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Surface Analysis of Asymmetrically Aged 400 kV Silicone Rubber Composite Insulators

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ABSTRACT

Surface analysis of 400 kV silicone rubber composite insulators is presented. These insulators have experienced 15 years of service on a coastal 400 kV transmission line. Inspection of the insulators shows low levels of degradation through cracking and oxidation of the surface. This has been quantified by microscopy, energy dispersive X-ray analysis (EDX), Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy. The analysis shows non-uniform ageing over each shed and ageing on the south side more advanced than on the north side. It is believed that non-uniform ageing was due to environmental factors including natural UV radiation and prevailing wind direction, and the resultant pattern of growth of organic species. EDX and FTIR were found to be the most useful and effective tools for analysis of these polymeric insulators.

Index Terms — silicone rubber, composite, insulators, material analysis, ageing, transmission line, NCI.

1 INTRODUCTION

SILICONE rubber (SiR) polymeric insulators have found increased usage around the world. They have advantages over ceramic insulators due to their unique hydrophobicity, lightweight structure and easy installation. In service however, polymeric insulators suffer degradation from environmental factors such as UV radiation and surface corona activity. These factors may change the surface properties and reduce hydrophobicity on the surface. As a result, higher leakage currents may flow through water and other deposits on these aged surfaces. With evaporation of the water and enhanced electric fields, dry-band arcs may form, further ageing the surfaces and leading to a deteriorating situation. In extreme cases, flashover may result [1]. From the perspective of system operation, it would be very useful to be able to assess the extent of degradation of installed SiR insulators and, therefore, to be able to predict remaining service life or insulation failure likelihood. To meet this aim, surface degradation requires detailed investigation.

There are various constituents of silicone rubber compounds. The typical structure of silicone rubber contains a repeating silicone-oxygen (Si-O) backbone and two methyl groups (CH₃) for every one silicon atom. The methyl groups play a key role in maintaining the highly hydrophobic surface

[2]. When the surfaces are aged due to environmental stress resulting from electrical and thermal activity, methyl groups are oxidized into O-H groups which are hydrophilic in nature. At the same time, the scission and ablation of polymer chains by electrical energy from corona and arcing produces layers of residues composed of hydrophilic substances such as SiO₂ and SiC that are dependent on the discharge temperature [3]. On heating above 200 °C through discharge activity, the filler alumina trihydrate (ATH) also decomposes in a reaction to produce a residue of alumina [2].

Techniques have previously been explored for monitoring and quantifying degradation on SiR and EPDM, the most frequently used material for high voltage application. Scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) provide information on the chemical elements within the aged surfaces [4-7]. In silicones the change of the proportion of the elements can provide quantitative information about the extent of degradation [8]. FTIR generates an absorption spectrum of the sample surface. For example an absorption peak corresponding to wave number 1270-1255 cm⁻¹ is related to the Si-CH₃ group. The peaks corresponding to 1100-1000 cm⁻¹ and 840-790 cm⁻¹ are associated with the Si-O-Si group and the Si-(CH₃)₂ groups respectively. Peaks corresponding to wave numbers 3700-3200 cm⁻¹ and 1640 cm⁻¹ are related to hydroxyl groups [3]. In practice Raman spectroscopy gives similar information to

FTIR, but the selection rules are different. The bands due to silicone (490 cm^{-1}), ATH (537 cm^{-1} , 567 cm^{-1}) and hydrophilic groups (520 cm^{-1}) are studied in this paper.

The majority of ageing measurements reported previously have been made on laboratory aged samples under controlled conditions. In addition to the chemical approach outlined above more empirical measurements such as hydrophobicity and leakage currents are often preferred, giving a more direct measure of performance. This is particularly the case for silicone composites since their hydrophobicity is key to their enduring performance [9] and in particular their ability to prevent formation of dry-band arcs and flashover [10].

Previous studies on service-aged high voltage composite insulators have been for a limited time period and so often show only slight degradation [11]. Such studies are dependant upon the material of the insulator, so that experience with EPDM cannot be directly overlaid onto silicone rubber for example. Some of the more detailed and longer service ageing periods are reported by Sundararajan et al [5] who give a detailed account of EPDM ageing after 5 years in service, Liu et al [4] providing a detailed analysis of silicone rubber after an undisclosed period and Gubanski et al [9] and Shaowu [12] reporting hydrophobicity tests on a range of service aged insulators after service times of up to 10 years.

One issue found in service conditions not seen in standard accelerated testing concerns organic growth on the surface of an insulator. This has been widely reported after longer term testing in the natural environment [13].

Recently eighteen 400 kV SiR polymeric insulators were decommissioned during a routine refurbishment after 15 years of service. This has provided an opportunity to extend knowledge of longer term service ageing in one particular situation. This paper describes the ageing as determined by visual observation and the results of material analysis using the surface analysis techniques of SEM, EDX, Fourier transform infrared spectroscopy (FTIR), and Raman spectroscopy. The measurements taken have been over more regions of the surface area than has been reported before, allowing comparisons of the different insulator surfaces.

2 THE INSULATORS AND THEIR LOCATION

The insulators studied were deployed approximately 10 miles from the Plymouth coast, in the south of England, on suspension towers along a 400 kV twin-circuit line. This line extends from the National Grid's Laundulph substation, and follows the profile of a river valley. The line lies approximately 50° N , 5° W . The south side of the insulators are exposed to the sunshine. The monthly average wind speed is fairly uniform throughout the year at around 12 knots, predominantly from the South West (and the Atlantic Ocean). The greatest wind speeds are seen from the Atlantic. Detailed climate conditions are given elsewhere [14].

The composite insulator consists of a pultruded glass-reinforced polymeric core, which is covered with an extruded silicone rubber sheath which is then co-vulcanized with 72 identical silicone rubber sheds. The core is rated with a tensile strength of 120 kN. The ends of the insulators are terminated

with forged steel end fittings, which have been crimped to the pultrusion and sealed from the environment. The sheds consist of a proprietary silicone rubber filled with a high level of ATH. The core is sheathed with an identical polymer, but with a reduced level of ATH.

To investigate the degradation around the sheds, samples were cut from typical locations as shown in Figure 1. The samples were taken from the mid-section of each string. The samples studied are compared directly to the bulk material, 1 mm under the surface, at the sheath and the sheds.

Sample surfaces were gold coated and examined using a Topcon SM-300 SEM at 15 kV. EDX analysis was undertaken using a Hitachi SM-2000 at 15 kV. The penetration beam depth into the sample is about $3\text{ }\mu\text{m}$. The sample size was approximately $10\text{ mm} \times 10\text{ mm} \times 5\text{ mm}$. FTIR analysis was undertaken by a Nicplan spectrometer with a Nicolet IR detector. The spectrum was obtained from the integration of 100 scans, and the resolution of the spectrometer is 5 cm^{-1} . A Renishaw Raman spectrometer was used to collect the Raman spectra. This system used a Spectra Physics 633 nm Helium Neon Laser which delivers 10 mW to the sample. The laser was used in un-attenuated mode and was focused using a $50\times$ objective, giving a spatial resolution of approximately $2\text{ }\mu\text{m}$.

3 RESULTS

3.1 VISUAL OBSERVATIONS

Visual observation showed that the shed sides facing the south (locations A and C) had lost their original blue color and become pale. Some edges of the bottom surfaces of sheds also presented white rings on some insulators. These are visible on the underside of the right-hand side of the top-most shed in Figure 1. The sides of sheds facing north (locations B and D) had a higher degree of contamination accumulation on the sheds and were dark in color. The dark surface deposits had a green hue and appear to be associated with algae growth. The bottom surfaces of sheds showed varied degrees of visible contamination accumulation. The insulator core (locations E and F in Figure 1) did not show discoloration, but there were signs of white residue being present. There was some variation between the insulators examined, but in the centres of the strings all showed the features typified by Figure 1.

Previously it has been reported that when these insulators were removed from service there was clear difference in hydrophobicity from the north to the south sides [14]. Visual observations on site revealed the discolored material on the south-facing side to be hydrophilic with a contact angle of less than 90 degrees and sheens of water forming, whereas the material with brown or green deposits on the north facing side was found to be more hydrophobic with a greater contact angle and water readily forming droplets.

3.2 SEM

The surface topographies of the samples were examined by SEM. Typical images of the surfaces A to F identified in Figure 1 are shown in Figures 2 to 7. No cleaning was performed before imaging. No severe cracking or erosion was

Surface	North facing	South facing
Top of shed	B	A
Bottom of shed	D	C
Core	F	E

Figure 1. Illustration of test sample locations.

identified anywhere on these insulators, and they looked in general to be in ‘good health’.

SEM images provide a qualitative estimate of the type and extent of degradation. It can be seen that the top surface on the south side of the shed had some small cracks and was clear of debris. The top surface on the north side of the shed is dark and rougher due to contaminant deposit and algae growth. The bottom surfaces show a range of surface deposits with the north showing the greatest density. The surfaces on the south side of the core had become porous and showed some rough residues more obvious at greater magnification. The surfaces of the core showed slight degradation.

3.3 EDX

EDX results are shown in Table 1. Data given is an average of four measurements within 5mm on the same sample. The standard deviation (S.D.) of oxygen percentage is given to be indicative of variation between sample locations. As a ‘norm’ against which to identify surface changes, data is presented from freshly exposed material from the centre (bulk) of the material. No surfaces have been artificially cleaned before measurement. The aluminum percentage in the core bulk material shows a lower value than the shed bulk material as expected, however a quantified value less than half is

Figure 2. Top surface of shed on the south side, location A.

Figure 5. Bottom surface of shed on the north side, location D.

Figure 3. Top surface of shed on the north side, location B.

Figure 6. Core surface on the south side, location E.

Figure 4: Bottom surface of shed on the south side, location C.

Figure 7. Core surface on the north side, location F.

unexpectedly low. All aged surfaces examined showed various degrees of increased oxygen levels. In all the aged surfaces, the oxygen percentage increased and the carbon percentage decreased compared with the bulk samples. Samples with a higher percentage of oxygen have a lower percentage of carbon. Samples with a higher percentage of silicon have a lower percentage of aluminum. Their relationships can be expressed as the O/C and Al/Si atomic ratio and the results are given in Figure 8.

Locations A and C (south side) had the highest O/C ratio at 1.4 and 1.3, indicating the level of the oxygen present on the surface is a useful indicator for the extent of degradation. The degradation may be partially due to the exposure to the sunshine on the south side. The Al/Si atomic ratios on samples E and F (the core region) were lower than those of the sheds. In particular virtually no aluminium was detected on the south side of the core. The Al/Si ratio is unchanged from the new state on the south side of the sheds.

Table 1. Results of EDX chemical analysis.

Sample	Shed Bulk	A	B	C	D	Core Bulk	E	F
Atom%								
C	38	34	43	34	38	54	44	49
O	38	46	40	44	39	34	37	35
Al	8	7	3	6	5	3	0	3
Si	14	12	13	14	16	9	18	12
S.D. of O	3.1	2.4	2.1	2.2	2.9	2.8	2.9	3.3

Figure 8. Atomic ratios at different locations from EDX.

3.4 FTIR

The FTIR results obtained from the aged, uncleaned samples are shown in Figure 9 and Table 2. These are the average of 4 measurements. After the samples were aged, it is seen that the polymeric groups corresponding to 1270-1255, 1100-1000 and 840-790 cm^{-1} were reduced. The reduction is greatest on the south and top sides of sheds (A, B, C and E) than other areas. The hydrophilic peaks corresponding to wave number 3700-3200 cm^{-1} increased slightly on all surfaces, but particularly the top and south sides of the insulator.

The polymeric bond intensities can be normalized as a ratio to the hydrophilic hydroxyl-bond peak height, providing quantitative information about the extent of degradation. The ratios are given in Table 3. Care must be taken in interpretation of the OH peak data since the response from that bond in ATH and the polymer are in the same band. It is likely that the peak in new material is due to ATH. In polymer which

has seen discharges, ATH will be degraded to form alumina, and OH peaks are due to oxidation of the polymer. Any increase in such peaks is due to polymeric oxidation. Samples A and C (south side of sheds) had lowest ratios indicating that the methyl groups were oxidized into O-H groups in these regions. The ratios of molecular group FTIR peaks between aged and virgin material are shown in Figure 10. The amplitudes have been normalized to unity for the bulk material. Comparing the north and south sides of the insulation (that is B to A, D to C and F to E) the south side is always more damaged. In particular, on the south side the $\text{Si}(\text{CH}_3)_2$ peak was reduced to the lowest level of 0.2. The values on the north side maintained relatively high values of about 0.8.

Table 2. Results of FTIR analysis.

wave no. (cm^{-1})	Bond	Bulk (shed/core)	A	B	C	D	E	F
3700-3200	OH	0.1	0.3	0.3	0.3	0.1	0.2	0.2
1270-1255	Si-CH ₃	0.4	0.2	0.3	0.2	0.3	0.3	0.3
1100-1000	Si-O-Si	1.1	0.5	0.6	0.6	1.0	0.7	1.1
840-790	Si(CH ₃) ₂	0.9	0.2	0.4	0.4	0.8	0.6	0.9
Stand. dev. of Si-O-Si		3.2	4.2	6.8	4.3	4.9	5.3	3.5

Figure 9. FTIR results at various locations.

Figure 10. Ratios of molecular group peaks compared to virgin material from FTIR.

Table 3. The ratios of polymeric group to hydrophilic groups.

Ratio	Bulk (shed/core)	A	B	C	D	E	F
Si-CH ₃ /OH	4	1	1	1	3	1	2
Si-O-Si/OH	11	2	3	2	10	4	7
Si(CH ₃) ₂ /OH	9	1	2	1	8	3	6

3.5 RAMAN SPECTROSCOPY

Typical spectra corresponding to the various locations are shown in Figure 11 and relative comparisons with the new sample are shown in Table 4. The spectra cannot be detected on sample B due to the deposits on the surface, but can be detected after the deposits are cleaned. Due to the fact that cleaning may change the nature of the sample, the spectra of sample B after cleaning is not shown here. All samples were compared with the spectra of new sample. Sample A and C showed a lower band corresponding to Si-O-Si (490cm⁻¹), but higher bands corresponding to ATH (537 cm⁻¹, 567 cm⁻¹) and Si-OH (320 cm⁻¹). The spectra of sample D is almost the same as a new sample. Samples E and F showed lower band intensities corresponding to ATH (537 cm⁻¹, 567 cm⁻¹).

Figure 11. Raman spectra of samples.**Table 4.** Comparison of typical spectrum of all samples.

Sample	320 cm ⁻¹ (Si-OH)	490 cm ⁻¹ (Si-O-Si)	537 cm ⁻¹ ATH
Bulk (Shed/core)	1	1	1
A	1.5	0.6	1.5
C	1.6	0.6	1.4
D	1.2	0.9	1
E	1.2	0.9	0.2
F	1	1	0.3

4 DISCUSSION

All the measurements reported here relate to one material used in one insulator design, installed on 18 towers in one location. Care must therefore be taken not to over generalise from these results. Nonetheless it might be expected that the general discussion will apply to most ATH filled silicone systems, and this view is confirmed by comparing results to those on other reported trials.

When the surfaces are aged due to environmental, electrical and thermal stresses, methyl groups are expected to be oxidized into O-H groups which are hydrophilic in nature. This behaviour, shown in Tables 1 and 2, is in general agreement with other studies using EDX and FTIR on service-aged and laboratory-aged samples [3,6,8]. The quantitative measurements comparing north- and south-facing sides have no comparison in the literature except on EPDM [5]. In this case Sundararajan et. al. report on an insulator which was on a line experiencing unexplained outages, and perhaps was towards the end of its life. Chalking and discoloration were also seen on the sun-facing side, the core showed less discolouration than other surfaces but the discoloured surfaces were more wettable than the less discoloured, as reported here. Chemical analysis showed CH₂ and CH₃ groups slightly diminished on the dark side and heavily diminished on the light side.

The differences between sides witnessed here and in [5] have not been reported in accelerated laboratory testing. It is likely therefore that some differences in mechanisms are being seen in each case. For example, corona effects have been shown to cause ageing which results in many of the features reported here. Whitening of surfaces has been reported in accelerated SiR composite tests and shown to be due to corona alone in a test which included UV, rain and salt fog [15]. Thus it is important to distinguish the degradation caused by UV radiation and discharge activity in isolation, or when combined.

Polymer chemistry dictates that UV radiation and discharge activity degrade the polymeric groups in different ways. The bonding energy of Si-C is 301 kJ/mol, and that of Si-O is 447 kJ/mol so sunshine can break the former but not the latter [17]. Electrical discharges have the energy to break both bonds. ATH may also decompose during discharge activity, but is stable under UV exposure.

Discolouration of polymers by UV radiation is well reported [16]. On the other hand, asymmetry is not often reported, and so is presumably not apparent if it does exist. The detailed report on field ageing of 275 kV EPDM and SiR insulators from Australia makes no mention of rotational asymmetry [6]. Also a nine year trial in China identified no such effects on SiR composites [18]. Another report from China identifies more degradation on the side of the prevailing wind but no mention is made of the sun-facing side [12]. [9] reports surface hydrophobicity tests on insulators in service for up to nine years, but no north-to-south variations are reported. Clearly the distance from the equator (latitude) will impact any expected orientational variation as a result of solar radiation. The UK is further from the equator than for example South Africa, Australia and China. However, the intensity of

the solar radiation may also play a part and this is reduced in the far north and south.

The second half of the 6 month trial reported in [17] on EPDM and SiR experienced wind predominantly from the same direction as the sun (the north), and also showed some of the asymmetry described here. No asymmetry was reported on glass insulators in the same location. In the work reported here, the sun-facing (southern) side also faces close to the predominant wind from the sea (south westerly). It may be therefore that if the wind is predominantly from one direction, and that side also faces the sun it provides a particular situation in which asymmetry will develop.

World-wide experience of biological contaminant growth on composite insulators is summarised in [13] and it is reported that growth on the parts of the insulator shaded from the sun is not unusual. [19] also found algae in shaded parts and noted that dirt was concentrated on areas exposed to the prevailing wind and that areas exposed to prevailing wind became more wettable.

In this study, the oxidation is more obvious on the sheds than on the sheath. O/C ratios in Figure 8 are also higher on the south side of sheds indicating a greater tendency to form O-H groups on the south side of sheds. The increased oxidative state on the south side of the insulator is also consistent with the decreased hydrophobicity witnessed. The Raman spectroscopy also showed higher OH bands and reduced Si-O-Si bands. This can be expressed as the ratio of the magnitude of the Si-O-Si peak to the OH peak using FTIR and Raman results, respectively. The comparison of FTIR and Raman results is shown in Figure 12. Qualitative agreement can be seen between the techniques, but the scatter of results at low concentrations for the OH group (for the less aged material) demonstrates that the data needs to be interpreted with care. FTIR is considered to be the more sensitive of the two tests, and better able to distinguish differences. It is seen in Figure 9 that on the south side the $\text{Si}(\text{CH}_3)_2$ peak was reduced to a relatively low level compared to the Si-O-Si peak.

Although such differences between north and south have not been measured previously these results are consistent with previous measurements on silicone rubber aged both in the laboratory and in service. [8] reports an increase in oxygen and decrease in carbon in salt fog aged RTV silicone rubber. Wang et al [20] artificially aged SiR with acid rain and used FTIR to show a reduction in CH_3 and no change in Si-O-Si levels. [4] reports on an insulator which was installed in a coastal environment. Cracks and various extents of degradation were reported including white powder residues. Increased O/Si ratios and reduced C/Si ratios were reported in aged materials. For an extreme case of degradation they give O/Si ratios increasing to 3.5, and C/Si ratios decreasing to 1.7. The equivalent values for the average of aged shed values in Table 1 here are 3.1 and 2.7. It is noticeable however that the insulators measured here were not considered to be heavily damaged whereas those in [4] are reported as severely damaged, and SEM pictures show much greater physical changes than seen in Figures 2 to 7. After an ageing program of 6 months, Noel et. al. report different absolute magnitudes of elemental content but a reduction in the C/Si ratio to 1, and an

Figure 12. A comparison of FTIR and Raman ratios of Si-O-Si to Si-OH peak height from Tables 3 and 4.

increase in O/Si ratio to 0.8 after a six month ageing period [7]. The surprising low levels of atomic Si measured here have also been reported in [16], with a similar variation in atomic ratios. It is evident that care must be taken when comparing such results of different materials in different circumstances. This is thought to be partly due to the depth of surface studied by the techniques not being consistent.

Visual observation and SEM also showed more obvious physical ageing on the south side of sheds than on the north side, manifested as discoloration and cracks. On the other hand, the aluminium percentage on the south side of sheds (A and C) is still close to bulk values. The results of Raman spectroscopy on the south side (A and C) also did not show signs of ATH reduction. The heating by UV radiation is insufficient to decompose ATH fillers and supports the view that UV radiation is the main ageing mechanism in this region. On the north side of sheds there is little to distinguish the rate of damage to Si-O-Si and Si-(CH_3) groups, suggesting discharge activity is the main ageing mechanism on the north side. Discharge on the north side of sheds may also result in the lower aluminium levels being measured. Although designed to have lower ATH levels, the very low levels of aluminium seen in the core material after ageing is of concern. This is the area where discharge activity is expected to be highest and so requires the protection of ATH filler. This might suggest this material was moving towards a state where rapid ageing might ensue on the core.

The core is protected by the sheds from UV radiation. Certainly electrical activity is more likely on the core due to geometric effects although the oxidation is not obvious which indicates electrical discharges are not intense enough to cause such oxidation. The low aluminium level on south side of the core may be due to decomposition of ATH during discharges or the surface residues covering the aluminium content. [5] reports for an EPDM composite insulator that aluminium is sometimes not detected and not a useful measure of ageing. It has also been suggested that aluminium is not detected in new SiR composites because of thin layers of pure polymer over its surface [4]. It is possible that the resulting alumina residues from degraded ATH are not well bound to the polymer and are eroded, resulting in reduced aluminum levels [16]. This would be consistent with a decrease of the Al/Si ratio. It might be concluded that surface chemical analysis for aluminium is not a reliable tool for quality assessment. Certainly a coherent picture of ATH levels is not evident over the surfaces studied.

This may be due to the two different materials, the numerous surface orientations and geometries in addition to the asymmetry of the natural environment.

5 CONCLUSION

The service-aged samples of silicone rubber insulation have been taken out of service as a result of a routine refurbishment programme, not because of any degradation in performance. These have been studied by visual observation and various material techniques. Visual observation showed non-uniform degradation over the sheds. The degradation can be qualified by using material techniques among which EDX and FTIR have been proved to be the most effective tools. The analysis has shown the ageing is an oxidation process, resulting in the formation of Si-OH groups. The data reported here is consistent with other reported literature, however it has been shown that direct comparison of quantitative chemical data does not necessarily allow correlation between different materials and sites.

By considering the concentration of polymeric groups and atomic species, it is suggested that UV radiation plays a key role in accelerated ageing on the south side of sheds, while heavier discharge activity is the main factor on the north side. Consistent southerly wind from the sea may also have had an impact on promoting electrical ageing on the south side. Further work is required to identify how these factors work together and the impact of asymmetric ageing on insulator performance in service. The data reported here and existing literature on a variety of composite insulators in various locations, suggest that a prevailing wind on the side of an insulator facing the sun may cause the insulator to develop heavy asymmetry in its surface ageing. Growth of organic species on the shaded leeward side may be critical in this difference.

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REFERENCES

- [1] G.G. Karady, M. Shah and R.L. Brown, "Flashover mechanism of silicone rubber insulators used for outdoor insulation-I", IEEE Trans. Power Delivery, Vol. 10, pp.1965-1971, 1995.
- [2] S. Sundhar, A. Bernstorff, W. Goch, D. Linson and L. Huntsman, "Polymer insulating materials and insulators for high voltage outdoor applications", IEEE Intern. Sympos. Electr. Insul. (ISEI), pp. 222-228, 1992.
- [3] S. Kumagai, X. Wang and N. Yoshimura, "Solid residue formation of RTV silicone rubber due to dry-band arcing and thermal decomposition", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 281-289, 1998.
- [4] H. Liu, G. Cash, D. Birtwhistle and G. George, "Characterisation of a severely degraded silicone elastomer HV insulator - an aid to development of lifetime assessment techniques", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, pp. 478-486, 2005.
- [5] R. Sundararajan, A. Mohammed, N. Chaipanit, T. Karcher and Z. Liu, "In service ageing and degradation of 345 kV EPDM transmission line insulators in a coastal environment", IEEE Trans. Dielectr. Electr. Insul., Vol. 11, pp. 348-361, 2004.
- [6] D. Birtwhistle, P. Blackmore, A. Krivda, G. Cash and G. George, "Monitoring the condition of insulator shed materials in overhead

- distribution networks", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 612-619, 1999
- [7] M. Noel, J.-M. Fourmigue and G. Riquel, "Evaluation of diagnostic techniques for non-ceramic outdoor high voltage insulators", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 639-644, 1994.
- [8] K. Seog-Hyeon, E.A. Cherney, R. Hackam, K.G. Rutherford, "Chemical changes at the surface of RTV silicone rubber coatings on insulators during dry-band arcing", IEEE Trans. Dielectr. Electr. Insul., Vol. 1, pp.106-123, 1994
- [9] S.M. Gubanski and A.E.Vlastos, "Wettability of naturally aged silicone and EPDM composite insulators", IEEE Trans. Power Del., Vol. 5, pp. 1527-1535, 1990.
- [10] G.G. Karady, M. Shah and R.L. Brown, "Flashover mechanism of silicone rubber insulators used for outdoor insulation", IEEE Trans. Power Del., Vol. 10, pp. 1965-1971, 1995.
- [11] J. Ramirez, M. Sabino, E. Da Silva, J. Rodriguez, M. Martinez, J. Bermudez, J. Ren and A. Ferraz, "Studies on polymeric insulators for transmission systems under natural aging conditions", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 719-722, 1998.
- [12] W. Shaowu, L. Xidong, G. Zhicheng, Y. Jun and S. Qinghe, "Investigation on hydrophobicity and pollution status of composite insulators in contaminated areas", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 628 - 631, 2001.
- [13] S.M. Gubanski, S. Karlsson and M.A.R.M. Fernando, "Performance of biologically contaminated high voltage insulators", Int. Conf. Industrial and Information Systems, pp. 30-35, 2006.
- [14] S. M. Rowland, Y. Xiong, J. Robertson and S. Hoffman, "Ageing of Silicone Rubber Composite Insulators on 400 kV Transmission Lines", IEEE Trans. Dielectr. Electr. Insul., Vol. 14, pp. 130-136, 2007.
- [15] A.J. Phillips, D.J. Childs and H.M. Schneider, "Water drop corona effects on full-scale 500 kV non-ceramic insulators", IEEE Trans. Power Del., Vol. 14, pp. 258-263, 1999.
- [16] N. Yoshimura, S. Kumagai and S. Nishimura, "Electrical and environmental aging of silicone rubber used in outdoor insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 632-650, 1999.
- [17] W.L. Vosloo, J. P. Holtzhausen and A.H.A. Roediger, "Leakage current performance of naturally aged non-ceramic insulators under a severe marine environment", IEEE Africon, Vol. 1, pp. 24-27, 1996.
- [18] C. Zixia, L. Xidong, W. Yongyong, W. Xun, Z. Zuanxiang and L. Zhi, "Investigation on composite insulators in contaminated areas", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 327-330, 2002.
- [19] M.A.R.M. Fernando, S. Karlsson and S.M. Gubanski, "Performance of silicone rubber composite insulators in Sri Lanka", Int. Conf. Industrial and Information Systems, pp. 14-19, 2006.
- [20] X. Wang, S. Kumagai, and N. Yoshimura, "Contamination performances of silicone rubber insulator subjected to acid rain", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 909-916, 1998.

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