CONDITION ASSESSMENT OF A FIELD-AGED 150 kV HTV SIR SUSPENSION INSULATOR FOLLOWING FLASHOVER

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Abstract: Condition assessment results are presented for a field-aged 150 kV HTV SIR suspension insulator following its flashover due to bird nesting activity. The insulator, equipped with arcing horns, was operated for 10 years in a coastal transmission network under heavy environmental pollution. In order to evaluate flashover effects on insulator housing, several macroscopic and microscopic diagnostic techniques were employed including visual inspection, hydrophobicity classification, Fourier Transform Infrared spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray (EDX) analysis. Arcing affected the morphological structure and elemental composition, thus also hydrophobicity of the housing surface in proximity to arcing horns. The protection offered by the arcing horns together with the synthesis of the insulator housing material resulted in flashover deteriorating effects solely restricted to the upper surface layer of the housing. However, arcing caused excessive damages to the arcing horns. In addition to flashover, ageing and environmental pollution effects were detected on the insulator housing and further analysed.

1 INTRODUCTION

Composite insulators have been increasingly used in overhead transmission lines and substations for the last 20 years. The new generation of composite insulators can provide similar reliability levels to that of ceramic insulators [1, 2]. As a result of material innovative advantages, composite insulators are certainly attractive for utilization, especially under heavy polluted conditions where the traditional porcelain and glass insulators commonly fail.

Several field guides describe the most common faults occurring on composite insulators in service and the appropriate remedy actions, such as monitoring, maintenance and replacement [3 - 6]. Many factors, difficult to be controlled, can cause composite insulator failures in service, including severe weather conditions, bird and rodent's activity as well as vandalism. As these factors are not related to the ageing conditions of composite insulators in service, the associated faults are not possible to be predicted, thus also, avoided.

Condition assessment of composite insulators in service is of great importance for the reliability of the power network. Especially in the case of insulator flashover, utilities have to decide if the flashed insulator should be allowed to continue in service or be urgently replaced. The present study deals with the evaluation of a field-aged 150 kV HTV SIR suspension insulator following its flashover due to bird nesting activity. Macroscopic and microscopic diagnostic techniques, including visual inspection, hydrophobicity classification, FTIR-ATR, SEM and EDX, were employed for assessing flashover effects on the insulator housing. Although the insulator was equipped with arcing horns, flashover arcing affected the morphological structure and elemental composition, thus also, hydrophobicity of the housing surface in proximity to arcing horns.

2 CONDITION ASSESSMENT PROCEDURE

2.1 Characteristics of the evaluated insulator

The investigated HTV SIR suspension insulator was operated for 10 years in the 150 kV overhead line Atherinolakos–Ierapetra of the coastal transmission network of Crete (Fig. 1). It was located close to Ierapetra city, in an agricultural/ suburban area at a distance less than 3 km from the Libyan Sea (35° 1'53.86"N, 25°46'12.36"E).

Figure 1: 150 kV overhead transmission line Atherinolakos – Ierapetra; white arrow denotes the location of the evaluated insulator on the line.

The climate conditions and the pollution mapping of Cretan high voltage network are detailed in [7]. The region around the location of the evaluated insulator can be classified as heavy polluted area according to IEC 60815 [8]. On September 2014 the evaluated insulator experienced flashover, caused by bird nesting activity. According to Hellenic Electricity Distribution Network Operator, HEDNO, the fault was classified as a single phase-to-ground line fault at the tower AΘI99 associated with a short circuit current of 4 kA for 2 seconds. Based on visual inspection in situ, replacement of the flashed suspension insulator was decided.

The evaluated insulator comprises an epoxy & glass fiber rod covered by HTV silicone polymeric housing and hot dip galvanized cast iron fittings. It is important that the insulator was equipped with arcing horns made of hot dip galvanized steel. The electrical and mechanical characteristics of the insulator complied with IEC 383 [9] and IEC 1109 [10], respectively; the fittings were in accordance to IEC 120 [11]. Figure 2 shows a 3D drawing and the basic characteristics of the evaluated insulator.

Housing material	Arcing distance (mm)	Leakage distance (mm)	Number of sheds	Total length (mm)
HTV Silicone	1264	5740	51	1659

Figure 2: 3D drawing and characteristics of the evaluated 150 kV HTV SIR suspension insulator.

2.2 Diagnostic techniques

The procedure for the condition assessment of the insulator combined several diagnostic techniques as shown in Table 2. Specifically, first visual inspection was conducted so as to detect traces of damage and deterioration in all components of the insulator. Second, hydrophobicity classification of the housing surface was determined according to methods A and C of IEC 62073 [12]. Finally, microscopic techniques were applied to several specimens, sampled from different insulator surface areas based on flashover path. Material analysis techniques included Fourier Transform Infrared Analysis–Attenuated Total Reflection (FTIR-ATR), Scanning Electron Microscopy (SEM) and Energy Dispersive X Ray (EDX) spectroscopy.

Table 2: Condition assessment techniques

Diagnostic techniques	Investigated area
Visual inspection (Prior to cleaning)	Metal fittings, polymeric housing, arcing horns
Hydrophobicity Test, Method C (Prior to cleaning)	Polymeric housing
Hydrophobicity Test, Method A (Prior to and after cleaning)	Samples along the polymeric housing
FTIR-ATR, SEM and EDX (Prior to and after cleaning)	Samples from flashed and non-flashed shed areas

Both flashed and non-flashed surface areas of the insulator housing were examined, prior to as well as 24 hours after their cleaning with distilled water (Table 2), in order to evaluate flashover effects; the bulk material of the insulator housing was considered as reference.

3 CONDITION ASSESSMENT RESULTS

3.1 Visual inspection

Visual inspection was performed according to STRI, EPRI and ESCOM guides [3 - 6]. Flashover effects were easily discernible on individual parts of the insulator along its polymeric housing and especially on the metal arcing horns. Focusing on flashover effects on insulator housing (Fig. 3), it was observed that the surface area at the side of arcing horns, especially close to the metal end fittings, was more severely affected than the remaining areas of the housing.

Three regions differing in surface state could be distinguished in the sheds and sheaths over the glass fiber core depending on the severity of flashover effects. According to Fig. 4, over surface area A, the most severely influenced by flashover, a thin white powder layer existed, as a result of burnt polymeric material. In addition, microscopic splits, irregularly spaced and variably intense, were detected, indicating increased surface roughness over area A. In area B neither damage nor pollution accumulation was optically detected. It is most likely that arcing removed the environmental pollution layer without causing surface damage. Area C was the part of insulator housing which remained unaffected by flashover. The surface environmental pollution accumulation was the dominant characteristic of this area.

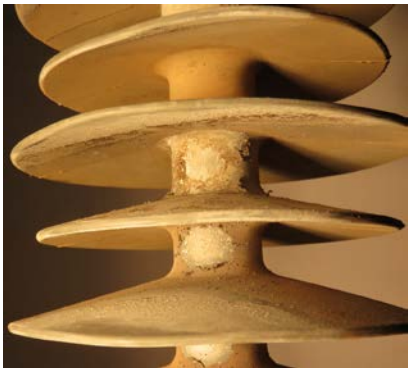

Figure 3: Flashover effects on insulator housing.

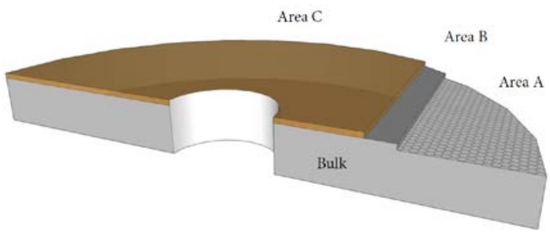

Figure 4: Categories of insulator shed areas following flashover.

Concluding, visual inspection showed that flashover effects on the insulator's polymeric housing were not critical; no intense punctures and splits were detected, most probably due to the protection offered by the arcing horns. However, arcing caused excessive damage to the arcing horns. As evident in Fig. 5, their hemispherical ends were thermally damaged, actually deformed due to melting, and considerably oxidized.

Figure 5: Flashover effects on a 150 kV SIR insulator.

3.2 Hydrophobicity classification

In order to evaluate flashover effects on hydrophobicity of the polymeric insulator housing, hydrophobicity classification measurements were conducted in accordance to IEC 62073 [12]. Methods C (spray test) and A (contact angle measurement) were implemented in both flashed and non-flashed surface areas of the housing.

3.2.1 Spray test

The insulator housing was sprayed with fine water mist, applied from a distance of 25 cm for a time period of 25 seconds. Immediately after, the surface hydrophobicity of the polymeric housing was evaluated on the basis of formation of water droplets or film on the spayed surface.

Spray test measurements showed that the flashed surface areas of the housing at the side of the arcing horns, areas A in subsection 3.1 (Fig. 4), were categorised into hydrophobicity class 1. On the contrary, along the non-flashed areas of the housing a thin surface water film was formed, corresponding to hydrophobicity classes of 4 and 5 (Fig. 6). These results indicate that the flashed areas of the housing were relatively free from environmental pollution accumulation.

Figure 6: Hydrophobicity classification; (left) flashed side and (right) non-flashed side of insulator housing.

3.2.2 Contact angle measurements

Static contact angle measurements were performed by using an optical contact angle and surface tension meter (type CAM 101) prior to and after cleaning the insulator housing specimens. The latter were sampled from the upper, middle and lower parts of the insulator housing both from flashed and non-flashed surface areas.

The contact angle measurements conducted before cleaning showed that specimens sampled from the flashed areas of the housing were more hydrophobic than those from the non-flashed ones (Table 3). In addition, specimens from the upper and lower parts were more hydrophobic than that from the middle part of the insulator housing. It is interesting that after cleaning the contact angle measurements showed a similar hydrophobic behaviour for all specimens (Table 3).

Both spay test and contact angle measurement results indicate that the most hydrophobic surface areas of the insulator housing were those along or adjacent to the arc channel developed, that is, the housing areas in proximity to the arcing horns. Along these areas the environmental pollution layer was completely removed. Arcing could, additionally, cause chain scissioning of the polymer due to the associated excessive heat. The latter has been shown to assist the formation of low molecular weight components, responsible for the dynamic hydrophobic properties of SIR material [13]. Indicative for the existence of low molecular weight components on the flashed surface areas of the housing is the fact that the hydrophobicity of these areas was reduced after their cleaning.

Table 3: Contact angle measurements

Insulator housing area	Prior to cleaning		After cleaning	
	Flashed	Non-flashed	Flashed	Non-flashed
Upper (Ground)	160°	124°	144°	142°
Middle	130°	108°	142°	141°
Lower (High Voltage)	148°	123°	142°	141°

3.3 FTIR-ATR analysis

FTIR analysis was performed to study molecular structural changes in the material bonds of the housing at the surface. A Bruker Vertex 70v FTIR spectrometer equipped with an A225/Q Platinum attenuated total reflection (ATR) integrating sphere with single reflection diamond crystal was employed. FTIR-ATR settings were selected in accordance to CIGRE 595 guide [14]. The penetration depth of the surface layer of the SIR samples was calculated 0.4 μm up to 4 μm for the full range of the excitation wavenumber [15].

The characteristic absorption bands of SIR insulators are shown in Table 4.

Table 4: Characteristic FTIR absorption bands for PDMS [16]

Wavenumber (cm^{-1})	Bond
700	Si- of Si-$(CH_3)_3$
840-790	Si-O of O-Si$(CH_3)_2$-O
855-800	Si-$(CH_3)_2$
870-850	Si-O of O-Si$(CH_3)_3$
1100-1000	Si-O-Si
1270-1255	Si-CH_3
1440-1410	CH in CH_3 (bending)
1640, (1601-1640)	OH in H_2O
2280-2380	CO_2
2962-2960	CH in CH_3 (stretching)
3700-3200	OH from ATH and Si-OH

Fig. 7 shows the characteristic FTIR spectra obtained before cleaning housing samples. it is evident that:

- The absorptions of trihydrate alumina are greatly reduced for both flashed and non-flashed samples as compared to the bulk material (Fig. 7, (i)).
- The absorbance of CH in CH_3 and SiCH_3 of the flashed sample is similar to that of the bulk material, whereas that of the non-flashed sample is greatly reduced (Fig. 7, (ii)). As these methyl groups are related to the hydrophobic properties of SIR, the non-flashed samples show reduced hydrophobic properties, most probably due to pollution deposition.
- An increase in OH bond of H_2O is evident for both flashed and non-flashed samples as compared to the bulk material (Fig. 7, (iii)); this indicates that the solid deposits in the flashed sample and the pollutants on the non-flashed sample were both water absorbing.

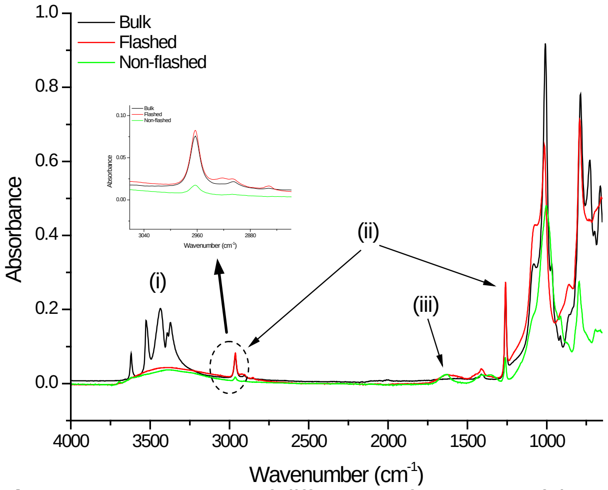

Figure 7: FTIR spectra of different surface areas of the insulator prior to cleaning.

Fig. 8 demonstrates the effects of cleaning of the housing samples on the characteristic FTIR spectra. For the flashed sample a reduction in absorbance for all characteristic wavenumbers is evident after cleaning. For the non-flashed sample

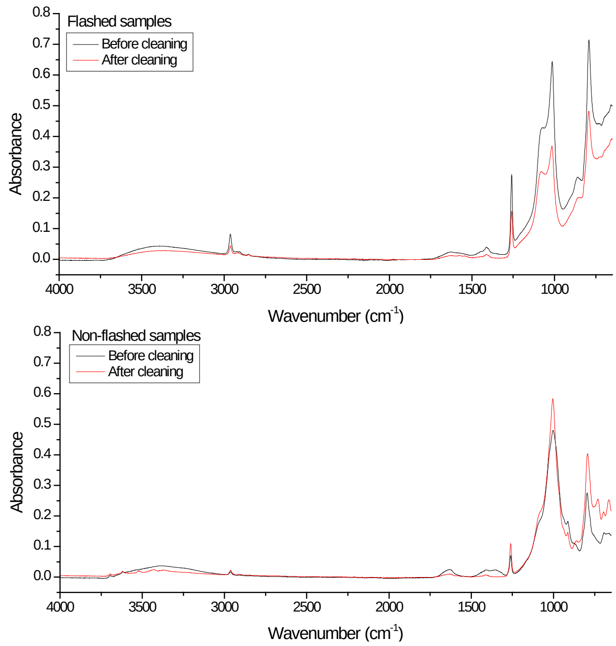

Figure 8: FTIR spectra of flashed and non-flashed insulator samples before and after cleaning.

a relatively reduced absorbance is observed only for bands corresponding to OH vibration from alumina trihydrate and in H_2O, whereas for wavenumbers related to SIR polymer bonds the absorbance is enhanced.

In an effort to further evaluate the hydrophobic properties of the housing samples, the ratio of the integral areas of the CH and SiCH_3 to Si-O-Si were calculated based on the FTIR absorbance spectra [17, 18]. According to Table 5, showing results obtained before cleaning, the higher values of the ratios for the flashed than non-flashed sample indicate a better hydrophobicity for the former.

Table 5: FTIR integral areas and ratios

Sample	Integral area			Ratio	
	Si-O-Si	SiCH_3	CH	SiCH_3/ Si-O-Si	CH/ Si-O-Si
Bulk	17.59	3.19	1.08	0.18	0.06
Flashed	11.07	3.10	1.08	0.28	0.10
Non-flashed	6.81	0.90	0.19	0.13	0.03

FTIR analysis results of the examined housing samples can be interpreted based on ageing, pollution and flashover effects on the structural changes of the surface material. The reduction in absorbance in all wavenumbers, especially those of SIR polymer bonds, for the surface samples as compared to the bulk material (Fig. 7) clearly indicates ageing effects. The higher absorbance of OH bond from H_2O for the surface samples than the bulk material (Fig. 7, (iii)), reduced after cleaning (Fig. 8), is associated with water absorbing pollutants. The removal of the latter from the non-flashed sample resulted in increased absorbance for wavenumbers related to SIR polymer bonds (Fig. 8).

Flashover affected considerably the characteristic FTIR spectra of the housing surface material. The highest absorbance was observed for the flashed sample for the wavenumber band of 840-790 cm^{-1}, related to Si-O of O-Si$(CH_3)_2$-O, whereas for the non-flashed sample and bulk material for the wavenumber band of 1000-1100 cm^{-1} associated with Si-O-Si backbone chain (Figs. 7 and 8). The fact that the absorbance of CH in CH_3 and $SiCH_3$ for the flashed sample is similar to that observed for the bulk material (Fig. 7, (ii)) and significantly higher than that for the non-flashed sample (Fig. 8) indicates that arcing removed the surface pollution layer. This is substantiated by the findings of Table 5 and those of subsection 3.2, especially when considering that these methyl groups are related to the hydrophobic properties of SIR.

3.4 SEM – EDX analysis

Scanning Electron Microscopy was implemented in order to investigate the morphological changes in the surface of the insulator housing after flashover. Prior to investigation the samples were sputtered with gold ~10 nm in thickness. The examination of the flashed area showed that the damage due to arcing was limited to the upper surface layers, up to a depth of 50 μm (Fig. 9) significantly smaller than the thickness of the housing. On the non-flashed surface area environmental pollution deposition was detected (Fig. 10). Sodium chloride salt (NaCl) pollutants were transferred on the insulator housing by strong marine winds.

EDX analysis was performed by using a JEOL 6390 scanning electron microscope equipped with an INCA X-Act detector at 20 kV. Excitation depth was estimated approximately 6 μm [19]. Table 6 summarizes elemental compositions of different insulator housing areas. Obviously, there is an absence of non-structural elements related to environmental pollution for the flashed surface area. Also, for the latter similar concentrations of structural elements were measured before and after cleaning. These results confirm that arcing

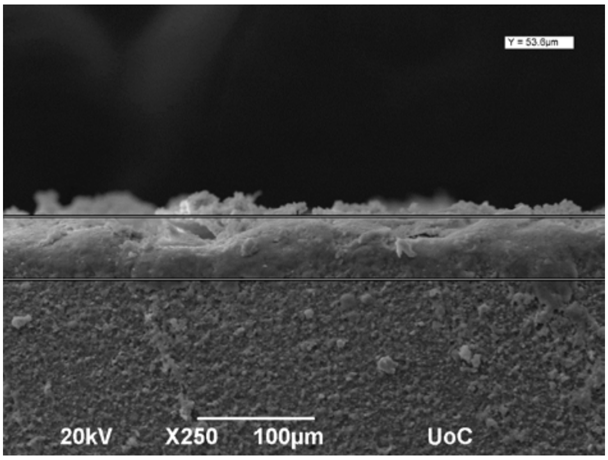

Figure 9: Cross section of a flashed surface area of the insulator housing (SEM image).

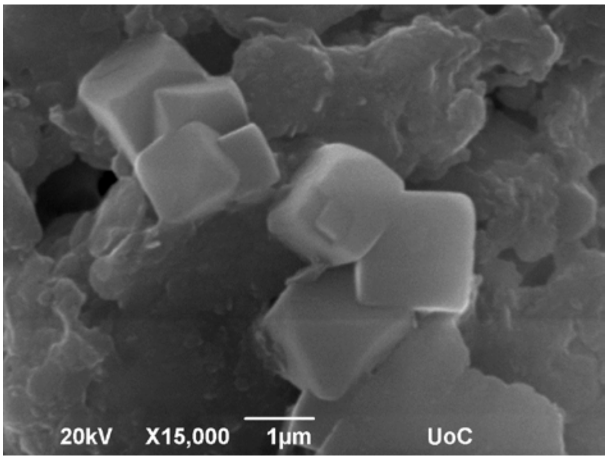

Figure 10: Salt (NaCl) deposited on non-flashed surface area of the insulator housing (SEM image).

Table 6: Elemental composition of different insulator housing areas (EDX analysis results)

	Area	Elements (%)									
		C	O	Al	Si	Na	Cl	Mg	K	Fe	Ca
	Bulk	20.3	56.7	12.2	10.9	-	-	-	-	-	-
Before cleaning	Flashed	20.3	52.8	17.2	9.7	-	-	-	-	-	-
	Non-flashed	2.1	61.1	5.1	24.2	1.2	1.1	1.6	1.1	1.4	0.8
After cleanin	Flashed	19.7	49.9	19.1	11.4	-	-	-	-	-	-
	Non-flashed	19.6	49.8	5.9	20.2	-	-	-	-	-	-

removed the surface pollution layer. However, due to the excessive heat involved with arcing, the concentration of Al was measured higher for the flashed area than the bulk material.

5 CONCLUSION

Condition assessment of a field-aged 150 kV HTV SIR suspension insulator following its flashover has been made, through macroscopic and microscopic diagnostic techniques, including visual inspection, hydrophobicity classification, FTIR-ATR, SEM and EDX. Both flashed and non-flashed insulator housing areas, before and after cleaning, as well as bulk material were evaluated.

Visual inspection showed that arcing caused excessive damage to the arcing horns but non-critical effects on insulator housing. Three regions differing in surface state could be distinguished in the sheds and sheaths depending on the severity of flashover effects. The insulator was heavily polluted; however, hydrophobicity measurements showed a superior performance for the flashed areas of the housing. It appears that arcing removed the environmental pollution layer from the flashed surface areas and assisted to the formation of low molecular weight components.

Ageing, environmental pollution and flashover effects on housing surface were detected through FTIR-ATR, SEM and EDX techniques. Flashover affected considerably the characteristic FTIR spectra of the housing surface material; arcing affects more the bonds related to the Si-O-Si chain than those of methyl groups. The damage due to arcing was limited to the upper surface layers, up to a depth of 50 μm. The concentration of Al was measured higher for the flashed area than the bulk material.

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