Evaluation of Actual Field Ageing on Room Temperature Vulcanized Silicone Rubber Coating of Ceramic Insulators on 230/63 Substation

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Abstract: Ceramic insulators are used in electrical substation. As outdoor insulators, the ceramic insulators are subjected to environmental stresses. In particular case, the insulators may severe high pollution exposure. Several methods are presently available to improve performance of post insulators under contaminated conditions. Recently, adding of hydrophobic agent on the insulators surface was present to improve the feature of ceramic insulators under polluted condition. The chief concerns with this method are the time of effectiveness of the coating, and insulator performance with time in service. This paper presents investigations on the performance of two different room temperature vulcanized (RTV) silicone rubber coating on the ceramic insulators after 7 and 11 years of field exposure respectively. The characteristics of RTV silicon rubber coated insulator were analyzed, such as, visual inspection, contact angel measurement and material diagnostic technique have been used to detect defective in service RTV Coated silicone rubber insulators. The coating content of some surface regions decreased as degradation increased. Scanning electron microscopy, thermo-gravimetric, attenuated total reflectance, fourier transform infrared spectroscopy analysis and energy dispersive x-ray analysis used to identify the elemental composition of samples. The changes in the surface morphology and material structure were examined before and after the ageing.
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1. Introduction

The reliability of a power system is reduced whenever the flashover strength across an insulator falls below the breakdown strength of the air in its working environment. Contamination caused flashovers are still a major problem. Ceramic insulators are widely used at substations apparatus. (Farzaneh et al, 2009). There are some solutions present to solve the environmental problem on the insulator surface. They are periodic washing of insulators, improvement of insulator design such as Silicon grease coating and coating with hydrophobic compound. RTV silicone rubber coated insulators is a practical option for improving the flashover performance in presence of the pollution without compromising on the mechanical aspects of the substation and transmission design (Suwarno et al, 2009, Devendranath et al, 2002).

RTV silicone rubber coated insulator is a hydrophobic compound system which consists of a base silicone rubber, Aluminia Trihydrate (ATH) or alternative fillers for increased tracking and erosion resistance. Coating life depends to site pollution degree, insulator dimension and coating application. According to IEC 60815, additives can increase life and creepage distance (IEC 60815, 2008). Commercially available RTV insulator coating system typically consist of a base silicone polymer, ATH, or alternative fillers for increased tracking and erosion resistance, a catalyst, reinforcing filler, pigment, and a cross-linking agent. Several systems also contain an adhesion promoter, reinforcing filler, or a pigment. These systems are dispersed in a solvent such as naphtha. The solvent merely acts as a carrier medium to transfer the RTV rubber to the insulator surface. As the solvent evaporates from the surface, moisture from the air triggers vulcanization forming a solid rubber coating (IEEE Std 1523, 2002).

The thermal decomposition of silicone rubber coating can be caused by different chemical processes depending on the environmental conditions, and be related to the hydrolysis of siloxane bonds (Ramirez et al, 2008). Thermo-Gravimetric Analysis (TGA) is a thermal analysis technique used to determine changes in weight of a sample in relation to changes in temperature. The filler and polymer content can be estimated according to the weight loss values at different steps. By analyzing the evolved gas with mass spectrometry, detailed information about the decomposition products can be obtained (Ahmadi-Joneidi et al, 2013).

Small samples (1cm × 1cm) were removed from the high voltage end of each coating and their surface analysis was performed using Scanning Electron Microscope (SEM). The analyses were made in high vacuum mode in order to avoid sample charging. SEM photographs were captured for analyzing surface condition for SiR coated insulators at magnifications of 1000× (Liu, 2005).

Energy Dispersive X-Ray Analysis (EDX) is a very effective surface sensitive technique for the assessment of degradation. It involves rastering (rectangular arrays of cells or pixels, each of which stores a value for the part of the surface) the surface to be studied with monochromatic X-rays which in turn eject electrons from the surface. The energy of these electrons is characteristic of the element from which it comes and varies slightly depending upon the bonding to adjacent elements. EDX technique can be employed to study elemental changes on the surface during ageing processes (Krivda, 2006).

Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectra of the samples have been used to detect bands related to the silicone and filler which provide information on the change in silicone and filler content (Sundararajan et al, 2004).

2. Field ageing and insulator characteristic

Two RTV silicone rubbers coated Insulators were chosen from 63kV-side of a 230/63 kV substation. The content of ATH was approximately 50%. Two Samples used in actual field ageing used for 63 kV substations. The sample one was coated on March 2005 and another insulator (sample 2) was coated on April 2001 under coastal and high humidity site. Insulators were exposed to UV radiation with high temperature, salt and material near the coastal sea. During the years, after 7 and 11 years, insulators were removed on January 2012 to material and electrical test in laboratory. Figure (1) shows the general view of 230/ 63 kV substation. The characteristic of the test sites and insulators are provided in Table (1).

3. Field inspection and Visual observation

Normally, in the operation of substations, maintenance personnel make yard inspections at least once per shift. This inspection is sometimes called a walk around and is nothing more than a visual and audible check as to the service conditions in the yard. After a coating operation and during wet conditions, the first thing that maintenance personnel detect in a switchyard is the near absence of audible noise. The reason for this is the elimination of dry band activity on insulation and a reduction in corona from insulator hardware, both of which are a consequence of the hydrophobicity exhibited by the RTV coating (Jahromi et al, 2004).

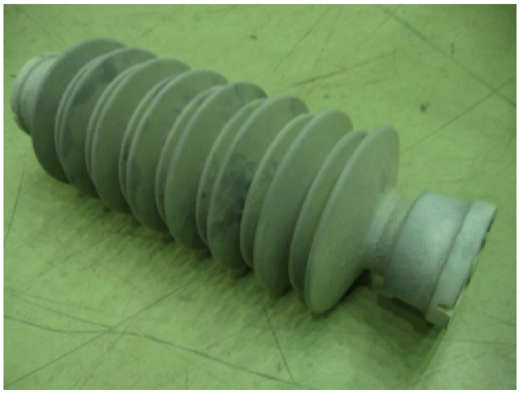
Figure 1. General view of 230/ 63kV substation

Table 1.Characteristics of the test sites and insulators

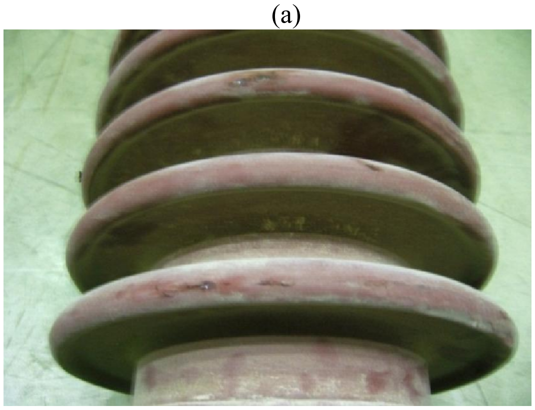
Test Site	Coastal site	
Contamination	Very Heavy	
Weather conditions	Max. Temperature:50 Max. Humidity:95% Ave. Annual rainfall:120mm	
Coating insulator number	Sample 1	Sample 2
Life time Voltage (kV)	7 years 63	11 years 63
Specified mechanical load (kN)	80	80
Arcing distance (mm)	930	930
Creepage distance (mm)	3550	3550
Number of sheds	15	16
Shed diameter (mm)	160/ 130	160
Core diameter (mm)	22	22

An increase in audible noise on insulation during moist conditions is the first sign of a loss of hydrophobicity, at least near the electrodes. When this occurs, it is imperative that a visual check be made. During the close-up visual inspection, if the RTV coating shows either a hard crust-like or soft putty-like appearance, then it will be necessary to take remedial action. The affected coating must be removed and fresh coating reapplied (Elini et al, 2009).

A visual inspection revealed that all the samples presented small cracks and in their polymer sheath, corrosion and oxidation in the end fitting, especially in the live fitting. By looking at the insulators, no significant surface changes were found on the insulators and that was seen that the color of the surface compared to the virgin sample changed. Figure (2) shows the picture of insulator after 7 years and 11 years in service.



(a)



(b)

Figure 2. Visual observation a) after 7 years, b) after 11 years

4. Contact angle measurement

Good outdoor insulators have a strong ability to repel water and pollution from their surfaces. This property is called as hydrophobicity. Hydrophobicity is indicated by its contact angle. Hydrophobic surface has contact angle more than 90° while hydrophilic less than 90°. Also, the contact angle (θ) between the water drops and the surface must be taken into account. The contact angle is defined in Figure (3). There exist two different contact angles, the advancing contact angle (θa) and the receding contact angle (θr). A drop exhibits the angles on an inclined surface (IEEE Std 1523, 2002).

The contact angle of the water droplets was measured after the water droplets were put on the samples. Amount of distilled water was squeezed three times on the surface of insulators. Table (2) shows the contact angles of aged and virgin SiR coated insulator. Comparing angles concludes that the hydrophobicity of the samples after ageing is decrease and the sample 2 has hydrophilic surface after 11 years. The Swedish Transmission Research Institute (STRI) method is applied (STRI Guide, 1992). This method classifies the hydrophobicity of surfaces to seven hydrophobicity Categories, HC1 to HC7. The HC2 refers to the surface of sample 1 while HC3 represents the sample 2.

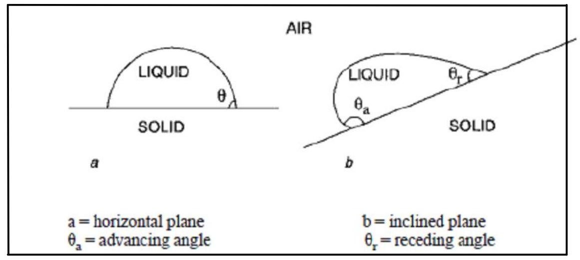


Figure 3. Definition of contact angle

Table 2. Result of contact angle analysis

sample	Contact angle			Average Contact angle
Virgin	119	99	127	115
1	97	102	100	99.6
2	84	63	75.5	74.1

5. Thermo-Gravimetric analysis

The weight loss and rate of weight change in a material, as a function of temperature was recorded for both aged and virgin silicone composites .The temperature is increased from 25 to 600˚C. Figure (4) shows the TGA curve of RTV silicone rubber coated insulator samples. The samples are chosen after separating the coated layers from the insulator surface. It can be observed that increasing temperature up to ~200°C does not affect on samples' weight. Figures show that over 200 ˚C all samples decompose at two stages. The first is due to the conversion of ATH to Al_2O_3. During this reaction, water is released. Also it has been found that evaporation of LMWS species can be started at this stage (Ahmadi-Joneidi et al. 2013).

It can be seen that temperature of First drop in sample 1 and sample 2 are 210˚C and 220˚C. The second weight loss belongs to the degradation of silicone rubber in forms of LMWS, cross-linked silicone elastomer, and silica. It can be observed that temperature of second drop in aged and virgin sample are 290˚C and 300˚C respectively.

First drop in the sample weights is not major and Water started to be detected when the weight loss began at just over 190 ˚C. It ended at the same time when the first weight loss finished. However, the second drop is caused by the break of the side chain (CH3) from the Si backbone (Si-O-Si). At the end, only a non-volatile residue remains. Residual ash in sample 1 was 26% and in sample 2 was 35%.

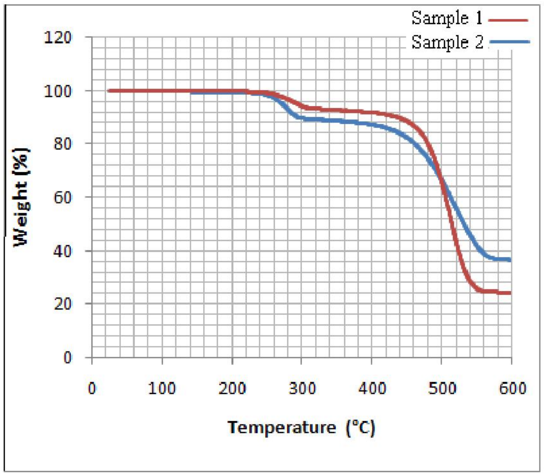


Figure 4. TGA curve for two RTV coating

6. Image Analysis

An analysis of the surfaces using SEM shows the molecular structural changes of the surface of the silicone rubber. The specimen size was 1x1x 0.2 cm^3 approximately.

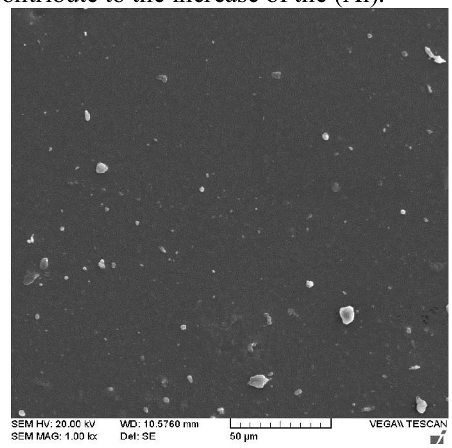
Figure (5) show the micrographs for virgin and aged samples at 1000x. The overall observation is that there is no major degradation, such as cracking; also the sample 1 has a smooth, more homogeneous and less porous surface while the surface roughness and porosity increases with ageing for sample 2 after 11 years.

7. Energy dispersive x-ray

EDX is an x-ray technique used to identify the elemental composition of materials. EDX systems are attachments to SEM instruments. The data generated by EDX analysis consist of spectra showing peaks corresponding to the elements making up the composition of the sample. The EDX survey spectrum of the aged and virgin sample revealed the presence of Oxygen (O), Carbon (C), Silicon (Si) and Aluminum (Al).

A distinct difference between aged and virgin samples is found. An increase in both the (Si) and (O) concentrations is observed for the aged sample compared to the virgin sample and the atomic concentrations of carbon decreased significantly for aged sample (Ehsani et al, 2004).

The results of quantitative analysis of EDX are represented in Table (3). It shows atomic percentage of the elements on the surface of the virgin and aged samples. Also the carbon to silicon(C/Si) and oxygen to carbon (O/C) ratios for sample are given in Table (3). Si-CH3 bonds are broken as a result of ageing and at broken chain. OH bonds are formed and created silanol groups. Therefore it can be proved that surface of the insulators loss their hydrophobic nature and gradually become hydrophilic. There was a decrease in the (C/Si) atomic ratio from virgin sample to aged samples from 5.07 to 4.05 and 2.68. There was an increase in the (O/C) ratio from 0.73 to 0.81 and 0.99 respectively. The exposure of the ATH due to erosion of the polymer in these samples may also contribute to the increase of the (Al).



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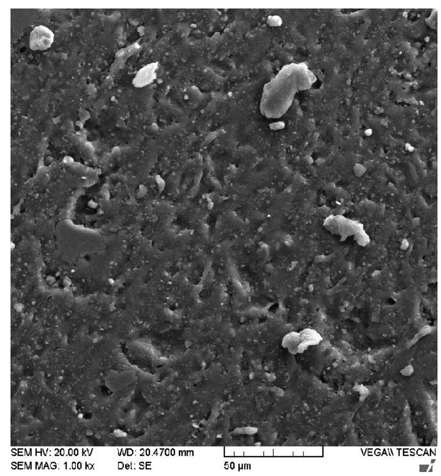

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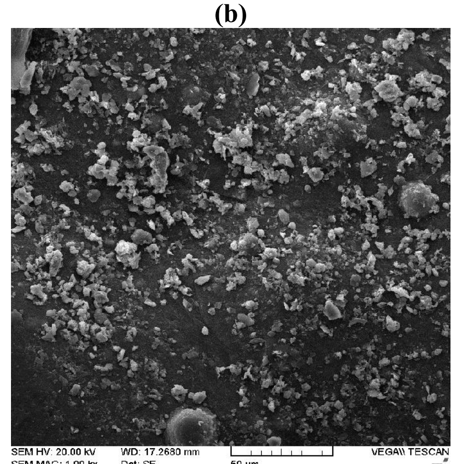

(c)

Figure 5. SEM analysis on the surface of samples, (a) Virgin sample, b) Sample 1, C) Sample 2

On the surface of sample 1, there was a little amount of ATH and a thin layer of silicone covered due to the migration of the LMW silicone. That means that a little aluminum was detected. Aluminum levels of virgin sample, sample 1 and sample 2 were detected on the surface 3.3%, 3.7% and 4.8% respectively. However, due to the non uniform particle size and the heterogeneous nature of ATH, change in aluminum content alone can not be used as a quantitative measure of degradation but provides supplementary evidence that the polymer has degraded.

Table 3. Result of EDX analysis

Atomic percent (%)	C	O	Al	Si	(O/C)	(C/Si)
Virgin sample	49.7	36.3	3.3	9.8	0.73	5.07
Sample 1	46.6	38.1	3.7	11.5	0.81	4.05
Sample 2	40.3	39.9	4.8	15	0.99	2.68

8. **Attenuated total reflectance-Fourier transform infrared**

ATR-FTIR is a tool which has been proven to be useful in chemical analysis on the surface of material. ATR-FTIR spectra of aged and virgin insulator samples were measured. The spectra were recorded for both aged and virgin silicone composites from 500 to 4000 cm^{-1}.

The absorbance at 840- 790 cm^{-1} is characteristic for Si-alkyl group such as Si-$(CH_3)_2$. Absorption occur between 2962- 2920 cm^{-1} due to an aliphatic C-H stretch in CH_3 and between 1270-1255 cm^{-1} due to asymmetric CH_3 deformation of Si-CH_3.Also, the absorbance at 1100-1000 cm^{-1} is due to asymmetric Si-O-Si stretching vibration. The absorption from 3700- 3200 cm^{-1} is due to Hydrogen bonding from ATH.

The size of specimens was approximately (1×1×0.2) cm^3 cut from the last shed on the high voltage end of each insulator. They were cleaned using isopropyl alcohol to remove deposition of pollution layer. When the spectra of the aged and virgin samples are compared, there were no significant changes in the bonding functional groups in the samples, indicating that the functional group change of the insulator samples was not identified by the ATR-FTIR technique employed.

Figures (6-8) show ATR-FTIR transmission spectra as a function of time before and after ageing. The transmission peaks at 3570 and 3670 cm^{-1}(O–H), 2960cm^{-1}(C-H in CH_3), 1260cm^{-1}(Si–CH_3), 1015cm^{-1}(Si-O-Si) and 795cm^{-1}(Si–CH_3)$_2$ correspond to the molecular vibration. As can be seen from these figures, pick of IR spectra of aged insulator samples compared with virgin samples was decreased which means the number of C-H bonds decreases. Pick areas in Si-CH_3 in virgin and aged samples are 85, 81.4 and 79 respectively. Also, Peak areas in Si-O-Si in virgin, sample 1, sample 2 are 202, 176.4 and 167.1 respectively. Increasing of ratio (Si-O-Si/Si-CH3) is an index for ageing. In virgin sample, peak area is 0.42 and with increasing ageing it reached to 0.473. Table (4) shows the result of ATR/FTIR analysis.

Table 4. Result of ATR/FTIR analysis

Sample	Peak area			
	Si-O-Si	Si-CH_3	OH	Si-CH_3 / Si-O-Si
Virgin	202	85	345	0.42
1	176.4	81.4	357.5	0.46
2	167.1	79	362.4	0.473

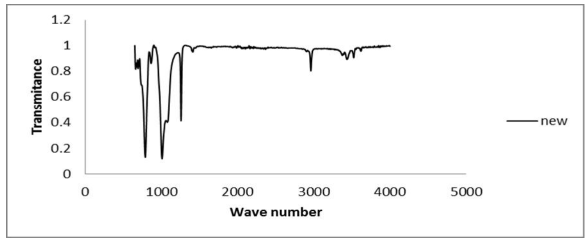

Figure 6. FTIR analysis of Virgin sample

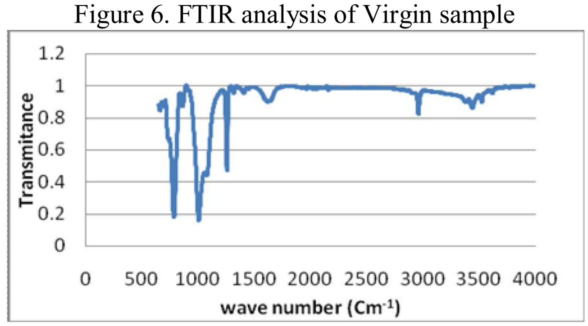

Figure 7. FTIR analysis of sample 1

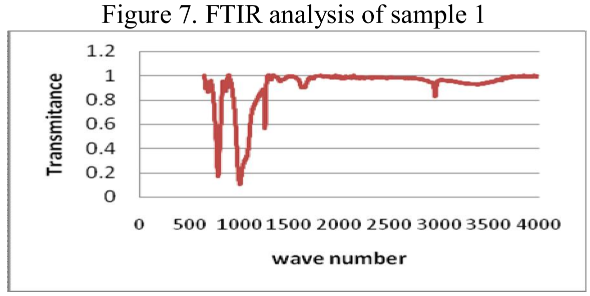

Figure 8. FTIR analysis of sample 2

9. Conclusion

The performance of two room temperature vulcanized (RTV) silicone rubber coating of ceramic insulators in 230/63 kV substation after 7 and 11 years of field exposure under actual field ageing have been investigated. From the ageing results, it was obvious that hydrophobicity and contact angle was decreased with ageing because of formation of carbonyl groups and loss of methyl groups on surface. The aged samples have the highest porosity and roughness of the virgin sample. The hydroxyl and carboxyl groups were formed when Si-CH3 and C-H were broken by ageing. Also, XPS and FTIR-

ATR tests released that the number of methyl groups at the surface of RTV coating is reduced by the treatment.

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