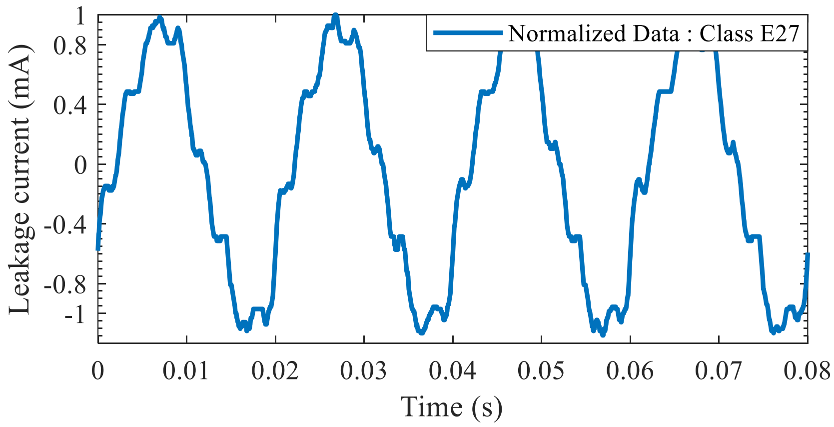

Fig. 5.12. Normalized leakage current signal of the Class E27 at 11kV.

5.4. Feature Extraction by Mathematical Morphology

The mathematical morphology theory was first proposed by the French mathematicians G. Matheron and J. Serra, and after years of development and improvement, it is now extensively used in pattern recognition, image processing, signal processing, and other domains, among others. A number of researchers suggested the mathematical morphological, which is effective in extracting some characteristics for one-dimensional signals, based on this method. The MMF includes a variety of filters for one-dimensional signal processing, including alternate, hybrid, and alternate-hybrid filters [53]. The effect of the length and style of symmetric structuring features, as well as their applications, are present areas of research analyses. The data the research used, however, had already been captured and saved in PCs, and the MMF was used for analysing the data offline. People always concentrate on the results but neglect the time requirements. As a result, some of the research's findings are useless in the signal acquisition and processing system [54-57].

Mathematical morphology, a branch of image processing, offers tools to analyze shapes and structures within data. Mathematical morphology is a theory and technique used in image processing and analysis to extract useful information from images or signals. It involves operations such as dilation, erosion, opening, closing, and more [56]. Here are some fundamental concepts in mathematical morphology along with their mathematical equations:

- **Dilation (⊕):**

Dilation expands the shape of an object in an image by adding pixels around its boundary. It is often used to enhance or enlarge features in an image.

Mathematically, dilation of a binary image A by a structuring element B is defined as:

$$(A \oplus B)(x, y) = \max\{A(x - a, y - b) + B(a, b)\} \quad (5.1)$$

for all (a, b) in B

Where:

(x, y) is a pixel coordinate in the output image.

(a, b) is a pixel coordinate in the structuring element B.

A(x - a, y - b) and B(a, b) are the values of the image A and structuring element B at their respective coordinates.

- **Erosion (⊖):**

Erosion shrinks the shape of an object by removing pixels from its boundary. It can be used to remove small noise and fine details from an image.

Mathematically, erosion of a binary image A by a structuring element B is defined as:

$$(A \ominus B)(x, y) = \min\{A(x + a, y + b) - B(a, b)\} \quad (5.2)$$

for all (a, b) in B

- **Opening (∘):**

Opening is an erosion operation followed by a dilation operation. It is used to remove small objects and thin connections while preserving larger structures.

Mathematically, opening of an image A by a structuring element B is defined as:

$$(A \circ B) = (A \ominus B) \oplus B \quad (5.3)$$

- **Closing (●):**

Closing is a dilation operation followed by an erosion operation. It is used to fill small gaps and connect nearby features.

Mathematically, closing of an image A by a structuring element B is defined as:

$$(A \bullet B) = (A \oplus B) \ominus B \quad (5.4)$$

These are just a few fundamental operations in mathematical morphology. The theory extends to more complex operations, such as morphological gradient. The effectiveness of mathematical morphology lies in choosing appropriate structuring elements and operations to extract meaningful features from images or signals. Keep in mind that while these equations provide a mathematical foundation, practical implementations often involve discrete image sampling and computational approximations.

There are some steps to determine the features from the normalized leakage current data:

Record and preprocess leakage current data, including noise reduction and normalization.

Apply various morphological operations to the leakage current data. Common operations include erosion, dilation, opening, closing, and gradient.

The leakage current data is recorded from insulators with different localized contamination. Then the recorded data is normalized. The normalized data is used for feature extraction by Mathematical Morphology. Apply various morphological operations to the normalized leakage current data. Mathematical morphology can be employed to extract relevant features from normalized leakage current signals. Morphological operations such as erosion, dilation, opening, and closing can enhance the distinguishability of contamination-related patterns [53-57]. There are some steps for Features extraction from leakage current data:

- Handling 35 classes for feature extraction from leakage current data involves managing a multi-class classification problem with a considerable number of Classes.
- Collect, preprocess, and organize our leakage current data for the 35 classes. This might involve normalizing the data, and ensuring consistent data format.
- Apply Mathematical Morphological operations (e.g., erosion, dilation, gradient) to the leakage current data for each class.

The objective of this work is location identification of contamination of Polymer insulator. Total 1225 leakage current signals, 35 for each class (E1-E35), are considered for this analysis. The following steps are followed for identification of localized contamination of overhead line polymer insulator.

To bring out the inherent information from leakage current, first normal time domain leakage current signal are normalized then features extracted with the help of Mathematical Morphology from normalized leakage current signal. Location identification of the contamination of insulator some simple features (F1-F39) are extracted from normalized leakage current signal. These features details are shown in the Table 5.2. The extracted features of the different class have been tabulated in Table 5.3. The mathematical operation of the features are shown in equations (5.5) to (5.14).

$$D = \text{Dilation of Leakage Current Signal} \quad (5.5)$$

$$E = \text{Erosion of Leakage Current Signal} \quad (5.6)$$

$$O = \text{Opening of Leakage Current Signal} \quad (5.7)$$

$$C = \text{Closing of Leakage Current Signal} \quad (5.8)$$

$$DEDF = D-E \quad (5.9)$$

$$OCDF = O-C \quad (5.10)$$

$$MMF1 = (D+E)/2 \quad (5.11)$$

$$MMF2 = (Dilation(MMF1,g,1) + Erosion(MMF1,g,1))/2 \quad (5.12)$$

$$OCM1 = (O+C)/2 \quad (5.13)$$

$$OCM2 = (Dilation(OCM1,g,1)+Erosion(OCM1,g,1))/2 \quad (5.14)$$

Table 5.2. Extracted Features Details

Sl. No.	Feature Number	Features Name
1.	F1	Maximum of D
2.	F2	Maximum of E
3.	F3	Maximum of O
4.	F4	Maximum of C
5.	F5	Maximum of DEDF
6.	F6	Maximum of OCDF
7.	F7	Maximum of MMF1
8.	F8	Maximum of MMF2
9.	F9	Maximum of OCM1
10.	F10	Maximum of OCM2
11.	F11	Variance of D
12.	F12	Variance of E
13.	F13	Variance of O
14.	F14	Variance of C
15.	F15	Variance of DEDF
16.	F16	Variance of OCDF
17.	F17	Variance of MMF1
18.	F18	Variance of MMF2
19.	F19	Variance of OCM1
20.	F20	Variance of OCM2
21.	F21	Skewness of D
22.	F22	Skewness of E
23.	F23	Skewness of O
24.	F24	Skewness of C
25.	F25	Skewness of DEDF
26.	F26	Skewness of OCDF
27.	F27	Skewness of MMF1
28.	F28	Skewness of MMF2
29.	F29	Skewness of OCM1
30.	F30	Skewness of OCM2
31.	F31	Kurtosis of D
32.	F32	Kurtosis of E
33.	F33	Kurtosis of O
34.	F34	Kurtosis of C
35.	F35	Kurtosis of DEDF
36.	F36	Kurtosis of OCDF
37.	F37	Kurtosis of MMF1
38.	F38	Kurtosis of MMF2
39.	F39	Kurtosis of OCM1

Table 5.3. Extracted Features by Mathematical Morphology

Sl.	Features												CL
No.	F1	F2	F3	…..	F11	F12	F13	F14	…..	F37	F38	F39	
1	0.984	2.044	0.050	…..	0.002	0.002	-3.650	3.672	…..	0.240	2.900	-1.015	E1
2	0.992	2.040	0.052	…..	0.001	0.001	-3.750	3.751	…..	0.165	2.403	-0.994	E1
….	…..	….	….	…..	….	….	….	….	…..	….	….	….	….
36	1.152	2.348	0.060	…..	0.004	0.003	-2.743	3.491	…..	0.374	3.616	-1.049	E2
37	1.112	2.300	0.057	…..	0.003	0.002	-3.116	3.523	…..	0.341	3.457	-1.031	E2
….	…..	…..	…..	…..	…..	…..	….	….	…..	….	….	….	….
71	0.988	2.060	0.049	…..	0.004	0.003	-3.432	3.524	…..	0.380	3.646	-1.043	E3
72	0.992	2.064	0.049	…..	0.003	0.003	-3.473	3.579	…..	0.322	3.356	-1.044	E3
….	….	…..	…..	…..	…..	….	….	….	…..	….	….	….	….
106	1.064	2.132	0.052	…..	0.001	0.001	-3.578	3.739	…..	0.190	2.579	-1.010	E4
107	1.076	2.148	0.053	…..	0.001	0.001	-3.617	3.782	…..	0.156	2.336	-1.000	E4
….	….	…..	…..	…..	….	….	….	….	…..	….	….	….	….
141	0.988	2.032	0.050	…..	0.001	0.001	-3.775	3.769	…..	0.172	2.451	-1.002	E5
142	0.984	2.024	0.050	…..	0.001	0.001	-3.784	3.791	…..	0.153	2.311	-0.996	E5
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
176	0.980	2.028	0.050	…..	0.001	0.001	-3.767	3.771	…..	0.166	2.413	-1.010	E6
177	0.988	2.032	0.050	…..	0.001	0.001	-3.769	3.785	…..	0.148	2.275	-1.000	E6
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
211	1.100	2.188	0.057	…..	0.001	0.001	-3.614	3.665	…..	0.204	2.669	-1.002	E7
212	1.104	2.196	0.058	…..	0.001	0.001	-3.604	3.670	…..	0.179	2.505	-1.004	E7
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
246	1.052	2.180	0.054	…..	0.001	0.001	-3.677	3.660	…..	0.233	2.857	-1.012	E8
247	1.060	2.184	0.054	…..	0.001	0.001	-3.664	3.664	…..	0.237	2.880	-1.012	E8
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
281	1.120	2.204	0.060	…..	0.001	0.001	-3.503	3.709	…..	-0.048	2.547	-0.997	E9
282	1.128	2.224	0.061	…..	0.001	0.001	-3.494	3.693	…..	-0.044	2.678	-0.997	E9
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….

Sl. No.	Features												CL
	F1	F2	F3	…..	F11	F12	F13	F14	…..	F37	F38	F39	
316	1.084	2.192	0.057	…..	0.001	0.001	-3.632	3.692	…..	0.122	2.068	-1.015	**E10**
317	1.080	2.200	0.057	…..	0.001	0.001	-3.643	3.700	…..	0.114	2.001	-1.014	**E10**
….	….	….	…..	…..	….	….	….	….	…..	….	….	….	….
351	0.976	2.020	0.049	….	0.001	0.001	-3.761	3.768	…..	0.187	2.555	-1.008	**E11**
352	0.980	2.020	0.050	…..	0.001	0.001	-3.777	3.787	…..	0.164	2.395	-1.000	**E11**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
386	0.976	2.060	0.048	…..	0.002	0.002	-3.678	3.671	…..	0.275	3.104	-1.031	**E12**
387	0.980	2.024	0.050	…..	0.001	0.001	-3.777	3.784	…..	0.159	2.359	-1.006	**E12**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
421	0.980	2.028	0.050	…..	0.001	0.001	-3.754	3.750	…..	0.179	2.504	-1.004	**E13**
422	0.984	2.020	0.051	…..	0.000	0.000	-3.791	3.797	…..	0.130	2.129	-0.988	**E13**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
456	0.976	2.020	0.049	…..	0.001	0.001	-3.761	3.768	…..	0.187	2.555	-1.008	**E14**
457	0.984	2.024	0.050	…..	0.001	0.001	-3.772	3.788	…..	0.164	2.396	-1.000	**E14**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
491	0.984	2.028	0.050	…..	0.001	0.001	-3.760	3.766	…..	0.140	2.211	-1.002	**E15**
492	0.988	2.024	0.051	…..	0.001	0.001	-3.774	3.781	…..	0.141	2.219	-0.994	**E15**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
526	0.984	2.076	0.048	…..	0.002	0.002	-3.662	3.659	…..	0.215	2.741	-1.044	**E16**
527	0.988	2.080	0.048	…..	0.002	0.002	-3.655	3.660	…..	0.200	2.644	-1.041	**E16**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
561	0.992	2.036	0.050	…..	0.001	0.001	-3.729	3.760	…..	0.191	2.583	-1.007	**E17**
562	0.988	2.024	0.051	…..	0.001	0.001	-3.776	3.778	…..	0.149	2.283	-0.993	**E17**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….
596	0.988	2.024	0.050	…..	0.001	0.001	-3.694	3.696	…..	0.230	2.835	-1.010	**E18**
597	0.984	2.020	0.051	…..	0.001	0.001	-3.762	3.771	…..	0.173	2.462	-0.993	**E18**
….	….	….	….	…..	….	….	….	….	…..	….	….	….	….

Sl. No.		Features											CL
	F1	F2	F3	…..	F11	F12	F13	F14	…..	F37	F38	F39	
631	0.988	2.028	0.050	**…..**	0.002	0.002	-3.669	3.686	**…..**	0.229	2.828	-1.015	**E19**
632	0.992	2.028	0.050	**…..**	0.001	0.001	-3.675	3.708	**…..**	0.214	2.735	-1.011	**E19**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
666	1.016	2.052	0.053	**…..**	0.000	0.000	-3.763	3.756	**…..**	0.126	2.096	-0.988	**E20**
667	1.032	2.060	0.053	**…..**	0.000	0.000	-3.738	3.756	**…..**	0.126	2.096	-0.988	**E20**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
701	0.992	2.060	0.051	**…..**	0.001	0.001	-3.731	3.703	**…..**	0.202	2.657	-1.011	**E21**
702	0.988	2.064	0.051	**…..**	0.001	0.001	-3.713	3.682	**…..**	0.205	2.680	-1.013	**E21**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
736	0.996	2.060	0.051	**…..**	0.001	0.001	-3.736	3.738	**…..**	0.175	2.475	-1.006	**E22**
737	0.992	2.060	0.051	**…..**	0.001	0.001	-3.738	3.740	**…..**	0.175	2.475	-1.005	**E22**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
771	1.112	2.204	0.058	**…..**	0.001	0.001	-3.614	3.671	**…..**	0.104	1.906	-1.002	**E23**
772	1.108	2.184	0.058	**…..**	0.001	0.001	-3.632	3.639	**…..**	0.128	2.114	-1.002	**E23**
….	**……**	**……**	**…..**	**…..**	**…..**	**……**	**…..**	**…..**	**…..**	**…..**	**…..**	**…..**	**……**
806	1.040	2.176	0.055	**…..**	0.001	0.001	-3.705	3.682	**…..**	0.162	2.382	-1.012	**E24**
807	1.036	2.172	0.055	**…..**	0.001	0.001	-3.708	3.684	**…..**	0.166	2.411	-1.011	**E24**
….	**……**	**……**	**…..**	**…..**	**…..**	**……**	**…..**	**…..**	**…..**	**…..**	**…..**	**…..**	**….**
841	0.984	2.040	0.049	**…..**	0.002	0.002	-3.629	3.664	**…..**	0.288	3.174	-1.029	**E25**
842	0.976	2.040	0.049	**…..**	0.002	0.002	-3.666	3.685	**…..**	0.258	3.002	-1.025	**E25**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
876	0.960	2.128	0.046	**…..**	0.002	0.002	-3.710	3.595	**…..**	0.241	2.902	-1.064	**E26**
877	0.960	2.176	0.046	**…..**	0.003	0.003	-3.638	3.334	**…..**	0.427	3.868	-1.085	**E26**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**
911	0.920	2.104	0.044	**…..**	0.002	0.002	-3.725	3.757	**…..**	0.179	2.502	-1.074	**E27**
912	0.928	2.096	0.045	**…..**	0.002	0.002	-3.738	3.745	**…..**	0.181	2.519	-1.059	**E27**
….	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**	**…..**	**….**	**….**	**….**	**….**

Sl. No.	Features												CL
	F1	F2	F3	…..	F11	F12	F13	F14	…..	F37	F38	F39	
946	0.996	2.064	0.050	…..	0.002	0.002	-3.589	3.653	…..	0.882	0.289	3.182	**E28**
947	0.992	2.068	0.050	…..	0.002	0.002	-3.577	3.655	…..	0.301	3.246	-1.023	**E28**
……	……	……	……	…..	……	……	……	……	…..	……	……	……	……
981	0.952	2.088	0.046	…..	0.002	0.002	-3.712	3.692	…..	0.324	3.368	-1.062	**E29**
982	0.944	2.088	0.046	…..	0.002	0.002	-3.693	3.684	…..	0.324	3.365	-1.063	**E29**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	……
1016	0.984	2.040	0.049	…..	0.002	0.002	-3.629	3.664	…..	0.288	3.174	-1.029	**E30**
1017	0.976	2.040	0.049	…..	0.002	0.002	-3.666	3.685	…..	0.258	3.002	-1.025	**E30**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	……
1051	0.984	2.048	0.050	…..	0.001	0.001	-3.727	3.748	…..	0.220	2.775	-1.018	**E31**
1052	0.988	2.060	0.050	…..	0.001	0.001	-3.705	3.742	…..	0.220	2.774	-1.019	**E31**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	……
1086	0.996	2.036	0.051	…..	0.001	0.001	-3.665	3.690	…..	0.265	3.048	-1.010	**E32**
1087	1.004	2.056	0.052	…..	0.001	0.001	-3.699	3.700	…..	0.243	2.916	-1.005	**E32**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	……
1121	0.976	2.044	0.050	…..	0.002	0.002	-3.630	3.619	…..	0.296	3.221	-1.025	**E33**
1122	0.980	2.044	0.050	…..	0.002	0.002	-3.623	3.641	…..	0.289	3.183	-1.023	**E33**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	……
1156	0.960	2.120	0.046	…..	0.002	0.002	-3.727	3.706	…..	0.104	1.908	-1.077	**E34**
1157	1.000	2.072	0.048	…..	0.002	0.002	-3.695	3.712	…..	0.015	0.731	-1.047	**E34**
……	……	……	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	….
1191	0.952	2.032	0.046	…..	0.002	0.002	-3.703	3.729	…..	0.283	3.147	-1.046	**E35**
1192	0.960	2.032	0.047	…..	0.001	0.001	-3.750	3.782	…..	0.218	2.761	-1.028	**E35**
…..	…..	…..	…..	…..	…..	……	…..	…..	…..	…..	…..	…..	…..

5.5. Feature Selection by mRMR algorithm

The Minimum Redundancy Maximum Relevance (mRMR) algorithm is a feature selection technique commonly used in machine learning and pattern recognition. It aims to identify a subset of features from a larger set that collectively provide the most relevant information for a given task while minimizing redundancy among the selected features. mRMR is particularly useful when dealing with high-dimensional data, as it helps improve model performance, reduce overfitting, and enhance interpretability [62,63].

Here's a step-by-step overview of the mRMR algorithm:

- **Relevance Ranking:**

Calculate the relevance of each feature with respect to the target variable. For classification tasks, this could involve measuring the mutual information between each feature and the class labels.

- **Redundancy Measurement:**

Calculate the redundancy between pairs of features. Redundancy indicates how much information one feature provides about another feature. This is often measured using mutual information or other similarity measures.

- **mRMR Criterion:**

Compute a combination of relevance and redundancy scores for each feature. The mRMR criterion is usually defined as the relevance minus a weighted sum of redundancies with previously selected features.

- **Feature Selection:**

Select features based on their mRMR scores. Features with higher mRMR scores are more relevant and less redundant with already selected features.

- **Iteration:**

You can iteratively select features one by one, each time updating the mRMR scores based on the features already selected. This helps refine the feature selection process.

- **Final Subset:**

Once a predefined number of features is selected or a stopping criterion is met, the algorithm terminates, and you have a subset of features chosen based on the mRMR criteria.

The key idea behind mRMR is to strike a balance between features that are informative and those that are diverse. This ensures that the selected features collectively carry relevant information while avoiding redundancy that might not add new insights.

The Minimum Redundancy Maximum Relevance (mRMR) algorithm aims to select a subset of features from a larger set of features by maximizing the relevance of the selected features to a target variable (e.g., class labels) while minimizing the redundancy between the selected features. This helps in choosing features that provide valuable information for the task at hand while avoiding redundancy that might not contribute new insights [63,64].

Mathematically, the mRMR algorithm can be represented as follows:

For n samples (data points), and d features, X be the feature matrix of shape (n, d), where each row represents a sample and each column represents a feature.

Y be the target variable vector of shape (n), where each element represents the class label or target value for a sample.

S be the set of selected features.

F be the set of remaining features to choose from.

mRMR Score for Feature f: The mRMR score for a feature f quantifies its relevance to the target variable Y and its redundancy with the already selected features S. It is given by:

$$mRMR(f) = relevance(f, Y) - \alpha * average(redundancy(f, s) \text{ for } s \text{ in } S) \quad (5.15)$$

Where:

relevance(f, Y) measures the relevance of feature f with respect to the target variable Y (e.g., mutual information, correlation, etc.).

redundancy(f, s) measures the redundancy between feature f and an already selected feature s (e.g., correlation).

α is a weighting parameter that balances the trade-off between relevance and redundancy [58-64].

Selection Process:

Initialize the set of selected features S as empty.

Calculate the relevance scores for all features.

For each remaining feature f in F, calculate its mRMR score.

Select the feature f with the highest mRMR score and add it to S.

Repeat steps 3-4 until the desired number of features are selected or a stopping criterion is met.

The extracted features are used as input to mRMR algorithm. Here mRMR is used for feature selection because this method has the capability to find out a smaller set of uncorrelated features from higher order statistical data.This feature selection method reduces the features from 39 to 25. mRMR based selected features are presented in Table 5.4.

The extracted features are used as input to mRMR algorithm. Here mRMR is used for feature selection because this method has the capability to find out a smaller set of uncorrelated features from higher order statistical data.This feature selection method reduces the features from 39 to 25. The mRMR based selected features have been tabulated in Table 5.5.

Table 5.4. mRMR Based Selected Features

Sl. No.	Feature Number
1.	F1
2.	F2
3.	F3
4.	F4
5.	F7
6.	F8
7.	F10
8.	F12
9.	F15
10.	F16
11.	F17
12.	F18
13.	F19
14.	F21
15.	F25
16.	F27
17.	F28
18.	F29
19.	F30
20.	F32
21.	F34
22.	F35
23.	F36
24.	F38
25.	F39

Table 5.5. mRMR Based Selected Features of Different Classes

Sl. No.	Features												CL
	F1	**F2**	**F3**	**…..**	**F17**	**F18**	**F119**	**F21**	**…..**	**F36**	**F38**	**F39**	
1	0.984	2.044	0.050	**….**	-3.811	-2.263	-0.138	-0.067	**….**	0.883	2.900	-1.015	**E1**
2	0.992	2.040	0.052	**….**	-3.813	-1.427	-0.046	-0.083	**….**	0.906	2.403	-0.994	**E1**
….	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**	**….**
36	1.152	2.348	0.060	**….**	-3.468	-2.918	-0.538	-0.369	**….**	0.899	3.616	-1.049	**E2**
37	1.112	2.300	0.057	**….**	-3.574	-2.904	-0.793	-0.624	**….**	0.905	3.457	-1.031	**E2**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**
71	0.988	2.060	0.049	**….**	-3.811	-0.873	-0.346	-0.346	**….**	0.861	3.646	-1.043	**E3**
72	0.992	2.064	0.049	**….**	-3.810	-1.256	0.106	0.086	**….**	0.860	3.356	-1.044	**E3**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**
106	1.064	2.132	0.052	**….**	-3.781	-5.299	0.226	0.285	**….**	0.896	2.579	-1.010	**E4**
107	1.076	2.148	0.053	**….**	-3.773	-5.290	0.633	0.698	**….**	0.907	2.336	-1.000	**E4**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**
141	0.988	2.032	0.050	**….**	-3.814	-1.875	0.710	0.715	**….**	0.894	2.451	-1.002	**E5**
142	0.984	2.024	0.050	**….**	-3.815	-0.345	0.943	0.945	**….**	0.897	2.311	-0.996	**E5**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**…..**
176	0.980	2.028	0.050	**….**	-3.813	-1.365	1.055	0.939	**….**	0.888	2.413	-1.010	**E6**
177	0.988	2.032	0.050	**….**	-3.814	-0.737	1.116	1.052	**….**	0.894	2.275	-1.000	**E6**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**…..**
211	1.100	2.188	0.057	**….**	-3.722	-2.075	-0.655	-0.490	**….**	0.941	2.669	-1.002	**E7**
212	1.104	2.196	0.058	**….**	-3.709	-2.066	-0.630	-0.303	**….**	0.945	2.505	-1.004	**E7**
…..	**…..**	**……**	**……**	**…..**	**…..**	**…..**	**……**	**……**	**…..**	**…..**	**…..**	**……**	**…..**
246	1.052	2.180	0.054	**….**	-3.753	-2.088	-0.578	-0.182	**….**	0.923	2.857	-1.012	**E8**
247	1.060	2.184	0.054	**….**	-3.757	-1.982	-0.562	-0.232	**….**	0.922	2.880	-1.012	**E8**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**…..**
281	1.120	2.204	0.060	**…..**	-3.700	-1.929	1.092	1.441	**…..**	0.957	2.547	-0.997	**E9**
282	1.128	2.224	0.061	**….**	-3.701	-1.581	0.546	0.923	**….**	0.963	2.678	-0.997	**E9**
…..	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**……**	**….**	**…..**	**…..**	**……**	**…..**

Sl. No.	Features												CL
	F1	F2	F3	…..	F17	F18	F19	F21	…..	F36	F38	F39	
316	1.084	2.192	0.057	….	-3.764	-0.974	-0.329	-0.789	….	0.945	2.068	-1.015	E10
317	1.080	2.200	0.057	….	-3.761	-1.081	-0.071	-0.476	….	0.944	2.001	-1.014	E10
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
351	0.976	2.020	0.049	….	-3.815	-1.456	0.844	0.838	….	0.886	2.555	-1.008	E11
352	0.980	2.020	0.050	….	-3.815	-0.609	0.982	1.001	….	0.892	2.395	-1.000	E11
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
386	0.976	2.060	0.048	….	-3.811	-0.728	0.076	0.181	….	0.872	3.104	-1.031	E12
387	0.980	2.024	0.050	….	-3.814	-1.525	1.132	1.055	….	0.888	2.359	-1.006	E12
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	…..
421	0.980	2.028	0.050	….	-3.814	-1.612	0.156	0.197	….	0.893	2.504	-1.004	E13
422	0.984	2.020	0.051	….	-3.815	-0.800	0.788	0.905	….	0.903	2.129	-0.988	E13
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
456	0.976	2.020	0.049	….	-3.815	-1.456	0.844	0.838	….	0.886	2.555	-1.008	E14
457	0.984	2.024	0.050	….	-3.815	-0.860	0.954	0.987	….	0.893	2.396	-1.000	E14
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
491	0.984	2.028	0.050	….	-3.815	-1.396	0.616	0.615	….	0.893	2.211	-1.002	E15
492	0.988	2.024	0.051	….	-3.815	-1.310	0.813	0.788	….	0.899	2.219	-0.994	E15
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	..….
526	0.984	2.076	0.048	….	-3.803	-2.609	0.568	0.381	….	0.866	2.741	-1.044	E16
527	0.988	2.080	0.048	….	-3.802	-2.662	0.499	0.281	….	0.868	2.644	-1.041	E16
…..	…..	……	……	…..	…..	…..	……	……	…..	…..	…..	……	……
561	0.992	2.036	0.050	….	-3.814	-0.588	0.455	0.486	….	0.890	2.583	-1.007	E17
562	0.988	2.024	0.051	….	-3.814	-0.852	0.472	0.541	….	0.901	2.283	-0.993	E17
…..	…..	……	……	….	…..	…..	……	……	….		…..	…..	……
596	0.988	2.024	0.050	…..	-3.814	-0.102	-0.116	-0.157	…..	0.887	2.835	-1.010	E18
597	0.984	2.020	0.051	….	-3.815	-0.057	0.016	0.125	….	0.899	2.462	-0.993	E18
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……

Sl. No.	Features												CL
	F1	F2	F3	…..	F17	F18	F19	F21	…..	F36	F38	F39	
631	0.988	2.028	0.050	….	-3.814	-1.606	0.042	-0.011	….	0.882	2.828	-1.015	E19
632	0.992	2.028	0.050	….	-3.814	-1.664	0.073	0.025	….	0.884	2.735	-1.011	E19
….	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
666	1.016	2.052	0.053	….	-3.809	-2.582	-0.039	-0.080	….	0.914	2.096	-0.988	E20
667	1.032	2.060	0.053	….	-3.806	-2.256	0.075	-0.022	….	0.917	2.096	-0.988	E20
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
701	0.992	2.060	0.051	….	-3.809	-1.068	-0.080	-0.154	….	0.895	2.657	-1.011	E21
702	0.988	2.064	0.051	….	-3.803	-1.387	-0.216	-0.324	….	0.896	2.680	-1.013	E21
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
736	0.996	2.060	0.051	….	-3.808	-1.620	0.150	0.095	….	0.900	2.475	-1.006	E22
737	0.992	2.060	0.051	….	-3.809	-1.746	0.134	0.068	….	0.900	2.475	-1.005	E22
….	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
771	1.112	2.204	0.058	….	-3.750	-0.680	-0.120	-0.130	….	0.953	1.906	-1.002	E23
772	1.108	2.184	0.058	….	-3.748	-0.878	-0.291	-0.250	….	0.953	2.114	-1.002	E23
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
806	1.040	2.176	0.055	….	-3.761	-1.965	-0.119	0.063	….	0.929	2.382	-1.012	E24
807	1.036	2.172	0.055	….	-3.766	-2.082	-0.213	-0.038	….	0.927	2.411	-1.011	E24
….	….	…..	…..	….	…..	…..	……	……	….	…..	…..	……	……
841	0.984	2.040	0.049	….	-3.812	-1.583	-0.023	0.001	….	0.871	3.174	-1.029	E25
842	0.976	2.040	0.049	….	-3.813	-1.862	0.040	0.082	….	0.873	3.002	-1.025	E25
…..	…..	……	……	…..	…..	…..	……	……	….	…..	…..	……	…..
876	0.960	2.128	0.046	….	-3.787	-2.115	0.432	0.686	….	0.855	2.902	-1.064	E26
877	0.960	2.176	0.046	….	-3.744	-3.352	-0.076	0.206	….	0.847	3.868	-1.085	E26
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……
911	0.920	2.104	0.044	…..	-3.802	-0.507	1.691	1.380	…..	0.836	2.502	-1.074	E27
912	0.928	2.096	0.045	….	-3.803	-1.399	1.360	1.172	….	0.845	2.519	-1.059	E27
…..	…..	……	……	….	…..	…..	……	……	….	…..	…..	……	……

Sl. No.	Features												CL
	F1	F2	F3	…..	F17	F18	F19	F21	…..	F36	F38	F39	
946	0.996	2.064	0.050	….	-3.809	-1.138	-0.408	-0.457	….	0.882	0.289	-1.023	E28
947	0.992	2.068	0.050	….	-3.808	-1.321	-0.511	-0.525	….	0.881	3.246	-1.023	E28
…..	…..	……	……	….	….	….	….	….	….	….	….	….	….
981	0.952	2.088	0.046	….	-3.803	-0.747	0.564	0.625	….	0.852	3.368	-1.062	E29
982	0.944	2.088	0.046	….	-3.802	-1.386	0.607	0.585	….	0.848	3.365	-1.063	E29
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1016	0.984	2.040	0.049	….	-3.812	-1.583	-0.023	0.001	….	0.871	3.174	-1.029	E30
1017	0.976	2.040	0.049	….	-3.813	-1.862	0.040	0.082	….	0.873	3.002	-1.025	E30
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1051	0.984	2.048	0.050	….	-3.811	-1.612	0.545	0.641	….	0.886	2.775	-1.018	E31
1052	0.988	2.060	0.050	….	-3.808	-2.533	0.443	0.510	….	0.885	2.774	-1.019	E31
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1086	0.996	2.036	0.051	….	-3.813	-1.064	-0.456	-0.434	….	0.896	3.048	-1.010	E32
1087	1.004	2.056	0.052	….	-3.809	-2.222	-0.413	-0.323	….	0.901	2.916	-1.005	E32
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1121	0.976	2.044	0.050	….	-3.811	-1.313	-0.349	-0.314	….	0.878	3.221	-1.025	E33
1122	0.980	2.044	0.050	….	-3.812	-1.345	-0.334	-0.317	….	0.879	3.183	-1.023	E33
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1156	0.960	2.120	0.046	….	-3.783	-1.702	1.375	1.334	….	0.852	1.908	-1.077	E34
1157	1.000	2.072	0.048	….	-3.807	-1.297	1.176	0.984	….	0.869	0.731	-1.047	E34
……	……	……	…..	….	….	….	….	….	….	….	….	….	….
1191	0.952	2.032	0.046	….	-3.814	-0.461	0.739	0.815	….	0.853	3.147	-1.046	E35
1192	0.960	2.032	0.047	….	-3.813	-1.581	1.229	1.164	….	0.868	2.761	-1.028	E35
……	……	……	…..	….	….	….	….	….	….	….	….	….	….

5.6. Classification of Feature by SVM

Support Vector Machines (SVMs) are versatile machine learning algorithms that can be used for both classification and regression tasks. They work by finding a hyperplane that best separates data points of different classes while maximizing the margin between the classes. Depending on the nature of the problem and the data, different types of SVMs and variations can be used. In this work, the Quadratic SVM has been chosen for classification and analysis [65].

Quadratic SVM:

Here, we classify the features by quadratic SVM. Certainly, we can delve into more detail about the mathematical theory behind a quadratic SVM. A quadratic SVM involves using a quadratic kernel function to transform the input data and enable the SVM to capture quadratic relationships in the data. Let's explore the mathematics involved:

Quadratic Kernel Function:

The quadratic kernel function is a specific type of polynomial kernel. It allows the SVM to capture quadratic relationships between data points. Mathematically, the quadratic kernel function can be defined as:

$$K(x, y) = (x^{\wedge T}\, y + c)^{\wedge 2} \qquad (5.16)$$

Here, x and y are the input data points, and c is a constant term. The kernel function computes the dot product of the transformed data points and adds a constant term, and then squares the result. This transformation effectively allows the SVM to learn quadratic decision boundaries.

Due to not all data sets are linear, the kernel concept was developed and used with SVM models to classify non-linear binary data sets. Although the SVM with kernels achieves excellent results in non-linear binary classification, they do have significant limitations. There are no general rules for selecting a kernel function that is suitable for a certain set of data from the beginning. Additionally, it has been found that the hyper-parameters of the kernel function have an important effect on the performance of SVM models that use that kernel function. The kernel-free quadratic surface SVM (QSSVM) model, which implements non-linear separation directly using quadratic surfaces instead of applying kernels at all, was developed to solve these drawbacks of kernel SVM models. Although QSSVM works well with some types of data, it difficulties with highly non-linear data sets, which is the reason it isn't commonly used. In comparison to a quadratic or cubic function, it is more non-linear. Additionally, a quadratic kernel-free least squares SVM was recommended and its use for the actual-world classification of target data was presented. These kernel-free quadratic SVM models have various drawbacks while being useful in specific circumstances. When solving both primary and dual problems in the kernel-free quadratic model, it can be costly to compute the inverse and decomposition of the kernel matrix [66,67]. Additionally, it's probably that the singularity issue associated with a kernel matrix will reduce classification accuracy. To get around these restrictions, we suggest a brand-new separation margin, known as Q-margin for data point separating and applied to SVM for the binary classification of data sets as "Q-SVM," which obtains a quadratic separation surface for classification.

To show the usefulness and efficiency of our recommended Q-SVM, certain theoretical SVM properties are examined, and numerical experiments are carried out using accessible standard data sets [66-71].

Feature Space Transformation:

The quadratic kernel function implicitly maps the input data points into a higher-dimensional space where quadratic relationships are considered. This is done without explicitly calculating the transformed feature vectors, which would be computationally expensive for high-dimensional spaces.

Optimization Problem:

The goal of the SVM is to find the optimal hyperplane that separates different classes of data while maximizing the margin (the distance between the hyperplane and the nearest data points of each class). In the case of a quadratic SVM, the optimization problem involves finding the optimal coefficients for the quadratic kernel function.

The optimization problem can be formulated as follows:

Minimize*: 0.5 * ||w||^2 + C * Σ(max(0, 1 - y_i * (w^T φ(x_i) + b)))*

Here:

||w||^2 represents the squared Euclidean norm of the weight vector w.

C is the regularization parameter that balances the trade-off between maximizing the margin and minimizing classification error.

y_i is the target output (+1 or -1) for the *i-th* data point.

φ(x_i) represents the transformed feature vector of the *i-th* data point using the quadratic kernel function.

b is the bias term.

Dual Formulation:

Just like in standard SVMs, the quadratic SVM's optimization problem can be reformulated into its dual form using Lagrange multipliers. The solution to the dual problem involves calculating the Lagrange multipliers for each data point [67-71].

A quadratic function (*V*, *a*, *e*) that is capable of separating non-linearly the data into two classes is given by

$$f(X)= \frac{1}{2} X^T V X + a^T X + e \quad (5.17)$$

$$V=V^T=\begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1m} \\ v_{21} & v_{22} & \cdots & v_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{1m} & v_{2m} & \vdots & v_{mm} \end{bmatrix} ;\ a=\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \quad (5.18)$$

The following two important comments should be stated:

- The decision surfaces f(X) = et can assume any of the general forms of hyper-planes, hyper-spheres, hyper-ellipsoids, hyper-paraboloids, hyper-hyperboloids of various types.
- f(X) can be considered as the sum of two terms: the non-linear term ($f_{non-linear}(X) = \frac{1}{2} X^T$ VX) and the linear term ($f_{linear}(X) = a^T$ X + e)

Using Fig. 5.17, the derivation of the QSVM optimization problem is done as follows:

$$\overrightarrow{OX_B} = \overrightarrow{OX_\iota} - X_i\ \overrightarrow{X_B} \ \Rightarrow XB = Xi - \gamma\ (i)\ \frac{\Delta f(X_B)}{\Vert \Delta f(X_B) \Vert} \tag{5.19}$$

Applying the first order Taylor Series expansion:

$$f(X_i) \approx f(X_B) + \Delta^T f(X_B)(X_i - X_B) \tag{5.20}$$

XB is on the decision function:

$$f(X_B) = 0 \tag{5.21}$$

And the functional margin is given by:

$$f(X_i) = \hat{\gamma}(\mathrm{i}) \tag{5.22}$$

Equations (5.20–5.22) will give:

$$\hat{\gamma}\ (i) \approx \gamma(\mathrm{i})\Vert\ \Delta f(X_B)\Vert \Rightarrow \gamma(\mathrm{i}) \approx \frac{\hat{\gamma}(i)}{\Vert \Delta f(X_B) \Vert} \tag{5.23}$$

It should be noted that this equation is valid for the hyper-plane decision function:

$$\Delta f(\mathrm{X}) = \mathrm{V} \Rightarrow \gamma\ (\mathrm{i}) = \frac{\hat{\gamma}(i)}{\Vert V \Vert} \tag{5.24}$$

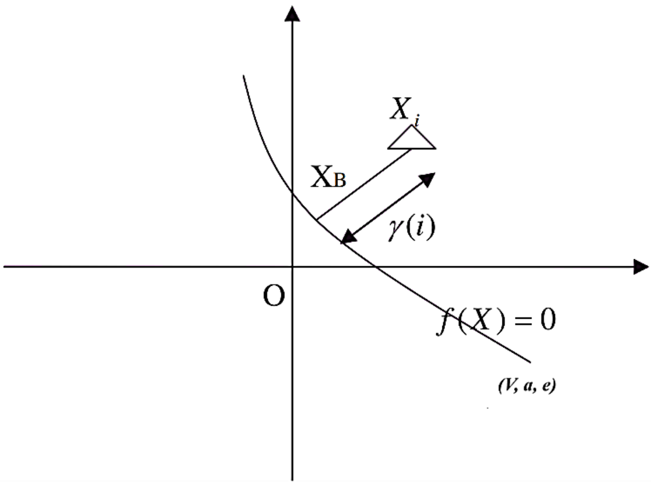

Fig. 5.13. Quadratic decision surface.

The QSVM optimization problem is given by:

$$\text{Maximize, } \gamma(\mathrm{i}) \approx \frac{\hat{\gamma}}{\Vert \Delta f(X_B) \Vert} \tag{5.25}$$

$$\text{subject to: } \gamma\ (\mathrm{i}) \geq \hat{\gamma} \tag{5.26}$$

Letting $\hat{\gamma} = 1$, the QSVM optimization problem can be restated as follows:

Minimize $\Vert\ \Delta f(X)\Vert \Leftrightarrow$ Minimize $\Vert \Delta\ f(X)\ \Vert^2$

subject to: γ (i) $\geq$ 1.

For n training data, the QSVM optimization problem becomes:

Minimize $\sum_{i=1}^{n} \Vert \Delta f(X_i) \Vert^2$

Subject to: γ (i) ≥ 1 for i = 1, K, n.

The gradient of the quadratic objective function is given by:

$$\Delta f(X) = VX + a$$

The norm of the gradient is given by:

$$\| \Delta f(X) \|^2 = (VX + a)^2 (VX + a) = X^T V^T VX + a^T a + 2a^T V \qquad (5.27)$$

In this paper, the following approximation is done:

$$\text{Minimize } \| \Delta f(X) \|^2 \approx \text{Minimize } X^T V^T VX + a^T a \text{ (5.28)} \qquad (5.28)$$

This approximation can be justified as follows:

$$\| \Delta f(X) \|^2 \geq 0 \Rightarrow X^T V^T VX + a^T a \geq -2a^T V \qquad (5.29)$$

$$\Rightarrow \text{Minimize } X^T V^T VX + a^T a \Leftrightarrow \text{Maximize } -2a^T V \Leftrightarrow \text{Minimize } 2a^T V \Rightarrow$$

$$\approx \text{Minimize } \| \Delta f(X) \|^2 \qquad (5.30)$$

This approximation made it easy for the QSVM optimization problem to be put as a quadratic optimization problem. It contains two terms: One term related to the linear part of the quadratic function and another term related to the non-linear term.

For the linear part:

$$\Delta f_{linear}(X) = a \Rightarrow \|\Delta f(X)\|^2 = a^T a. \qquad (5.31)$$

The quadratic form of the linear part is:

$$\| \Delta f_{linear}(X) \|^2 = \frac{1}{2} a^T H_{linear} a \qquad (5.32)$$

$$\text{where } z_{linear} = a;\ H_{linear} = \begin{bmatrix} 2 & 0 & \dots & 0 \\ 0 & 2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & 2 \end{bmatrix} \qquad (5.33)$$

The constraints for the linear part are given by:

$$-y_i (a^T X_i + e) \leq -1; \quad i = 1, \dots, n. \qquad (5.34)$$

For the non-linear part:

$$\Delta f_{non-linear}(X) = VX \Rightarrow \| \Delta f_{non-linear}(X) \|^2 = (VX)^T (VX) \qquad (5.35)$$

Equation (36) can be put in a quadratic form as follows:

$$\| \Delta f_{non-linear}(X) \|^2 = \frac{1}{2} V_1^T M_1^T M_1 V_1 \qquad (5.36)$$

Where $V_1$is the vector formed by taking the $\frac{m^2+m}{2}$ parameters of the upper triangle of the matrix V (eq. 5.37)

$$V_1 = [\text{uppertriangle (V)}] = [v_{11} \dots v_{1m} v_{22} \dots v_{2m} \dots v_{mm}]. \qquad (5.37)$$

And M_1 is a $(\frac{m^2+m}{2}) \times m$ matrix formed as follows:

Assuming that the data X is given by $[x_1 x_2 \dots x_m]^T$ then in each ith column of M_1, find the positions of all the components of V_1 which have the form v_{id} or v_{di} (where d can be any value) and set those positions in the ith column of M_1 to $[x_1 x_2 \dots x_m]$ and set the other positions to zero.

This can be illustrated for m = 3:

$$V=\begin{bmatrix} v_{11} & v_{12} & v_{13} \\ v_{21} & v_{22} & v_{23} \\ v_{13} & v_{23} & v_{33} \end{bmatrix} \Rightarrow = V_1 = [\, v_{11} v_{12} v_{13} v_{22} v_{23} v_{33} \,] \qquad (5.38)$$

$$M_1 = \begin{bmatrix} x_1 & 0 & 0 \\ x_2 & x_1 & 0 \\ x_3 & 0 & x_1 \\ 0 & x_2 & 0 \\ 0 & x_3 & x_2 \\ 0 & 0 & x_3 \end{bmatrix} \qquad (5.39)$$

The constraint equations for the non-linear part can be obtained by looking at the components of the V_1 vector and replacing every v_{ij} by $\begin{cases} x_i x_j & i \neq j \\ \frac{1}{2} x_i x_i & i = j \end{cases}$

The constraint equations (n equations corresponding to n data) of the previous example are (assuming m = 3)

$$-y_i \left[\frac{1}{2} x_1 x_1 x_1 x_2 x_1 x_3 \frac{1}{2} x_2 x_2 x_2 x_3 \frac{1}{2} x_3\ x_3\right]_i \leq -1;\ i = 1, \ldots, n. \qquad (5.40)$$

The sum of the two parts (the QSVM optimization problem) can be put as a one quadratic optimization problem as follows:

$$\text{Minimize } \|\Delta f(X)\|^2 \Leftrightarrow \text{Minimize } \frac{1}{2} z^T \text{H } z \qquad (5.41)$$

subject to: γ (i) ≥ 1 subject to $Az \leq k$,

$$where\ \text{H} = \begin{bmatrix} \text{H}_{\text{non-linear}} & \mathbf{0} & 0 \\ \mathbf{0} & \text{H}_{\text{linear}} & 0 \\ 0 & 0 & 0 \end{bmatrix}\ and\ z = \begin{bmatrix} \mathbf{V}_1 & \boldsymbol{a} & \boldsymbol{e} \end{bmatrix}^T$$

$$-y_i \left[\frac{1}{2} x_1.x_1 \ \cdots \ x_1.x_m \ \frac{1}{2} x_2.x_2 \ \cdots \ x_2.x_m \ \cdots \ \frac{1}{2} x_m.x_m \ x_1 \ x_2 \ \cdots \ x_m \ 1 \right]_i \leq -1$$

$$i = 1, \cdots, n \qquad (5.42)$$

Decision Boundary:

The decision boundary of a quadratic SVM is determined by the support vectors and the Lagrange multipliers associated with them. These support vectors are the data points that lie closest to the decision boundary and have non-zero Lagrange multipliers. The decision boundary is a quadratic curve in the transformed feature space.

In summary, a quadratic SVM utilizes a quadratic kernel function to capture quadratic relationships between data points, enabling the SVM to learn complex decision boundaries. The mathematical theory involves formulating and solving an optimization problem with a quadratic kernel and finding the support vectors that determine the decision boundary. The choice of parameters, such as the regularization parameter C, needs to be carefully tuned to avoid overfitting or underfitting.

Advantages of QSVM:

- QSVM gave better performance than the SVM with polynomial kernel (PSVM).
- The value of and the percentage of training data affect the SVM with Gaussian kernel's performance. The QSVM's performance is independent of any tuning parameter.
- Irrespective of the σ used, QSVM gave better performance for the partial contaminated of polymer insulator database, the database using the 40% training data.

Scatter Plot:

A scatter plot is a type of data visualization that displays individual data points as dots or markers on a two-dimensional plane. It's commonly used to visualize the relationship between two variables and to identify patterns, trends, or correlations within the data. Each dot on the scatter plot represents a single data point, and its position is determined by the values of the two variables being compared.

Here's how to interpret a scatter plot:

Horizontal Axis (X-axis): This axis represents one variable (usually the independent variable) of the data.

Vertical Axis (Y-axis): This axis represents the other variable (usually the dependent variable) of the data.

Data Points: Each data point is plotted at the intersection of the corresponding values on the X and Y axes. The position of a data point on the scatter plot provides information about the relationship between the two variables.

Patterns and Relationships:

Positive Correlation: If the data points tend to move upwards from left to right, there is a positive correlation between the two variables. This means that as one variable increases, the other tends to increase as well.

Negative Correlation: If the data points tend to move downwards from left to right, there is a negative correlation between the two variables. This means that as one variable increases, the other tends to decrease.

No Correlation: If the data points are scattered randomly without any noticeable pattern, there might be little to no correlation between the two variables.

Scatter plots are particularly useful for:

Identifying patterns and trends in the data.

Visualizing the strength and direction of the relationship between two variables.

Detecting outliers and unusual data points.

Assessing the distribution and spread of data.

In cases where we have more than two variables, we can also create scatter plot matrices (also known as pairs plots), where each combination of variables is plotted against each other. This can help us understand multiple relationships within the data at once [65-71].

The scatter plot of the different classes has been shown in Fig. 5.14.

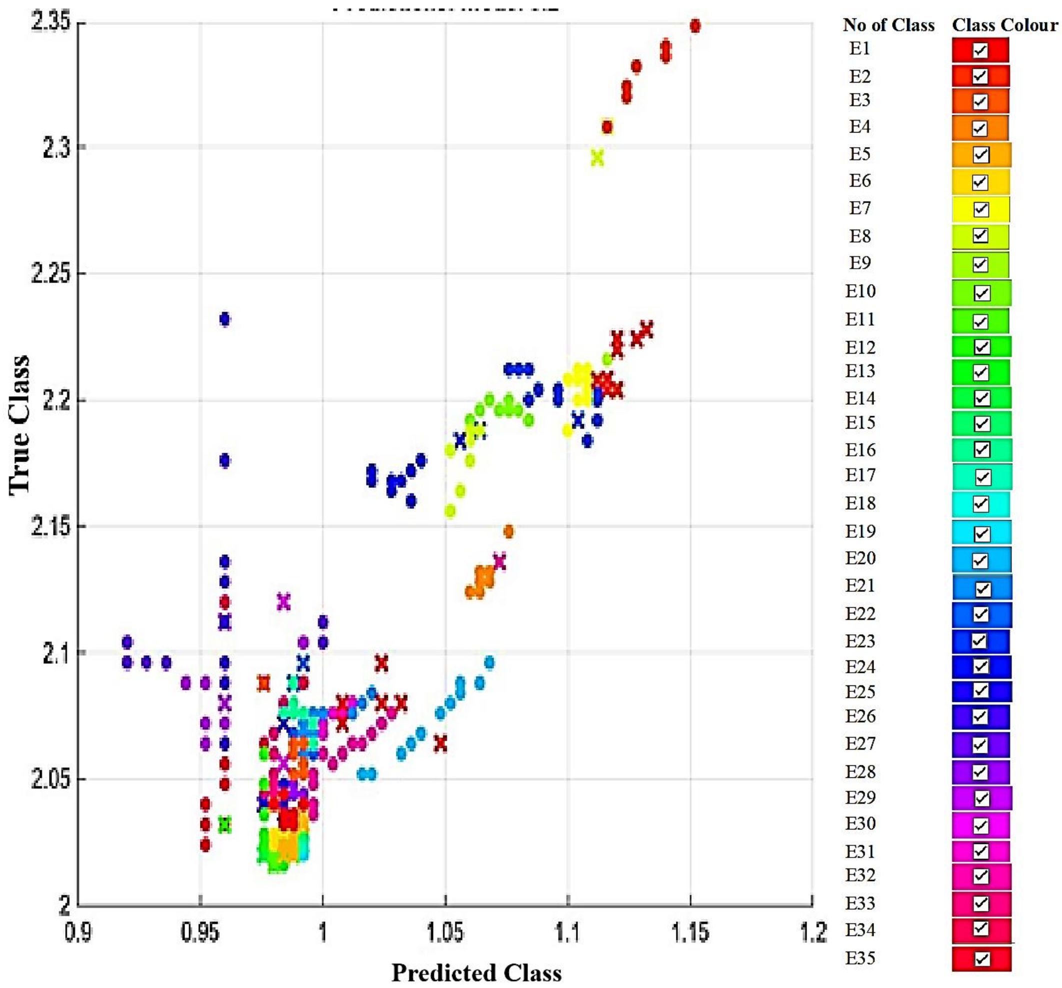

Fig. 5.14. Scatter Plot of the Different Classes.

Confusion Matrix:

A confusion matrix is a table often used in classification tasks to describe the performance of a classification algorithm, such as Support Vector Machines (SVM). It helps in understanding how well the algorithm is performing in terms of different classes and their predictions.

In this confusion matrix:

True Positive (TP): Instances that are actually positive and were correctly predicted as positive by the SVM.

True Negative (TN): Instances that are actually negative and were correctly predicted as negative by the SVM.

False Positive (FP): Instances that are actually negative but were incorrectly predicted as positive by the SVM.

False Negative (FN): Instances that are actually positive but were incorrectly predicted as negative by the SVM.

Based on these values, several metrics can be calculated to evaluate the performance of the SVM, including:

Accuracy: (TP + TN) / (TP + TN + FP + FN)

Precision: TP / (TP + FP)

Recall (Sensitivity or True Positive Rate): TP / (TP + FN)

Specificity (True Negative Rate): TN / (TN + FP)

F1-Score: 2 * (Precision * Recall) / (Precision + Recall)

With this confusion matrix, we can calculate various metrics to evaluate the performance of our SVM in identifying contaminated locations. These metrics could include accuracy, precision, recall, F1-score, and possibly additional domain-specific metrics that are relevant to contamination identification. The specific values in the confusion matrix and the resulting metrics will depend on how well our SVM performs on our dataset for this specific task [65-71]. The confusion matrix of the prosed model has been tabulated in Table 5.6.

The above (25×35 ×35) or 30625 features have been used for location identification of contamination of polymer insulator by Quadratic SVM classifier. Among those 12250 features (40%) have been used for training purpose whereas 18375 features (60%) are used for testing purpose.

Here diagonal elements of the above confusion matrix represent correctly classified event whereas off-diagonal elements are represented as miss-classified events. Overall accuracy of this classification is given by the ratio of correctly classified events divided by total number of events.

The maximum classification accuracy obtained in this method is 92%. Also, it is observed that classification accuracy decreases with the increasing of humidity. It must be noted that with an increase in the number of feature set belonging to each class, the overall accuracy increases.

This work has proposed a new technique for sensing the location identification of contamination of polymer insulator. In this proposed method Mathematical Morphology has been applied as a feature extraction tool because it is amplified the inherent characteristics of leakage current signal. Quadratic support vector machine Classifier is applied here for classification purpose. In this proposed technique overall classification accuracy is 92%. Result indicates that the proposed method is very much suitable for identify the location of contamination of polymer insulator with very high degree of accuracy as compared to other feature extraction tools and classifier algorithms, presented by other authors.

Table 5.6. Confusion Matrix of the Test Data Sets of the Proposed Model.

True Class

1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	3	0	0	11	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	9	0	0	5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	1	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Predicted Class

ROC Curve:

A Receiver Operating Characteristic (ROC) curve is a graphical representation that illustrates the performance of a binary classification model, such as a Support Vector Machine (SVM), across different discrimination thresholds. The ROC curve plots the True Positive Rate (TPR) against the False Positive Rate (FPR) at various threshold settings.

However, please note that constructing an ROC curve typically involves adjusting the decision threshold of a classifier to generate different pairs of TPR and FPR values. SVMs inherently do not provide probability estimates directly like some other classifiers (e.g., logistic regression). Instead, they classify data points based on their position relative to the decision boundary.

Still, you can achieve a pseudo-ROC curve for an SVM-based location identification of contamination by utilizing the decision values (also known as "distance from the decision boundary") assigned to each data point during classification.

Here are the steps to create a pseudo-ROC curve for an SVM:

Obtain Decision Values: During SVM classification, SVM assigns decision values to each data point, representing their distance from the decision boundary. These decision values can serve as proxies for confidence scores.

Vary Decision Threshold: Start by choosing a range of decision values as thresholds. For each threshold, classify the data points based on whether their decision value is above or below the threshold.

Calculate True Positive Rate (TPR) and False Positive Rate (FPR): Count the number of true positive, false positive, true negative, and false negative instances for each threshold setting. Calculate TPR (Sensitivity) as TP / (TP + FN) and FPR as FP / (FP + TN).

Plot ROC Curve: Plot the TPR on the y-axis against the FPR on the x-axis for each threshold setting. This will give you a pseudo-ROC curve.

It's important to remember that the ROC curve might not be as informative for SVMs as it is for classifiers that provide explicit probability estimates. Additionally, you might consider using other evaluation techniques, such as Precision-Recall curves or area under the ROC curve (AUC-ROC), to assess the SVM's performance for location identification of contamination [65-71].

The ROC curve of the different classes has been shown in Fig. 5.14.

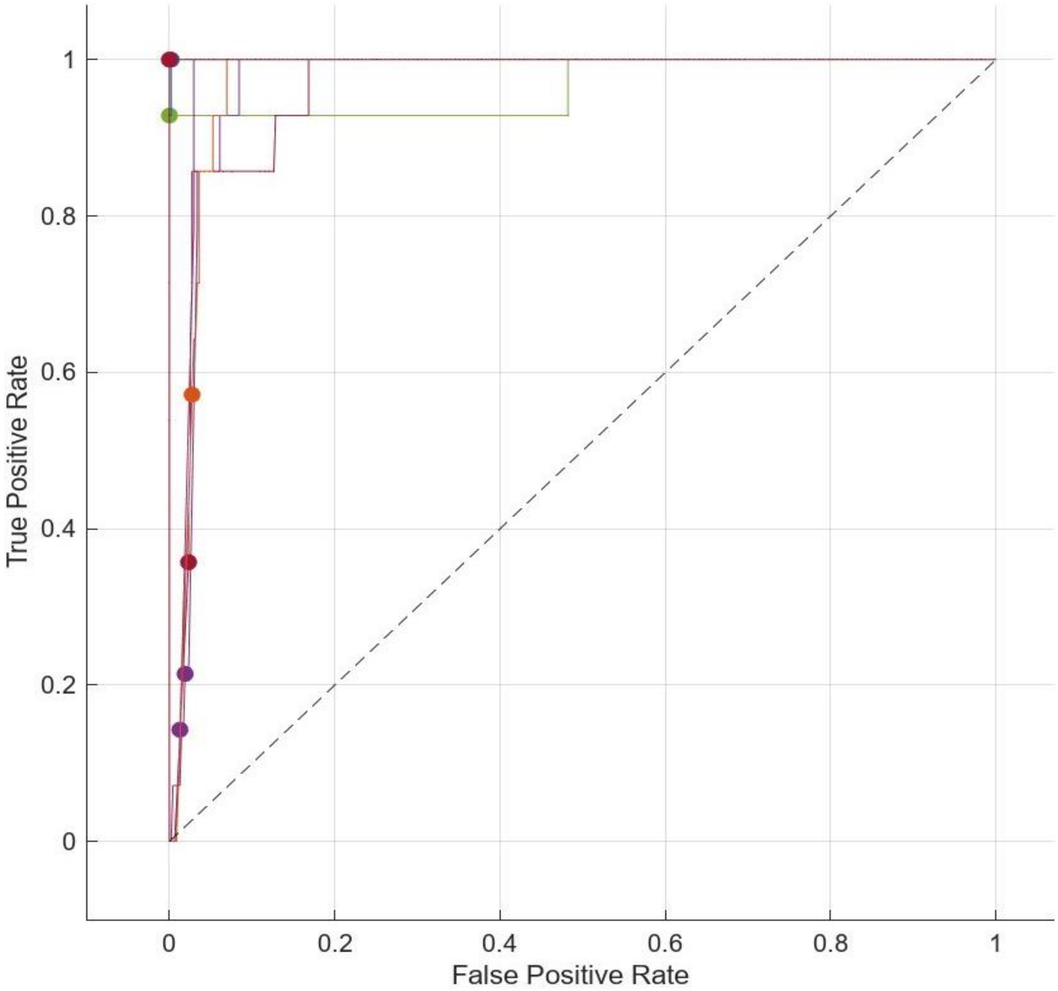

Fig. 5.14. ROC Curve of the Different Classes.

Summary:

This work has proposed a new technique for Location identification of contamination on polymer insulators. In this proposed method Mathematical Morphology has been applied as a feature extraction tool because it is amplified the inherent characteristics of leakage current signal. Minimum Redundancy Maximum Relevance (mRMR) is a feature selection technique that is used for features selection purpose in this thesis. Quadratic SVM Classifier is applied here for the purpose of location identification of contamination on Silicone Rubber insulator. In this proposed technique overall classification accuracy is 92%. Result indicates that the proposed method is very much suitable for Location identification of contamination on polymer insulators with very high degree of accuracy as compared to other feature extraction tools and classifier algorithms, presented by other authors.

6. CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

This submitted thesis discusses typical difficulties with maintaining the condition of the insulators on overhead power lines. Transmission line insulators degrade over time as a result of different pollutants in the atmosphere, such as salt, dust, and chemical pollutants. As a result, monitoring the condition of overhead insulators is essential for increasing electrical system stability. Leakage current signal-based techniques have been suggested in this thesis as a method to achieve it. The surface state of an overhead insulator can be almost accurately predicted according to the methods suggested.

In the present work, the effects of contamination on the magnitude of leakage current of an 11 kV silicone rubber insulator were conducted in the High-Tension Laboratory, Jadavpur University. This experiment was conducted on partially contaminated silicone rubber insulator at different voltage levels. To record the leakage current of an overhead Silicone Rubber insulator, an experimental setup has been set up. In order to address the effect of surface contamination, insulator sample has been artificially contaminated using solid layer method. It is noteworthy recorded leakage current through this setup carries significant information about the surface condition of the insulator. It was also seen that the rate of rise of leakage current in case of contaminated insulator is more than that of clean.

In chapter 5, a framework has been proposed combining Mathematical Morphology, Minimum Redundancy Maximum Relevance(mRMR) along with Support Vector Machine classification (SVM) to classify leakage current signal for different partially contaminated silicone rubber insulators.

Mathematical Morphology has been applied as a feature extraction tool because it amplifies the inherent characteristics of leakage current signal. Mathematical morphology is a valuable tool for feature extraction from leakage current data. It allows for the extraction of relevant features that capture the spatial and structural characteristics of contamination on silicone rubber insulators. These features provide essential information for distinguishing between normal and partially contaminated insulators.

Minimum Redundancy Maximum Relevance (mRMR) is a feature selection technique that is used for features selection purpose in this thesis. The mRMR algorithm plays a crucial role in improving classification accuracy by selecting the most informative and non-redundant features from the extracted features set. This step helps reduce the dimensionality of the data while retaining the most relevant information, which is essential for enhancing the classification performance.

Quadratic SVM classifier is applied here for the purpose of location identification of contamination on silicone rubber insulator. Quadratic SVMs offer an excellent choice for classifying leakage current data. Unlike linear SVMs, quadratic SVMs can capture more complex decision boundaries and handle situations where the relationship between features is non-linear. In this proposed technique overall classification accuracy is 92%. Result indicates that the proposed method is very much suitable for location identification of contamination on silicone rubber insulators with very high degree of accuracy as compared to other feature extraction tools and classifier algorithms, presented by other authors.

In conclusion, the integration of mathematical morphology feature extraction, mRMR feature selection, and Quadratic SVM classification provides a comprehensive and robust solution for the location identification of contamination on silicone rubber insulator using leakage current data.

6.2. Future Work

The observations obtained and discussed in this thesis can be used as a basis for further research in many fields. The present thesis predicts for Location identification of contamination on polymer insulators. The framework provided in this thesis is quite effective and can be used to monitor the condition of an overhead insulator that is currently in use. The following list includes a few of possible scopes

- In this thesis work, only polymer insulator has been used. In future this work can be extended to other types of insulators including porcelain and glass insulators.
- Implementing modern signal processing techniques like graph signal processing to improve the accuracy of location identification of contamination on polymer insulators. This can capture complex spatial relationships among contamination spots on the insulator surface.
- The manual feature extraction approach requires knowledge about signal processing. In recent times, deep learning has been used in various engineering problem. The advantages of deep learning framework is that it can extract feature from input data automatically. Deep learning models like Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and Autoencoders (AEs) can be applied for this purpose. Autoencoders can be used for feature learning and dimensionality reduction, which can be beneficial for processing complex data related to insulator conditions.
- Various classification techniques such as ANN (Artificial Neural Network), SRC (Sparse Representation Classifier) etc. can be applied on the data for Location identification of contamination on polymer insulators.
- Insulators may be affected due to acid rain. Effect of acid rain on porcelain, polymer and glass insulators can be the point of interest in future
- Various chemicals have different impact on insulators in industrial belt which must have to investigate by researchers for condition monitoring of it.

Combining data from multiple sources, such as visual images, leakage current measurements, and infrared imaging, can offer a more comprehensive understanding of insulator conditions and enhance the accuracy of predictions.

References

[1] IEC 60433, “Insulators for Overhead Lines with a Nominal Voltage Above 1000 V- Ceramic Insulators for a.c. Systems - Characteristics of Insulator Units of the Long Rod Type”, 1998.

[2] IEC 60720, “Characteristics of Line Post Insulators”, 1981.

[3] IEC 60507, “Artificial Pollution Tests on High-Voltage Insulators to be Used on A.C. Systems”, 1991.

[4] IEC Standard 60815, “Guide for Selection of Insulators in Respect of Polluted Condition,” 1986.

[5] IEC Standard 60273, “Characteristic of Indoor and Outdoor Post Insulators for Systems with Nominal Voltages Greater than 1000V”, 1990.

[6] STRI Hydrophobicity Classification Guide, Guide 1, 92/1.

[7] http://www.electricaltechnology.org

[8] http:// www.hbjinyong.com

[9] P.J. Lambeth, “Variable Voltage Application for Insulator Pollution Tests”, *IEEE Trans. Power Deliv.*, Vol.3, No.4, 1988.

[10] IEC 60071 "Insulation Coordination", Part 1: Terms, Definitions, Principles and Rules (1993), Part 2: Application Guide (1996).

[11] D.A. Swift *et. al*, “Hydrophobicity Transfer from Silicone Rubber to Adhering Pollutants and its Effect on Insulator Performance,” *IEEE Trans. Diele. Electr. Insul.*, Vol. 13, No. 4, pp. 820-829, 2006.

[12] D.C. Jolly, “A Quantitative Method for Determining the Resistance of Polymers to Surface Discharges,” *IEEE Trans. Electr. Insul.*, Vol.17, No. 4, 1982.

[13] A.C. Baker *et. al*, “A Comparison of HVAC and HVDC Contamination Performance of Station Post Insulators”, *IEEE Power Eng. Rev.* Vol. 9, pp. 1486–1491, 1989.

[14] F. Cevik *et. al*, “An assessment of Metal Pollution in Surface Sediments of Seyhan Dam by Using Enrichment Factor, Geo Accumulation Index and Statistical Analyses”, *Environ. Monit. Assess.,* Vol. 152, pp. 309–317, 2009.

[15] K.L. Chrzan *et. al*, “Probes for Spot Measurement of Surface Conductivity on Polluted Insulators”, *IET Sci. Meas. Technol.,* Vol. 1, pp. 295–300, 2007.

[16] C. N. Richards *et. al*, “Development of a Remote Insulator Contamination Monitoring System”, IEEE Trans. Power Deliv., Vol. 12, No. 1, pp. 389-397, 1997.

[17] A.H. El-Hag *et. al*, “Prediction of Leakage Current of Non- Ceramic Insulators in Early Ageing Period.” *Electric Power Systems Research, Elsevier*, Vol. 78, pp. 1686-1692, 2008.

[18] B. Subba Reddy *et. al*, “Study of Leakage Current Behaviour on Artificially Polluted Surface of Ceramic Insulator”, *Plasma Sci. & Tech.*, Vo1.5, No. 4, pp.1921-1926, 2003.

[19] H. Homma *et. al*, “Comparison of Leakage Current Properties between Polymeric Insulators and Porcelain Insulators Under Salt Polluted Conditions”, *Proc. IEEE Int. Conf. on Elec. Insul. Materials (ISEIM)*, Japan, 2005.

[20] H. Ahmad *et. al*, “Harmonic Components of Leakage Current as Diagnostic Tool to Study the Aging of Insulators”, *J. Electrostatics*, Vol. 66, pp. 156-164, 2008.

[21] S. Chandrasekar *et. al*, “Investigations on Flashover Performance of Porcelain Insulators Under Contaminated Conditions”, *Proc. Nat. Conf. on Elec. Engg. Embedded Sys. (NCEEE)*, pp.112-116, 2008.

[22] I. Ramirez *et. al*, “Measurement of Leakage Current for Monitoring the Performance of Outdoor Insulators in Polluted Environments”, *IEEE Electr. Insul. Mag.*, Vol. 28, No. 4, pp.29-34, 2012.

[23] IEC Pub. 587, The Method for Evaluating Resistance to Tracking of Electrical Insulating Materials under Severe Ambient Conditions, 1984.

[24] TF 33.04.03 CIGRE: “Insulation pollution monitoring”, *Eleatra*, No. 152, pp.79-89, Paris, France, 1994.

[25] G. Montoya *et. al*, “Correlation among ESDD, NSDD and leakage current in distribution insulators,”

Proc. IEE Gen. Trans. and Dist., Vol. 151, No.3, pp. 334-340, 2004.

[26] ASTM G154-06, Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.

[27] D. Devendranath *et. al*, “Leakage Current and Charge in RTV Coated Insulators Under Pollution Conditions”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 9, No. 2, pp. 294-299, 2002.

[28] E. Thalassinakis *et. al*, “Measurements and Interpretations Concerning Leakage Currents on Polluted High Voltage Insulators”, *Meas. Sci. Techn.*, Vol. 14, pp. 421-426, 2003.

[29] E. Fontana *et. al*, “Novel Sensor System for Leakage Current Detection on Insulator Strings of Overhead Transmission Lines”, *IEEE Trans. Power Deliv.*, Vol. 21, pp. 2064-2070, 2006.

[30] K. Petcharaks *et. al*, “An Investigation of ESDD on Porcelain Insulators Along the Coastal Region of Thailand”, *Proc. IEEE Int. Conf. (TENCON)*, Thailand, 2004.

[31] I. Ramirez-Vazquez *et. al*, “Accelerated Ageing Test of Non-Ceramic Insulators Using Solid Layer Method”, *Proc. IEEE Int. Conf. on Electr. Insul. Dielectr. Phenomena (CEIDP)*, 2001.

[32] M. A. R. M. Fernando *et. al*, “Leakage Current Patterns on Artificially Polluted Composite Insulators”, *Proc. IEEE Int. Conf. on Electr. Insul. Dielectr. Phenomena (CEIDP)*, 1996.

[33] S. Chandrasekar *et. al*, “Investigations on Leakage Current and Phase Angle Characteristics of Porcelain and Polymeric Insulator Under Contaminated Conditions”, *IEEE Trans. Dielectr. Electr. Insul*, Vol. 16, pp. 574-583, 2009.

[34] A. K. Chaou *et. al*, “Recurrence Quantification Analysis as a Novel LC Feature Extraction Technique for the Classification of Pollution Severity on HV Insulator Model”, *IEEE Trans. Dielectr.Electr.Insul.*, Vol. 22, No. 6, 2015.

[35] H.H. Kordkheili *et. al*, “Determining the Probability of Flashover Occurrence in Composite Insulators by Using Leakage Current Harmonic Components”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 17, pp. 502-512, 2010.

[36] J.Y. Li *et. al*, “Humidity and contamination Severity Impact on Leakage Currents of Porcelain Insulators” *IET Gener. Trnas. Distrib.*, Vol.5, pp. 19-28, 2009.

[37] A. Nasir *et. al*, “Characterization of Acoustic Signals Due to Surface Discharges on H.V. Glass Insulators Using Wavelet Radial Basis Function Neural Networks”, *J. Appl. Soft Comp.*, Vol. 12, pp. 1239- 1246, 2012.

[38] J. Li *et. al*, ‘‘A Novel GIS Partial Discharge Detection Sensor with Integrated Optical and UHF Methods”, *IEEE Trans. Power Deliv*., Vol. 33, No. 4, pp. 2047-2049, 2018.

[39] G. Haddad *et. al*, “Study of surface degradation of HTV silicone rubber under thermal and ultraviolet exposures,” *Proc. IEEE Int. Conf. on High Voltage Engineering and Application*, China, 2012.

[40] Y. C. Cheng *et. al*, “Online Detecting Insulator Corona for Diagnosing Faulty Insulators on Transmission Line,” *Proc. Int. Elec. Insul. Dielectr. Pheno.*, China, 2001.

[41] J.Y. Li *et. al*, “Use of Leakage Currents of Insulators to Determine the Stage Characteristics of the Flashover Process and Contamination Level Prediction”, *IEEE Trans. Dielectr. Electr.Insul.*, Vol. 17, No.2, pp. 490–501, 2010.

[42] M. A. R. M. Fernando *et. al*, “Leakage Current Patterns on Contaminated Polymeric Surfaces”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 6, pp. 688-694, 1999.

[43] D. F. Kawa *et. al*, “Practical PCA-DA System for Measurements of Leakage Current Pulses on Polymer Insulators under Wet Contaminated Conditions*,” IEEE Electr. Insul. Mag.*, Vol. 8, No. 2, 1992.

[44] G Besztercey, GG Karady and DL Ruff, “A Novel Method to Measure the Contamination Level of Insulators – Spot Contamination Measurement”, *Proc. IEEE Int. Conf. on Electr. Insul.*, Arlington VA, USA, 1998.

[45] M.A. Douar *et. al*, “Welch Periodogram Analysis of the Leakage Current on Insulator Model Under Wetted Contaminated Conditions for Flashover Prediction”, *Proc. IEEE Int. Conf. on Electro. Tech. (MELECON)*, Valetta, pp. 1636–1641, 2010.

[46] M. Otsubo *et. al*, “Evaluation Of Insulation Performance of Polymeric Surface using a Novel Separation Technique of Leakage Current”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 10, No. 6, pp. 1053–1060, 2003.

[47] F. Amarth *et. al*, “Level Crossing Analysis of Leakage Current Envelope Of Polluted Insulators”, *IEEE Power Eng. Rev.*, Vol. 21, No. 8, pp. 4-5, 2001.

[48] D. Pylarinos *et. al*, “Impact of Noise Related Waveforms on Long Term Field Leakage Current Measurements”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 18, No. 1, pp. 122-129, 2011.

[49] A. Banik *et. al*, “Autocorrelation Aided Rough Set Based Contamination Level Prediction of High Voltage Insulator at Different Environmental Condition”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 23, pp. 2883- 2891, 2016.

[50] K. Mathes *et. al*, “Surface Electrical Failure in the Presence of Contaminants: The Inclined-Plane Liquid-Contaminant Test,” *Trans. Am. Inst. Electr. Eng., Part I (Commun. Electron.)*, Vol. 80, pp. 281–289, 1961.

[51] T. Suda, “Frequency Characteristics of Leakage Current Waveforms of Artificially Polluted Suspension Insulator”, *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 8, pp.705-709, 2001.

[52] IEC-60507, "Artificial pollution tests on high-voltage ceramic and glass insulators to be used on a.c. systems," *IEC*, 2014.

[53] S. Gautam *et. al*, "Overview of mathematical morphology in power systems — A tutorial approach," *IEEE Power & Energy Society General Meeting, Calgary*, AB, 2009, pp. 1-7.

[54] P. Maragos. Morphological signal and image processing. CRC Press, 2000

[55] P. Maragos *et. al*, “Morphological systems for multidimensional signal processing” *Proceedings of the IEEE*, Vol. 78, No. 4, 1990.

[56] I. Serra, “Image analysis and mathematical morphology”. *New York Academic*, 1982.

[57] J. Serra *et. al*, "Image analysis and mathematical morphology Volume theoretical advances", Academic Press, 1988.

[58] J. Miao *et. al*, "A Survey on Feature Selection”, *Procedia Computer Science*, Vol. 91, pp. 919-926, 2016.

[59] C. Ding, "Minimum Redundancy Feature Selection from Microarray Gene Expression Data”, *Journal of Bioinformatics & Computational Biology*, Vol. 3 No. 02, 2005

[60] H. Peng *et. al*, "Feature Selection Based on Mutual Information: Criteria of Max-Dependency, Max-Relevance, and Min-Redundancy”, *IEEE Computer Society*, 2005.

[61] X Jin *et. al*, "Health Monitoring of Cooling Fans Based on Mahalanobis Distance With mRMR Feature Selection”, *IEEE Transactions on Instrumentation & Measurement*, Vol. 61, No. 8, pp. 2222-2229, 2012

[62] Y. Zhang *et. al*, "Gene selection algorithm by combining relief and mRMR” *Bmc Genomics*, Vol. 9, No. 2, 2008.

[63] T Wang *et. al*, "Ordered Incremental Attribute Learning based on mRMR and Neural Networks”, *International Journal of Design Analysis & Tools for Integrated Circuits & Systems*, Vol. 2, No. 2, pp. 53-66, 2011.

[64] B. Q. Li *et. al*, "Identification of Colorectal Cancer Related Genes with mRMR and Shortest Path in Protein-Protein Interaction Network”, *Plos One*, Vol. 7, No. 4, pp. 33393, 2012.

[65] L.J. Cao *et. al*, "Support Vector Machine with Adaptive Parameters in Financial Time Series Forecasting”, *IEEE Transactions on Neural Networks*, Vol. 14, No. 6, pp. 506–1518, 2003.

[66] O.l. Chapelle *et. al*, "Support Vector Machines for Histogram-Based Image Classification”, *IEEE Transactions on Neural Networks*, Vol. 10, No. 5, No. 1055–1064, 1999.

[67] E.K.P. Chong *et. al*, "An Introduction to Optimization”, *Wiley Inter-Science*, 1996.

[68] C. Cifarelli *et. al*, "P.M.: K-T.R.A.C.E: A kernel k-means procedure for classification”, *Journal Of Computer Operational Research*, Vol. 34, No. 10, pp. 3154–3161, 2007.

[69] N. Cristianini *et. al*, "An introduction to support vector machines (and other kernel-based learning methods)”, *Cambridge University Press*, 2000.

[70] H. Drucker *et. al*, "Support Vector Machines for Spam Categorization”, *IEEE Transactions on Neural Networks*, Vol. 10, No. 5, pp. 1048–1054, 1999.

[71] H Alshamlan *et. al*, "A Hybrid Gene Selection Algorithm for Cancer Classification Using Microarray Gene Expression Profiling”, *Biomed Research International*, Vol. 2015, No. 4, pp. 1-15, 2015.