CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

In an Electrical Power System, outdoor insulators play a significant role in maintaining the reliability of the network. Porcelain insulators are widely used in power transmission and distribution lines for a long time. In the recent times, polymer insulators are mostly preferred because of their superior insulation performance, 90% weight reduction, reduced breakage, lower installation costs, better handling of shock loads, superior contamination performance and they can also easily be used for upgrading existing lines for transmitting higher voltages compared with conventional porcelain insulators. (Looms 1997). The use of these insulators for a practical high voltage transmission line may vary from country to country. Some countries have adopted 50 to 60% of transmission line insulators which are composite, a few countries are investigating their performance, and some countries are testing about their long term reliability. However, the applications will continue to grow, because of results observed in artificial and field ageing tests. A recent worldwide survey done by CIGRE (2000) showed that there are thousands of polymeric insulators in services at all voltage levels.

When these insulators are installed near industrial, agricultural or coastal areas, airborne particles are deposited on the surface of the insulators and as a result pollution builds up gradually. These particles do not decrease
the insulation strength when the insulators are dry. However, when fog or light rain wets the surface of polluted insulators, a conductive layer is formed on the contaminated insulator surface, which initiates LC on the surface of insulator. The LC density is high and nonuniform near the electrodes which results in heating and drying of the pollution layer. It prompts the formation of dry bands and partial arcs are generated if the electric field intensity across the dry band exceeds the withstand value. When the surface resistance is adequately low, these partial arcs will elongate along the insulator profile which may ultimately cause flashover. Flashover of contaminated insulators in polluted areas has proved to be one of the most important factors influencing the operation of Extra and Ultra High Voltage (EHV, UHV) transmission lines. The economic impact of insulator flashovers exercise can be severe. According to CEA Enquiry Committee report (2008) and Rebati Dass (2001) report, a grid disturbance in India on 2\textsuperscript{nd} January 2001, December 2002 and 2005, Jan/ Feb 2007 and March 2008 has resulted in huge loss to the value of five thousand million rupees.

The surface condition diagnosis is the fundamental to reduce flashover risk at extreme circumstances at electric power utilities and they spend significant amounts of money on preventive maintenance, which includes insulator surface washing and cleaning. This operation is scheduled by the decision of line engineers, based on historical experience. A condition based maintenance program requires insulator washing if specific diagnostic standard indicates that such washing is necessary. Evidently, an accurate diagnostic standard is needed to determine the condition of the insulator surface and to identify the possibility of flashover. Laboratory investigation has shown that insulator surface Leakage Current carries information about the condition of insulator and LC can be easily measured. Hence, a new automated condition monitoring system based on surface L.C analysis is proposed in this work.
1.2 PHYSICAL DESCRIPTION OF COMPOSITE INSULATORS

Composite insulators have three main components, which are shown in Figure 1.1.

![Insulator Components and Cross-Section](image)

**Figure 1.1 Cross Section Diagram of Composite Insulators**

At the center of the insulator is a Fiberglass Reinforced Polymer (FRP) rod. The FRP rod is the most important part of a composite insulator because it is the mechanical load bearing part. The FRP rod is reinforced with either polyester, vinyl ester or epoxy resin to provide the appropriate mechanical strength. In order to avoid brittle fracture, Electrical grade Chemical Resistant (ECR) glass fibers are to be used. The metal end fittings are typically forged steel, ductile cast iron, malleable iron or aluminum and are selected for mechanical strength. The end fittings are usually crimped or swaged to the FRP rod.

The polymeric weather sheds and sheath are shaped and spaced over the FRP rod to prevent the rod from damage and to provide the required leakage distance. Therefore, the materials for sheds and sheath are required to have excellent ageing resistance under multiple environmental stresses. The possible materials of the weather sheds include epoxy resins, Ethylene-Propylene Diene Monomer (EPDM), Ethylene-Propylene Rubber (EPR) and silicone rubber (SiR). The long-term performance of silicone rubber (SiR) in
polluted environments is satisfactory than the other materials. The reason for the superior pollution performance of SiR is its ability to transfer the hydrophobic characteristic to the pollution layer on the surface at heavily polluted sites.

**1.3 FACTORS AFFECTING THE PERFORMANCE OF POLYMERIC INSULATORS**

The factors affecting the composite insulator are categorised by mechanical factors, environmental conditions, power system design and operation. The mechanical factor includes polymer base quality, core quality, end fitting gap attachment method and damage during installation. The environmental condition includes Ultraviolet radiation (UV), wind, ozone, temperature, pressure, humidity, rain, fog, snow and organic or inorganic pollution. Power system design and operation includes Electric field stress and leakage distance. Due to the above factors the composite insulator surface can be degraded. The degradation of insulator is called ageing. Among the above factors, the electric field stress and pollution become the very important factor to be investigated thoroughly. The thorough study of the electric field strength enhancement due to water droplets on the surface of composite insulators under various wet conditions is important for the in-depth understanding of the discharge process and the pollution flashover initiation mechanism on composite insulators.

In practice, there are actually various types of pollutants that tend to settle on the insulators. These contaminants can be classified as soluble and insoluble. Insulators that are located near coastal regions are typically contaminated by soluble contaminants, especially NaCl (Sodium chloride). Insulators that are located near cement or paper industries or thermal power stations are contaminated by a significant amount of non-soluble contaminants. Some of the pollutants include calcium chloride, carbon and
cement dust. Irrespective of the nature of the contaminant, flashover can occur as long as the salts are soluble enough to form a conducting layer on the surface of the insulator. In order to quantify the contaminants on the surface of the insulators, the soluble contaminants are expressed in terms of Equivalent Salt Deposit Density (ESDD), which correlates to mg of NaCl per unit surface area. Non-soluble contaminants are expressed in terms of Non-Soluble Deposit Density (NSDD), which correlates to mg of kaolin per unit surface area.

### 1.4 CONDITION MONITORING SYSTEM FOR POLYMERIC INSULATORS

The design of condition monitoring system is one of the important system aspects in power system networks. In literature, different condition monitoring systems for polymeric insulators such as measurement of ESDD level, measurement of NSDD level, surface conductivity measurement and LC measurement are proposed. The general technique for measuring ESDD involves dissolving the surface pollutant deposits in known quantity of water, preferably distilled water. The temperature of the solution has measured, and then the ESDD in mg/cm$^2$ has been calculated from the measured conductivity, the volume of water and the insulator surface area. The ENSDD is measured by filtering the wash water used for ESDD measurement through filter paper that are pre-dried in an oven and re-dried after waiting for the solution of drain through the filters. The dried and re-dried filter papers are weighed accurately using a scale with accuracy of the order of 0.0001 gram. The ENSDD is the difference between the original dried filter paper and re-dried filter paper divided by the surface area of the insulator. These methods are time consuming and difficult to automate.
The surface conductivity can be measured from the conductance using insulator based on the form factor (FF). The difficulty of this method is that the pollutant can be washed away by heavy rain and uncontrolled wetting of the surface. Any current flowing from hot conductor to ground over the outside surface of a device is called Leakage Current (LC). In case of insulators, it is the current that flows over the surface of insulator. The LC is measured by instrumentation system installed in the tower. The main advantage of this method is that main parameters like pollution deposit, wetting area etc. are taken into consideration.

In general, silicone rubber material offers good hydrophobicity for a long time. The long term maintenance of hydrophobicity is attributed due to its chemical stability and recovery phenomena resulting from diffusion of low molecular weight contents forming bulk volume of the insulator on the surface of the material. The hydrophobic characteristics are normally measured in the laboratory through static contact angle measurement. Hydrophobic polymers are characterized by electrical surface resistance which however decreases due to water absorption during ageing and with increasing environmental temperature contamination buildup. The hydrophobicity measurement requires human intervention close to insulators. The LC measurement, however, is very feasible. Thus it is very popular and widely adopted all over the world for condition monitoring of energized transmission using composite insulator.

1.5 LITERATURE REVIEW

The literature review of this dissertation is divided into five groups such as (i) artificial pollution test and leakage current measurement analysis (ii) Ageing of outdoor polymeric insulators (iii) artificial intelligence in condition monitoring of outdoor insulators (iv) Electric field and voltage distribution calculation and (v) Predictive Dynamic Arc Model.
1.5.1 Artificial Pollution Tests and Leakage Current Measurement and Analysis

Understanding the time-frequency characteristics of LC pattern is important in order to develop better diagnostic tools for preventive maintenance work. Gorur et. al. (1997) have proposed new laboratory test for evaluating the tracking and erosion performance of HV outdoor polymeric insulating materials and they have identified that the frequency contents of the leakage current signal obtained with polymeric insulators varies during surface discharge and tracking condition. Suda (2001) has studied the LC waveforms and frequency characteristics of an artificially polluted cap and pin type insulator and classified the transition of LC waveforms into six stages in order to predict the flashover. Felix Amarh (2001) has developed a theory that links the flashover mechanism to measurable quantities which are suitable for flashover prediction, Experimental validation of the theory of flashover prediction using signature analysis and also developed electronic sensor system for flashover prediction and validation of system operation. This dissertation has described the signature analysis of the easily measurable insulator leakage current, as a means of predicting flashover. Also, this concept of signature analysis of the leakage current has been evolved to create an online computer-based diagnostic system. Siderakis et. al. (2002) have investigated the development of surface activity on porcelain high voltage insulators. The Leakage current measurements shown in this case indicate that the initial surface activity corresponds to a pure sinusoidal leakage current, which although small is capable of drying the insulator surface.

Subba Reddy et. al. (2003) have studied the leakage current behaviour on artificially polluted ceramic insulator surface and derived the relationship between the surface resistance and leakage current. Jayaram et. al (2003) have shown that the variation in third harmonic components of leakage
current waveform and the formation of tracking path of polymeric insulators have a good correlation. Montoya et. al. (2004) have made an attempt to correlate the ESDD, NSDD values to leakage current in ceramic insulators located in distribution side. Sarathi et. al.(2004) have shown that application of moving average technique for the trend analysis of leakage current signal could be useful to predict the surface condition of outdoor polymeric insulators. And also they have applied the wavelet transform to extract the features of the leakage current and also developed automatic surface condition prediction system based on neural network. Metwally et. al. (2006) have conducted comprehensive standard tests conducted on 33 kV line-post porcelain insulators in order to improve their performance in harsh environment in comparison to the newly introduced polymeric insulator. The results show that the polymeric insulator has better performance than the porcelain one.

Long-term cold-fog condition is presently one of the main causes of the flashover fault of outdoor insulators. To monitor the surface performance of silicone rubber (SiR) insulators in such conditions, Du. et. al.(2007) has carried out an artificial salt-fog test to investigate frequency characteristics of the leakage current by utilizing a wavelet transform technique. Leakage current (LC) leading to dry-band arcing is one of the main causes of aging in non-ceramic insulators. For considering this, Ayman et. al. (2007) have correlated the average value of LC during late aging period (LAP) with the damage of non-ceramic insulators. It has been found that the average level of both the fundamental and third harmonic component of LC is well correlated with the different degrees of damage of non-ceramic insulators’ surface.

Chandrsekhar et. al. (2008,2009) have made artificial pollution test experimental setup and measured the leakage current and investigated the harmonic content and phase angle between applied voltage and measured
leakage current in polluted porcelain insulator and concluded that the harmonic content analysis is the effective diagnosis tool for outdoor insulators. And also they have (2010) made an attempt to measure the partial discharge in ceramic and polymeric insulators.

1.5.2 Ageing of Outdoor Polymeric Insulators

Kumagai et. al. (2006) have compared the LC characteristics and aging of porcelain and polymeric insulator in both field and salt fog tests. They have concluded that the time variations of cumulative charges and their component ratios were useful for estimating the conditions of ceramic and polymeric insulating surfaces. Naderian et. al. (2007) have done a comprehensive study of the performance characteristics of RTV silicone rubber coatings for high voltage insulators which has shown considerable variation in the physical properties of the coatings affecting life. Muhammad Amin et.al. (2007) have investigated the aging survey of the polymeric insulators. Laboratory aging tests must reflect the changes that would occur to the insulators during their long time in service.

Rowland et. al. (2007) have studied 400kV field aged silicone rubber insulator. Measurements of hydrophobicity and visual observations of the surface of field-aged 400 kV silicone rubber composite insulators show variations from end to end and circumferentially. Most of the breakdowns are caused by aging effects of high-voltage insulation used within these components, and there is still a need of suitable tools to diagnose such systems non-destructively and reliably in the field. Ehsani et. al. (2007) have made an attempt to measure the dielectric properties of aged polymeric insulators. UV and thermal stress can deteriorate polymeric materials. Silicone rubber shows better dielectric behaviour than the other samples after heat and UV aging.
1.5.3 **Artificial Intelligence in Condition Monitoring of Outdoor Insulators**

Neural networks have been intensively studied in the past decades. Clian et. al. (1997) have implemented a neural network to interpret data from two pollution-related monitoring devices to estimate the imminence of flashover on substation insulators. Ugur et. al. (1997) have analyzed the insulator surface tracking on solid insulators using neural network. Ahmad et. al. (2004) have successfully implemented the ANN model to predict the ESDD for contaminated porcelain insulators, but in this work meteorological data like rainfall, wind velocity etc. are considered as inputs to ANN model, which will vary according to the area and climate. Saleh Al Alaw et. al. (2006) have implemented the neural network to predict the insulator flashover voltage under contaminated conditions. Ali Naderian et. al. (2006) have used back BP network to predict the leakage current of the polymeric insulator. Kontargyri et. al. (2007) have applied an artificial neural network in order to estimate the critical flashover voltage on polluted insulators. Ekonomou1 (2007) have applied the neural network to estimate the critical flashover voltage of polluted insulator and lightening performance of the transmission line.

Most recently Gencoglu et. al. (2009) have proposed a new non linear model to predict the flashover voltage where diameter, height, length and conductivity, etc are considered as inputs for the model. Jingyan Li et. al. (2010) have studied the time domain parameter of leakage current and provided these parameters as inputs to ANN to predict the ESDD value. Considering the above facts, it is important to predict that the pollution severity of the transmission line insulators take into account both time and frequency domain characteristics of LC along with environmental factors.
1.5.4 Electric Field and Voltage Distribution Calculation

Rasolonjanahary et al. (1992) have proposed a new method based on boundary integral equation to calculate the Electric field and voltage distribution of polluted insulators. Hartings (1994) also conducted a series of experiments to study the ac behaviour of hydrophilic and hydrophobic post insulators during rain. The radial and axial components of the electric field strength along an insulator under dry and rain conditions were measured. El-Kishky and Gorur (1994) used a modified charge simulation method for calculating the electric potential and field distribution along AC HV outdoor insulators. Accurate modelling of a non-ceramic insulator could be achieved with a significant reduction in the number of charges used in this method.

Kaana-Nkusi et al. (1996) calculated the voltage and electric field distribution along a post-type insulator shed. The system was modelled with 146 ring charges, with 30 charges modelling each electrode. The calculation results showed that the maximum values of the electric field strength along the surface increased with higher dielectric permittivity of the insulating material. Decreasing the radius of curvature of the insulator shed increased both the normal and tangential components of the electric field strength. Gutfleisch et al. (1997) described a new algorithm based on the BEM to calculate the electric field strength. The potential formulas of the different types of surface elements, such as rectangular, triangular, cylindrical, spherical, conical and toroidal were presented in this paper. The accuracy of the results could be checked by computing the potential and electric field strength at the contour points or at test points at given contours. Two application examples were given in their paper. One was a disc insulator of a three-phase GIS and the other one was a transformer.

Basappa et al. (2001) have investigated the three different numerical methods like analytical method, finite difference method, finite
element method to calculate the electric field around the cylindrical insulator specimen model. The agreement between the solutions obtained from the three methods was found to be within 10 to 20%. Weiguo Que et. al. (2002) have calculated the electric field and potential distributions along wet non-ceramic insulators using COULOMB software. They concluded that electric field enhancement was taking place on top of the water surface and at the interface of the water drop, air and insulating material in the sheath region of the non-ceramic insulators. Zhicheng Guan et. al.(2005) have studied the water corona on composite insulator surface by Finite Element method(FEM). Electric Field enhances the most when several water drops are in the direction of the EF. Electric Field increases when the number of the water drops increases or the distance between the water drops decreases. Christophe Volat et. al.(2005) have determined the potential and electric-field distributions along a typical ceramic extremely-high-voltage post insulator covered with atmospheric ice during a melting period. The results obtained have shown that numerical simulations can be a good alternative to experimental measurements. Andrew Phillips et. al. (2008) have studied the E-Filed distribution around the polymeric insulators with corona rings. For most transmission line applications, the dominant direction of the E-field is along the axis of the insulator.

1.5.5 Predictive Dynamic Arc Model

In order to determine flashover voltage of insulators through leakage current prediction, a number of studies on model-based techniques were reported in the literature. Among these, a model was firstly proposed for contamination flashover by Obenaus (1958) and Rizk (1986). Followed by this work many of them developed mathematical models to predict the flashover voltage. Sundarajan et.al. (1993) have developed a dynamic arc model to predict the flashover voltage of ceramic insulators under DC voltage. Zhang et. al. (2000) have investigated the arc propagation in ice
surface based on dynamic arc model. This model has made some assumption like Single dominant arc, uniform pollution distribution and uniform wetting. Dhahbi-Megriche et al. (2000) have devolved dynamic arc model for polluted ceramic insulators under AC voltage. Tsarabaris et al. (2005) have proposed a new equivalent circuit model for predicting the pollution insulator surface arc and partial discharge activities. Venkataraman et al. (2006) have developed a new dynamic arc model for polluted polymeric insulators based on E-filed calculation. Farzaneh et al. (2007) have introduced new multi arc model to predict AC critical flashover voltage of the ice covered porcelain insulators.

1.6 MOTIVATION FOR RESEARCH

The primary motivation for the research presented in this thesis document is to investigate the performance of the composite insulator under different environmental conditions through laboratory testing to study the electrical stress in the surface of the insulator under polluted conditions through computer simulation and to study the physical behaviour of the dry band arcing and predict the leakage current through dynamic models. The above mentioned investigation has been reported in the literature but there are still many issues need to be addressed. The issues are: (i) how the composite insulator leakage current varies with respect to relative humidity under polluted conditions (ii) where exactly the maximum electrical filed stress occurs in the polluted composite insulator under different wet conditions (iii) how different types of features can be extracted from the measured LC and (iv) which type of feature among that will be used to predict the surface condition exactly. Methods were developed to predict the surface condition of insulator but these are mostly based on the ceramic insulator models. Hence, there is a need for developing accurate automated surface condition monitoring system for composite insulators. The testing of insulator in laboratory is very expensive. Many models have been proposed to predict the
insulator leakage current but only a few models are related to composite insulator with many assumptions. This thesis document is mainly addressing the above mentioned issues.

1.7 OBJECTIVES OF THE RESEARCH

The primary objective of this research is to investigate the composite insulators under different polluted conditions. For the efficient use of the composite insulator in the power transmission line, the following research objectives are set:

- Investigation of the 11kV polymeric insulator under NaCl pollutant with various pollution level conditions at different relative humidity, through measurement of peak and RMS values of the Leakage Current.
- Investigation of the 11kV polymeric insulator under cement pollutant with various pollution level conditions at different relative humidity, through measurement of peak and RMS values of the Leakage Current.
- Investigation of the different LC signature analysis methods to extract the features of the LC and develop a high resolution spectrum estimation method to estimate the frequency spectrum with high resolution.
- To develop a new automated condition monitoring system for the composite insulator based on artificial intelligent technique.
- Investigation of the electric field and potential distribution of the composite insulators under different surface conditions using Finite Element based models.
- To develop a new dynamic arc model to predict the pre-flashover LC of the composite insulators.
1.8 ORGANIZATION OF THESIS

Chapter 1 addresses the research trends in the area of composite insulators and a brief description of the composite insulator structure followed by a presentation of different condition monitoring methods. The research motivation and objectives are explained.

Chapter 2 describes the laboratory pollution test setup, LC measurement method, different pollution levels of the composite insulator, testing results and observation.

Chapter 3 reviews the concept of signature analysis of the leakage current. Some frequency domain techniques are presented.

Chapter 4 presents the Adaptive Neuro fuzzy technique and its training algorithm, and condition monitoring system based on Adaptive Neuro Fuzzy Inference System (ANFIS).

Chapter 5 presents the Finite Element Method based insulator model under different surface conditions, solving technique of the model, electric filed and voltage distribution and electrical field enhancement under different fog conditions.

Chapter 6 reviews the dynamic arc modelling of the composite insulator, calculation of pollution resistance under the arc conditions, prediction of leakage current and validates with practical measurement.

Chapter 7 concludes this work and presents future research related to composite insulator testing and performance measurement methods.