**학회 창립 10주년 기념 논문**

# Status Assessment of Composite Insulators for Outdoor HV Applications

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## Abstract

An attempt has been made to summarize the research and development on the topic of assessing the status of composite Insulators used for outdoor power delivery. Advances made in the evaluation of the electrical performance are discussed. The findings are applicable to other composite insulating systems, as well. Aspects that have been understood well enough to be of practical use, and those needing further research are outlined.

## 1. Introduction

HV outdoor insulators are required to mechanically support the energized conductor and withstand the service voltage. These functions must be accomplished under all conditions during the anticipated life lime of about 30 years or more, and at a reasonable cost. Obviously these are the "ideal" requirements, and practical systems are not ideal. Failure of insulators to perform any of these functions can result in a power interruption. Being able to assess the status of outdoor insulators is essential to determine when and how the devices will fail, so that proper steps can be taken to prevent failure. It is also needed for the development of suitable laboratory tests that can be used for a rapid evaluation of device performance, comparison of different products and creation of improved materials and device designs.

HV outdoor insulators have been traditionally made from inorganic materials, chiefly, porcelain and glass. The use of organic materials, especially, synthetic polymers, for outdoor HV line insulators dates back about 30 years. Such insulators are referred by various names, composite, nonceramic, synthetic, polymeric, etc., with the first two names being more widely used. A combination of factors, such as, similar or better performance than porcelain/glass insulators, light weight, improved resistance to vandalism, easy installation and handling, and competitive pricing has contributed to the widespread use of composite insulators in recent years.

Composite insulators have a central fiberglass core for mechanical strength, an elastomeric covering or weathershed for electrical insulation, and metal hardware. Recently composite systems have made inroads for use in station Applications, such as station posts, switch mounts, apparatus (transformers, circuit breakers) bushings. In North America, composite materials are used extensively for terminations of distribution cables. Material families used widely for weathersheds are silicone rubber, ethylene propylene rubber, cycloaliphatic epoxy and ethylene vinyl acetate.

It is worthwhile to mention at the outset that the service experience of composite insulators has generally been very good. Nevertheless, some problems have occurred periodically, thereby necessitating research and development efforts. Given the wider range in materials and designs that are available with composite insulators as compared to porcelain/glass insulators, and the fact that, unlike porcelain/glass insulators, there is yet no industry standard for insulator selection, a thorough understanding of the various facets that determine composite insulators performance is beneficial.

## 2. The Aging Factor

An important factor that must be considered in the operation of power systems with composite insulators is the possible variance in electrical and mechanical strength with time under the applied stresses, due to the phenomenon of aging. Aging refers to the reduction in performance, and is caused by exposure to a multitude of stresses encountered. Weathering (UV in sunlight, moisture, humidity, temperature, etc.), mechanical loads, and electrical discharges in the form of corona or surface sparking/arcing are among the more important stresses responsible for aging. These stresses also have a synergistic effect that can hasten the degradation.

Inorganic porcelain and glass, have been thought of as inert materials whose properties are time invariant. While this is not entirely true, the conservative design approach used is adequate to ensure acceptable performance in service.

Of the two desired functions of composite insulators. electrical and mechanical, it has been shown that if properly designed and completely protected from nature, the mechanical strength of the fiber glass core will not diminish to be of concern. It has been well established that if the applied stress is below the "damage limit", the glass fibers will not break and there will be no reduction in the mechanical strength [1]. The aspect of concern is the long term electrical performance, which is primarily related to the insulator weathershed and design. Aging of the weathershed material can (1) reduce the ability of the insulator to hold the service voltage as compared to the new insulator, thereby leading to flashover at the service voltage; and (2) cause degradation of the weathershed by tracking (carbonization and/or erosion of the weathershed material. Tracking can cause a flashover, and erosion if significant can lead to exposure of the fiber glass core to the environment, at which point, the insulator could be expected to fail relatively soon.

So there are two aspects, namely, flashover and degradation, that dictate the overall electrical performance. These two aspects may or may not be dependent on each other. Service experience has shown that composite insulator flashovers can occur without significant degradation (tracking or erosion) and in some cases, insulator erosion has occurred without leading to a flashover [2].

## 3. Assessment of Flashover Performance

The flashover voltage with steady state (ac or dc) is lower than the surge flashover voltage, and is further reduced if the insulator surface is contaminated and wet. Therefore, the performance of insulators with power frequency voltage and contamination, i.e., the contamination performance, forms the basis for insulator selection for power transmission. Standard laboratory tests, such as the IEC Salt-Fog and Clean-Fog tests [3], have been developed for evaluating the contamination performance of porcelain/glass insulators.

The Clean-Fog test is the more widely used test. It evaluates the performance of a precontaminated insulator that is gradually wetted uniformly by steam condensation. It has been established for porcelain and glass insulators, that this wetting mode results in the most reduction in the flashover voltage [4] from the clean condition. Insulator design based on this test is thought to be conservative.

The variation of flashover voltage with contamination severity of the insulator is obtained from the Clean-Fog test. Contamination severity is expressed in terms of Equivalent Salt Deposit Density (ESDD) [3], a parameter that is measurable in the field. If the transmission line has already been built, this test can also be used to assess the amount of contamination that is withstood by the insulator without flashing over, i.e., the contamination withstand capability.

Due to the lack of a better test, the IEC Clean fog lest is being used for evaluating contamination performance of composite insulators. This test is also being used on composite insulators removed from service, in order to determine any reduction in the contamination withstand capability due to aging that may have occurred during service. Recent research has shown that assessment of the flashover performance of composite insulators from the clean fog test may not be as straight forward as it is for ceramic insulators.

### 3.1. Role of Insulator Geometry and Wetting Modes:

The spacing between the bells or units in a porcelain/glass suspension insulator string is typically 15 cm. This spacing is usually sufficient to discourage arc bridging the rims of the bells. A majority of composite insulators used currently have the skirts spaced much closer to each other (typically 5 cm). This can lead to arc bridging the skirts in service, but not necessarily in the clean fog test, as the discharges tend to follow the surface of the insulator.

Insulators in service are wetted in several forms such as rain, dew, mist, in addition to fog. Also in service, nonuniform wetting is a distinct possibility owing to weather, insulator shape and dimensions and variations in surface wettability of materials due to aging. It is therefore desirable the evaluation of composite insulators' performance be performed with due consideration to all these factors. A research project was initiated at ASU to study these factors. Composite insulators with variations in geometry and weathershed materials were evaluated in three test procedures. The first was the conventional Clean-Fog lest, the second was a test that ensured non-uniform wetting [5], and the third was a test with artificial rain [6], In each test, the critical contamination ESDD window was established. For ESDD's lower than the first value, no flashovers occurred, and for ESDD's above the second value, flashovers consistently occurred

**Table 1**: Important details of silicone (SR) and Ethylene Propylene (EP) composite insulators evaluated, LD=Leakage distance, SL=Section Length, s=shed spacing, p=shed projection, Q =shed inclination.

| Insulator ID | P (cm) | s (cm) | ∢, 0 | LD (cm) | SL (cm) |
|---|---|---|---|---|---|
| SR1 | 3.4 | 3.5 | 20 | 168 | 67.3 |
| SR2 | 3.8/5.3 | 4.0 | 20 | 165 | 59.0 |
| SR3 | 3.8 | 4.2 | 55 | 180 | 55.0 |
| SR4 | 5.5 | 5.2 | 40/20 | 180 | 64.8 |
| SR5 | 5.0 | 4.7 | 5 | 174 | 59.7 |
| EP1 | 3.4 | 3.5 | 20 | 168 | 67.3 |
| EP2 | 3.8/5.3 | 4.0 | 20 | 165 | 59.0 |
| EP3 | 3.8 | 4.2 | 55 | 180 | 55.0 |

Table 1 lists the relevant details of the insulators. Table 2 lists the critical window. Two important observations from this study are:

(1) The Clean-Fog Test which uses only fog and where the insulator is uniformly contaminated and wetted, does not represent the worst-case scenario. Other tests which induce non-uniform wetting and other forms of wetting, in this case-rain wetting, cause the insulator to flashover at considerably lower levels than obtained by the Clean -Fog method.

(2) The ranking of insulators for a given weathershed material family depends on the geometry of the insulator and test method. Insulator design and selection should consider all these factors.

**Table 2**: Critical Contamination window from different test conditions. NT: Not Tested.

| Insulator ID | Uniform Fog ESDD (mg/cm$^2$) W - F | Uniform Rain ESDD (mg/cm$^2$) W - F | Non-uniform Fog ESDD (mg/cm$^2$) W - F |
|---|---|---|---|
| SR1 | 0.40-0.45 | 0.15-0.18 | NT |
| SR2 | 0.25-0.30 | 0.13-0.18 | 0.15-0.20 |
| SR3 | 0.25-0.30 | 0.20-0.25 | NT |
| SR4 | 0.80-0.90 | 0.18-0.22 | 0.20-0.25 |
| SR5 | 0.25-0.30 | 0.11-0.15 | 0.20-0.25 |
| EP1 | 0.10-0.15 | 0.10-0.15 | 0.03-0.06 |
| EP2 | 0.10-0.15 | 0.08-0.10 | 0.05-0.09 |
| EP3 | 0.08-0.10 | 0.20-0.25 | NT |

## 3.2 Role of Surface Wettability and its Assessment:

Porcelain and glass are high surface energy materials that support a sheet of water on the surface. Organic weathershed materials are inherently low surface energy materials. But, most organic materials easily wet out in the presence of contamination. Materials employing silicone polymers will however resist, for substantial periods of time, the transformation to a wettable or hydrophilic surface even in the presence of contamination.

Flashover of a contaminated insulator occurs when localized dry band arcs propagate over the insulator surface whose resistance has been sufficiently lowered by the presence of moisture and contamination. For low surface energy materials like silicone rubber, the resistance of a contaminated surface can still be high as water tends to remain as droplets rather than as- a sheet on the surface.

The data shown in Table 2 are for insulators that had not visibly recovered their hydrophobicity. For silicone rubber insulators that had recovered their hydrophobicity, as is usually the case in service, the flashover performance was found to be much better than suggested in Table 2. It is therefore suggested to evaluate the flashover performance of silicone rubber composite insulators before and after hydrophobicity recovery in order to obtain the complete range of contamination withstand capability.

Surface hydrophobicity is definitely beneficial to improve the flashover performance. But the loss of hydrophobicity does not indicate an unacceptable flashover performance as insulators can be designed suitably (shape. leakage distance) to retain an adequate contamination withstand capability.

It is interesting to note that for silicone polymers even if the surface is visibly wettable (or hydrophilic), the contamination withstand capability can be higher than that of other insulators (of similar dimensions) with completely wettable surfaces. This is illustrated in Fig. 1 below [7].

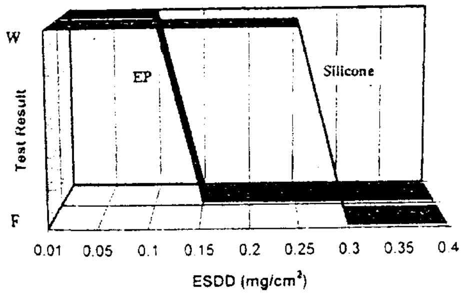

Fig. 1 Contamination Withstand Capability of Silicone Rubber and EP Rubber insulators of identical geometry and wettable surfaces. W=Withstand, F=Flashover.

There are several diagnostic techniques for assessing the hydrophobicity of composite insulation already in service. Some of these are non-destructive and can be performed in the field [8], while others need to be performed in the laboratory on small pieces cut from the insulator.

One laboratory technique for assessing the status of surface hydrophobicity of silicone polymers is X-ray mapping. This technique is performed on a small specimen, roughly 1cm2. An indication of the change in hydrophobicity with aging can be obtained fairly quickly, This technique can also be used to characterize different formulations of silicone rubber for the ability to retain the initial hydrophobic surface and for determining the speed of hydrophobicity recovery [9].

Fig. 2 shows the surface resistance of three materials with same shape and tested under identical experimental conditions. [10]. It is clear that although the ESDD measured on these materials is the same, the surface resistance that determines whether an insulator will flashover or not, is significantly different for the silicone rubber material. Therefore, for composite insulators, there is a need for characterizing contamination severity with a parameter that is more sensitive than ESDD to the true status of the insulator surface.

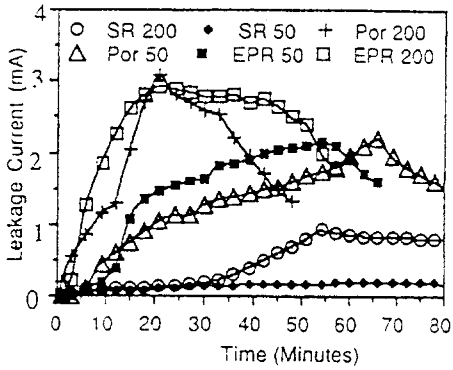

**Fig. 2** Illustration of the effect of material on wet surface resistance at different steam input rates on Silicone (SR), Ethylene Propylene Rubber (EPR) and Porcelain (Por) rods.
ESDD=0.07 rmg/$cm^2$ NSDD=0.1 g/ $cm^2$ for all samples.

From the above, it might appear that surface resistance could be used as an indicator for predicting the performance of composite insulators in service. This method has promise, and is being explored in an IEEE working group.

### 3.3: Role of Test Conditions:

The IEC Clean-Fog test recommends a steam input rate of 0.05 kg/$m^3$/h or 50 g/$m^3$/h for fog generation. This seems to be appropriate for evaluating porcelain and glass as the variation in the flashover voltage with higher steam input rates is marginal, and can be quantified [10]. It has been shown that this value may be adequate for evaluating composite insulators that do not use silicone polymer for the weathersheds. For silicone composite insulators, a higher value is needed. With a value of 50 g/$m^3$/h, the flashover voltages can be extremely high, as the insulator is hardly wetted. With a higher steam input rate, say 200 g/$m^3$/h, the wetting pattern similar to that observed in the field during early morning dew, is obtained. Also there is considerable reduction in the flashover voltage when compared to that obtained with 50 g/ $m^3$/h. Since one of the purpose of laboratory test is to ensure a safe design, the higher value of steam input rate appears to be adequate for evaluating all types of composite insulators.

For conducting the clean fog test, it is necessary that the test object be precontaminated in a manner that is representative of that expected in the field. It is also important that the contamination procedure itself not alter the material characteristics. To satisfy these requirements was a considerable problem. But methods have now been developed recently that have solved these issues [10].

## 4. Assessment of Degradation Performance

It is known that organic materials possess a lower resistance than inorganic porcelain/glass to degradation from surface discharges or corona. Surface discharges are caused by leakage current that is promoted on an insulator when it is covered by an electrolytic layer, typically composed of moisture and contamination. Corona is caused by localized electric field enhancements and can be a problem of increasing severity with higher voltages as the electric field non uniformity increases with insulator length.

What is not known is the intensity and duration of discharges that can be expected in service. This is due to various reasons, such as, the wide range of environmental conditions that exist in nature, and incomplete knowledge of the manner in which different materials respond to the various stresses encountered in service. For these reasons, the most reliable method of assessing the degradation performance is by field trials. But this method is time consuming and may not always be possible. Therefore there is a need to quickly assess the degradation performance in the laboratory, via accelerated aging tests.

Many tests have been developed recently, for quick evaluation of the degradation performance, each with their own advantages and limitations [11]. These tests could also be used for quality control for detecting defects in material formulation, processing or design. However, there is still no reliable method of extrapolating the expected life in service from laboratory data. This is a topic for further research.

A research project was performed to monitor the performance of composite cable terminations in test stations for several years [12]. Electrical parameters and changes in materials that occurred were monitored. This knowledge was valuable to develop laboratory tests that result in similar changes on the device, but in a much shorter time. As a first approximation the ratio of the times in the field and laboratory to produce similar changes was taken as the acceleration factor.

Several diagnostics are available to quantify the aging produced changes in the weathershed material, Infra-Red Spectroscopy, Energy Dispersive X-ray Analysis, X-ray Diffraction, Electron Spectroscopy for Chemical Analysis, are some of the promising techniques. Their use for aging studies is illustrated in several published works [8, 13]. However, more research is needed to determine what level of changes can be tolerated before there is a threat to the device's integrity.

## 5. Summary

A meaningful assessment of the status of composite insulators should include aspects of flashover and aging performance. Analysis of composite insulators is much more complicated than porcelain and glass. Weathershed mater formulations that are presently used vary considerably, and is their response to various stresses encountered in service While standards are needed, a hastily written standard with adequate understanding the important factors that determine electrical performance, and the relationship of t experimental conditions imposed in the tests to reality, c undermine the tremendous advantages that composite insulation systems have to offer. Substantial progress has already been made. But there is a need for a coordinate research effort in order to obtain answers to the important unsolved issues listed in the paper in a timely manner.

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< This paper was also published on Proceedings of 5th ICPADM, pp.35-38, May 25-30 >