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Composite insulators and their aging: An overview

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The aging (biological deterioration) is a major problem of composite insulators now-a-days. The main thing in aging is to predict how, when and with what speed it occurs and under what conditions it can lead to failure and what overall average expected life of a composite insulator is. For this a lot of researches have been done. This review summarizes the methods of artificial field testing (aging), natural testing, standards the developed for aging, techniques of analysis, results achieved until now about various parameters from various locations, handling guidelines and a conclusion on what is further needed.

polymeric insulators, aging, composite, SEM

1 Introduction

Reliability is the most important property of an insulator whether it is a polymeric (composite) insulator or ceramic one. The reliability of an insulator depends upon its electrical and mechanical strengths. With the advent of modern manufacturing, mechanical molding and fixture technique, the mechanical strength is quite reliable. However the electrical strength over decades is not fully guaranteed. The modern style polymeric insulators were introduced about 25 years ago with most recent version about 13 years ago. The reason for this was not failure of ceramic insulators, but the other benefits such as 90% weight reduction, better pollution performance and low associated costs of polymeric insulators over ceramic ones[1−3].

Experience of outdoor insulation started from the introduction of telegraphic lines. The pin and cap type insulators have been used since the last quarter of the 18th century. These insulators are very reliable. Glass and porcelain insulators were the only type available before the introduction of newer polymeric insulators and thus had fully ruled over the market till late second half of the 20th century. The polymeric insulator has a fiber rod structure covered with weather resistant rubbers and fillers and fitted with end fittings. Such a type of insulator is also called composite insulator.

The most critical thing to be considered in outdoor insulators is the interface between the solid insulting body and the surrounding air. The problem appears at the interface because it is the in-

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terfering point of air and the solid insulator. This problem arises due to the effects of pollution, rain, dust, salt, corona, arcing over surfaces, nitric acid in air, etc.

These things increase the leakage current and deteriorate its performance. Surfaces of insulating bodies were therefore coated with glazed material for glass and porcelain insulators, and organic or semi-organic polymer rubbers for composite insulators.

A typical composite insulator is composed of a glass fiber reinforced (GFR) epoxy or polyester core (rod), attached with metal end-fittings. This is the load bearing structure. GFR plastics are mechanically very strong but are not able to bear the outdoor environmental effects. The presence of dirt and moisture in combination with electrical stress causes the material to degrade by tracking and erosion. So the rod is covered by a coating that protects it from outside stresses such as rain, salt, fog, pollution, etc. This coating is referred to as housing.

A housing material should be able to protect the load-bearing core and provide sufficient pollution withstand. The reason of use of rubbers instead of ordinary plastics is simply the fact that the housing must be flexible enough to follow the changes in dimension caused by temperature or mechanical load.

The early developments of modern polymeric insulators started in 1964, and prototypes for field installations started in 1967[1], and a report from 1996 stated that insulators installed in 1969 were performing well[4]. The early types had an epoxy bonded E-glass fiber core covered with a thin room temperature vulcanized (RTV) silicon rubber housing[1].

A major change in production technology occurred in 1978, when the housing material was replaced with ATH-filled high temperature vulcanized (HTV) silicon rubber.

Composite insulators can be manufactured by different techniques. One way is to first manufacture the sheds separately and push them onto the core[5].

This technique was abandoned because these insulators experienced a lot of problems. The weak spots were the interfaces between the sheds where moisture could penetrate into the insulator causing internal tracking. A better way is to first cover the core with housing, add the sheds onto it and then vulcanize the parts together. This reduces the number of interfaces where moisture can penetrate to the GFR rod.

Today the most commonly used technique is one-shot molding[5]. 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, and the number of interfaces where moisture can penetrate is minimized. This technique is the most attractive to manufacturers because of the lower number of steps involved and short time of processing. There are three main types of silicone rubbers used in high voltage insulation applications: high temperature vulcanizing (HTV) silicon rubber, room temperature vulcanizing (RTV) silicone rubber and liquid silicone rubber (LSR). HTV is cured at high temperature and pressure, catalyzed by peroxide induced free radicals or by hydrosilylation catalyzed by a noble metal, i.e. platinum[6]. RTV is cured at lower temperature, i.e. around room temperature, by condensation reaction as one component system. The one component system is cured by moisture diffusion from the surrounding air into the material and is rarely used for the production of insulators.

Fillers are added to the rubbers to control different properties of the product, such as mechanical stability and resistance to tracking, as well as to reduce the cost. Fumed silica is necessary for achieving good mechanical properties during processing, and alumina trihydrate (ATH) is added as a flame-retardant[7]. Adding ATH also has the positive effect of improving the dielectric strength and tracking resistance[8,9].

End fittings are made of metal and the most common materials are cast, forged or machined aluminum and forged iron or steel[9]. The end fittings can be attached to the core by different methods. Today, the most common technique is swaging (crimping) and gluing. The wedges are inserted in fiber rod by some manufacturers[5]. However, the swaging is the strongest type of attachment and hence most popular. The two modern designs, straight shed and alternate shed are shown in Figure 1.

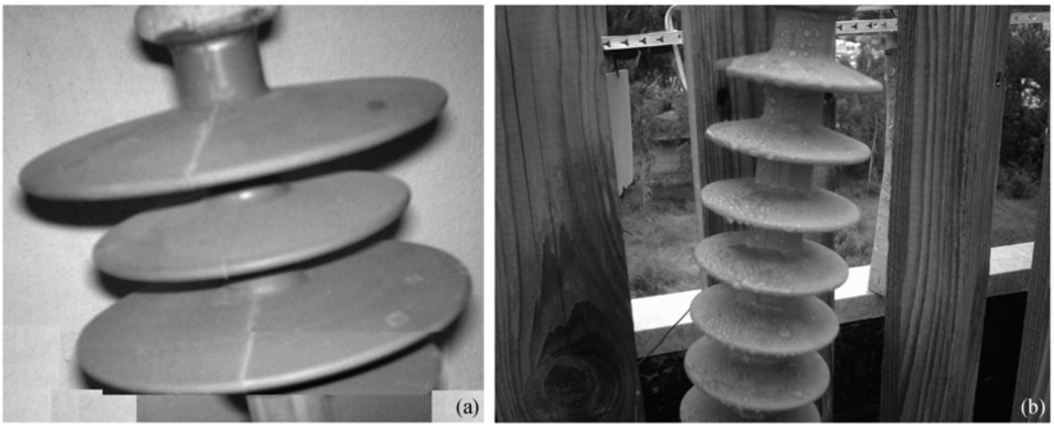

Figure 1 Typical modern polymeric insulators. (a) An alternate shed insulator; (b) a straight shed insulator installed in Pakistan.

2 Methods of aging

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

2.1 Short term artificial aging tests

In such tests, the effects of environment for a short time (say one year) are observed and arrangements are made which can produce the same effects in less time. This takes much less time to present long term effects of field aging. This knowledge helps in designing, improving and selecting an insulator for any specific application. Many accelerated aging methods have been developed; some of them are discussed here.

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

(2) Hydrolysis test. Hydrolysis is measured by exposing samples 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.

(3) Accelerated QUV-aging. Samples are exposed to UV in a weather meter chamber. The UV carbon arc lamp is used as light source. It has the wave length in a range of 300—400 nm. The relative humidity is maintained at (50±5)% and temperature is kept at 30℃. Samples are subjected to UV light normally for 1000 h. It is well known that 200 h of test period is equivalent to 1 year of actual outdoor exposure considering only the UV wavelength (300—400 nm) that is mainly related

to the deterioration of polymers[10].

(4) 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 days per week for a period of three weeks. Sample breakdown for chemical and physical decomposition is monitored on a weekly basis.

(5) Thermal test. It is performed by placing the insulator at 100℃ for 600 h in a circulating oven. Any de-shaping or defect caused by heat is observed.

A detailed performance of change of dielectric behavior of composite insulator during the above aging tests can be seen in ref. [11]. After completion of six months of artificial aging, if the product (insulation material) still possesses good electrical performance and low leakage current then it is accepted for general use. If it shows same behavior even after one year it is acceptable for use in extremely polluted environments[2].

These aging tests can be performed individually or collectively as done in multi stress aging chambers discussed later[10,12].

2.2 Rotating wheel dip test

This method performs aging which represents 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. The necessary resting periods for the SiR are also introduced. When a sample exhibits 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. The wheel revolves in 900 steps so that each sample is placed 1 min at each of the four positions shown. In this way it completes one revolution in 4 min. The first position is immersion in saline water, the second is a horizontal de-wetting position allowing the water to drip off as a consequence of hydrophobicity, the third is an energized position in which the 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 a ratio of 1.5 g/L. Copper chloride is added which lowers the chance of algae growth.

2.3 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 have 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 specimen 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 that occurs in service, correlation with experience has been good.

2.4 Long term natural and accelerated aging facilities

2.4.1 KOEBERG natural aging test station. This test station at KIPTS[13] consists of test bays for 11, 22, 33, 66 and 132 kV with control room, environmental monitoring station, pollution monitors and leakage current logger systems. The pollution index at KIPTS is of the order of 2000 μS/cm, which is extremely high.

In this natural aging 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 the results from any other year.

2.4.2 Fog chamber at Okinawa. This was built by Furukawa Electric Co.[14]. This is according to 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 is about 4.4 m^2 by 3.3 m in height. It was designed to investigate the effect of temperature change, humidification, precipitation, and salt exposure and UV irradiation as demanded by IEC 61109. It is also capable of performing accelerated aging tests on the adhesion of the end-fitting and terminal portion of the housing rubber. A steady load of 20 kN could be applied.

2.5 Multi stress environmental aging facilities

The conventional aging tests described above such as the salt fog test, the tracking wheel test, rotating wheel dip test, etc., limit the number of concurrently applied stresses. Using the above tests, the compound effects operating on the insulation system of actual field are not reproduced[7,15]. 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 by humidity, fog or rain.

2.5.1 Coastal environment aging chamber[7]. 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 are 6 ft × 6 ft × 6 ft walk-in Plexiglas cube. Eight 4-feet long UVA-340 lights are used to simulate 1 mW/cm^2 UV radiation, at the wavelength of around 313 nm. Four fog nozzles produce salt fog and clear mist. Two rain nozzles are also provided. A 1450 W heater is used for heating. Cooling is 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).

2.5.2 Full scale insulator aging chamber. This was developed in Japan[8]. 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 aging deterioration by surface discharge do not necessarily show the 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.

2.5.3 Aging test setups developed at Pakistan. A setup was developed to investigate the behavior and performance of polymeric insulators in the extremely polluted and hot areas of Pakistan along with lab aging faculties as shown in Figure 2. The test setups developed were for three different purposes listed below.

A) Setup for natural outdoor aging in clean environment. In this setup a facility for fixing the insulators in open atmosphere at height of about 10 m 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 the 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 μA with time.

Currently the NGK commercial insulators of model numbers E121-SS080-SB, E121-SE090SB, and E121-SE-050-SB have been installed and energized at 10 kV for one and a half years. 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 environment. In this setup the insulators are installed in open atmosphere at height of about 15 m from ground. The insulators of various kinds and sizes can be attached and energized with high voltage from a 1 kVA commercial high voltage transformer. A high voltage insulated cable runs from transformer to the 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 μA.

Currently the NGK commercial insulators of model numbers E121-SS060-SB, E121-SE090SB, and E121-SE-050-SB have been installed and energized at 10 kV for one and a half years. 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.

C) Setup for lab aging tests. The setup developed at university lab comprises of the following facilities: 1) Accelerated UV-aging; 2) ozone resistance test; 3) thermal aging test; 4) multi stress aging; and 5) 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[15].

UV aging chamber is of size 24″ × 24″ × 24″ with six UV lamps each of 20 W to make luminance intensity as prescribed by IEC 61109 Annex C. Temperature controlling system and 10 kV are available for energization.

Multi stress aging chamber has facilities for humidity control, heat, UV light, energization voltage up to 10 kV, salt/fog spray, etc.

A few photographs of the setup are shown in Figure 2.

Figure 2 Photographs of aging test facilities developed by University of Engineering & Technology, Taxila, Pakistan. (a) Lab aging chamber with humidity, temperature and other parameters control; (b) insulator installed in a polluted industrial area of Pakistan during hydrophobicity test; (c) polymeric insulators installed in outdoor environment of Pakistan under natural aging tests since last two years.

3 Effect of various factors on degradation of electrical performance

3.1 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℃ increase in temperature.

3.2 Effect of heavy contamination

Contamination forms a layer on surface which causes a loss of LMW. The LMW is responsible for maintaining good hydrophobicity of surface which in turn resists formation of conducting water tracks. When hydrophobicity is lost the leakage current and arcing activities over the surface of insulator are increased, which degrade its performance[10].

A stiff power source should be used for evaluation of contamination flashover/withstand voltages of hydrophobic polymer insulators, especially under heavily contaminated conditions because failure of power source may occur.

3.3 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 cyclo-aliphatic epoxy system) was found to be better than that of CEP (cyclo-aliphatic epoxy system) and closely comparable to that of LSR (liquid silicon rubber). The findings of this study are consistent with 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 other tested materials[16,17].

3.4 Effect of humidity

It was clearly found that humidity could originate surface discharges, and then could damage silicone rubber housed arrestors. The damage can be detected by measuring leakage current pulse duration and analyzing the pattern of the surface discharge that occurs. Moreover, the discharge pattern can be used to identify damage to the surface condition. Measurement of the 50 Hz total surface leakage current did not provide any significant correlation with surface damage[18].

3.5 Effect of increased conductivity

An increase in conductivity and flow rate of the contaminant causes a speed up in tracking of the silicon rubber insulation material. Brittleness in sheds has also been observed in aging tests continuing in Pakistan.

3.6 Effects of miscellaneous parameters

In general for all polymeric material it is confirmed that the material properties significantly effect the tracking time. The contact angle and the surface roughness of the material vary irrespective of the type of aging. 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 aging 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 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) indicates that the storage modulus of the material increases with the increase in frequency. The variation in the storage modulus of the material with aging 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 multi-resolution 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 increases when surface discharge occurs. Characteristic increase in values at all points is observed in the standard MRA curve with the tracking current[18].

4 Testing, transporting, handling, storing and installing composite insulators

4.1 Handling

Polymer insulators (composite insulators) are lightweight and easy to install. They are flexible and do not chip, crack or shatter like the more brittle glass and ceramic materials.

However, incorrect handling of the units or damage to the moisture seal during transport, storage or installation can precipitate complete mechanical and/or electrical breakdown. A damaged sheath will expose the core to moisture and this will result in brittle failure or tracking of the fiberglass rod during service. Mechanical injury is not easily detectable in polymer insulators and can result in catastrophic failures after installation. Hence, precaution shall be taken at every stage to avoid damage to these insulators[19].

4.1.1 Receipt inspections. On receipt of the insulators at main stores, inspection should be carried out for detecting any damages caused to the sheaths, sheds, end seals and metal fittings during handling and transport. When opening the packing with a knife for inspection, care should be taken to ensure that the insulator sheds are not cut. Any nails, protrusions from inner walls of the case should be eliminated before the insulators are taken out. Damaged insulators should be rejected and replaced. Corona ring surface should be inspected. Damages such as deep scratch and sharp protrusion should be removed to avoid corona discharge[19,20].

4.1.2 Re-packing. When re-packing, the shipping crates in which they are supplied should be used to ensure that there is no loose sitting of the insulators in the crates. On replacement of the lid, it should be ensured that no nails, staples or other sharp objects come in contact with the insulators. Strapped crates should be re-strapped.

4.1.3 Storage. The insulators should be stored indoor and preferably in the cases in which they were supplied. The walls of the cases should be solid to prevent entry of rodents. If insulators have to be uncrated, no additional material should be placed or stored on top of them. They should be stored in a clean and dry area, free of oils or petroleum derivatives.

• Line post insulators. When stacked, care should be taken that the metal ware does not make contact with the housings of adjacent units.

• Long rod insulators. The long rod insulators should be placed in plastic pipes when they are stacked, or hung from suitably designed racks with free swinging hook, tongue or ball attachments as appropriate.

4.2 Transports to site

To the extent possible, the insulators should be transported to site in their original, closed shipping/storage crates. If only part of a crate requires to be delivered, the insulators must never be transported loosely or without adequate protection. Placing of other materials on top of the insulators in transit should be strictly avoided, and the insulators must not be tied down or tied together with chains, ropes, etc. Hardware or heavy tools should not be thrown on top of the insulators.

4.2.1 Site inspection. On arrival at site, the packaging should again be carefully checked. If any signs of breakage or rough treatment are evident, each insulator should be examined for signs of damage. Units of which the core is exposed, or the end sealing has been affected, or sheds damaged, should immediately be rejected and replaced.

4.2.2 Storage[21,22]. The insulators should be kept in their original packing for as long as possible and stored in a dry covered area with the crates raised off the ground. Lids should remain sealed to prevent entrance of rodents.

If the insulators are dirty, they should be cleaned with dry/wet cloth and if necessary, rinsed thoroughly with clean water and then wiped. Solvents of any kind or abrasives should not be used for cleaning of polymer insulators. In severe cases it is very important that the manufacturer be consulted prior to cleaning.

4.2.3 Handling at site[19,23].

• Delivery to point of installation. Proper length crate or cushion should be used for transportation of the insulators to protect insulators from damage.

Damage to insulators at point of installation due to construction activities can be reduced, if their delivery is properly planned, i.e. to occur immediately before they are required and thus not left on the ground for lengthy periods. At the point of installation the insulators should be adequately protected, placed at a sufficient distance from the main areas of activity and their position clearly marked.

• Un-packing at site. Insulators should be removed from containers only when they are ready for installation. When taking the insulators out of the containers, a temporary re-usable packing system should be introduced to provide protection during transport and short-term storage. This temporary packing should be by means of a wrap-on shield over the sheds, with the end fittings only exposed. These wrap-on shields may be left in place until the line construction is complete.

Care should be taken to prevent sharp edges or abrasive materials from coming into contact with the insulator surfaces. The insulators should be laid carefully on the ground over a clean plastic sheet under the specific pole or structure positions. Hardware or heavy tools should not be thrown on or placed on the insulators. Never drag the insulators on the ground and keep them away from possible contaminants and abrasive materials.

4.3 Precautions during installation[21,22]

• Line post insulators. Before attachment of line post insulators to the pole, it should be checked to ensure that it agrees with the structure drawing. Often line posts of lower strength rating are specified for jumper support positions and these must not be used as normal suspension insulators.

Line post insulators should be hoisted by the metal end fittings only. They should be carefully lifted in a horizontal position by two nylon ropes. It should be ensured that no cantilever loads are applied to the insulators as a result of bending in any part of the assembly during installation.

When single steel pole structures are dressed with horizontal line post insulators before being lifted into position, it is important that the pole is supported well above the ground on suitable trestles to avoid any rotation of the pole on lifting. The position of the sling on the pole should be fixed with a pin or locating lug and arranged in such a way that it cannot come into contact with, or apply bending loads, to the insulators.

Under no circumstances it should be attempted to deform the base of the insulator to fit the pole, by over-tightening of the mounting bolts. The bolts should be only tightened to the extent as recommended by the manufacturer.

Under no condition, a line should be thrown over the post insulator to pull other components to the pole top. It should be ensured that the keeper pieces of turn-on clamps are placed in the correct way to suit the conductor type or the conductor plus armor rod diameter.

Proper precaution should be taken during installation such that the hot dip galvanizations of metallic parts i.e. end fittings and base are not damaged. Any damage to galvanization during installation should be repaired as per the recommendation of manufacturer and to the satisfaction of company representative.

• Long rod insulators. When handling long insulators, one person each should lift the insulator at each end fitting, with a third person supporting carefully at the middle portion. The bending angle of each end should be within 30° from the horizontal when carrying the insulators

When lifting the insulators, the rope should be tied only to the end fitting portion. Tying the rope directly to the polymer housing can damage the insulator. Fixtures or rope should not be tied on the installed corona ring.

Climbing, riding or standing on the insulator or the installed corona ring should be strictly avoided. Suitable working platforms should be mounted on the pole or bucket trucks should be used. Care should be taken to avoid the insulators from being struck or stressed by the equipment. The insulators should not be used as anchoring points for tools and safety belts. The insulator has limited torsion and bending strength. Therefore care should be taken to avoid excessive torsion or bending strain on the rods.

4.4 General precautions[19]

Ladders, tools, blocks and other equipment should be prevented from coming into contact with the insulators. Care should be taken on angle suspension poles where pulling equipment is employed in close proximity to the insulator to facilitate conductor attachment.

A locked or loaded insulator should not be twisted during stringing. The installation personnel should not rotate one end of the insulator while the other end is fixed. Care should be taken that no bending loads are applied to the insulators during attachment of the hardware or lifting of the assemblies to the pole top. The lifting line should be attached to the earth-end insulator cap or fitting only. The attachment to the cross arm should be checked so that it is free before any load or weight is applied to the insulator string.

When corona rings are fitted, it should be ensured that these are properly located and the mounting bolts tightened to the manufacturer's recommended torque. A loose ring resting on the insulator can wear through the core. This can result in damage to the fiberglass rod being exposed to moisture and cause the line to drop due to brittle, fracture of the rod.

• Conductor stringing bending or torsional loads.   It is critically important that long rod insulators are not subjected to bending or torsional loads during stringing operations. A proper stringing swivel should be used when tensioning the conductor.

The conductor should be rolled off the drums and carefully handled to avoid the formation of loops and twists which on tensioning apply a torsional stress to the insulator.

For vertical suspension strings, it must be ensured that the insulators are able to swing freely and follow the movement of the running-out blocks without being subjected to any binding stress.

When line posts are used at the suspension positions, jamming of the conductor in the running-out blocks will result in a high, and possibly damaging, longitudinal cantilever load being applied to the insulator. It is thus important that all blocks are checked and serviced before the commencement of stringing.

• Tensioning of conductor.   Tensioning equipment should be attached to the pole itself and the operation undertaken with the strain string left well out of the way.

• Sag adjustments.   If turnbuckles are provided in the assembly for final sag adjustment, the insulator end cap should be held and prevented from rotating while the turnbuckle is tightened or loosened. Under no circumstances the insulator should be allowed to twist.

4.5 Pre-energization checks

Very close inspection[22] should be done by means of high patrol. Checks should be made, including but not limited to, puncture, shed cutting, discoloration, hardware problems and any other mechanical defects. Any insulator found damaged should be marked accordingly and replaced immediately. It should be ensured that only sound insulators are installed on the line during energization.

The insulators should be examined for the following:

(1) Damage to the sheath resulting in exposure of the core. Damage to the end seals where the rod enters the caps. Broken or torn sheds. A split in the sheath, which may reflect a corresponding split in the core caused by severe cantilever or torsional loading.

(2) A misalignment of the clevis and tongue end fittings, which would indicate that the insulator has been subjected to, or is being subjected to, a torsional stress.

(3) Marks on the end caps, which indicate that the insulator may have been subjected to bending, torsional or impact forces.

(4) Severe deflection of line post insulators——the live end horizontally with, or below, the base attachment point——indicating either damage to the core from, for example, overloading during

stringing, or misapplication of the insulator.

(5) Loose bolts, missing split pins, incorrectly applied corona rings, etc.

4.6 Certification

The agency carrying out the installation of the polymer insulators should provide a letter stating that the line has been highly patrolled and all the insulators installed are in sound condition before energization.

5 Methods of analysis

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 FTIR, X-ray photoelectron spectroscopy, energy dispersive X-ray, secondary ion mass spectroscopy, gas chromatography, laser-induced fluorescence spectroscopy, thermal gravimetric analysis, surface inspection by scanning electron microscopy, loss factor measurement, acoustic measurements, electric filed distribution measurements, etc. These will now be discussed.

5.1 Measuring leakage current[24]

Degradation of silicon rubber insulators is mostly caused by flow of leakage current on the surface in contaminated environments and by the erosion resulting from thermal and electrical factors. It is thought that leakage current is the most suitable parameter to evaluate this erosion deterioration. To obtain a clear picture of erosion deterioration by long-term reliability tests, the leakage current is monitored continuously. Place a current transducer in series with insulator at dead end and measure the voltage across it by a precision amplifier and record them manually after a few days period or by a computer after any desired interval. The measurement by a computer involves conversion of analog volt reading to digital and then to RS232 format. This all can be easily done by cheap hardware. The reading is imported to a computer by its ports and saved in some file.

The leakage current activity is very rapidly affected by any change in weather or any other parameter. Even slight humidity changes show effect in change of value of leakage current. That is why it is very frequently used parameter for analysis.

5.2 Hydrophobicity measurement[25]

It is a simple procedure for manually obtaining a collective measure of the hydrophobic properties of insulating surfaces in outdoor environment.

For practical purposes the degree of the water repellency of an insulator surface may be divided into seven hydrophobicity classes (HCs) according to the STRI classification guide[25].

HC1 is the most water repellent class whereas HC7 refers to completely hydrophilic surfaces. The intermediate classes are defined by receding angles of the majority of the droplets and size of wetted areas in each case.

5.2.1 STRI hydrophobicity classification. One of the manual methods for obtaining a measure of hydrophobic properties of surfaces is STRI hydrophobicity classification valid for use in outdoor environment. First, the surface to be studied (50—100 cm^2) is sprayed with water. The obtained drop pattern is observed and attributed to one of the seven hydrophobicity classes. As help, the examiner has a set of reference images of typical wetting patterns representing each HC class.

Disadvantage of the method is that the measure is dependent on human judgment. To deal with this problem digital image analysis is used. In such a procedure, computer software interprets the image, taken by a high resolution digital camera, and makes the examination while increasing its accuracy. To deploy and calibrate the software for this method aged samples can be used or artificial methods like sand blasting can be used, which reduces hydrophobicity to HC7 in short time. Then the images of these samples can be taken and imported to software to calibrate image analysis for the first time.

One thing to consider while spraying for hydrophobicity test is to keep samples at inclinations of 10° to 35° from the horizontal. These inclinations should be chosen as they represent well typical inclinations of insulator surfaces in actual service. In order to make measurements comparable all directions and distances from camera, illumination levels and sample position should also be fixed. To take this factor into account taking a large number of photographs for each HC is a good practice.

Reliability of image analysis by software increases if the images are stored and reviewed at least twice at different times or by different persons.

5.2.2 Sessile drop technique. The hydrophobicity of silicone rubber materials is also measured by measuring contact angles between the material and water drops on its surface. The most commonly used method is the so-called sessile drop technique.

In this technique 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 or a computer with some image analysis software like MATLAB, etc. Addition of more water drops on an already sprayed surface results 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.

There is correlation between tropical weather of natural environment and the contact angle. The pollution accumulates on the surface to result in a contact angle increase due to the higher roughness of the surface. The samples having lower pollution on surface result in lower contact angle[25].

5.3 Fourier transform infrared (IR) spectroscopy

Fourier transform infrared spectroscopy is a material analysis technique, which provides us structural information and compound identification. 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[12,26].

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.

Infrared radiation spans a section of the electromagnetic spectrum having wave numbers from roughly 13000 to 10 cm^{-1}, or wavelengths from 0.78 to 1000 μm[12].

The mechanism of a typical FTIR spectrometer is shown in Figure 3.

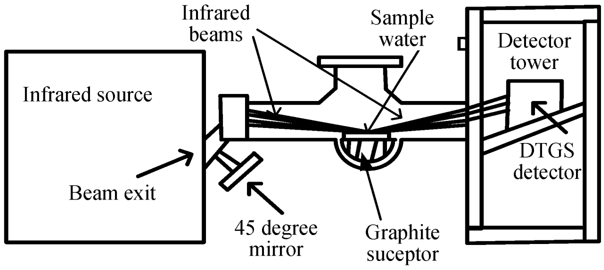

Figure 3 Mechanism of a typical FTIR spectrometer.

5.4 Techniques utilizing X-ray and spectroscopy

5.4.1 X-ray photoelectron spectroscopy (XPS). It is sometimes also called electron spectroscopy for chemical analysis (ESCA), and 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.
5.4.2 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.
5.4.3 Secondary ion mass spectroscopy (SIMS). In this technique the samples are bombarded by neutrons. 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[12].

5.5 Scanning electron microscopy (SEM)

It is used to collect information about the surface topography of silicone rubber materials[27]. 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: stopped electrons which stop upon striking specimen, 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 produced that depicts the details of surface shape and roughness of material up to micro-meter scale. This image can be exported to view at other places like in form of a digital stored image that can be viewed on any computer. Figure 4 shows the SEM micrographs of virgin and aged samples.

5.6 Loss factor (TAN (δ)) measurement[27]

The dielectric loss factor measurement relies on the results of FTIR and is used to interpret the deterioration profile of silicone rubber and EPDM. The more absorption frequencies in FTIR spectrum, the more dielectric loss. Or we can say that reduction in transmittance dictates deterioration.

5.7 Acoustic measurements

Since electrical discharges generate audible noise, this can be detected using a microphone mounted on a parabolic dish, to create a structure like ear, along with a high gain amplifier[28]. Phillips et al. have investigated the possibility of using ultrasonic emission to detect faulty insulators. They performed measurements of frequency and magnitude distributions in laboratory on insulators suffering from artificial defects causing partial discharge activity. It was found that most of the emission occurred in the 15—45 kHz range. The main conclusion of their work was that defects causing serious damages and hence producing reasonable audio noise can only be detected with this method.

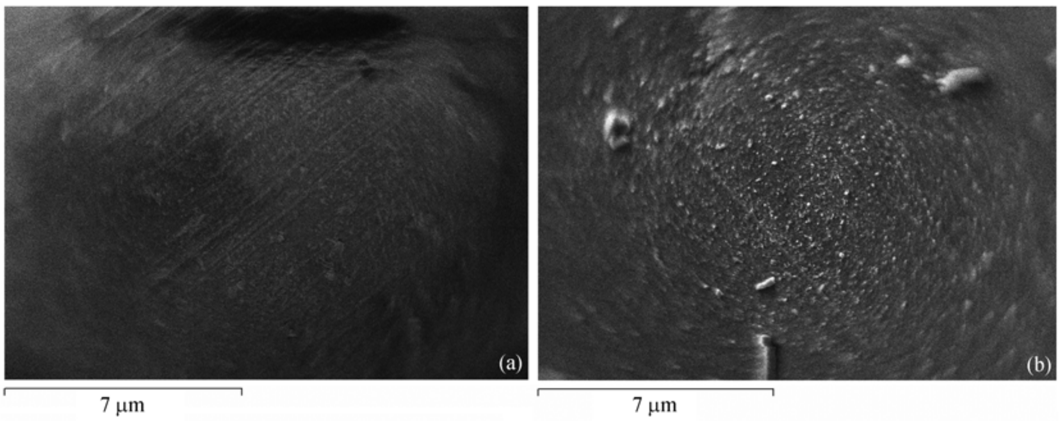

Figure 4 SEM images of a virgin and aged polymeric insulator surface. The line indicated below is 7 micro meter scale. (a) Virgin sample surface of an insulator; (b) 35 days aged under UV sample of an insulator.

5.8 Electric field distribution measurements

Electric field distributions around insulators are effected by conductivity of surface material of insulator and by its geometry. The nature of defects, pollution and humidity level also affect this distribution to some extent. However, the most obvious change in electric field around an insulator occurs due to formation of high leakage current zones and that is why electric field measurements are the best index for diagnosis of electrical degradation[29]. A highly conductive zone lowers the longitudinal electric field strength in its vicinity significantly, just like a short circuit reduces voltage around it to zero.

6 Conclusion

Silicone rubber insulators with known differences in material compositions have been energized in different countries of the world since 1990, under ac and negative dc voltages varying from 10 to 500 kV with sample lengths of both 10 cm to 1 m[30]. Some of them are installed on test setups while a few on actual lines. The electrical performance is the major concern, because mechanical failure is never reported before insulators become electrically useless. In majority of cases electrical performance is quantified by counting the number of peak leakage current values. In addition, visual inspection of the samples for erosion and hydrophobicity are evaluated during the test. Cut samples from these insulators are also analyzed by means of IR-spectroscopy and SEM micrograph.

A ranking of how great an influence the different parameters had on the electrical performance revealed that sample length had a much larger impact than the material formulation[31,32]. The current peak counts have shown that the highest activity had been on the short dc energized samples, followed by decreasing electrical activity: short ac, long dc and finally long ac energized samples. Of the material parameters, the addition of silicone oil had a larger impact on the electrical performance than filler content[33].

Polymer insulators also need care at each and every stage, e.g. from packing to installation and from installation to repairment and maintenance[34]. If the above stated precautions are implemented, the performance would be better than ceramic insulators.

Based on the experiences gained from the tests with material samples, line insulators have been redesigned by some manufacturers and are now ready for contributing market share. But in spite of all these things awareness on their use is still very much limited[35]. The need for following things is specially required:

(1) A free of cost/cheap cost supply of samples of assembled insulators from major manufacturers to consumer countries for testing or trial installation purpose. It is observed that large manufacturers of these insulators are reluctant to supply their products to different universities who intend to test them in their respective countries.

(2) Application wise testing of these new products in every region of the world will promote their use.

(3) Publication of results reported from all over the world on testing/aging of polymeric insulators[36].

1 Reynders J P, Jandrell I R, Reynders S M. Surface aging mechanisms and their relationship to service performance of silicon rubber insulation. In: 10th International Symposium on High Voltage Engineering, London, UK, 22-27 August, 1999. 54－58

2 Gorur R S, Cherney E A, Burnham J T. Outdoor Insulators. Phoenix: Ravi S. Gorur Inc., 1999

3 Phillips A. Ceramic vs. Polymer (Non-Ceramic) Insulators. EPRI. March 2002

4 Hillborg H, Gedde U W. Hydrophobicity recovery of poly dimethyl siloxane after exposure to corona discharges. Polymer, 1998, 39(10): 1991－1998 [DOI]

5 Sharma K. Polymer insulators, available on-line at http://www.aset.ab.ca/pdffiles/article3.pdf

6 Gerdinaud F M, Kurrat B M. State estimate of mineral filled insulators with loss factor measurement. Institute for High Voltage Technology and Electric Power System, Technical University of Braunschweigh, Germany

7 Multistress Aging of Polymeric Insulators in Various Environmental Conditions. www.east.asu.edu/ctas/multistress/Papers/nsf-2-5.pdf

8 Sampe T, Ito A, Hirayama T, et al. Department of Electrical Engineering, Chubu University, Japan. 275 kV full scale outdoor exposure test result of RTV silicon rubber coated polymeric insulator. In: The 8th Korea-Japan Joint Symposium on Electrical Discharge and High Voltage Engineering (2003 K-J Symposium on ED & HVE), Chongqing, China, Nov. 2003

9 Jellinek H H G. Degradation of Vinyl Polymers. New York: Academic Press Inc. Publishers, 1955

10 Sarathi R, Chandrasekar S, Giri V S, et al. Analysis of surface degradation of high density polyethylene material due to tracking. Bull Mater Sci, 2004, 27(3): 251－262[DOI]

11 Kim S H, Cherney E A, Hackam R, et al. Chemical changes at the surface of RTV silicone rubber coatings on insulators during dry-band arcing. IEEE Trans Dielectr Electr Insul, 1994, 1(1): 106－123 [DOI]

12 Sörqvist T. Polymeric outdoor insulators──A long-term study. Ph. D. Thesis. Chalmers University of Technology, Gothenburg Sweden, Technical Report No. 313, 1997

13 Swinny R, Holtzhausen J P. Koeberg insulator pollution test station (KIPTS)──An in house insulator product aging test

standard. W L Vosloo, Division of tsi, and eskom enterprises, Insulator Centre, Po box 222, Brackenfell, 7561, South Africa
14 Kobayashi S, Matsuzaki Y, Masuya H, et al. Development of composite insulators for overhead lines. Furukawa Review, 2000, 19: 129－135
15 Tuncer E, Gubanski S, Lambrecht J, et al. Thermally stimulated depolarization currents of silicone rubbers immersed in water. In: Proc. of IEEE 6th ICSD´98, Västerås, Sweden, 1998. 193－197
16 Kim J, Chaudhury M K, Perz S V, et al. Corona-Discharge-Induced Hydrophobicity Loss and Recovery of Silicones. Austin: IEEE CEIDP, 1999. 703－706
17 Cherney E A, Biglar B, Jayaram S. Salt fog testing of polymer housed surge arrestors. IEEE Power Engin Society (PES) Trans Power Delivery, 2001, 16: 252
18 Kim J, Chaudhury M K, Owen M J. Hydrophobicity loss and recovery of silicone HV insulation. IEEE Trans Dielectr Electr Insul, 1999, 6(5): 695－702[DOI]
19 New EPRI Training Video on Handling Polymer Insulators, 2004
20 Guide to Visual Inspection of NCI-10000998
21 Educational Video Storing, Transporting and Installing Polymer Insulators-1006353, 2000
22 Storing, Transporting and Installing Polymer Insulators. A Practical Guide
23 De T C. Some recommendations on handling of composite insulaters, INMAR Insulator, 2000, Barcelona Spain, 1999, 102－111
24 Matsuoka R, NaitoK, Irie R. Evaluation Methods of Polymer Insulators under Contaminated Conditions. IEEE/PES T and D 2002; Asia Pacific, Yokohama Japan October 6-10-2002
25 STRI. Hydrophobicity Classification Guide, Guide 1, 92/1
26 Grigorias S, Lane T H. Conformational analysis of substituted polysiloxane polymers. In: Zeigler J M, Fearon F W, eds. Silicon-based Polymer Science. ISBN O-8412-1546-4, 1990
27 Kindersberger J, Schütz A, Kärner H C, et al. Service performance, material design and applications of composite insulators with silicone rubber housings. CIGRE, Paper No. 33-303, 1996
28 Application Guide for Transmission Line NCI-TR 111－566
29 Clarson S J, Semlyen J A. Siloxane Polymers. Prentice Hall, 1993
30 Winter H –J. Advanced Materials, Elastomers. CIGRE WG 15-09, Meeting August 19th, 1997
31 Tomas D K. Network scission processes in peroxide cured methylvinyl silicone rubber. Polymer, 1966, 7: 99－105
32 Thomas T H, Kendrick T C. Thermal analysis of polydimethylsiloxanes. Thermal degradation in controlled atompheres. J Polymer Sci, 1969, 7(A-2): 537－549
33 Garbassi F, Morra M, Occhiello E. Polymer Surfaces, from Physics to Technology. New York: John Wiley & Sons, 1998
34 Fleszynski J, Pohl Z, Wankowicz J G, et al. Experience with application of polymeric materials to outdoor high-voltage insulators in Poland. CIGRE, Paper No. 15-301, 1998
35 Dietz H, Kärner H, Müller K H, et al. Latest developments and experience with composite longrod insulators. CIGRE, Paper No. 15-09, 1986
36 Amin M, Amin S. Aging of polymeric insulators. Rev Adv Mater Sci, 2006, 13(2): 93－116