Rev.Adv.Mater.Sci. 13 (2006) 93-116

AGING OF POLYMERIC INSULATORS (AN OVERVIEW)

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Received: November 05, 2006

Abstract. With the advancement of chemical engineering many newer insulation materials have been developed that have advantages over older materials which are still in use. Polymeric materials are also one of them. From materials point of view their invention can not be marked as new, but their use in insulation system is not older than 25 years. The insulators made up of these materials are correspondingly called polymeric or composite insulators. Since these materials suffer from the problem of environmental degradation due to organic in nature so this time is not enough to guarantee that they can sustain in environments for long time where biological degradation is fast. So to have a correct fact file of prediction of their behavior over a long time (also called aging) a lot of work is in progress. This review describes the work done on their aging until now e.g. Introduction, design and, development history of different types polymeric insulators, Natural and Environmental factors that age insulators, man made factors that damage them, effect of each natural factor in detail and its remedy, artificial and field aging test setups dev eloped in different places in the world ,different techniques and methods of analysis used for detection of aging phenomena, results obtained from various aging sites about various parameters such as high temperature, rain, material additives, pollution, humidity, increased conductivity, sequence of aging phases as they appear in service mentioning affordable, unaffordable effects, service life prediction and testing Standards/Guidelines developed for polymeric insulators.

1. INTRODUCTION

Since long time in the world glass and porcelain insulators collectively treated under the name ceramic insulators are in use. These insulators appeared in high voltage transmission lines near last quarter of 18th century. These insulators have passed from many steps before achieving their final versions of disk strings for high voltage applications. This was only type of insulators that were available before the introduction of newer insulators made up of organic polymer materials, commercially about 30 years ago. These insulators are now days called composite insulators. A typical modern composite line insulator consists of a glass fiber reinforced resin (GFR) bonded rod onto which two metal end-fittings are attached. This is the mechanically supporting structure that has high weight carrying capacity. To improve its resistance to environmental stresses, it is covered with a polymeric rubbery cover, called Housing. Common housing materials are ethylene-propylene-diene monomer Rubber (EPDM), different types of silicone rubbers (SIR), and mixtures of these two.

In addition to the protection from moisture and pollution, the housing material is also shaped like sheds to provide the extra creepage distance (surface current leakage distance) needed to get the desired pollution performance. This is done by varying the shed diameters and/or the number of Sheds [1-3].

The use of these insulators as practical high voltage transmission line insulators is different in different countries. Some countries have adopted them like in USA 60% of transmission line insulators are of polymeric Type. But some countries are doing research on them to first predict their performance

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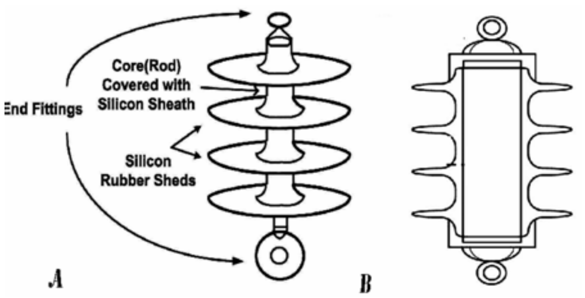

Fig. 1. (A) Old style polymeric insulator. (B) Modern polymer insulator.

before adopting them. Some countries have adopted them on actual lines but on limited scale to see their actual filed behavior. Some countries are totally hesitant of them either due to cost incurred because of need to import them or due to the fact that their long term behavior is not still fully known like ceramic insulators. However, it is expected that there share of the market will continue to grow, because of results observed in artificial as well as field aging.

The term aging refers to degradation of an insulator by different environmental effects and electrical stresses. The environmental effects include ultraviolet, moisture, heat, light, atmospheric pressure and biological degradation caused by microorganisms in air. While electrical stress include corona, formation of dry bands, arcing over surface of insulators, roughness and erosion of surface. All these factors also affect ceramic insulators, except biological degradation which is specific only to polymeric insulators. So when we want to predict long term aging of polymeric insulators we have to give most of attention to biological effects, although other effects mentioned above are also included and have their own importance.

The term field aging refers to installation of insulator on actual transmission line in outdoor open environment and monitoring effects produced on it. Where as artificial also called lab aging is normally done is a specially designed chamber in which different field conditions and weather cycles are simulated on a scaled down line voltage.

2. POLYMERIC INSULATORS DEVELOPMENT

With the passage of time different possible designs were presented in accordance with technology achieved. The initial designs presented about 30 years ago have a rod coated with silicon rubber and shed that were separately mounted on them. These suffered failure because of the slipping of sheds from rod or opening/damage of rod shed interface. Then following designs improved this by mounting shed on the rod directly and then encapsulating it with silicon rubber. However these designs also failed shortly. With the advancement of molding and fabrication techniques in last 15 years, new designs were introduced that have a rod covered with silicon rubber having sheds in it own mould as a one unit. This whole outer portion is called sheath. This modern structure proved to be very success full and is adopted till today. Both older and modern designs are shown in Fig. 1.

2.1. Materials used for outer sheath

There are three different materials that have been used for making outer sheath. HTV (high temperature vulcanizing) silicon rubber, RTV (room temperature vulcanizing) silicone rubber and LSR (liquid silicone rubber). Since the rubbers do not have sufficient stiffness so some materials are added in it to improve it. These materials are classified under the name fillers. Fillers also control some other properties of the finished product, such as mechanical stability and resistance to tracking. The use of filler also reduces the amount of rubber required and hence the cost. Commonly used fillers are fumed silica sand and alumina trihydrate. Fumed silica is necessary for achieving good mechanical properties during processing, and alumina trihydrate (ATH) is added because it acts as a flame-retardant. Adding ATH also has the positive effect of improving the dielectric strength and tracking resistance. It should be clear that sheath refers to coating on rod and sheds in older polymeric insulators and for newer designs it refers complete housing over the molded shed and rod structure. Due to this complete one unit design, today polymeric insulators are also called composite insulators.

End fittings are made of metal and the most common materials are; cast forged or machined aluminum and forged iron or steel. [1,2].

3. AGING OF POLYMERIC INSULATORS

Aging of an insulator is the effect produced on it in field after a specified period of service. It is also one of the elements that damages composite insulators but it is natural so it is classified under the

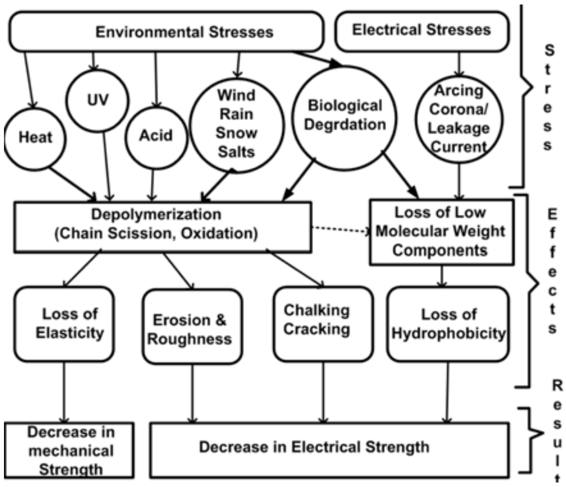

Fig. 2. Factors involved in aging of a polymeric insulator.

name Aging. Aging of polymeric insulators is mainly concerned with aging of outer sheath/shed. Outdoor weathering is a natural phenomenon which ages all materials to some extent. The most important properties of polymers result from their high molecular weights. Their strength results from the entanglement of the polymer chains. Degradation of polymers is concerned with the breakdown of macromolecules causing reduction in molecular weight. This breakdown can be caused by various environmental factors as stated below [4,5], see Fig. 2,

· **Biological Degradation**
· **Chemical Pollutants:-** Sulpher dioxide, Oxygen, Ozone, NO_2
· **Environmental Stresses: -** Heat, Light, Moisture**.** Wind, Dust, Rain, precipitation and UV light due to corona.

3.1. Biological degradation

Since polymeric insulators are made up of organic materials and all organic materials more or less have property to support the growth of biological microorganisms on them. Microorganisms colonize the surface in the form of Biofilms.

The requirements for formation of Biofilms on a surface are rather simple, only water, nutrition and microorganisms should be present. Microorganisms are always present outdoors and nutrients may come from the material itself or from its surroundings. Adhesion to surfaces is a common microbiological strategy for survival in low nutrient environments and Biofilms can thus be found in a wide range of environments. This is in direct consequence with the reports on biological growth on outdoor insulators, which reveal that, microbiological [2,6] colonization of ceramic as well as composite insulators takes place in all parts of the world. The biological elements that can grow on surface were not known fully until recent researches on 'Growth on insulators' have identified most widely grown microorganisms as algae, fungi or lichen. These are briefly described below.

Algae

Algae is a simple plant, producing its food by photosynthesis it has six categories; blue-green (Cyanophyta), green (Chlorophyta), Yellowgreen (Xanthophyta), brown (Phaeophyta), red (Rhodophyta) and Diatoms (Bacillariophyta). Algae are found almost everywhere, even in arctic climates. They spread through water, wind and animal movements, and multiply under certain climate conditions, i.e. favorable temperature, humidity and sun irradiation.

Fungi

Fungi are eukaryotic multicultural organisms, like plants and animals. Their structure is however rather different, since they are composed of long, thread-like filaments called hyphae. Fungi cannot manufacture their own food through photosynthesis; instead they absorb nutrients from the surrounding environment. They use enzymes for breaking down the substrate to enable absorption of nutrients contained therein. The process is facilitated through the large contact area of the hyphes growing on and inside the substrate material. Since fungi consumes material from surrounding environment so it is observed and believed that in service, composite insulators are mostly attacked by fungi. The establishment of design tests that can evaluate the resistance of various housing materials to specific fungal growth is a solution to this problem [7].

Lichen

Lichen can grow on almost any surface, which has sufficient sun illumination. They are a combination of fungi and algae living together intimately. Most of the lichens consist of fungal filaments and algae cells living among these filaments. The fungi and Algae that make the lichen can often be found living on their own, but many Lichens consist of fungi that are dependent on its algae partner and cannot survive without it, for instance on rocks and trees.

Basically, the algal cells provide the required Nutrition through photosynthesis, but even then fungi may use mineral nutrients from the surface. Most lichen types grow in temperate or arctic locations, but some can even grow in tropical and desert locations. One reason of its existence in extreme environments is probably that lichens dry completely when moisture is unavailable, i.e. loose all body water and stop growing. But when moisture becomes available again, they absorb water and continue to grow. Since lichens are reproduced by dispersion of algal cells wrapped in fungal filaments so they spread rather slowly.

The growth of microorganisms on the surface of composite insulators is of special concern. Biological deterioration of polymer surfaces is an interfacial process, controlled by the local conditions at the surface. Biofilms as introduced earlier are highly hydrated consisting of 80-95% water. Biofilms offer several advantages to growth of microorganism cells. These include forming a stable micro consortium, facilitated exchange of generic material, accumulation of nutrients in the bulk water phase, protection against toxic substances and protection against desiccation.

3.1.1. Effects caused by biological deterioration

There are several different ways in which microorganisms can influence the structure and function of synthetic polymers covering the composite insulators. The five major effects are

· Fouling (contamination)
· Degradation of leaching components
· Corrosion
· Hydration
· Discoloration.

Fouling is an unwanted deposition and growth of microorganisms on surfaces. The surface does not need to support growth or to be affected, but the presence of the Biofilms may interfere with the function and the properties of the material, such as masking hydrophobicity or increasing surface conductivity.

Degradation of leaching components. Additives, fillers, and unreacted material leaching out of the polymer may provide a food source for the microorganisms in the Biofilms. Consumption at the surface leads to concentration gradient flow from inside of polymer to surface, leading to subsequent deterioration. For instance, consumption of plasticizers leads to mechanical degradation of the remaining polymer through increased embitterment and loss of mechanical stability.

Corrosion is a process that is strongly influenced by the local conditions at the surface. Biofilms give rise to gradients in pH value, redox potential, concentrations in oxygen and salts, and all this influence parameters relevant to corrosion at the surface. The degradation involves reactions initiated by free radicals and extra cellular enzymes, generated by fungal metabolism. This ability of fungi of secreting a number of extra cellular enzymes, as well as its ability to easily colonize surfaces, both contributes to a rapid degradation of materials. These reasons make fungi especially relevant in bio- resistance tests.

Hydration. It is penetration of water in a material. Due to the fact that Biofilms mainly consist of water, they act as electrolytes increasing conductivity of surfaces. Fungal and mold growth on circuit boards and in computers have been found to cause short circuits and subsequent failure of electronic equipment. In a similar way conductivity of polymeric materials is also increased through penetration of water. It leads to high leakage currents which at the same time reduce mechanical stability.

Discoloration. Biofilms contain organisms that produce pigments causing serious discoloration. Some pigments, especially the ones produced by certain fungal spices, are known for easily defusing into lipo-philic polymers, such as PVC. This discoloration is not removable through cleaning. Further, some microbial degradation products cause severe problems due to odour.

3.1.2. Protection from microbiological attack

To protect a polymeric material from microbiological attack, different measures can be taken. Since the microorganisms cannot digest the inorganic parts so their growth can be restricted to some extent by making the insulator from a mixture of both organic as well as inorganic materials.

In general, the addition of different types of additives depending on application, together with an optimization of the base polymer formulation will make the material more resistant to biodegradation. For example, addition of the flame-retardant zincborhydrate to different silicon rubber formulations has been observed to suppress fungal growth. Further improvements can be obtained by addition of so-called biocides, i.e. active ingredients that kill or inhibit reproduction of microorganisms. This method has for instance been suggested by

Gubanski *et al.* to prevent algae growth on silicone rubber insulators. A god biocide should have a broad spectrum, easily diffuse to the surface to be protected without being washed out, have a small probability of resistance building, not affect the properties of the material, and, at the same time, be environmentally friendly. Protection of the final product can be accomplished by periodic removal of organic contamination (cleaning), control of environmental conditions, and, if needed, decontamination by sterilization.

3.2. Chemical pollutants

Sulpher dioxide is frequently present in air that comes from the gaseous wastes of industries. It forms a layer of pollution (mostly containing Sulpher) on the surface of insulator that finally causes flash over. However, the pollution performance of polymeric insulators is much better than that of ceramic insulators. Oxygen is also a source of degradation of insulating material because it supports the growth of microorganisms. Finally ozone and NO_2 are produced by the corona effect around high voltage lines. The ozone is destructive for all materials including insulators. NO_2 reacts with water on the surface of insulator to form HNO_3. Obviously, this tends to dissolve the surface leading it towards failure.

3.3. Environmental stresses

Heat, light and moisture produced by environment effect an in service insulator. Heat and light produce surface cracking and erosion. In absence of light, most polymers are stable for very long periods at ambient temperatures. The effect of sunlight is to accelerate the rate of oxidation. Photo oxidation leads to chain scission of hydrophobic methyl groups leading to the production of aldehydes, ketones and carbolic acids at the end of polymer chains. The breakdown may be comparatively mild, affecting only side groups, or it may be of a severe nature, causing a reduction in the size of macromolecules. Considering that even one chain scission per molecule in a polymer with a molecular weight of 100,000 destroys its technical usefulness [4]. The moisture goes into these cracks and finally causes a flash under of the rod.

3.4. Ultraviolet light [8]

Ultraviolet light is one of the major factors responsible for degradation of polymer insulators. Main sources of ultraviolet light are: sun, corona formation and dry-band arcing activities on insulator surface. The energy from sunlight that is destructive to polymers is between 320 and 270 nm. This destructive energy constitutes less than five percent of the total radiation reaching the surface of the planet. The absorption of this UV radiation results in mechanical and chemical degradation of the polymer structure which can affect the dielectric and weathering properties of that polymer. The rate at which the degradation occurs depends on the intensity and wavelength of the radiation. These factors vary with season, elevation, latitude and the time of the day. The degrading effects of these radiations are accelerated further if there is moisture on the polymer's surface. It therefore, suggests that polymer compounds for use in outdoor environments should be evaluated in the combined presence of UV radiation and high humidity.

The effects of UV radiation on a polymer include: crazing, chalking or cracking of the surface, discoloration and loss of hydrophobicity these are discussed in following sections.

3.5. Effect of corona

Corona discharges occur on the surface when electric field intensity exceeds the breakdown strength of air, which is around 15 kV/cm. Atmospheric conditions which effect corona generation are air-density and humidity. The geometry of insulator itself has a role in the initiation of corona activity. The Corona generates ultraviolet light, heat, and gaseous byproducts (ozone, NO_2).

The corona discharges subject the insulator to severe electrical strains and chemical degradation. Continued degradation may render the polymer ultimately unusable. A polymer insulator must have the right chemistry to be able to withstand this chemical degradation throughout its service lifetime. The other undesirable effects of corona are noise generation, TVI, RI, ozone generation and the loss of energy.

When corona generation occurs on a wet surface, this results in 'wetting corona activity'. Wetting corona activity is the outcome of a non-uniform wetting causing high electric field. This activity depends on the type and magnitude of wetting as well as on the intensity of surface electric field. The magnitude of wetting depends on the surface characteristics (hydrophobic or hydrophilic) and on the type of wetting whether it is produced by rain, mist, fog or condensation. Magnitude of surface electric field depends upon the dimension of grading ring, its position, live-end hard wares and end fittings.

Wetting corona activity occurs mainly at live and ground terminals. Lower hydrophobicity makes discharge activity more likely. Besides the undesirable effect discussed earlier, corona in the presence of water generates nitric acid ($NO_2+H_2O=HNO_3$) which may cause surface deterioration [9].

Wind, dust, rain and salt precipitation all these factors can change the insulating material physically by roughening and cracking and chemically by the loss of soluble components and by the reactions of the salts, acids, and other impurities deposited on the surface. Surfaces become hydrophilic and water penetrates in the insulating materials causing material breakdown. As obvious from the Fig.1, nearly all the factors result in decrease of electrical strength. The electrical, physical and chemical properties of the surface of the polymer insulators are critical to the reliable performance of the insulators throughout its service plan. The practical significance of the polymer breakdown cannot be over-emphasized [4,10]. So it is very important to predict the effects of aging on these X-tics of insulator.

4. DAMAGING ELEMENTS NOT INCLUDED IN AGING

Composite insulators can easily be damaged by some other elements that are not natural or environmental and several failures of composite insulators in service have been attributed. The major damaging was caused by improper handling during transportation or installation [11]. To deal with the handling problem, Cigrй working group prepared a handling Guide for composite insulators [12]. It contains recommendations for handling Insulators from the point they leave their manufacturer until they are energized. A general point is that all contacts with sharp edges should be avoided. Moreover, lifting, transportation and installation at site are identified as most dangerous for insulator integrity, making training of personnel critical. Cracking of the rod can for instance be induced through too large cantilever loads during installation. Walking or crawling on the installed insulator during maintenance may damage the sheds.

5. ACCELERATED AGING SETUPS FOR POLYMERIC INSULATORS

Long term exposure of the insulator surfaces of polymers to environmental and operational stresses causes several changes on the composition, and surface morphology, and reduces their water repellency. These changes occur typically at the top few monolayers [4].

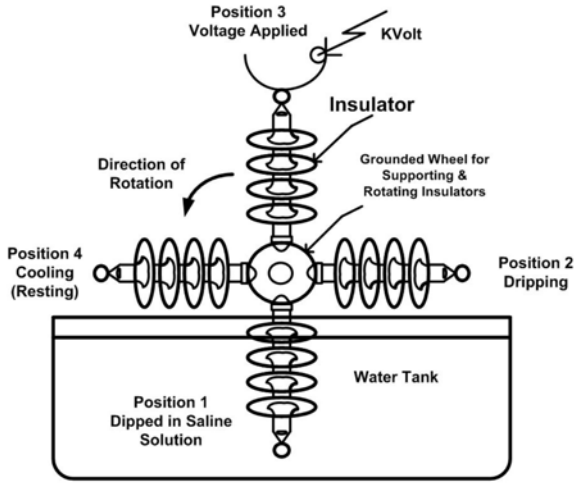

Fig. 3. Rotating wheel dip test setup (Wheel rotating at 1 Rev/Min).

In order to develop materials with satisfactory resistance to aging caused by all the effects stated above, it is necessary to simulate the aging as experienced in a service environment. To simulate aging different facilities and types of tests have been developed till now which predict the aging effects in advance and thus are called accelerated aging methods.

To develop an accelerated aging technique, the effects of environment for a short time (say half or one year, etc.) are observed and arrangements are made which can produce same effects in less time. This takes much less time and produces a sample of insulator that presents long term effects of field aging. In addition this knowledge helps a lot in designing, improving and selecting an insulator for any specific application or place. Accelerated aging methods developed until now are discussed in the following.

5.1. Rotating wheel dip test

This method [13,14] performs aging which represent the effect of short term field conditions under low to medium stresses. The main purpose of this is to monitor the early aging period. The test is terminated before any tracking occurs; also the necessary resting periods for the SiR are introduced. When a sample exhibit peak leakage current exceeding 1 mA, for more than 5 revolutions in a row, it defines the end of the early aging period. The test set- up consists of 4 samples of insulators, each mounted on a wheel frame 90° apart from each other, Fig. 3. The wheel revolves in 900 steps so that each sample is placed 1 minute at every of the four positions shown. In this way it completes one revolution in 4 minutes. The first position is immersion in saline water, the second is a horizontal dewetting position allowing the water to drip off as a consequence of hydrophobicity, the third is an energized position in which sample is supplied a high voltage from upper end and peak leakage current is recorded by a current recorder, and at the fourth position the sample rests at a horizontal position. The saline water used in position 1 is deionized water having sodium chloride in ratio of 1.5 g/l. Copper chloride is added which lowers the chance of algae growth.

Voltage supplied at energized position is obtained from a transformer 0.22/30 kV 50 Hz. Test is done at 6 kV. Oscilloscope measurements at 500 MHz show discharge currents in the range of 5 to 10 mA. The maximum observed peak current is 20 mA. Since these are low amounts of currents so there are no significant drops in power supply voltage.

5.2. Tracking wheel tests

The long-term performance of a polymer material used in electrical insulation design is directly related to the leakage current and the dry-band discharges that develop in service. Service experience has shown that the amplitude and frequency of dry-band discharges on electrical insulation are not dependent on design alone but also dependent on the surface properties of the polymer material used. For many years, tracking chamber methods had been proven to be very reliable in providing enough data on expected performance for a particular model insulator under severe contaminated conditions.

Tracking chambers can be classified in terms of the process of wetting the sample into three groups namely tracking wheel chambers salt- fog chambers and drizzle chambers. The tracking wheel test methods impose wet and dry cycles on a stressed surface of specimens in order to simulate the formation of dry-band arcing. Erosion or tracking takes place only in association with arcing over dry bands, which develop during or immediately after precipitation. The surface damage, erosion, or carbonization results from the heat of the arc, and this damage accumulates until the surface between the electrodes can no longer sustain the applied voltage and a flashover or even failure occurs. As this mechanism is the same as occurs in service, correlation with experience has been good.

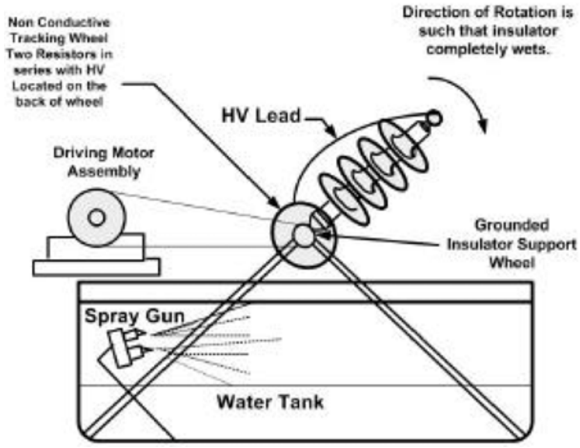

Fig. 4. Tracking Wheel test No.1

Tracking wheel Test No.1

This test [15] simulates the effect of continuous operation of insulator in wetting conditions. This test subjects composite insulators to a continuous, current limited 50/60 HZ voltage while rotating them also, see Fig. 4. Two series current limiting resistors, total value of 135 kV (225W each), are dedicated for each insulator. The insulators are sprayed with a saline solution (NaCl in the deionized or distilled water). The spray is done at the bottom position of the rotating cycle. The positioning of the spray nozzle and flow rate of the dropped water is such that the insulator is completely wetted. The distance between the spray nozzle and the test sample should be at least 125 mm. The insulators are positioned on the wheel in such a way that water runs off easily even when insulators with a non–uniform shed are tested.

Test Conditions

- Minimum electrical stress … 35V/mm
- NaCl content of water……..0.22 g/l
- Minimum duration……..1000h
- Speed of rotation…………..69±10 rev/h

Tracking wheel Test No.2

This test simulates the effect of periodic light wetting of insulators in the atmosphere e.g. due to Rain, fog etc. In this test four insulators are tested on a tracking wheel apparatus. The test setup used is same as shown in Fig. 4. The only difference each insulator remains stationary for about 8 s i.e. 90 degrees rotation from one position to the next takes place after every 8 seconds contrary to case of rotating wheel dip test where one revolution takes place in one minute. In the first part of the cycle the insulator is dipped into a saline solution. The second part of the test cycle permits the excess saline solution to drip off the insulator ensuring the light wetting of the surface, on which sparking across dry bands will form in the third part of the cycle. In that part of the cycle high voltage of 50/60 Hz is applied across insulator. In the last part of the cycle the insulator surface that had been heated by the dry band sparking is allowed to cool.

Test Conditions

· Minimum electrical stress …35 V/mm
· NaCl content of water ……. 1.40 g/l
· Minimum duration ………… 200 hours
· Speed of rotation………….. 1 Rev/ 24 Sec.

At the end of tracking tests, there shall be no significant signs of erosion and tracking. Each individual insulator should not suffer more than two flashover provided no damage occurs to the surface of the insulator [4].

5.3. Accelerated aging facilities

5.3.1. Koeberg natural ageing test station

This test station at KIPTS [3] consists of test bays for 11, 22, 33, 66, and 132 kV complete with control room, environmental monitoring station, pollution monitors and leakage current logger systems. The pollution index at KIPTS is of the order of 2000 S/cm, which is extremely high.

In this natural ageing chamber insulator is monitored over a period of either six and/or twelve months. Test results are time independent, which means that test results from one year can be compared to results from any other year. Following procedure is adopted.

1. A sample of the insulating material to be tested is stored for future reference in a sealed container. Prior to this, material analysis is also performed in order to determine a new material's 'fingerprint';
2. The insulator product is X-rayed to check for internal defects if present already due to any manufacturing fault;
3. Artificial ageing tests like UV weathering, Acid resistance test, and Hydrolysis test are then performed;
4. A natural ageing test is then performed according to IEC1109 Annex C.
5. After this a material analysis is done to determine changes as compared to sample stored in step 1.

Material analysis

The main purpose of the material analysis is to 'fingerprint' the material when new for future reference and to determine the condition of the material at the end of the natural ageing and artificial ageing cycles. The material analysis consists of the following tests: Hydrophobicity, Surface evaluation by optical microscopy, Fourier transform infrared (FTIR), Thermal gravimetric analysis (TGA). Details of these tests are given in following section and also in [3].

6. Upon completion of the above test procedure the insulator product shall be rated acceptable or unacceptable based on acceptance criteria explained in the following.

The acceptance criteria used at KIPTS is similar to those used for the IEC [14] and ANSI [16] tests.

5.3.2. Fog chamber at Okinawa

This was built by Furukawa Electric Co. [17]. This is designated by IEC 61109 for accelerated aging tests of the housing material of composite insulators. It specifies evaluation of short specimens that satisfy unit electrical stress levels (77 kV AC to ground). Chamber measures about 4.4 m square by 3.3 m in height. In order to be able to investigate the temperature change, humidification, precipitation, salt exposure and UV irradiation set forth in IEC 61109, at the same time as performing accelerated aging tests on the adhesion of the end- fitting and terminal portion of the housing rubber, this facility is provided with equipment for applying a steady load of 20 kN.

Fig. 5 shows this chamber. Evaluation of the test results can be carried out by continuous measurement of leakage current, regular measurements of the hydrophobicity of insulator surfaces, and analysis of surface conditions after the completion of the tests using scanning electron microscopy (SEM) and X-rays photoelectron spectrometry (XPS) hydrophobicity is adequately maintained throughout the test period of 5000 hr.

Visual observation of insulators after the completion of test in this chamber revealed a certain degree of gray discoloration, but SEM results showed no difference from the initial conditions. XPS observation of coupling energy also showed no change from initial rubber coupling, thus confirming that no aging occurred. We can conclude that composite insulators showed no great leakage current and no tracking or erosion of the insulator surface in ac-

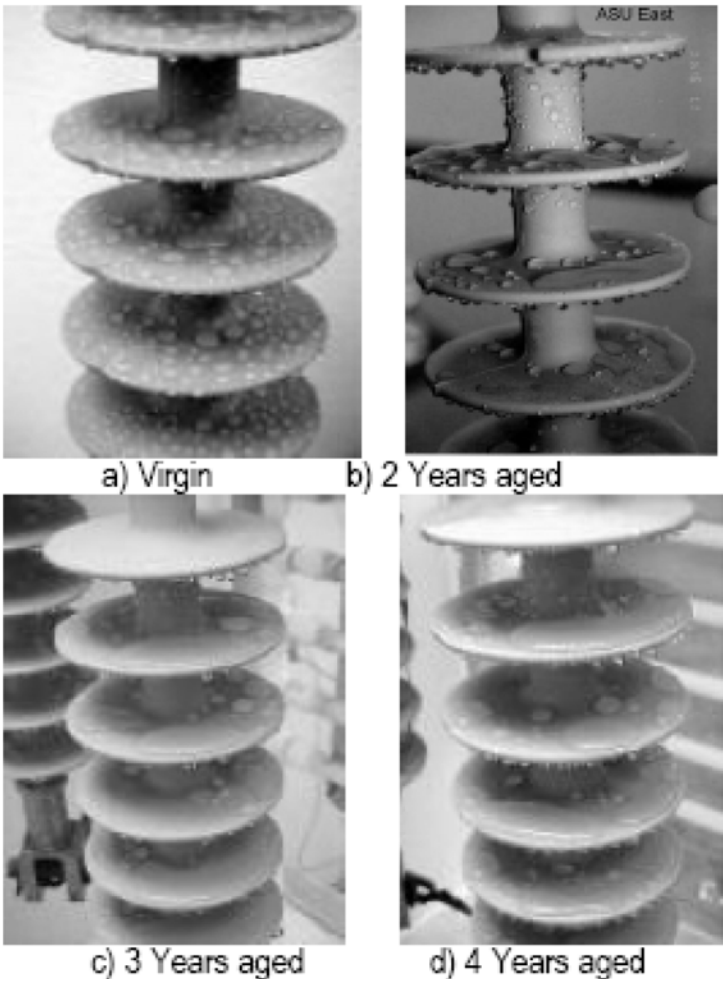

Fig. 5. Results of 4 year aging.

tual-dimension accelerated aging tests conducted in accordance with IEC 61109 Annex C.

5.4. Multi stress environmental aging facilities

The need for multi stress aging

The conventional aging tests described above such as the salt fog test, the tracking wheel test, rotating wheel dip test and IEC 1109 1000 h *etc.* limit the number of concurrent applied stresses. Using the above tests, the compound effects operating on the insulation system of actual field are not reproduced. [4,18]. Moreover, the stresses associated with individual tests are often unrealistic. The modes of failure caused by excessive stresses are not encountered in actual service. Therefore, the multi stress tests are applied in repetitive cycles that simulate actual service conditions. Weather cycles are developed to represent service conditions. The stresses are created by simultaneous applications of combinations of voltage, UV radiation, moisture and contamination, just as in service. Moisture is introduced in the form of humidity, fog or rain. Contamination is applied by various levels of salinity introduced with moisture.

5.4.1. Coastal environment aging chamber

To simulate the weather cycles at San Francisco coastal environment a multi stress environmental chamber was developed for 28 kV silicon rubber insulators. The dimensions of chamber were 6’x6’x6’

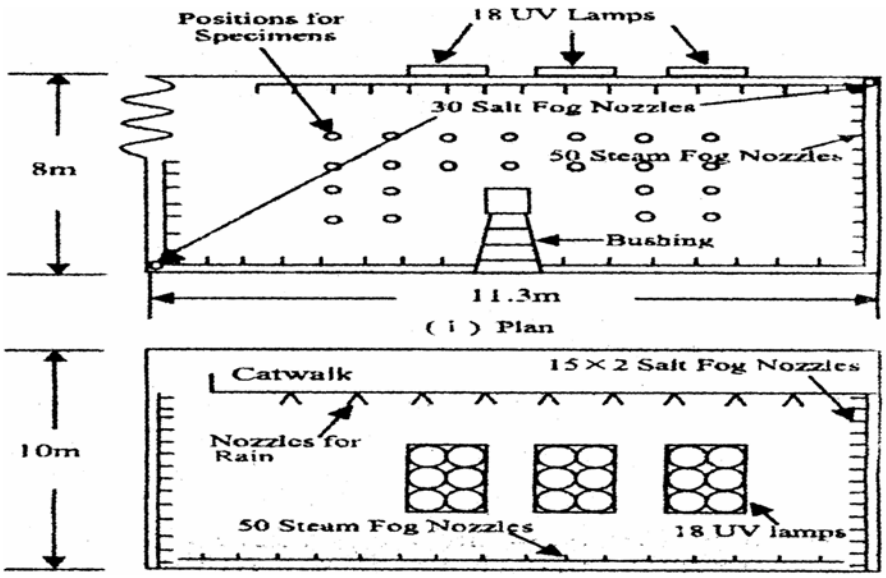

Fig. 6. 275 kV full scale insulator test chamber.

walk- in Plexiglas cube. Eight 4-foot long UVA-340 lights are used to simulate 1mW/cm^2 UV radiation, at the Wavelength of around 313 nm. Four fog nozzles produce salt fog and clear mist. Two rain nozzles were also provided. A 1450 W heater was used for heating. Cooling was done using a Movin Cool system.0-100 kV, 40 kVA HV testing transformer is used for energizing the insulators to the required voltage stress. This transformer allows aging of insulators up to 138 kV (Line).

Lab VIEW, the industry standard control, instrumentation, and data acquisition software is used for automatic on/off of the various stresses, as well as to collect the aging parameters.

The results reported after 4 years are shown in Fig. 5. Virgin sample has a smooth, more homogeneous and less porous surface. For 2 and 3 year aged samples, roughness and porosity increases. The longer the aging time the more porous the sample. Year 3 sample is most porous of all. However, year 4 sample have less porosity than year 3 sample and also looks smoother it. This indicates that sample has regained trying to regain its original characteristics in the 4th year.

5.4.2. 275 kV full scale insulator aging chamber

This was developed in Japan [20,21]. Its construction was mainly aimed at evaluating long-term performance of new type of insulators, such as semi conducting glaze, RTV silicone rubber coated and polymer insulators in the presence of uneven voltage stresses. Insulation performance and ageing deterioration by surface discharge do not necessarily show linearity between the size/scale of specimen and applied voltage. Voltage distribution along an extra high voltage (EHV) or ultra high voltage (UHV) insulator string is very non-uniform, especially in the case of long rod type polymer insulators. Even in the case of porcelain insulators having relatively uniform resistance distribution on the glaze, non-uniform voltage distributions are observed under severely contaminated and wet conditions, resulting in thermal runaway on some units. Therefore, full scale aging (testing of complete insulator under stresses) tests are necessary before insulators are to be adopted in important EHV or UHV transmission lines or stations.

275-kV full- scale insulator strings can be tested in this chamber under energized and combined stress conditions. A diagram of this test chamber is shown in Fig. 6. Voltage is supplied by a 300kV/300kVA testing transformer installed outside the chamber through a wall bushing. Approximate 20 strings of specimen insulators can be tested together. Two rows of salt fog nozzles are diagonally located at the corners, 50 steam fog nozzles are located on the floor, and 25 spray nozzles for simulated rain are located at the bottom of catwalk. Water used for simulating rain, steam fog and salt fog, is recycled after filtering and UV treatment. UV radiation is applied to some specimens by 18 units of 2 kW metal halide lamps through filter glasses. Chamber temperature is increased about 15 degrees in 2 hours and humidity is increased up to 95% in 15 to 20 minutes under steam fog conditions. The other conditions are:

· **AC Voltage Available : -** 200 KV w.r.t. ground.
· **Salt /Fog :-** IEC Nozzles,15X2 lines, Injection Rate 0.4 Vh/m 3 Salinity-1-6 mS/cm, Air Pressure 0.6 M Pascal.
· **Steam / Fog: -** Nozzles-' 50 Input Rate: 86 Wh
· **Simulated Rain: -** 4+2 mm/min (precipitation).
· **UV: -** 2kW X 18 Intensity: 6±1 mW/cm2

In all of the above accelerated aging tests of polymeric insulators involving any form of humidity, surfaces may get colonized by bacteria leading to formation of conductive slime layers which can influence the test results. These problems could be avoided by proper use of microbiological substances, for example Cu^{2+}ions [21]

5.4.3. Aging test setups developed at Pakistan

To investigate the behavior and performance of polymeric insulators in the extremely polluted and hot areas of Pakistan as well to perform lab aging faculties were developed at University of Engineering and Technology, Taxila. Using these facilities the prediction of aging and performance of polymeric insulators is being monitored since last three years and is still in progress.

The test setups were developed for three different purposes listed below.

A) Setup for natural outdoor aging in clean environment.

In this setup is developed at university in which a facility for fixing the insulators in open atmosphere at height of about 10 meter from ground is available. On this test stand insulators of various kinds and sizes can be attached and energized with high voltage provided by a 1 KVA commercial high voltage transformer installed in base laboratory. A high voltage insulated cable runs from transformer to top of test stand.

An indigenously developed leakage current monitoring system interfaced with computer is also installed that continuously monitors the current flowing over the surface of insulator and records any values above 5 micro Amperes with time.

Currently the NGK commercial insulators of Model Numbers E121-SS080-SB, E121-SE090SB, and E121-SE-050-SB are installed and energized at 11KV since last one year for testing. The aging parameters are measured by taking samples and performing tests FTIR, ESDD and NSDD, Hydrophobicity measurement and leakage current monitoring.

B) Setup for natural outdoor aging in extremely polluted and heated environment

In this setup is developed in a Cement industry with a facility for fixing the insulators in open atmosphere at height of about 15 meter from ground. On this test stand insulators of various kinds and sizes can be attached and energized with high voltage provided by a 1 KVA commercial high voltage transformer. A high voltage insulated cable runs from transformer to top of test stand. The worst effects of cement factory like dust, chemical pollution, and extreme heat effect insulator surface rapidly. Leakage current monitoring system described above is also installed there that continuously monitors the current flowing over the surface of insulator and records any values above 5 micro Amperes with time.

Currently the NGK commercial insulators of Model Numbers E121-SS060-SB, E121-SE090SB, and E121-SE-050-SB are installed and energized at 10 KV since last one year for testing. The aging parameters are measured by taking samples and performing tests FTIR, SEM, ESDD and NSDD, Hydrophobicity measurement and leakage current monitoring.

The samples removed from there show high NSDD and surface erosion. However further aging is in progress and to say something valid is before time.

C) Setup for lab aging tests.

In this setup is developed at university Lab with following facilities.

a) Accelerated UV-ageing;
b) Ozone resistance test;
c) Thermal aging test;
d) Multi Stress Aging;
e) Vacuum chamber Aging.

Thermal Aging Chamber contains water boiler, UV lamps and controller, Vacuum chamber has vacuum pump and has facility to hang insulators for energization.

UV aging chamber is of size 24" x 24" x 24" with six UV lamps each of 20 watt to make luminance

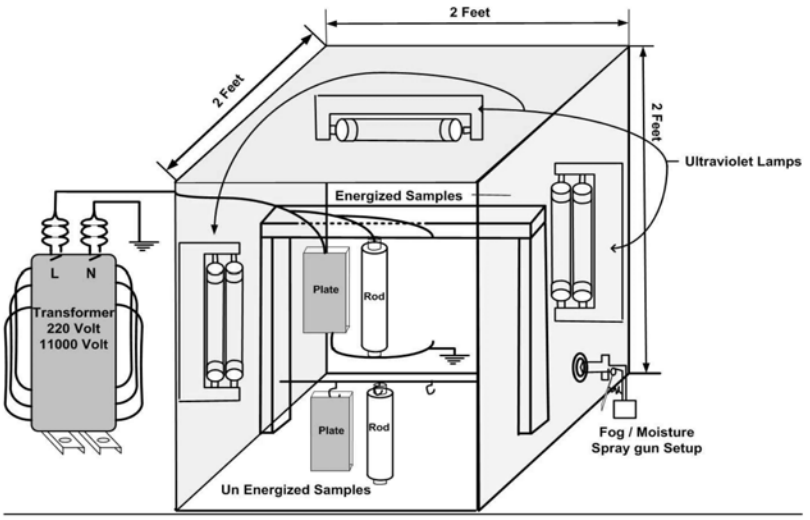

Fig. 7. Environmental Chamber setup at UET Taxila, Pakistan.

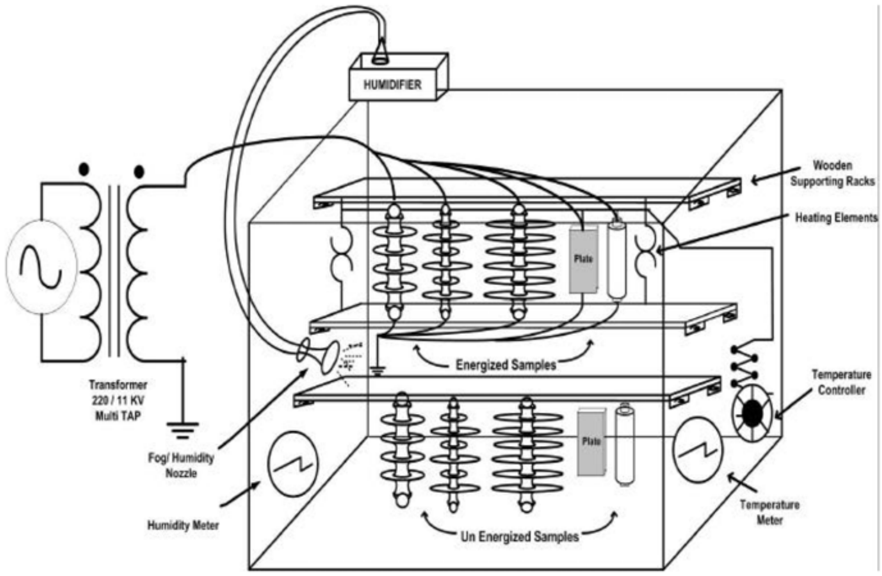

Fig. 8. Multi stress aging Chamber setup at UET Taxila, Pakistan.

intensity as prescribed by IEC 61109 Annex C. Heat and energization voltage is also available in it.

Multi Stress Aging Chamber has facilities for Humidity control, heat, UV light, Energization voltage up to 11 KV, and salt/ fog Spray *etc*. These facilities are in continuous use since last three years for testing various insulator samples. Layout diagrams of these lab setups are shown in Figs. 7 and 8.

5.5. Artificial accelerated ageing tests

These ageing tests can be performed individually or collectively as done in multi stress aging chambers. A detail of these test procedures is outlined here.

Accelerated QUV-ageing - Samples are exposed to UV in a weather meter chamber. The UV carbon arc lamp is used as light source, has the wave length in range of 300 and 400 nm. The relative humidity is ma intained at 50+5% and temperature is kept at 30 °C. Samples are subjected to UV light normally for 1000 h. It is well know that 200 hours of test period is equivalent to 1 year of actual outdoor exposure considering only the UV wave length (300-400 nm) that is mainly related to the deterioration of polymers [23].

Acid resistance test - Samples are exposed to dilute (1N) nitric and sulphuric acid at room temperature for a period of five weeks. Any chemical and physical breakdown is monitored.

Hydrolysis test - Hydrolysis is measured by exposing samples of the material to boiling water for a period of five weeks and the surface of the material is monitored by infrared to measure the chemical breakdown as well as under X10 magnification to monitor physical breakdown such as cracks.

Ozone resistance test - Samples are placed in a sealed vessel connected to an ozone generator. The ozone generator is run for 30 min per day to obtain a concentration of ozone that would not diminish during the ensuing 24 h period. The samples are exposed to this cycle that is run for five out of seven days for a period of three weeks. Sample breakdown for chemical and physical decomposition are monitored on a weekly basis.

Thermal aging test - it is performed by placing the insulator at 100 °C for 600 h in a circulating oven. Any de shaping or defect caused by heat is observed.

A detail of change in dielectric behavior of composite insulator after performing all the above aging tests can be seen in [5]. If upon completion of six months artificial aging period, the product insulation material passes UV, acid, hydrolysis and ozone resistance, and thermal aging tests, it is acceptable for general use, and if it shows same behavior even after one year it is acceptable for use in extremely polluted environments.

6. DIFFERENT TECHNIQUES AND METHODS OF ANALYSIS USED FOR DETECTION OF AGING PHENOMENA.

Aging phenomena can be detected by different methods. These methods are very useful to detect and to classify aging with non-destructive methods. The exact knowledge of the degradation state and residual life of the material used in a specific insulation can be detected by measuring the leakage currents, Hydrophobicity measurement, performing frequency absorption tests like FTIR, X-ray photoelectron spectroscopy (XPS), Energy Dispersive X-ray (EDX), Secondary Ion Mass Spectroscopy (SIMS), Gas Chromatography (GC), Gel Permeation Chromatography (GPC), Laser-Induced Fluorescence (LIF) spectroscopy, Thermal gravimetric analysis (TGA), Surface inspection by Scanning Electron Microscopy (SEM), Loss factor measurement [3]. Moisture induced ageing of insulation system by the glass transition temperature *etc*.

6.1. Measuring leakage current [5]

The deterioration that most generally affects composite insulator with a silicone rubber outer sheath of suitable mechanical design is caused by flows of leakage current on the surface in contaminated environments and by the erosion resulting from thermal and electrical factors. As erosion proceeds the silicone rubber sheath becomes corroded exposing the FRP, and this can lead to insulation breakdown and brittle fracture. It is thought that leakage current is the most suitable parameter by which to evaluate this erosion deterioration. To obtain a clear picture of erosion deterioration by long-term reliability tests, the leakage current resulting from dry-band localized arc discharge was classified in terms of waveform characteristics using the method described below and designated as intermittent current, and this was distinguished from continuous current, which is the resistance component of current [5].

(1) Definition of continuous current (resistance component current): a current which continues for a period longer than one sine-wave current cycle and of which the duration below the threshold value at the zero crossover is 1 msec or less.

(2) Definition of intermittent current (dry-band localized arcing current): A current which continues above the threshold level for 1 msec. or more, and of which the duration below the threshold value at the zero crossover is 3 msec. or more.

Method 1: By this method, using wavelet transformation of leakage current measured by sampling rate of 10,000 per second, leakage current is classified in to three types of components for each cycle of power frequency, conductive, dry band arc, and pulsive components, respectively. Leakage current having the magnitude of each half cycle less than .05 mA is treated as zero. Dry band arc component is such current whose build-up phase from zero is more than p/10 behind the voltage. Conductive and pulsive component are classified by the degree of distortion [21].

Method 2: By this method, instantaneous magnitude of leakage current is measured by sampling rate of 1,000 per second and accumulated charge is calculated and counted in the step of 1 C. Minimum measurable magnitude of leakage current is 1 mA. Numbers of surges beyond 10, 50, and 100 mA measured each 1 minute are also counted.

6.2. Hydrophobicity measurement

Hydrophobicity of any material is its resistance to flow of water on its surface. A material is highly hydrophobic if is resists flow of water dropped on it and is least hydrophobic if dropped water flows in form of tracks on its surface. The intermediate between above two has specific contact angle of water on its surface where it tends to flow. The hydrophobicity of silicone rubber materials is also measured through measuring contact angles between the material and water drops on its surface. The most commonly used method is the so-called sessile drop technique.

Sessile Drop Technique. In this techniques a water drop is placed on the surface using a syringe. The static contact angle is then measured manually using a goniometer or in an image using a camera fitted to a microscope. However, computerized fitting of theoretically derived drop profiles to collected contour images give more accurate results. Addition of more water to the drop will result in an increase of contact angle, finally causing the drop to advance over the surface. This angle is called advancing contact angle. Similarly, the angle at which the drop starts to recede during removal of water is called receding contact angle. The difference between these two angles depends on parameters like: surface roughness, surface heterogeneity, contact time of surface and water, and drop volume. The sessile drop method is applicable in laboratory environment only, since it requires good illumination and optimal view of single drops on flat horizontal samples. This lack of methods for estimating hydrophobicity of insulators in the field led to development of the STRI hydrophobicity classification method.

STRI Hydrophobicity Classification Method is a rather simple procedure for manually obtaining a collective measure of the hydrophobic properties of surfaces in outdoor environment. First, the surface to be studied (50-100 cm^2) is sprayed with tap water. The obtained drop pattern is observed and attributed to one of the seven hydrophobicity classes. Totally hydrophobic surfaces are denoted HC 1 and totally hydrophilic surfaces HC 7. The intermediate classes are defined by receding angles of the majority of the droplets and sizes of wetted areas. As help, the examiner has a set of reference images of typical wetting patterns representing each HC. However, a disadvantage of the method is that the measure is dependent on human judgment. To deal with this problem, Berg *et al.* proposed digital image analysis for estimating average hydrophobic properties of surfaces. Application of such procedure, where computer software interprets the image, makes the examination more objective and increases its accuracy. The aim of the work presented in was to find simple mathematical functions that could be applied to digital images of water drop patterns, indicating the level of hydrophobicity of surfaces. Further, it should correlate with the STRI hydrophobicity classification system and give reliable results for different angles of observation. Laboratory experiments were conducted on 2 mm thick sheets of a gray HTV SIR. Sandblasting was used to reduce hydrophobicity to HC7. Distilled water was sprayed onto the surfaces and digital photographs of the drop patterns were taken as the hydrophobic properties recovered. The samples were inclined at 10° and 35° from the horizontal. These inclinations were chosen as they represented well typical inclinations of insulator surfaces in service. As the samples recovered, 25 images were recorded for each HC and each angle giving more than 300 images. In order to make measurements comparable all directions and distances between camera, illumination and sample was fixed. Taking a large number of photographs for each HC was important to reduce the variance of the results. The authors checked various image analysis algorithms. The final function, best correlating with the STRI method and independent of small angular differences, was given a name ‘average of normalized entropies’ (ANE). It was based on histograms of nearest neighbor pixel differences and was fairly independent of illumination intensity as well as of total gain and offset in the camera system. Further, it was noted that reliability of image analysis techniques is increased if the images are recorded, enabling reexamination and use of other algorithms. Tokoro *et al.* have also applied image analysis to study hydrophobic properties of SIR, they used a high-speed camera equipped with a high magnification lens to observe behavior of water drops on small areas (1.5 x 1.5 mm). Small drops were chosen as influence of gravity became low compared to the effect of surface free energy, and thus problems associated with varying inclinations could thus be reduced. In [2], SIR samples were immersed in distilled water for different times to reduce hydrophobic properties. Images, made after the samples had been exposed to mist of different solutions, were analyzed with respect to size and shape distributions of created droplets. It was found that drops on highly hydrophobic surfaces were smaller and more circular than on less hydrophobic surfaces [2].

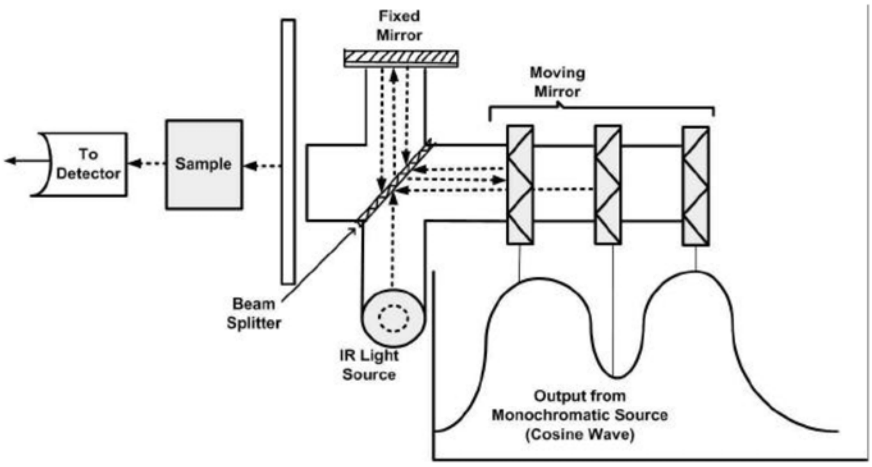

Fig. 9. A typical FTIR apparatus.

It is observed in service aging that hydrophobicity of silicon rubber does not always degrade, but after a certain time and under certain conditions it recovers itself to some extent in many cases and to large extent in some cases [4,18]. To explain this behavior we need to measure the some other parameters such as changes in frequency absorption of silicon rubber with time *etc.*; these techniques and parameters are now discussed.

6.3. Frequency absorption tests.

Study of smaller defects like micro cracks in surface housing materials, shallow channels, surface roughness at micro level, thin or transparent pollution layers, surface material erosion and its overall deterioration cannot be detected in the field. This has to be obtained through laboratory investigations that give detailed information about all these parameters. The techniques most commonly used in studies of silicon rubbers are described below [23-25].

6.3.1. Fourier transform infrared (IR) spectroscopy

Fourier Transform Infrared spectroscopy is a material analysis technique, which provides us

· Structural information

· Compound identification

Besides qualitative measurement, it can also be used for quantitative measurement as well. Mostly it is used to identify organic compounds but in some cases inorganic compounds can also be identified.

In this technique, the 'sample under test' is exposed to infrared radiation. The sample absorbs those frequencies which match with vibration frequencies of its atoms. A dip is obtained at these frequencies in the 'infra red spectrum'. This infra red spectrum is then matched with the standard curves stored in computerized reference libraries to identify the material or matched with virgin references to measure the deterioration of material, see Fig. 9.

Infrared radiation spans a section of the electromagnetic spectrum having wave numbers from roughly 13,000 to 10 cm^{-1}, or wavelengths from 0.78 to 1000 μm. It is bound by the red end of the visible region at high frequencies and the microwave region at low frequencies [26].

IR absorption positions are generally presented as either wave numbers or wavelengths. Wave number defines the number of waves per unit length. Thus, wave numbers are directly proportional to frequency, as well as the energy of the IR absorption. A typical FTIR Spectrum is shown in Fig.10.

IR absorption information is generally presented in the form of a spectrum with wavelength or wave number as the *x*-axis and absorption intensity or percent transmittance as the *y*-axis (Fig.11).

Transmittance, *T*, is the ratio of radiant power transmitted by the sample to the radiant power incident on the sample.

6.3.2. X-ray photoelectron spectroscopy (XPS)

It is sometimes also called Electron spectroscopy for chemical analysis (ESCA), has also been used in Characterizing SIR surfaces. It is much more surface specific than FTIR and gives information from depths down to 0.5-4 nm. During the measurement, which is performed in a high vacuum chamber, a sample is exposed to X-ray photons with enough energy to remove core electrons from the elements on the sample surface. The difference between the energy of the incoming X-ray photons and the kinetic energies of the ejected electrons is proportional to their bonding energy. The fact that this bond energy is characteristic for each element enables qualitative measurements of elements present at the surface. Comparison of the number of electrons ejected from Different elements give information about the atomic composition of the surface layer. Information about the chemical structure can also be obtained since bonds between atoms influence the energies required to eject electrons as well.

6.3.3. Energy dispersive X-ray (EDX)

The elements in the material also emit characteristic X-rays, so they can be identified using energy dispersive X-ray (EDX) analysis.

6.3.4. Secondary ion mass spectroscopy (SIMS)

In this technique the samples are bombarded either by ions or atoms. The secondary ions emitted from the surface during this process is detected and analyzed. Static SIMS is used for surface studies since it only considers secondary ions from the first one or two atomic layers. Dynamic SIMS on the other hand, erodes the surface and is used for depth profiling. This technique has been used to study aged silicon surfaces .Neutron reflectivity measurements are used for studying behavior of polymeric surfaces under atmospheric conditions. The principle is as follows. The incident neutrons interact with the nucleus of atoms through nuclear forces. Variations in scattering density as a function of depth are detected. The penetration depth of this technique is about 200 nm and it has a resolution below one nanometer.

6.3.5. Gas chromatography (GC)

Gas cromatography is used to separate compounds in a sample through their different volatilities. Sub-

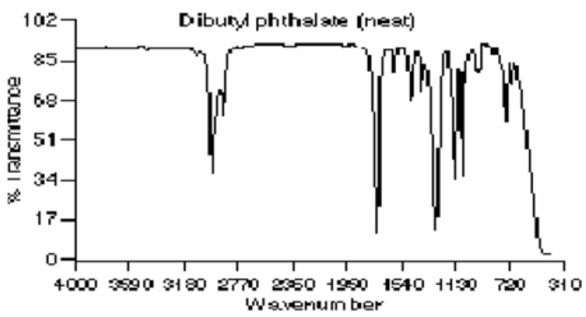

Fig. 10. A typical FTIR Spectrum.

sequent identification of these compounds can be performed using a mass spectrometer (MS), where the molecule dissociates Into smaller fragments. These fragments are characteristic for each compound and depend on its molecular structure.

6.3.6 Gel permeation chromatography (GPC)

GPC is used to measure molar mass and molar mass distributions of polymers. GPC is a relative technique and has thus To be calibrated using polymers with well-known molar mass and distribution .The sample, dissolved into a suitable solvent, is pumped through a column where the compounds are separated according to their hydrodynamic volume, closely corresponding to their molar mass. The solution from the column is analyzed using optical techniques. A method where samples are taken from energized insulators using a special Tool has been proposed for condition monitoring of EPDM insulators by Krivda *et al.* The tool can be used to cut small pieces of shed material, Swab the surface with cotton dipped in a suitable solvent, or to remove lose material on the surface. The sampled material can then be analyzed using SEM, FTIR, or XPS [2].

6.4. Scanning electron microscopy (SEM)

It is used to collect information about the surface topography of silicone rubber materials. It gives us a micro magnified image of surface of material to be analyzed. In SEM an electron beam is produced, accelerated and focused to strike the surface of material to be analyzed. When the beam strikes the sample, its electrons divide into four groups, see Fig.11.

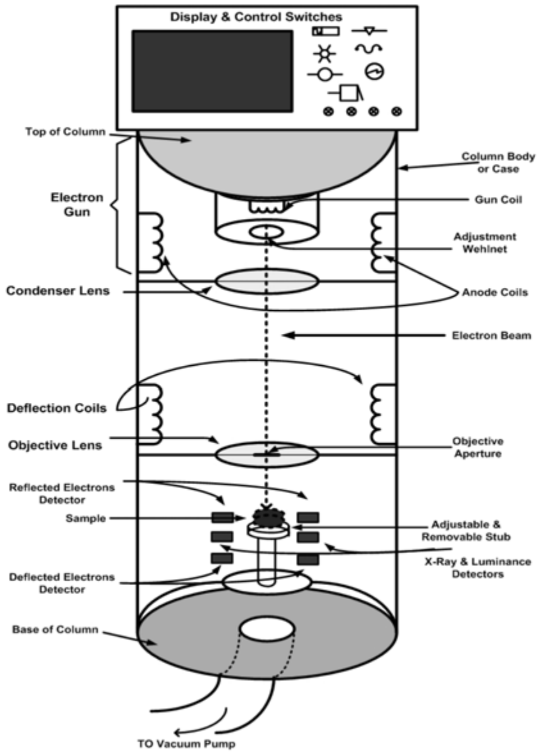

Fig. 11. A typical SEM apparatus.

Stopped electrons which stop upon striking specimen and give their energy to electrons of material and excite them, absorbed electrons which absorb into material and eject the electrons of material out of it, deflected and reflected electrons. All these electrons are detected by various detectors and correspondingly an image is produces that depicts the details of surface shape and roughness of material up to micro- meter scales. This image can be exported to view at other places like on in form of a digital strode image that can be viewed on any computer.

6.5. Laser-induced fluorescence (LIF) Spectroscopy

It is a new technique for remote detection of bio logical contamination on highvoltage door insulators [27]. It has been applied to study surfaces of real silicon rubber insulators from a distance of approximately 60 m. Measurements are performed outdoors on a number of clean, as well as, biologically contaminated insulators. Several types of biological contamination can be monitored using this method. However, this technique is still under further development.

6.6. Loss factor (TAN (d)) measurement

The dielectric loss factor measurement is based on results of frequency absorption tests and is a way to interpret the deterioration profile of silicon rubber or any other material. The more the dielectric loss the more absorption of specific frequencies occurs in frequency absorption test. Or we can say that reduction in transmittance dictates deterioration.

7. RESULTS OBTAINED FROM VARIOUS AGING SITES

A survey of literature however shows that a number of field (test sites) and laboratory accelerated aging studies were done, but no detailed quantitative study on actual insulators removed after many years of service is presented. Knowledge of what happened in the field is important because understanding why insulators fail in service is essential to finding ways of minimizing the likelihood of recurrence.

A few amount of literature reports how EPDM insulator surfaces vary with time in service and about their aging and degradation mechanisms. These will now be discussed.

7.1. 5 years aging in New Hampshire coastal area

This paper presents a detailed quantitative study of aging and degradation of 345 kV ethylene propylene diene monomer (EPDM) transmission line suspension type insulators removed from service, that were installed in a New Hampshire coastal area in 1995. Initially they were intended to be installed for 12 years but were removed after 5 years (in 2000) due to unexplained outages in that structure [4,29].

The insulators showed severe chalking and discoloration and partial loss of hydrophobicity on the side facing the sun. The surface structural changes were studied in detail using advanced surface analysis techniques, such as attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). For the first time, the significant differences in surface properties between the chalked/discolored (white) and the other surfaces (dark) were studied quantitatively. The Fourier transform infrared (FTIR) absorption spectra showed a significant decomposition of the CH groups of the white surface, elucidating the effect of photo-oxidation on the EPDM polymer. The SEM micrographs showed the cracking of the surfaces. The

XPS spectra showed the formation of various polar carboxyl groups and the presence of high surface energy compounds, such as silica, and silicates. This study provided valuable basic information on the changes in the surface properties of EPDM insulators during service in a coastal environment [4].

7.2. A Long term aging in San Francisco coastal environment

The long-term performance and the material state of polymeric insulators were examined from December 1987 to February 1997 [3,29]. The project comprised a great number of commercially available polymeric insulators from several prominent manufacturers. Each type of insulator was energized with high voltage alternating current (HVAC) as well as high voltage direct current (HVDC). The following results were obtained.

The silicone rubber (SiR) insulators maintained a high degree of their initial hydrophobicity and with respect to leakage currents performed better than the porcelain insulators. The obtained results show that heavily stressed SiR Insulators with specific creepage distances in the order of 8.2 mm/kV to 9.3 mm/kV had leakage currents exceeding 80 mA during a salt-storm in January 1993. However, after that occasion they showed relatively low leakage currents indicating that the SiR has the ability to recover its high surface resistivity and good performance. The measurements indicate that, at light levels of pollution, it is possible to reduce the creepage distance of the SiR insulator compared to that of a ceramic one.

Under severe field conditions the ethylene-propylene-diene monomer (EPDM) rubber insulators performed worse with respect to leakage currents and flashovers compared to the porcelain insulators with the same electric stress. Visual observations verified that the surfaces of most of the EPDM rubber insulators had eroded. The surface erosion included cracking and chalking due to environmental exposure and leakage current activity.

The material aging of the EPDM rubber resulted in a degraded performance of the insulators under contaminated conditions. In sum, the results suggest that the application of a higher electric stress of the EPDM rubber insulator compared to that prescribed for the ceramic one is not advisable.

7.3. Aging in Swedish coastal environment

Since 1989 to 1997, the group of Vlastos, at the Chalmers University of Technology, Sweden, reported field test site studies of aging and degradation of polymeric insulators in a Swedish coastal environment [2]. Both silicon and EPDM insulators were used for this purpose. They studied the difference in aging of the silicon and EPDM insulator materials and insulator designs and differences due to ac and dc voltages. The surface changes were studied qualitatively using various surface analytical techniques.

7.4. Tests in various other areas

Another field test site study involved aging of three kinds of 275 kV EPDM insulators, from 18 to 34 months in Australia. Here the focus was condition monitoring of insulator status using FTIR oxidation index. It was shown that energized ends had more oxidation than un-energized parts. Detailed XPS work was done on in-house EPDM samples that were UV aged using xenon lamps for 4000 h .Since no voltage or any other stress was applied in this study, so results could not be extended to a service environment. The study of non ceramic insulators under tropical weather conditions was done for 33 kV polymeric insulators for 2-3 years. The study reports hydrophobicity and surface resistance variation. A 160 h corona aging and its effect on the hydrophobicity were done by Kim and Kim using contact angle measurements and surface changes using SEM [1].

Another recent work on aging of polymers involved comparison of ac and dc voltages on in- house silicon rubber cylindrical samples, of length 10 cm and 20 cm, at a field site, at 11 kV ac and 10 kV dc was done. The focus of this work was to pinpoint the role of additives and differences due to ac and dc voltages and the length of samples [1].

An accelerated aging test with a small composite hollow insulator was conducted for up to 5000 h with conditions specified in IEC61109 Annex-C. Appearances, hydrophobicity, and surface deterioration were periodically analyzed. It was found green algae deposited on the surface of some portions of housing rubber of field test specimens, but was not associated with significant deterioration. Erosion developed on housing of specimens subjected to the accelerated aging test for 4000 h and 5000 h.The number eroded traces increased with time. Slight deterioration was found even on the areas without erosion analyzed by FTIR spectroscopy [5].

Specimen insulators (installed for 7 to 8 years on actual 110-kV line) [6,30] having shed punctures were installed in the large artificial ageing chamber. Humidity inside the chamber was controlled by injecting steam. After stabilizing the wetting conditions on specimens by keeping the target humidity for 30 minutes, AC voltage was applied to the specimens and gradually increased to find the corona inception voltage CIV at the punctures. Corona discharge was detected by an image intensifier after confirming the CIV; applied voltage was increased well above the CIV and then decreased gradually to confirm the corona extinction voltage CEV. CIV and CEV values were obtained under different humidity conditions by injecting steam fog into the test chamber.

8.0 RESULTS ACHIEVED ABOUT VARIOUS PARAMETERS

8.1. Effect of temperature

One of the most significant factors in degradation for aging organic materials is when exposed to UV radiation. The rate of aging doubles for every 10 degree centigrade increase in temperature. This is exploited as in following equation [4,31]:

$$\text{Relativ Aging Factor (RAF)} = 2\left(T_{\text{max}} - T_{\text{avgmin}}\right) / 10, \quad (1)$$

where T_{max} is maximum temperature during each month. T_{avgmin} is minimum temperature of all average temperatures, both expressed in degree Centigrade.

8.2. Effect of rain conditions on flash over voltage (F.O.V) of polymeric insulators

1. Heavier contaminant deposit should be considered on hydrophobic polymer insulators compared with conventional ceramic insulator [22].
2. A stiff power source should be used for evaluation of contamination flashover/withstand voltages of hydrophobic polymer insulators especially, under heavily contaminated conditions, in spite of smaller leakage currents measured both in fields and laboratories.
3. Contamination flashover/withstand voltages of hydrophobic polymer insulators should be evaluated under heavy wetting conditions. Both heavy fog and simulated rain tests may be good candidates for standard contamination flashover/withstand voltage tests methods for hydrophobic polymer insulators [22].

8.3. Effect of material additives

SIR material samples and SIR housed insulators with known differences in material compositions were aged under ac and dc voltage stresses, in coastal areas. All objects were tested with a higher electrical stress to accelerate the aging, i.e. the creepage distances ranged between 30% and 75% of what is normally used at this location for ceramic insulators. In the first step, a screening test with cylindrical samples was initiated. The electrical performance was quantified by counting the no. of peak leakage current values. In addition, the samples were visually inspected for erosion and hydrophobic during the test. After wards, the materials were analyzed for chemical changes and a dominating aging mechanism was identified. It was found that the thermal energy supplied by short pulsed discharges was the most probable origin for the observed surface changes.

8.4. Leakage current suppression capability

Significant differences were found for various insulator materials regarding leakage current suppressing capability of gradually contaminated insulators under clean fog conditions. Leakage current suppressing capability of HCEP (Hydrophobic Cycloaliphatic epoxy system) was found to be better than that of CEP (Cycloaliphatic epoxy system) and closely comparable to that of LSR (liquid silicon rubber) The findings of this study are consistent with the many published results of previous studies on hydrophobic Cyclo-aliphatic epoxy. As expected, standard CEP, which is not designed to yield a hydrophobicity transfer effect, showed higher leakage current activity than the other tested materials [32].

	CEP	HCEP	LSR
Accumulator Charge	3	2	1
Effective Current	3	1.5	1.5
Maximum Current	3	1	2
Pulse counts	2	2	2
Total Schores	11	6.5	6.5

8.5 Effect of pollution and humidity

It was clearly found that pollution and humidity could originate surface discharges, and then could damage Silicone Rubber Housed Arrestors .The damage could be detected by measuring PD magnitude and analyzing the pattern of the surface discharge that occurred. Moreover, the discharge preteen could be used to identify damage to the surface condition .In particular, the skew ness and the kurtosis of the PD pattern appear to be very sensitive to discharge generated damage of the surface. Thus, such statistical parameters may provide a useful diagnostic for damage monitoring polymeric insulators. Measurement of the 50 Hz total surface leakage current did not provide any significant correlation with surface damage [17].

8.6. Effect of increased conductivity and contamination flow on HDPE

It is believed that HDPE is an ideal outdoor insulation structure for low voltage applications. An increase in conductivity and flow rate of the contaminant exhibited a reduction in the tracking time of the insulation material.

8.7. Effects of miscellaneous parameters

In general for all polymeric material It is confirmed that the material properties significantly alter the tracking time of the insulation structure. The contact angle and the surface roughness of the material varies irrespective of the type of ageing. The diffusion coefficient of the samples increases with the temperature of the water bath. The wide angle X-ray diffraction (WAXD), differential scanning calorimetery (DSC) studies indicate no addition of new phases in the insulation structure due to ageing process. A variation in percentage of crystallinity of the material is noted with the thermally aged and the cyclic aged specimens. A reduction in the enthalpy of the material in the tracking formed zone is observed from the DSC results. This indicates that only the surface damage has occurred in the insulation structure. The mechanisms of degradation process which occurred in the material were explained. The tensile strength results indicate that aging of the material alters the mechanical property of the material. The impact and flexural test indicates that the material with high toughness/stiffness causes increase in the tracking time of the material. The dynamic mechanical analysis DMA analysis indicates that the storage moduli of the material increases with increase in frequency. The variation in the storage modulus of the material with ageing of the material was observed. The loss tangent of the material is high at low frequencies, irrespective of the type of aging of the material. The standard multiresolution signal analysis curve provides finger print identification of deviation of leakage current from normal sinusoid with the addition of harmonic content. The magnitude of high and low frequency contents increase when surface discharge occurs. Characteristic increase in values at all points is observed in the standard MRA curve with the tracking current [1].

9. DETERIORATION EFFECTS AS THEY APPEAR IN SERVICE

As mentioned earlier factors influencing deterioration of composite insulators are electrical, mechanical or a combination. Electrical factors cause tracking, erosion, puncture of sheds, cracking, *etc*., while mechanical factors cause degradation of tensile strength and degradation of strength due to repetitive bending and twisting.

As combination factors we may note brittle fracture, in which the glass fiber of the FRP core becomes corroded by acid so that it fractures under comparatively low levels of strain. It is thought that brittle fracture is caused by nitric acid that is generated when there are problems at the interface between the end fittings and the silicone rubber outer sheath, resulting in corona or partial discharge at those points where moisture penetrates to the FRP. In this respect Furukawa Electric’s composite insulators have a hermetically sealed structure in which the silicone rubber sheath is molded to cover the interface between the fittings and the FRP, to improve reliability against brittle fracture.

As the insulator ages, different patterns appear one after the other. Some of these conditions affect the whole insulator more or less uniformly; they are called affordable effects and no replacement of insulator while others are highly localized in nature, called unaffordable effects and necessitate the replacement of insulator [33]. These conditions are briefly discussed below.

9.1. Affordable effects

9.1.1. Loss of gloss and discoloration [33]

Normally, the first condition that indicates the aging of insulator is loss of gloss and discoloration.

9.1.2. Chalking [7,13]

Chalking is the appearance of a rough and whitish powdery surface giving the insulator a chalky appearance. The factors which are responsible for chalking are ultra-violet radiation and electrical activity. When a small quantity of rubber is removed from a surface because of these factors, the filler material is exposed. This filler material is a white powdery substance, giving the insulator a chalky appearance. One negative effect of chalking however, is that it allows more accumulation of water and contamination on the surface. Therefore, the insulator which has the tendency to develop chalking should not be installed particularly in areas where coastal pollution is experienced. Compared with other, EPR insulators are more prone to chalking.

9.1.3. Crazing [7]

It is appearance of shallow cracks on the insulator surface. Depth of these microfractures is less than 0.1 mm. The reason is electrical stress.

9.1.4. Loss of hydrophobicity [7]

Hydrophobicity is the wetting property of rubber material because of which it resists formation of film of water by forming beads of water, thus denying a path for leakage current and associated arcing. Loss of hydrophobicity results in the formatio n of hydrophilic surface. EPR insulators have been made hydrophobic by addition of fillers like alumina trihydrate. Therefore, the EPR insulators with heavy chalking have been found to lose all hydrophobicity.

9.1.5. Alligatoring (deep cracking) [7]

Alligatoring is surface fracture of a depth greater than 0.1 mm. In fact, it is a more severe form of crazing. It reduces contamination performance of insulator and may ultimately lead to rod exposure.

9.2. Unaffordable effects

9.2.1. Corona cutting

The cutting or aging induced by corona discharges is known as corona cutting. These discharges expose the insulators to severe electrical and chemical degradation [14].The cutting induced is usually due to improper bonding of material and poor hardware design. The gravity of damage increases with increasing voltage. This phenomenon can occur even in clean location [33].

9.2.2. Holes at the junction of shed and housing due to puncture

Disruptive electrical discharges occurring through the rubber or rod cause puncture. This results in permanent loss of dielectric strength. It is usually caused by an imperfection in the rubber or rod [7]. This phenomenon may even occur in clean location. The intensity of damage increases with increase in voltage [33].

9.2.3. Tracking/ Carbonizing

Tracking is caused by leakage current activity [33]. This is an irreversible deterioration by the formation of paths starting and developing on the surface of insulators. These tracks have the appearance of carbon tracks which cannot be easily removed and are conductive even under dry conditions [13,34].

9.2.4. Erosion

Like tracking, erosion is a degradation mode of housing caused due to leakage current activity. It is an irreversible and non-conducting degradation of the surface of the insulator that occurs by major loss of material (that is more than 1 mm). It significantly reduces the thickness of the polymer sheath that prevents ingress to the core rod [13,34]. Erosion can be localized, uniform or tree shaped [34]. It is a much slower form of degradation than tracking and normally does not lead to failure unless it is so severe that it reaches up to rod.

By adding inorganic filler (e.g. alumina trihydrate and silica) to the formulation improves the tracking and erosion resistance. However, what is not so well known is the amount of filler needed for satisfactory operation which depends on formulation (base–polymer, filler treatment etc). Generally, EP (ethylene propylene) rubber formulations need substantial amount of filler in order to obtain adequate erosion and tracking resistance. Also inorganic fillers containing water of hydration offer more tracking and erosion resistance than un-hydrated filler [33].

9.2.5. Exposure of fiber-glass rod due to tracking and / or erosion of sheath

A fiber-glass rod can be exposed due to erosion or cracking and tracking of sheath beside other factors. The exposed rod is prone to damage (fracture) due to UV radiation degradation, water intrusion and tracking.

9.2.6. Seal damage at end fittings [33]

The seal damage includes lifting of seals, seal erosion and tracking. The damage to seal at end fittings can promote tracking of the rod which is not visible from outside.

9.3. Service life prediction

After studying the aging conditions discussed above, a natural question arises, i.e. when the insulator should be replaced. It is very difficult to answer because very little data are available from the field and also it depends on many factors such as construction method, extent of degradation, type of insulator and maintenance practices.

Also, it is a valid question that in which order these conditions would appear on a newly installed insulator. In order to answer these questions, the aging conditions could possibly be expressed in the following order:

· New polymer insulator installed
· Loss of gloss and discoloration
· Hydrophobicity loss
· Light Chalking
· Crazing
· Alligatoring
· Sheath erosion away from terminals
· Sheath tracking
· Rod/ shed interface damage
· Localized sheath erosion
· Failure of rod or complete insulator

10. TESTING STANDARDS/ GUIDELINES DEVELOPED FOR POLYMERIC INSULATORS

There are currently a large number of organizations doing research [5] on the phenomenon of the deterioration of the outer sheath in composite insulators. Among internationally recognized standards, IEC 61109 Annex C establishes a method for accelerated aging tests by means of environmental stress, and IEC 60587 and IEC 61302 give tests for specific outer sheath materials. STRI Hydrophobicity Classification Method is a rather simple procedure for manually measuring the hydrophobicity of surfaces in outdoor environment. Since long-term sheath deterioration varies with environmental stress, the ideal method of determining the reliability of composite insulators would be by prolonged environmental aging [35].

11. CONCLUSION

Composite insulators are light in weight and have demonstrated outstanding levels of pollution withstand voltage characteristics and impact resistance. They have been widely used.

To investigate long-term degradation due to the use of organic insulation material, outdoor loading exposure tests and indoor accelerated aging tests are continuing, and based on the additional results that will become available, work will continue to improve characteristics and rationalize production processes in an effort to reduce costs and improve reliability.

However in some case Lab tests do not necessarily give valid results always because, the excessive stress damages the insulators by modes not encountered in actual service. Also, the frequencies of the repetitive cycles do not correlate with daily or seasonal cycles experienced under service conditions. For example, generally, it has been seen in the field that silicone rubber (SiR) materials have excellent hydrophobic and hence good leakage current suppression characteristic. However, often they fail in the above tests at lab conditions. This shows the unrealistic nature of these tests to some extent and their unreliability to evaluate the actual performance of an insulator design in some cases.

Composite insulators for overhead lines typically are used in a severe natural environment and are constantly subjected to tensile loads and electrical stress. Thus it is essential that they have mechanical properties such that the joints between the end fittings and the FRP have long term integrity, without slippage. Electrically it is essential that they withstand problems associated with organic materials, involving erosion due to dry-band localized arcing and corona discharge occurring under conditions of contamination or humidity [5].

Studies made up till now reveals that no mathematical formula/ rule can be applied that composite insulators follow strictly for aging and deterioration. Following future works are recommended.

1. Long term lab. Aging.
2. Development of monthly Weather Cycles.
3. Watts Loss Computation.
4. Material characterization of the un-aged, aged and recovered samples.
5. Correlation of lab. Aging with field aging.
6. Development of a hypothesis of aging.

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