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Ghunem, Refat Atef; Tay, Li-Lin

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Measurements of Hydrophobicity for Silicone Rubber Coating on Outdoor Insulators

Speaker: Refat Atef Ghunem
Measurement Science and Standards, National Research Council Canada
1200 Montreal Rd.
Ottawa, ON, K1A 0R6, Canada
Phone: (613) 990-4021, Email: Refat.Ghunem@nrc-cnrc.gc.ca

Authors: Refat Atef Ghunem and Li-Lin Tay
Measurement Science and Standards, National Research Council Canada

Abstract

In this paper condition assessment of silicone rubber coating applied to high voltage insulators is proposed. Electrical, thermal and chemical measurement methods are used to evaluate the condition of silicone rubber coating. From an asset management perspective, hydrophobicity is shown to be the key indicator of aging, and thus the remnant life, of the coating material. The increase in the content of surface oxygen is an indicator of hydrophobicity deterioration under the power system stresses. In addition, detecting the diffusion of the low-molecular-weight siloxane from the bulk to the surface can be utilized to indicate the relative ability to recover hydrophobicity after aging.

1. Introduction

With a recognizable number of the power system components operating close to their nominal life, crucial asset management decisions have to be taken by power utilities, either to "maintain in-service", "refurbish" or even "replace" the aged equipment. This issue is becoming a concern as the remnant life of the power apparatus has not been found to be well correlated with the in service age of the equipment. In addition, in light of the deregulation currently taking place in the electricity grid, a paradigm shift from corrective-based to condition-based maintenance strategies is required for minimization of operational costs, while still maintaining service reliability [1]. Insulation condition assessment has been identified as a key task through which the actual condition of different power system components can be obtained [2]. Such a task can be conducted with indicators of the insulation degradation in the power apparatus extracted using reliable measurements.

Conventional outdoor insulators made from porcelain or toughened glass, although considered as backbone components that can withstand the normal operating stresses in the power system, are prone to electrical failure leading to the interruption of power supply. In particular, the synergistic effects of voltage, moisture and contamination in polluted conditions are conducive to leakage current on the surface of the insulation housing, thereby prompting flashovers. As such, room-temperature vulcanizing (RTV) silicone rubber coating has been commonly utilized in order to maintain in-service insulators. The coated insulators possess hydrophobic surfaces, on which wet contaminants tend to form in a bead-like shape, thereby, providing discontinuous paths for leakage current. Most importantly, when the hydrophobicity is temporarily lost due to continuous wetting, silicone rubber has a unique property of retaining its hydrophobicity [3].

However, with time, the hydrophobicity deteriorates, leaving the insulation housing vulnerable to leakage current formation and eventually failure. It is believed that assessing the hydrophobicity is the key in assessing the condition of silicone rubber coating for high voltage insulators [4]. In this paper a novel measurement framework is proposed for condition assessment of the insulation coating in the power system, based on a mechanistic understanding to the degradation and retention mechanisms of hydrophobicity on silicone rubber.

2. Measurement Methods

Silicone rubber insulators are generally composed of polydimethylsiloxane (PDMS) as the base polymer, inorganic fillers, i.e silica to increase mechanical strength and alumina tri-hydrate (ATH) to enhance the tracking resistance, and coloring additives. PDMS possesses an alternating siloxane backbone bonded with terminal methyl functional groups (Figure 1), providing silicone rubber with an inherited low-surface tension (hydrophobicity).

Corona, dry-band arcing, ultra-violet (UV) radiation and wetting have been shown to be conducive to oxidation of the coatings, raising the oxygen content on the surface through forming silica or hydroxyl groups, reducing the carbon content, and thereby leading to a hydrophilic surface. Low-molecular-weight (LMW) siloxane diffuses from the bulk acting as a coating layer for the aged surface, washing off contaminants and thus recovering the hydrophobicity of the insulation housing [3]. However, depletion of the mobile siloxane occurs, slowing down the diffusion rate and thus the hydrophobicity retention mechanism.

Therefore measurement techniques for surface analysis and evaluation of the hydrophobicity retention are critical for reliable condition assessment of silicone rubber coatings in the power system. In this paper, a comprehensive measurement framework in which electrical, thermal and chemical measurements methods are proposed.

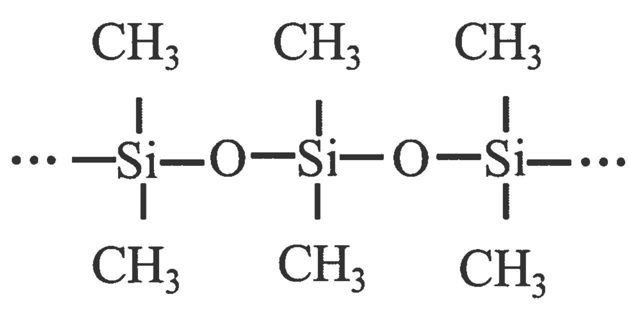

Figure 1. Structure of PDMS

2.1 Electrical Measurements: Dynamic Drop Test (DDT)

Figure 2 shows the basic circuit diagram of the DDT that can be used to evaluate the hydrophobicity retention of silicone rubber. Silicone rubber coating sample is continuously wetted under voltage, utilizing a liquid contaminant. The liquid contaminant constitutes of aqueous solution of sodium chloride with a conductivity of 1.5 mS/cm, and applied at a flow rate of 1mL/min by a peristaltic pump. The sample possesses a dimension of 120 mm×50 mm with a thickness of 6 mm, and mounted on an insulating support using stainless steel electrodes. With a standard 5 cm distance between the electrodes, the hydrophobic surface eventually becomes hydrophilic in a measured amount of time [5]. The relative time-to-hydrophilicity can be accordingly utilized to rank different coating materials or to asses aged samples with respect to a reference coating material.

During the test, the liquid contaminant forms in bead-like shape on the hydrophobic surface; whereas, a continuous channel can be observed on the hydrophilic surface. Measuring 2 mA (rms) leakage current (LC) is the stopping criterion for the DDT as it indicates a hydrophilic surface [5].The applied rms voltage is between 3-6 kV at power frequency [5]. The LC is sampled through shunt resistance using an oscilloscope as a digitizer with a minimum sampling rate of 30720 (512×60) sample/second. Each second a one-waveform window is acquired and post processing is applied to calculate the rms value of the LC, fundamental, third and fifth harmonic components.

The low order harmonics are extracted as potential diagnostic indicators for the degree of hydrophobicity during the test. Low order harmonics of LC have been successfully shown to be indicators of silicone rubber aging during standard accelerated aging conditions [6]. Such indicators, although extracted in laboratory conditions, can be of significant potential when successfully correlated with the actual conditions and the existing field experience.

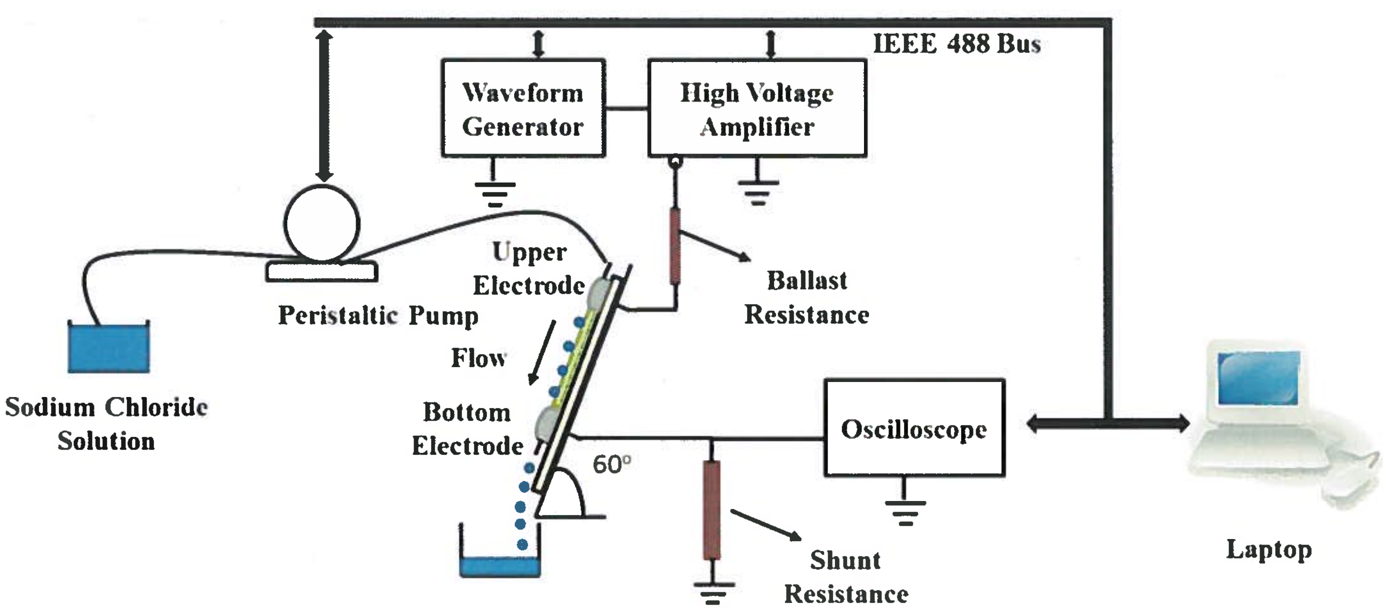

Figure 2. Schematic circuit of the DDT

2.2 Thermal Analysis

Thermal analysis can be utilized to detect and identify the byproducts of oxidation due to corona, partial discharges and wetting on the surface of the coating material. Figure 3 shows an example of the thermogravimetric analysis (TGA) conducted for a silicone rubber insulating material with a surface that has been subject to aging in a 400 kV power transmission system. The TGA was conducted in nitrogen for surface and bulk samples under temperature range between 80 and 800 °C with a 10 °C/min heating rate. The samples weighted around 3 mg and the TGA balance has a sensitivity of 0.1µg. Utilization of a bulk material that has not been subject to the outdoor aging conditions is important in order to develop a reference for the analysis of the surface.

Two decomposition stages can be identified for silicone rubber insulating materials in the TGA, A and B as shown in Figure 3. Stage A starts as approaching 200 °C, the dehydration temperature of the ATH filler, and stage B is initiated as approaching 400 °C, the decomposition temperature of silicone rubber [7]. The remnant residue obtained by the end of stage B mainly constitutes of alumina and silica char due to the dehydration of ATH and decomposition of silicone rubber, respectively.

Although aging of the surface was evident with visual observations, no evidence of erosion was observed. Erosion initiates as hotspots with temperatures exceeding 200 °C develop on the surface under the effect of dry-band arcing, leading to the dehydration of ATH and thus formation of alumina char on the eroded surface. With no evidence of erosion reported for the analyzed samples, obtaining an increase in the residue for the surface as compared to the bulk can be reported as evidence of increase in the silica residue (surface oxygen content) and thus aging [8], (Figure 3). Similarly a comparison can be made between an aged sample in the field and a reference (standard) sample for condition assessment of silicone rubber coating materials of high voltage insulators.

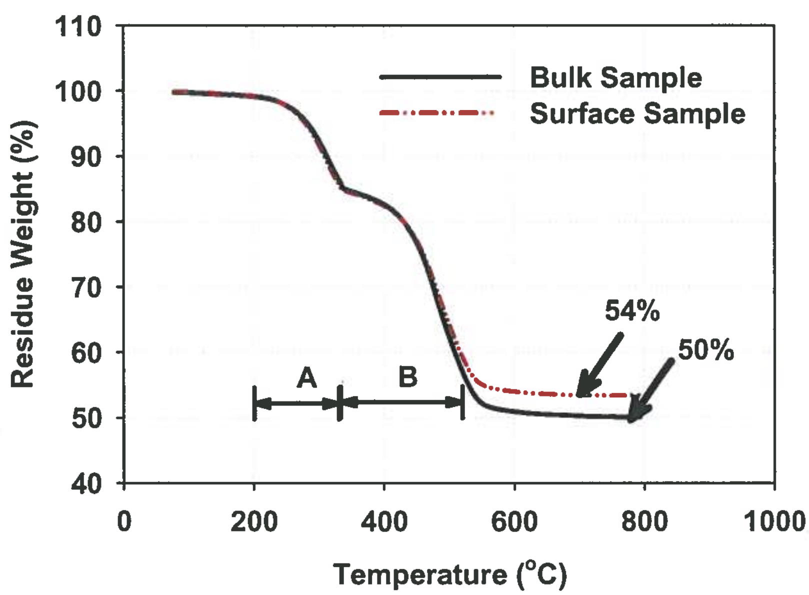

Figure 3. TGA of surface and bulk samples of silicone rurbber insulating material taken from a 400 kV power system.

2.3 Attenuated Total Reflectance (ATR) of Fourier transform infrared (FTIR) spectroscopy

ATR-FTIR measurements are conducted to detect byproducts of aging. Figure 4 depicts a typical ATR-FTIR spectrum of silicone rubber, showing the detection of C-H bond in CH_3 at wavenumber of 2962 cm^{-1} and the Si-O-Si bond at wavenumber between 100 and 1100 cm^{-1}. The relative ratio between the Si-O and C-H bonds for an aged coating material as compared to a reference or un-aged material is indicative in the degree of aging [8].

In addition the evolution of both the $-CH_3$ and Si-O bonds with time can be detected to indicate the diffusion of the LMW siloxane to the surface, thereby evaluating the relative hydrophobicity retention property of different coating materials [9]. In such a measurement, samples are deliberately subjected to pollutants in order to simulate surface pollution condition that stimulates the diffusion mechanism of the siloxane. The main challenge in this task is to apply the pollution under strict conditions in order to maintain a uniform pollution layer with a controlled thickness. This is crucial for calibrated measurements and thus reliable assessment of the coating material. A 20-50 nm layer of thin carbon film representing heavy and severe pollution on the surface is applied through carbon evaporators [9]. Kaolin powder deposited on the surface using electrostatic field generators has bee also utilized as a pollution layer [10].

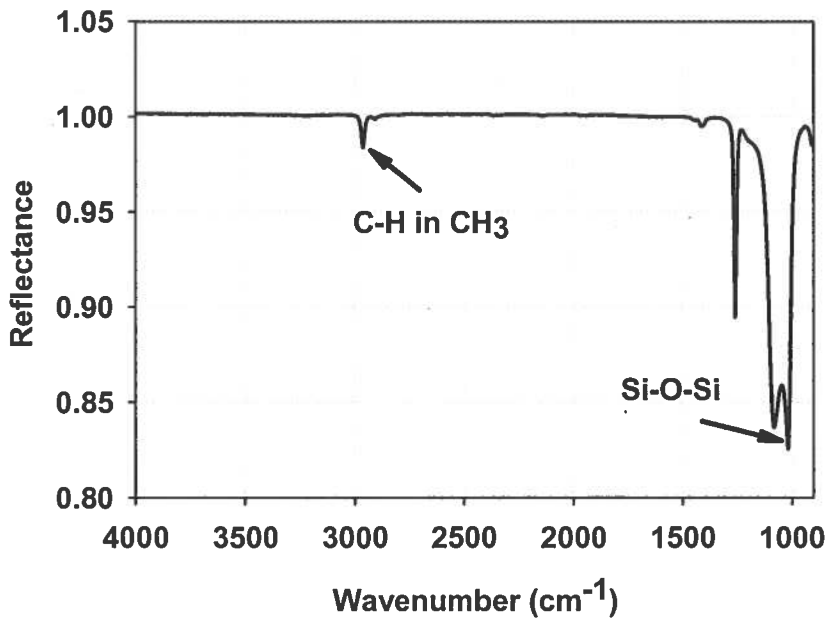

Figure 4. ATR-FTIR Analysis of silicone rubber

3. Conclusions

A novel measurement approach was proposed as an initial step towards the development of a condition assessment technique of silicone rubber coating materials for high voltage insulators in the power system. The approach included the utilization of electrical (DDT), Thermal (TGA) and chemical (ATR-FTIR) methods. The outlined approach provides a relative (rather than absolute) evaluation of the insulation condition of the high voltage outdoor insulators. In the long run, we hope to expand our research into the development of a standard (reference) coating materials for which the measurements can be correlated to the field aging process.

References

1. R. E. Brown and H. L. Willis, "The Economics of Aging Infrastructure," *IEEE Power Energy Mag.,* vol. 4, pp. 36-43, 2006.

2. M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Review of Condition Assessment of Power Transformers in Service," *IEEE Elect. Insul. Mag.*, vol. 18, pp. 12-25, 2002.

3. S. H. Kim, E. A. Cherney, and R. Hackam, "Suppression Mechanism of Leakage Current on RTV Coated Porcelain and Silicone Rubber Insulators," *IEEE Trans. Power Del.*, vol. 6, pp. 1549-1556, 1991.

4. E. A. Cherney, M. Marzinotto, R.S. Gorur, I. Ramirez, S. Li, A. El-Hag, and A. Tzimas, "End-of-Life and Replacement Strategies for RTV Silicone Rubber Coatings," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, pp. 253-261, 2014.

5. WG D1.14, "Evaluation of Dynamic Hydrophobicity Properties of Polymeric Materials for Non-Ceramic Outdoor Insulation", Electra Technical Brocure, 442, pp. 1-46, 2010.

6. A. El-Hag, S. H. Jayaram, and E. A. Cherney, "Fundamental and Low Frequency Harmonic Components of Leakage Current as a Diagnostic Tool to Study Aging of RTV and HTV Silicone Rubber in Salt Fog," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, pp. 128-136, 2003.

7. R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Investigation Into the Eroding Dry-Band Arcing of Filled Silicone Rubber under DC Using Wavelet-Based Multiresolution Analysis," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, pp. 128-136, 2003.

8. H. Cao, D. Yan, J. Han, H. Ren, M. Lu, and Z. Lv, "Investigation and Corroboration of a Novel Method to Estimate the Hydrophobicity of Composite Insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, pp. 713-720, 2014.

9. H. Homma, T. Kuroyagi, K. Lzumi, C. L. Mirley, J. Ronzello, and S. A. Boggs, "Diffusion of Low Molecular Weight Siloxane From Bulk to Surface," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, pp. 370-375, 1999.

10. H. Liu, G. A. Cash, R. D. Sovar, G. A. George, and D. Birtwhistle, "Studies of the Diffusion of Low Molecular Weight Silicone Fluids on Polluted HV Silicone Insulators. I. Use of Diffuse Reflectance FTIR," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 13, pp. 877-884, 1999.