Chapter 2

Literature Survey

2.1 Literature survey on polymeric insulators

This section summarises the developments and studies that have taken place in leading countries of the world in the field of non-ceramic (polymeric) insulators and their experience on the performance of these insulators.

Experience of the use of polymeric insulators has been gathered around the world for over 30 years. An extensive survey, published by CIGRE in 1989 [1], has revealed that the aging of the component materials, especially of the weathershed part, was the main cause of registered failures. Similar conclusions have been presented in CIGRE and IEEE reports describing the world-wide experience [2,3]. Despite this the majority of the users have been satisfied with the performance of their insulators. Since then, much research has been devoted to improve the quality of non-ceramic insulators (NCI) and the work done has been reviewed by Hall [4] and Gorur et al [5].

The main factors influencing the NCI’s performance are loss of hydrophobicity and material aging under naturally appearing electrical and environmental stresses. Especially when the stresses act together, the degradation of insulator surfaces are significant on the insulator surfaces. For example, the exposure of NCI to heavy marine pollution in UK [6] has caused surface defects such as erosion, splits, cracks, holes, broken rods etc.

The field investigations on NCI have been broadly carried out in many countries having temperate, arctic and desert climate conditions. However, information collected from the tropical climates is rather limited. Tropics are mainly characterized by high humidity so that one could expect biological contaminants on insulator surfaces especially on the non-ceramic ones. Reports are available on biological growth on ceramic insulators in tropical and sub tropical environments [7, 8, 9]. Biological contamination has also been found on silicone rubber insulators reported in Tanzania [10, 11], USA [12] and Germany [13].
Chemey et al [14] prepared a report in which minimum test requirements for non-ceramic transmission insulators are provided. The test requirements are divided into material test and insulator design test that are needed to assess the relative merits of a variety of possible materials and designs. The insulators failing to meet the minimum test requirements should not be considered for long term use because of unsatisfactory materials, design or both.

Tourreil et al [15] have conducted the laboratory-ageing test with four composite insulator shed materials and compared the results with naturally aged ones. The results showed that laboratory-ageing simulates well the outdoor ageing and it is possible to determine the acceleration factors relating the two ageing procedures.

Dietz et al [16] have reported by conducting the laboratory and field tests, that the silicone rubber (SIR) weather-shed materials will have outstanding properties. The problem of “brittle fracture” which was only the unsolved problem during 1980’s was solved during 1986 by straight and intensive development. They also suggested that the composite long rod insulators could be applied to HVDC transmission in pollution prone areas.

Gorur et al [17] have tried to use of certain filler materials to improve the tracking and erosion properties of composite insulators. The water of hydration has been found to play an important role for imparting better erosion and tracking performance. Hence the materials with hydrated forms of filler like aluminium tri hydrate (ATH) or silica are generally used. Optimum quantity of filler with good uniform dispersion has been found to give the best results. Further work in the direction of improving the performance of materials for composite insulators is still continuing.

James chang et al [18] have investigated the mechanism involved in the loss and recovery of surface hydrophobicity of SIR and EPDM materials. They carried out the experiment in the fog chamber under simulated outdoor environments. They employed contact angle measurement and some diagnostic techniques for the study. The main conclusions drawn from the above investigations are:
• Loss of surface hydrophobicity is due to the formation of hydroxyl species as a result of the interaction of the polymer and moisture caused by the dry band discharges.
• The recovery of hydrophobicity is due to the diffusion of low molecular weight polymer chains.

Sklenicka et al [19] experimented on 110 kV overhead line composite insulators in the laboratory by adopting the accelerated ageing test for about 1000 hours and quick flashover method, to compare the different composite insulators and to give some basic information to utilizers. They concluded from their investigations that
• The failure due to aging in salt fog depends not only on the type of insulating materials but also on the procedures adopted.
• The flashover voltage of the composite insulators after aging is higher than that of the porcelain insulators.

Orbeck et al [20] conducted accelerated test on polymeric insulating materials. The final conclusion made is that the prolonged hydrophobicity of the insulators is due to migration of silicone oil and/or low molecular weight polymer chains through the contamination to the surface.

El-Hag et al [21] suggested two different methods to calculate the current density along silicone rubber (SIR) insulator under salt-fog testing conditions. The first method which is based on field theory approach uses commercial software COMSOL to compute the current density. The conductivity of the contamination layer used in the calculations was extracted from the measured equivalent salt deposit density (ESDD) separately for different regions of the insulator surfaces. The second method is based on circuit theory approach. The insulator was divided into different sections for resistance calculations to account for different contamination levels. Rankings based on the calculated current densities based on segmentation of the insulator surface for ESDD measurements match with those extracted from measured leakage currents.

Composite insulators can be manufactured by different techniques. However, today the most commonly used technique is one-shed molding [22]. The whole insulator housing is
then injection molded directly around the core in one piece. In this way the housing can be chemically bonded to the core. The reason for using composite insulators varies significantly between utilities [23, 24, 25]. Service experiences shows that silicone rubber(SIR) insulators have usually better performance than EPDM, porcelain and glass insulators in polluted environments [25,26,27] and the hydrophobic property of the insulator surface is considered to be the main factor responsible for their high pollution flashover withstand voltage [28,29,30].

Phillips et al [31] conducted experiments on 500kV composite insulators with SIR housing to study water drop initiated corona. The flashover mechanism of SIR insulators is significantly different from that of glass and a porcelain insulator, which is attributed to the hydrophilic properties of ceramics [31, 32]. Wetting of polluted porcelain surface results in a continuous water film and dry band arcs can develop directly. The drying of the remaining part of the insulator and subsequent elongation of the arc causes the insulator to flashover. On a SIR surface the situation is different. The first steps are similar to what has been described regarding the corona deterioration above. Moreover, the conducting layer that develops is usually thin. It limits the current flow and consequently the flashover voltage increases [29, 33, and 32].

In the past 20 years, a large amount of information from on-line leakage current (LC) measurements has been collected in Sweden. On line LC monitoring systems have been installed at Anneberg, Bohus-Malmon and Ludvika field stations [33]. Similar facilities have also been established in Australia, France Japan, South Africa, the UK and the USA. Vlastos and his coworkers have presented the Swedish results in numerous publications [34-45]. A good correlation between the LC intensity and weather conditions, especially the humidity level, has been reported.

A technique to study the ageing of different polymeric materials has been reported by Hackam, Gorur and others [46-56]. Different material types (Silicone and EPDM rubbers, TV coatings) and compositions (filler and low molecular fraction contents) have been tested. In the tests, silicone rubber surfaces behave better than EPDM rubber surfaces when exposed to a fog of low conductivity (250μS/cm), under both AC and DC voltages. However, in tests
with a fog of high conductivity (1000\,\mu\text{Scm}) an opposite effect was found or no influence of the material type was observed [57].

Fillers such as alumina trihydrate (properly aluminum hydroxide) and silica are commonly used to impart tracking and erosion resistance to silicone dielectrics and numerous studies have examined the effectiveness of filler type, particle size, and concentration, on material erosion in artificial tests such as the inclined plane test [58-66]. These fillers enhance the thermal conductivity of materials thereby removing heat from the area of dry band arcing. This is a means of producing a material that is resistant to the effects of arcing on its surface rather than to reduce the surface electrical stress.

Silicone elastomers are used in outdoor high voltage applications to reduce surface electrical stress to a level where partial discharge, corona discharge or dry band arcing does not occur. Additions of suitable inorganic fillers impart resistance to the discharges [67-73].

Gorur et al [74] conducted experiments to measure surface resistance of nonceramic insulators (NCI). Nonceramic insulators (15\,kV rated) of identical design but with different housing materials were used. Two experimental parameters were paid special attention during the test. One was the applied voltage (magnitude, AC vs DC), and the second was the wetting method. Regarding the test voltage, it was realized that the voltage magnitude should be high enough to result in a measurable current, and yet low enough so as not to initiate rapid drying or discharge activity. The suggested voltage was about 3.5 kV (10V/mm of leakage distance). In addition, dc voltage was recommended to eliminate capacity current. For the wetting both spray wetting and fog wetting by condensing steam were used. End fittings were used as electrodes. Based on this study, guide lines have been provided for performing surface resistance measurements in the laboratory.

Chrzan et al [75] measured concentrated discharges on polluted insulators in the laboratory and in the field. The authors have observed the concentrated discharges at the high-voltage laboratories in Stuttgart, Zittau, and Mannheim, Germany, and Wroclaw, Poland. The concentrated discharges were also documented under natural conditions. These discharges are very dangerous especially for high-voltage apparatus, bushings and polymer insulators. It has been shown that due to uneven voltage distribution at very low surface
conductivity, the concentrated discharges can ignite even under uniformly polluted and uniformly wetted insulators. In this study following conclusions are drawn:

- Discharges and dry bands under natural pollution conditions can concentrate in relatively small regions. This phenomenon causes nonlinear voltage distributions along the leakage path.
- Conditions of slight wetting (drizzle, fog, high humidity) are probably most favorable for building up concentrated stable zones. Their temperature is higher than the ambient, and leakage current is in the range of 1mA
- Concentrated stable discharges cause the degradation of polymer insulation. The related very nonuniform voltage distribution along the leakage path can initiate the ignition of internal discharges.

Chughtai et al [76] carried out FTIR (Fourier transform infrared) analysis on non-ceramic insulators. In their study 5 non-ceramic composite suspension insulators and one composite guide were used. Out of the 6 failed units, 5 insulators showed significant levels of nitrate on their brittle fracture surfaces with small traces of nitrate also found on the fracture surfaces of the composite guide. The results strongly indicate that the most probable cause of brittle fracture failure of composite HV insulators in-service is the formation of nitrate and thus nitric acid. The main conclusions drawn from the above investigations are:

- Out of 6 units subjected to the FTIR analysis, 5 (all energized insulators) exhibited either significant or at least measurable amounts of nitrate on their brittle fracture surface. Only the compound guide did not show any significant amounts of nitrate present on its brittle fracture surfaces.
- Not only the type of corrosive environment was determined by FTIR, but also the location of acid generation was pinpointed in some cases. In the case of one insulator a large separation at the rod/housing interface was found with the highest acid concentration detected in its vicinity. It was also shown that the acid concentration decreased as the tip of the brittle fracture moved away from the initiation site.
- Nitric acid generated in service due to corona activities (failures inside the fitting) and the partial discharges at the rod/housing interfaces (failures outside the fitting) in the presence of moisture is the dominant cause of brittle fracture failures of composite suspension insulators.
Inorganic fillers added to silicone rubber dielectrics, enhance their properties [77] to make them useful materials for outdoor high voltage insulation applications. Fillers such as silica and aluminium trihydrate improve thermal conductivity of the composites and increase their resistance to erosion that results from heat produced in dry band arcing.

Yasin Khan [78] conducted aging test on HV Composite insulators in arid desert conditions. The test results indicated that the dielectric response of thermoplastic insulators under the tested thermo-electric cum UV-irradiations outperforms silicone rubber insulators.

Sokoliija et al [79] have calculated electric field distribution for composite suspension insulators. The approach illustrated in this study may assist in extent ending and improving the concepts and criteria used for an effective design of composite insulators. From the above study, following conclusions were drawn:

- Field intensity near the triple junction (housing, air and metal) must be controlled (by design) in such a way that discharges anchoring at the interface between housing and metal is prevented the design of end fittings and position of triple junction ought to provide for instability of the discharges burning from triple junction point.
- The design of the area close to the flanges and the distance to the nearest shed is based on electric field considerations rather than on creepage distance requirements.

Minesh Shah [80] suggested some new flashover mechanism in SIR insulators and verified the same by conducting experiments.

Jahromi et al [81] have proposed a neural network approach to the prediction of the leakage current (LC) on silicone rubber insulators exposed to salt-fog. The validity of the approach was examined by testing several insulators in a salt-fog chamber. Feed-forward back propagation was found as the best method among several training methods evaluated for the prediction of the LC.
Masahisa Otsubo et al [82] experimented to separate leakage current into three components. They carried out salt-fog aging test on polymeric surface. The test was performed in an acrylic chamber. They first focused on the relationship between optical emissions due to discharges and the leakage current obtained during a salt-fog aging test. The optical emissions brought by two kinds of discharges were observed using a spectroscope, a photo-multiplier and camera, and thereafter their characteristics were evaluated and compared with leakage current. In this study an attempt has been made to separate leakage current into three components such as the conductive current that flows in the water film on polymeric material, the corona (partial) discharge current and the dry band arc discharge current. Finally, the polymer surface was analyzed using an electron spectroscopy for chemical analysis, and thereafter the change in the polymer constituent was evaluated.

Two kinds of silicon rubbers were used in the experiment. One of them was a rod shaped silicon rubber with a diameter of 30 mm and 250 mm in length. The other was a plate shaped silicon rubber with a thickness of 2 mm, and its cross sectional area was 80×80 mm². In addition, a rod shaped rubber; two kinds of rubbers that differed in filler were used. One of them was a high temperature vulcanized (HTV) silicone rubber with fillers of alumina trihydrate (ATH) and SiO₂. The content of ATH was 50%. The other was a room temperature vulcanized (RTV) with a filler of only SiO₂. SiO₂ in the silicone rubber provides the reinforcement property, and alumina trihydrate provides resistance to tracking and corrosion. For the plate shaped sample, HTV was used.

A flow rate of salt-fog was kept at 0.9 l/h, and the water conductivity was 800 μS/cm. The applied voltage was 15kV with frequency of 60 Hz, and the average electric field was 60 V/mm. An aging cycle comprised two operations such as a salt-fog aging period of 8 h and a dry period of 16 h, and then a total aging test was set of 500 h. The leakage current was measured every 15 minutes and was separated into three components such as the conductive current, the dry band arc discharge current and the corona discharge current. The respective cumulative charges were calculated from those current components. Also, the polymer surface was analyzed using an electron spectroscopy for chemical analysis, and thereafter the bonding condition was evaluated. The separation of the corona discharge component from the leakage current was first carried out by means of a Fast Fourier transform (FFT). According to the FFT analysis, a frequency range of the corona discharge was above 5 kHz while those due to the conductive and dry band arc discharge currents were less than 2 kHz.
Then, the current components above 2.5 kHz were defined as those due to corona discharge. On the other hand, the initiation of dry band discharges was determined by a differential technique, in which a large rate of change in the leakage current was used as an index. Also, the conductive current was the difference between the leakage current and the corona discharge plus the dry band arc discharge current. The results showed that the leakage current including dry band arcing could be separated by differential technique. The proportions of the conductive, the dry band arc and the corona charges of the total cumulative charge about 70%, 20% and 10%, respectively. Also it was found that HTV silicon rubber with ATH could retain its insulation performance better than RTV.

George G. Karady [83] investigated the flashover mechanism in Non-ceramic (N€I7 insulators. This reveals that, the long term exposure of silicone rubber insulators produces a thin layer of pollution, which is a mixture of dust, salt and silicone oil. Fog or morning dew produces droplets on the flat surfaces and forms conductive regions. Spot discharge starts between the regions, which reduce hydrophobicity. Simultaneously, dry-band arcing starts on the shank of the insulator. The two arcs join together, which leads to flashover. The flashover voltage of polluted Non-ceramic insulators is significantly higher than porcelain ones. The author performed measurements on insulators collected from the California coast. The energy dispersive X-ray (EDX) analysis proved that a mixture of silicone oil and sea salt and dust covers the surface. Laboratory tests performed in a salt fog chamber reproduced the uniform deposition of salt and silicone oil mixture on energized insulators. However the same procedure produced spot contamination when the insulators were not energized.

The pollution severity is determined by washing the pollution from the surface by distilled water and the calculation of the equivalent salt deposit density (ESDD) from the conductivity of the solution. The surface resistivity of a wetted NCI is significantly higher than a porcelain insulator when the pollution level (ESDD) on the insulators is the same. The electric field strength is larger at the two ends of the insulator than at the middle section. It can be seen that the field strength, in spite of the grading rings, is significantly larger at the energized end than at the middle of the insulator. The larger electric field drives the particles to the surface. Measurement performed on several insulators show that the pollution deposit is higher at the ends than in the middle. The pollution distribution along a 500 kV silicone rubber insulator is analyzed. This reveals that the amount non soluble deposit density (NSDD) is decreasing from the end fittings towards the middle of the insulator. This effect is
particularly strong in the case of dc voltage, but a similar distribution was observed on ac insulator. The variation of the pollution level on ac insulators is less than in the dc case. Some insulators are built with two shed diameter. The shed diameters alternate along the length of the insulator. The smaller shed collect less pollution than the larger ones. The pollution is distributed uniformly on the insulator surface but the amount of pollution is different on the upper and lower surface of the shed. Also different amounts of pollution were observed on the shank.

The author studied the flashover mechanism on a polluted silicone rubber surface. For this purpose electrodes were placed on one shed of silicone rubber insulator. Both the upper and lower surfaces were polluted with a kaolin and salt mixture and were permitted to recover hydrophobicity. The insulator was energized to 10 kV (rms) and the pollution was wetted by steam. The fog or steam produces water droplets on the insulator surface. The diffusion drives the pollutant through the silicone oil layer. The droplet dissolves salt from the pollutant and become conductive. Simultaneously, diffusion drives the water into the pollution layer and produces a wet conducting region around each droplet. Spot measurements proved the validity of the increase of conductivity. The continuous wetting joins the wet regions and forms a highly resistant conductive path between the electrodes. This initiates small 60 Hz leakage currents. The water droplets increase the electric field strength at the edges of the wet regions. The increase of electric field strength may produce surface corona discharge, which ages the shed materiel. Also the corona discharge locally destroys the hydrophobicity, resulting in a spread of water on the surface and the formation of the filaments. The leakage current flows through the conducting path and dries tea surface these results in the interruption of the path and the formation of separated wet regions. The conductive strength filaments reduce the distance between electrodes and increase the field between them. If the local field strength >20 kV/cm spot discharge develops between the regions. This discharge produces nanosecond duration oscillatory current pulses. The pulse generation is due to the reoccurring ignition and extinction of the arc. The 5 to 10 MΩ resistance of the path limits the discharge current to 100 to 300 µA. As the voltage reaches the breakdown voltage of the gap between the filaments or wet regions, the discharge starts, but it extinguishes immediately because of the very low current. At this moment the voltage increases and the phenomena are repeated.

The spot discharge destroys the hydrophobicity which leads to the formation of irregularly shaped wet regions. The filaments and wet regions are distributed randomly on the surface.
The wet areas short the insulator by a wet, conductive path. This reduces the resistance that limits the current and provides a path for the arc. The arc current becomes a distorted sine wave. The arc travels above the wet layer and extends. Depending on the layer resistance and arc length this may lead to flashover or to the extinction of the arc. The described phenomenon is repeated until the arc bridges the insulator and flashover occurs or until the formation of a large dry area that eliminates the danger of flashover. Experimental studies showed that flashover occurred on one shed when the average electric field strength along the leakage path was 0.8 to 1.4kV/cm and the ESDD was 0.013 mg/cm$^2$. The flashover mechanism of an actual insulator is more complicated because the insulator is divided into four distinct areas. The areas are the upper shed, rim, lower shed and shank. The contamination survey showed that the contamination level on each area is different. Also the wetting process depends on the position of the surface. As an example, the water droplets tend to roll off the vertical surface. Fog and drizzle produces more or less uniform wetting. The rain, driven by wind, may wet only one part of the insulator, producing non-uniform wetting. Also, the wind may produce partially contaminated insulators. Pollution increase surface roughness, which in turn increases wetness.

Windmar [84] studied the behaviour of water droplets on non-ceramic surfaces and the associated electric discharges. A clear correlation between surface hydrophobicity, the salinity of water drops, the character of surface discharges and the flashover with stand voltage were found.

Blackmore [85] and Birtwhistle [86] also observed discharges between water droplets, which caused a loss of hydrophobicity on both silicone and EPDM rubber surfaces. The conductivity of the water droplets had a negative reaction on the loss of hydrophobicity; i.e. higher rate of hydrophobicity loss corresponded to lower conductivity.

Hafmann et al [87] observed lower leakage current (LC) levels on silicone rubber insulators. The obtained results indicated that 16-year old silicone rubber insulators performed well and their performance was evaluated by means of the flashover tests. A report from Egypt had presented a use of the clean-fog test to investigate insulators naturally aged from industrial pollution for two years. The Egyptian findings have indicated that
silicone rubber insulators covered with a cement contamination layer yield lower LCs than insulators polluted with fertilizers.

Sorqvist [88] had studied the LC behaviour of polymeric insulators under clean fog conditions. In all the reported cases the LCs of the field-exposed insulators were substantially higher than those of the equivalent reference insulators. When different housing materials, once again differences between silicone rubber, RTV coatings and EPDM rubber were distinct and these could be related to the state of surface hydrophobicity. It has also been illustrated that the LCs resulting from the DC energization of composite insulators may significantly vary with time.

Ringler et al [89] have developed a new cold fog test procedure for flashover testing of insulators under freezing conditions. DC resistance and the flashover voltage of different (porcelain, silicone coated, semiconducting glaze and silicone rubber) insulators were compared at low temperatures. The surface resistivity of new, contaminated lightly iced porcelain insulators at 0°C was increased by a factor of ten when a silicone coating was applied. This increase improved even further when temperature rose above 0°C. The importance of the information provided by the LC measurements has been recognized internationally. A special IEEE Task Force for Surface Resistance Measurements on Composite and Porcelain Insulators was established and, in cooperation with a number of laboratories, it is carrying out round-robin tests under clean fog conditions on a series of identical insulators in order to prepare a standardized measuring procedure.

Kurimoto et al [90] have conducted dynamic drop test on silicone rubber Insulators. That can evaluate the property of hydrophobic loss of silicone rubber easily and with small systems. So, they clarified the relation between processes of hydrophobicity deterioration or loss and leakage current wave form in Dynamic drop test. The hydrophobic conditions were classified into three categories. In the condition of keeping hydrophobicity, pulse discharges were repeatedly observed at the time when droplets ran down. The tendency of the current ingredient of 60Hz became more dominant and discharge light started to be observed continuously regardless of the timing of the drop lets just before when hydrophobicity lost. Then it was considered that a thin moisture layer was formed on the surface, although only droplets were observed with the naked eye. Finally, the leakage current flowed continuously.
Deterioration of hydrophobicity can promote occurrence of arc discharges that influence to considerable deteriorations of the surface material. Hence it is very important to observe the variation of hydrophobicity. With a context like that, CIGRE WG D1.14 is working to establish the lowest required standard of silicone rubber. It established the standards for mechanical, electrical and chemical properties. And then it has been developing the evaluation and examination method that considers hydrophobicity. In their work, they studied the mechanism of hydrophobicity loss of silicone rubber in dynamic drop test. In their test silicone rubber plate was used. NaCl solution was flowed down on the surface of specimens, from the hole at the high voltage electrode. The solution flowed through a pipe, reached to the earth electrode and accumulated in an earthed container. The conductivity of NaCl solution was set at 1.5±0.2 mS/cm, and drop frequency was set at 12±1 drops/min without applying voltage. Time for the adjustment of the drop frequency was established 5 min, after that measurement was readily started with applying voltage. A.C voltage with 60 Hz was increased to 5kV rms by a transformer. The increased voltage was applied to the upper side of the electrodes supported parallel through a protective resistance with 20 kΩ. The underside electrode was connected to current measuring circuit, and the wave forms of both ends of a cement resistance 1Ω in the circuit were recorded.

The distance of the two electrodes was 50mm. The voltage wave forms were recorded by an oscilloscope, and transferred to PC through GPIB. And then it was saved as binary data by the program made with lab view. Thereby it made the analysis possible.

Mechanism of loss of hydrophobicity in dynamic drop test isn't still clear. To know the mechanism it is important to set the standard as a method to evaluate the hydrophobicity stability. So, it is related the observed variation of the current waveforms to hydrophobicity of the surface, and tried to make it clear the transition process of the surface before the hydrophobicity loss. The surface conditions were classified in the three following categories according to the process from the start time through the loss of hydrophobicity.

- Droplets completely run down to the under side electrode, therefore a part of droplet could not remain on the surface of specimens. This condition dominates 80-90% of all time to loss hydrophobicity.
- A part of droplets adhered and remained on the surface of the specimens. Discharge light was sometimes observed in the video. This condition dominates about 10% of all time.
• Discharge light was also observed when droplets did not run down. The continuous current started after a few seconds since the surface condition transferred to this condition.

The main conclusions drawn from this study are:

• The current waveform in the condition of keeping hydrophobicity is observed as periodic pulse discharges. Only a pulse signal is often observed for a droplet runs down and multi pulses are hardly observed.

• A part of droplets adheres to the surface of the specimens in the condition of deteriorating hydrophobicity. The current waveforms also shows a pulse discharge when a droplet runs down. However the pulse discharge occurs innumerably in a short time.

• Discharge light starts to be observed continuously regardless of the timing when droplets run down just before loss of hydrophobicity. The current ingredient of the frequency being synchronized applied voltage becomes more dominant, and the amplitude increases gradually. Droplets can’t be recognized to form the conductive path in the video despite continuous current waveform. So, it is considered that a thin moisture layer dry band is formed and discharge occurs at the surface. It is considered that the discharge occurs especially near the electrodes because of the field concentration.

Otsubo et al [91] have conducted experiment to investigate leakage current and cumulative charge of an artificially polluted 22kV polymeric insulator. Leakage current is observed and analyzed by using differential method and FFT. This differential technique can separate conductive current in the water film on the polymer surface into each component, corona discharge current and dry band arc discharge current. Influence of pollution level of NSDD on the electrical discharge and its discharge current were investigated with the collapsed time. The result of the polymer was compared with one kind of porcelain insulator. The relation between pollution level and leakage current is discussed in comparison between polymer and porcelain. In this test a polymer insulator (arresters) and porcelain line-post type insulator after losing hydrophobicity. Polluted liquid was made by mixing tonoko(40g/l) and NaCl(12g/liter,24g/liter,48g/liter) in demonized water of 3 liters. The pollution level was respectively 0.03mg/cm²,0.06 mg/cm², 0.12 mg/cm² (ref).
The surface has been kept in moist condition up to experiment start, it is washed just before the test and loss of hydrophobicity is confirmed. In the test, the liquid was sprayed for 1 minute and kept for 3 minutes, and the ageing test in contaminated surface by spraying is performed for 10 minutes under energized condition. The applied voltage is increased to 13.3kV in 30 secs and kept constantly for about 10 minutes. Discharge emission was observed by using a photomultiplier and an oscilloscope. The emission of dry band arc discharge observed by a high speed camera with 1000 frames and leakage current was measured at the same time. Cumulative charge and characteristics of discharge emission were investigated for both insulators. Main results are as below:

- Cumulative charge of dry band arc discharge increases with the contamination level.
  Cumulative charge of the polymer insulator and occurrence frequency of dry band arc discharge decreases quickly because of recovery feature of hydrophobicity.
- Dry band arc discharge preceded streamer progresses from upper shed to lower shed.

Shaowu et al [92] evaluated the hydrophobicity status of silicone rubber insulators (SIR) in various polluted areas. Mechanisms related to hydrophobicity transfer and recovery of SIR insulators were studied in depth. From April 1999 to August 2001, about 80 HTV SIR Insulators were removed from areas near cement plant, thermal power plant, aluminium manufacturers and chemical industry plants. Several insulators operating in clean conditions were also removed as a reference. It is worth to emphasizing that the specific creepage distance of all SIR insulators in the transmission lines investigated are equal or about 20% less than that of the ceramic ones. Except for several bird dropping flashovers, there were no any other electrical related failures recorded. Examination on the sample insulator includes hydrophobicity measurement, pollution severity measurement and visual inspection. The target surface was firstly checked with a sprayer to get the HC value. Then it was uniformly cleaned by another 25 sprayings. During the spraying, water droplets slipping off the target surface were carefully collected. A special ESDD, named washing ESDD, can be calculated by measuring the conductivity of water collected. Finally, the residual pollutant was cleaned and measured. During test the following measures were taken:

1) Measure the hydrophobicity of different parts of the insulator.
2) Arrange the hydrophobicity measurement as soon as possible. A part of the tests was even carried out just after the insulator was removed.
3) Measure the pollution severity of the different parts of the insulator.
Main conclusions drawn from above investigations are:

- After 1 to 11 years operation in various polluted areas, all insulators removed preserve good hydrophobicity. No severe deteriorations such as tracking and erosion puncture and core exposure were observed. Insulators subjected to heavily polluted environment for 5 to 8 years still exhibit excellent hydrophobicity HC 2-HC 3.

- The hydrophobicity status does not show obvious correlation with the years in service. It actually only corresponds to specific environment investigated.

- In general, the hydrophobicity distribution of SIR insulator is non-uniform. Those areas liable to hydrophobicity deterioration include intersection areas between bottom shed and adjacent shank, and the rim of sheds. In general, the deterioration of hydrophobicity gradually extend from shank and sheds near end fittings, especially hot end, to the middle of the insulator

- In general, lower surface of sheds accumulates more pollutants than upper surface, and therefore, exhibits poor hydrophobicity.

The authors also conducted experiments to compute the distortion of electric field due to the presence of water droplets. For this purpose the insulator is subjected to uniform electric field. The distortion of electric field due to the presence of water droplets is first computed with a commercial software ANSYS. The simplification is based on a judgement that in the small local area of an insulator, water droplets, actually, are under a relative uniform electric field, although the electric field along the length of the insulator is non-uniform. For the convenience of computation, each water droplet has a spherical shape. The appearance of water droplets prominently distorts the original electric field. In the adjacent area of water droplets, electric field is strengthening to a large extent. For the horizontal electric field referred to the liquid-solid interface, the maximum electric field will occur in the triple junction area, i.e. the cross point of air, liquid and solid. According to the computation under a horizontal electric field, the electric field near triple junction point is about 2.5 ~ 4 times of the original value. When the number of water droplets along the electric field increases, the strengthening is more prominent, even reaching upto 4~ 8 times the original one.

Rajani et al [93] conducted experiment on ethylene propylene diepe monomer (EPDM) sheet and fractal analysis is carried out under a.c. voltage. This work is aimed at fractal analysis of surface tracking patterns propagating over gamma irradiated polymeric
materials using inclined plane test. Fractal theory has proven to be a very useful tool in quantifying the structure of a wide range of idealized and naturally occurring objects. The commercially available EPDM in the form of sheets was cut into required dimensions of $120 \times 50 \times 3$ mm. The surface of the samples was cleaned using acetone to remove any dust or grease present on the surface and dried. These samples were kept in the gamma irradiation chamber for the required dose. The tracking test was carried out, following the inclined plane test method, as suggested in IEC-587. The sample along with the electrodes was mounted in the inclined plane mounting. The gap distance between the HV and LV electrode was maintained at 50 mm. The top electrode was connected to HV source and the bottom electrode was connected to ground through $100\Omega$ resistor to measure tracking current. The potential drop across this was measured using THS-720P oscilloscope for further analysis of leakage current. To simulate pollution condition over the surface of the samples, NH$_4$Cl was allowed to flow at a constant flow rate using peristaltic pump. NH$_4$Cl was used as a contaminant for this study as it aggravates heat and does not leave any residue on the surface of the sample. A standard non-ionic wetting agent TRITON-X-100 was added to the contaminant to increase the wettability of the surface. The chemical equivalent of TRITON-X-100 is octyl phenol ethoxylate. AC voltage of $5kV$ was applied as the test voltage for all the test samples. The times to failure arrived at once arc inception takes place near bottom electrode and crosses two thirds of the gap or if the complete bulk volume of the material degrades at a particular location due to arcing. Otherwise, the process lasts for 6 h and the experiment was properly terminated. CCD camera was used to capture the progress of tracking.

In this study following conclusions are drawn:

- The tracking patterns are found to be unique and fractal dimension ranges from $\sim 0.8972$ for unaged sample to $\sim 1.3083$ for sample aged to 300 krad dosage. The fractal dimension of the track formed in sample aged by 1496 krad was $\sim 1.2915$. The experiments in this work should provide useful guidelines for researchers wishing to use fractal feature for pattern discrimination of tracked images and to quantify the damage caused by tracking.

- This work is based on the assumption that the 2-d image patterns qualify has a fractal pattern, and found to fractal dimensions with different voltages has to be studied thoroughly.
Moreover, ethylene propylene diene monomer was found to be less suitable for radiation prone environments. This may be due to the overall increase in temperature or localized hot spots within the material, which may eventually reduce the hydrophobicity of the surface and hence accelerate the aging of the sample.

Piah et al [94] have tried to use a certain filler materials to improve the tracking and erosion properties of composite insulators. In their work, a new formulated thermo plastic elastomometer materials that are composed of linear low-density polyethylene (LLDPE) and natural rubber (NR) filled with different loadings of alumina trihydrate (ATH) fillers is presented. A surface tracking and erosion test is conducted to investigate the characteristics of leakage current on the material surface under the influence of wet contaminated conditions. A computer-based leakage current monitoring system is developed to monitor the leakage current waveform pattern as well as its frequency spectrum. The scanning electron microscope is used to investigate the morphological properties of the materials before and after the tracking test. The newly formulated thermoplastics elastomer (TPE) used are the blends of linear low-density polyethylene and natural rubber with different loadings of alumina trihydrate fillers. The ATH filler is used with the base polymer to improve the surface tracking properties. The composition of compounds with ratio of 3:2 and 1:4 (NR: LLDPE) are selected because of the good overall properties and also good miscibility blends. The NR and LLDPE with ATH are blended in a Brabender Plasti-Corder at 160 °C for 13 minutes at a rotor speed of 40rpm. Then the samples of blends are compression moulded into a 120×50×6 mm dimension in an electrically heated hydraulic press at 160°C. The total moulding time is 15 minutes at pressure of 100-120 kg/cm².

The test is conducted based on inclined-plane tracking (IPT) test method of IEC 587. The sample is mounted with the flat test surface on the underside, at an angle 45° from the horizontal with the stainless steel electrodes of 50 mm apart. The sample is wetted and contaminated by flowing down continuously with 0.1% by mass of ammonium chloride electrolyte. A high voltage transformer pf rating1.0 kVA, 0-10kV is used to apply 2.5kV across the sample. The electrolyte flow rate of 0.15ml/min as per standard is used throughout the experiment. In order to get the proper flowing of electrolyte, 8 layers of filter paper clamped between the top electrode and the sample. Basically the test is successfully conducted when the effective scintillation is observed, which means the
existence of small yellow to white arcs just above the teeth of the ground electrode. This arc appears within a few minutes of applying the voltage. To study of surface discharge characteristics is carried out by measurement of surface leakage current (LC) that flows on the material surface. An on-line LC monitoring system is developed to monitor the test as well as to provide information on the performance of the material. A Lab VIEW program is written to communicate with an analog-to-digital converter (ADC) to sort out the LC signals. In addition, a Fast Fourier Transform (FFT) analysis is performed on-line and its normalized harmonic components are sorted out.

The IPT test is conducted continuously for five hours under wet contaminated condition with fixed applied voltage and electrolyte flow-rate. During the test, the different stages of LC behaviors are identified base on the waveform patterns. For the insulator, the LC waveforms are sinusoidal with very small value (a few µA) is observed. Once the insulator is completely wetted or the conducting film bridged the electrodes, the LC appeared to be sinusoidal and resistive in character. The value of LC suddenly increases due to the drastically dropped of surface resistivity. The cases in which a weak dry-band activity is started or the condition where the partially lost of hydrophobic properties occur, the LC pattern becomes resistive and non-linear. Small spikes are observed at the crests of the waveform due to the corona effect. At this stage, the LC is dropped to a lower value because of the high resistance from the existed dry band. From this experiment the authors have drawn following conclusions:

- Experimental results show that differential compositions as well as the condition of material surface clearly affect the characteristics of surface leakage current and discharges.
- In comparison to other polymer materials from previous works, it is observed that the use of LLDPE blended with natural rubber is reliable as an alternative high voltage insulating materials in the future.

Amin et al [95] have conducted experiments to measure both AC and DC leakage currents in composite insulators. The level of insulation safety provided by an insulator depends on the amount of leakage current flowing on its surface. Actually increased leakage current causes a part of high voltage to appear at dead end of insulator. This voltage may some times be of order of 1000 to 5000 volts depending upon whether conditions. A correlation between progressive degradation and the changes of leakage current components
was investigated in this study. Leakage current was monitored by a data acquisition system (DAS) with 12-bit, 8-channel analog/digital (AD) converter. The main conclusions drawn from the above investigations are:

- Leakage current is directly proportional to the hydrophobicity loss, especially for composite insulators.

- ESDD is directly proportional to the leakage current, so it can be concluded that as the leakage current increases, the voltage at which flashover occur decreases.

- Leakage current increases as the humidity increases.

- Temperature changes produce negligible effect on leakage current value.

Yasin Khan [96] conducted accelerated aging test on EPDM composite insulators and he simulated the arid desert’s atmospheric condition. The actual UV-A radiations level and temperature variations in central region of Saudi Arabia is quite higher as compared to the values recommended in the IEC standards. To simulate the ambient conditions of arid desert, a wooden chamber was fabricated for the accelerated aging process for the EPDM test composite insulators. Based on the above discussion, two types of experimental conditions were created in the accelerated aging test chamber. Three samples of EPDM suspension insulators procured from WT-Henley (UK) were used for accelerated aging process. In this study, the hydrophobic characteristics of a commonly used suspension type of composite EPDM insulator were studied by measuring the contact angel along the insulator surface before and after the accelerated aging as per IEC standard simulating the inland arid desert’s atmospheric condition and following conclusions were drawn:

- The average variation in the contact angels from HV to ground electrode for top as well bottom of insulator shed is more consistent, however, the wide variation in contact angel was observed when the insulator was aged under high UV radiation intensity.

- Due to high temperature, high UV radiation intensity in arid desert conditions and high current densities in the core, more hydrophilic properties were observed on the front side as compared to the back side of the aged insulator.

- The contact angel of the old aged insulator is more as compared to the newly aged insulator. This shows that the EPDM insulators recover its hydrophobic characteristics with the passage of time.
Michael et al [97] investigated the influence of various parameters on the polymeric insulators. They conducted inclined plane test to understand the droplet behavior in strong electric field. Parameters such as water droplet conductivity, droplet volume, polymeric surface roughness and droplet positioning with respect to the electrodes were studied. The flashover voltage is affected by all aforementioned parameters. The droplet positioning is in some cases more vital than the droplet volume. Surface damages were analyzed using Scanning Electron Microscopy (SEM) studies and by Energy dispersive X-ray Analysis (EDAX). It is observed that magnitude of the discharge have direct influence on amount of surface damage.

In their work, a study of the aforementioned parameters on the water droplet behavior under the influence of a uniform field in the range of 1.7μS/cm-2000μS/cm was carried out. All tests were preformed with an inclined test arrangement, in order to simulate the behaviour of water droplets on the surface of an outdoor insulator. The angel used with respect to the horizontal was 10°. Such an angel was chosen because of its immediacy to outdoor insulators. The high AC voltage was generated using a 20kV transformer. The electrodes were half cylindrical in shape and of copper material. Much attention was paid to the smoothness of the electrode surfaces, so that no field enhancements could be noticed in the operating zone. From above investigations authors have drawn following conclusions:

- Increased conductivity, smoother polymeric surfaces and increased droplet volume cause a reduction of the flashover voltage.
- The SEM and EDAX results confirm that surface composition variation is directly related to magnitude of discharges.

Gutman et al [98] have carried out field tests to distinguish between pollution performance (i.e. risk for flashover) and ageing of composite insulators. Silicone rubber composite insulators have also become more frequently used for HV equipment like surge arrestors, bushings and breakers. Composite apparatus insulators provide advantages not obtained with conventions porcelain insulators. To gain information of optimal creepage distance of HV apparatus in different environments, a number of surge arrestors, bushings and breakers with composite insulators comprising silicone rubber as external insulation have been installed in three test sites subjected to heavy or very heavy pollution levels. The test stations used are Dungeness, on the South East coast of England; Kelso, on the north east coast of South Africa and Beer Sheva in the Negev desert of Israel. In addition results are
reported from an inland test station in central Sweden. This station represents a typical clean environment, considered as representative of the majority of all high-voltage installations. Detailed inspections of the tested apparatus as well as a sophisticated data acquisition system at three of the stations have made it possible to cover both these aspects. Where possible the ageing performance of apparatus insulation is compared with the ageing performance of line insulators tested at the same site. A third parameter related to the effect of pollution environment and important for surge arrestors is a possible thermal stress. In the IEC 60099-4 standard for porcelain housed arrestors, the charge of external current at a particular site has been used as a measure of site severity. The charge of external surface currents on arrestors from the different test stations, therefore, has been determined and the result is compared with data for porcelain.

The data parameters which are either continuously monitored or periodically recorded at the test stations included: leakage current and weather parameters (continuously) and visual inspections and hydrophobicity measurements periodically. Inspections of the test sites were carried out on annual base. Based on the above study following conclusions can be drawn:

- With regard to ageing characteristics, the results of 2-7 years of field testing show that there is only slight deterioration for the apparatus insulators even with rather short creepage distance and in severe coastal environment.

- With regard to pollution performance, the short-term and long-term hydrophobicity characteristics of silicone rubber apparatus insulators are better than that of the porcelain insulators at the same site. The number of high pulses of the leakage current provoking a flashover is much lower for silicone rubber apparatus insulators than for the porcelain insulators at the same site.

- Considering both ageing as well as pollution performance, it is possible to reduce creepage distance in coastal areas with, as a minimum, one pollution level.

Zhu et al [99] have conducted experiments on HTV (High Temperature Vulcanized) silicone rubber insulators exposed to clean fog. Water droplets were placed on the surface of insulators energized with AC voltage and investigations of the surface state were done by a high-speed video camera in a wet condition produced by sprayed clean fog. Simultaneously, according to the experimental condition, a dynamic 3-D model was built to calculate the electric field and current density distribution on the insulator surface by finite element
software. A conducting water layer is formed due to deformation of the droplets and the development of dry band arcing. This caused large distortion and nonlinearity which increased the odd harmonic components in the leakage current waveform. This is in good agreement with the simulating calculation. In their work the leakage current frequency characteristics was extracted and correlated with the insulation surface condition. Finally they concluded that, it is a diagnostic index for electrical characteristics and insulation state of polymer insulators in the wet condition.

The details of few mathematical models for nonceramic (composite) insulators are discussed in the coming section.

2.2 Theoretical models for non-ceramic insulators (Composite insulators)

A model is a physical or mathematical construct which approximates to some degree certain aspects of natural or man made phenomena. The effectiveness of any mode totally depends on the effectiveness with which each process (and the influence of each parameter) is represented in the equation. In case of complex phenomena like pollution induced flashovers, the number of parameters is large and their involvement is quite intricate.

Chrzan [100] conducted an experimental investigation to measure the flashover voltages of notched silicone rubber (SIR) insulators under polluted conditions. The cylindrical samples were moulded with the smooth or notched surface using the RTV-2HV 1540/10P silicone rubber from Dow Corning. The samples with smooth surface had the diameter of 1, 6 cm; the diameters of notched samples were 1, 8 cm and 1, 5 cm. Both models of insulators had the electrode distance of 23 cm. However, the leakage distance of a notched sample was about 2, 5 times longer than that of a smooth sample. Tests in a fog chamber were carried out at Cardiff University. Four nozzles produced the fog from the tap water having conductivity of 250 μS/cm. The intensity of wetting could be changed by changing of water pressure; the droplets dimension was influenced by the air pressure. He proposed an equation to calculate pollution flashover voltage and it is as below:

\[ U_p = B X I^n + I r (L-X) + m \Delta U \] (2.1)

Where,

I=Current
L=Leakage distance
\(X\) = Critical arc length
\(m\) = number of serial arcs
\(\Delta U\) = Cathode and anode spot voltage
\(B, n\) = Constants of arc column

The SIR insulators with the notched surface and with the electrode distance of 105 cm have been tested for 3 years at Glogow station under the voltage of 75 kV.

The following conclusions are drawn from the above investigations:

- The pollution flashover voltage of samples with the notched surface is about 25% higher than the pollution flashover voltage of smooth samples.
- The small notches divide the discharges into many short arcs that increases the flashover voltage and limits the leakage current. The notched surface loses the hydrophobicity later than the smooth surface that should increase the resistance of the notched silicone surface against erosion under heavy pollution.
- The improvement of the notches profile can further increase the pollution performance of silicone insulators.

Jiang et al [101] have reported the effects of pollution and high altitude on the flashover performance of composite insulators. The exponent characterizing influence of salt deposit density on the flashover voltage is related to the profile and the material of the insulator shed. The values of the exponents vary between 0.24 and 0.3, which are smaller than those of porcelain and glass Cap-and-pin insulators. Thus, the influence of the pollution on the composite long insulators is relatively less. The best ratio of the leakage distance to the arcing distance is about 3.35. Even to date, pollution performance of polymeric insulators are poorly understood and it is felt that an effort should be made to better understand them. Pollution flashover of polymeric insulator depends on deposition of contamination, dry band formation due to surface leakage current flow and electrical breakdown of dry band propagation of discharge across the moist film, bridging the gap.

Based on their experimental results, an equation for the flashover voltage has been suggested which is of the form:

\[U_f = A \ (SDD)^a\]  \hspace{1cm} (2.2)

Where ‘A’ and ‘a’ are constants which depends on profile of the insulators and characteristic exponent respectively. According to them ‘A’ varies from 104 to 175.9 for 98.6 kPa and 93.2 to 153.7 for 74.6 kPa.
Jiang et al [102] conducted experiments on artificially contaminated various types of insulators. The experimental result shows that the polluted flashover voltage is affected by equivalent salt deposit density (ESDD) and non soluble deposit density (NSDD) the influence of which are independent of each other. Based on the analysis of flashover voltages, the correction formulas of the flashover voltages of various insulators at various ESDD and NSDD levels are pointed out. The experimental result also shows that there is a distinct difference among the flashover voltages of various types of polluted insulators. At the same pollution degree, the antipollution performance of the fog-type glass insulator is better than those of the outer-rib porcelain insulators. In terms of the effectiveness of creepage distance of the insulators, the antipollution performance of polymeric insulators is superior to those of porcelain and glass insulators. Based on the experimental results, an equation for the flashover voltage has been suggested which is of the form:

\[ U_f = K_f \cdot \rho_{\text{ESDD}}^{-c} \cdot \rho_{\text{NSDD}}^{-d} \]  

(2.3)

Where,

- \( U_f \): Flashover voltage
- \( K_f \): Coefficient related to the configuration of insulators ‘c’ and ‘d’ are exponents characterizing the influence of \( \rho_{\text{ESDD}} \) and \( \rho_{\text{NSDD}} \) respectively.

The final conclusions of this study are as below:

- The flashover voltage of polluted insulators decreases with the increase of \( \rho_{\text{NSDD}} \) and \( \rho_{\text{ESDD}} \). The influences of \( \rho_{\text{ESDD}} \) and \( \rho_{\text{NSDD}} \) on \( U_f \) are independent of each other. The equation (2.3) indicates the combined influence of \( \rho_{\text{ESDD}} \) and \( \rho_{\text{NSDD}} \).

- The polluted flashover voltages of various types of insulators drop at various rates with the increase of the pollution degree, and the influence of \( \rho_{\text{ESDD}} \) on various insulators is different.

- The flashover voltage gradients of polluted insulators will reduce with the increase of pollution degree, which depends on the shapes and materials of insulators.
• At the same pollution degree, the fog-type insulator has better anticontamination performance. The effectiveness of the creepage distance of outer-rib-type insulators is smaller, while that of polymeric insulators is high.

Venkataraman et al [103] have conducted experiments to predict the flashover voltages of SIR insulators under contaminated conditions. Based upon the experimental results they have fitted a curve to obtain theoretical model to predict flashover voltages of SIR insulators. This model is based on reignition and arc constants. The model is valid only when certain assumptions are satisfied and is applicable for a range of surface resistance values. The basic assumptions are as follows:

• Errors are normally distributed. This aspect is checked through normal probability plot of residuals.
• Errors have zero mean and constant variance. This is validated by plot of residuals vs. predicted data.
• Errors are uncorrelated, which is demonstrated by plotting residuals and run order. An extensive literature survey reveals there is no proper theoretical model to predict the flashover voltage of polluted SIR insulators in terms of dimensions and/or geometrical parameters.

2.3 Present Work

The overall objective of the present work is to explore the possibility of developing a mathematical model for flashover voltages of SIR insulators rated for higher voltages. The expression should also involve dimensions of the insulators and/or geometrical parameter such as form factor. Literature survey on SIR insulators reveals that there is no appropriate mathematical model to predict the flashover voltages of polluted SIR insulators in terms of dimensions and geometrical parameter.

In view of the above as a first step, experiments are conducted on artificially polluted 11kV silicone rubber insulator for different ESDD levels. Based on these a mathematical model has been developed comprising of dimensions of insulator and geometrical parameter such as form factor. The model also involves pressure parameter which takes in to account
the variation of air pressure. Finally, it has been possible to develop a mathematical model that can be used to predict the flashover voltages of polluted SIR insulators rated for higher voltages.

2.4 Organization of the Thesis

The research work carried out is presented in six chapters. The chapter 1 provides overview of polymeric insulators and chapter 2 deals with complete literature survey about outdoor insulation. Chapter 3 describes problem formulation. Chapter 4 presents the details of experiments conducted and the results. Chapter 5 presents the details of the new mathematical model and the validation of the proposed mathematical model for different SIR insulators. This chapter also includes the comparison of model results obtained from the present model with the experimental results of other researchers. Summary and conclusions of the present work are described in chapter 6.