This is the accepted manuscript, and which has been accepted by IEEE for publication. © 2012 IEEE.
Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The full reference is:

‘Asset Management Frameworks for Outdoor Composite Insulators’
A. Tzimas, E. Da Silva, S. M. Rowland, B. Boumeced , M. Queen, M.Michel

IEEE Transactions on Dielectrics and Electrical Insulation,
Vol. 19, Issue 6, pp. 2044-2054, 2012.

Digital Object Identifier: [10.1109/TDEI.2012.6396964](https://doi.org/10.1109/TDEI.2012.6396964)

Asset Management Frameworks for Outdoor Composite Insulators

Antonios Tzimas, Elizabeth Da Silva, Simon M. Rowland

The School of Electrical and Electronic Engineering
The University of Manchester
Manchester, M13 9PL, UK

Boud Boumecid

National Grid
Warwick, CV34 6DA, UK

Martin Queen

Scottish Hydro Electric Transmission Ltd,
Perth, PH1 3AQ, UK

and **Matthieu Michel**

UK Power Networks,
Crawley, RH10 1EX, UK

ABSTRACT

Power supply utilities are continuously working to maintain reliable and efficient electrical networks that meet the growing demand for electricity. This is a complex task in which appropriate maintenance, refurbishment and replacement policies for all the assets are critical. Optimising business processes through these constitutes a key challenge of balancing service quality and stakeholder value. Here we present two frameworks that can be used to effectively condition monitor both ethylene propylene diene monomer (EPDM) and silicone rubber (SiR) composite insulators during their lifetime in service. The frameworks are tools to assist asset management decision making. The first framework is derived from a generalized dielectric ageing framework and a more specific one on composite insulators that points out the elements that govern composite insulator materials' ageing on power transmission and distribution lines. The second framework defines four aged states in relation to the risk to failure that a composite insulator has in service before its replacement. Properties of materials that can be measured in order to identify ageing are reviewed. The techniques available as engineering tools for measuring these properties are introduced. These are distinguished as techniques that can be carried out on-line and off-line, and as destructive and non-destructive tests. These techniques are then reviewed in the context of monitoring and maintaining reliable and efficient operation of power networks.

Index Terms — Outdoor insulators; Asset management; Ageing; Condition monitoring techniques; silicone rubber; EPDM; composite insulators; Non-ceramic insulators.

1 INTRODUCTION

MEETING the continuously increasing demand for power and, at the same time, ensuring a reliable and cost effective transmission and distribution network is a complicated task for the power utilities. One improvement measure has been the adoption of non-ceramic overhead line

insulators. The hydrophobic properties of the polymeric insulation [1–4] especially under highly polluted environments [7, 8], their low weight and ease of installation as well as the recent advantages in their design and manufacture are the key features that are driving the replacement of the traditional ceramics [7]. However, limited service experience of polymeric insulation strings and the need to match the excellent performance of the ceramics [8] has led to a great number of papers on the ageing mechanisms [9-19] of

polymeric insulation as well as diagnostic techniques to evaluate and monitor the insulators' state [20-22]. The value of the diagnostic techniques available to date; whether assessing the ageing of the insulator visually, chemically, electrically or mechanically is indisputable. Nevertheless, a big question arises concerning the potential of these techniques to effectively manage ageing insulators' states within a utility. The answer to this question lies in understanding:

- The ageing processes of polymeric insulations;
- The failure modes that can occur;
- The potential of the diagnostic techniques available;
- The value of the potential diagnostic techniques to utilities.

The five-layer framework presented in [23, 24] is a tool that incorporates the above points by providing asset managers, engineers and scientists with a common platform where these can be discussed and missing "knowledge" can be easily identified. However, the framework presented is a general tool that is not specifically geared to individual plant items or insulation systems. For example it can be applied to cables, transformers, and transmission or distribution line ageing. In this work we are focused on how this general framework can provide a platform of information of ageing mechanisms and monitoring techniques in order to assist asset management of composite insulators. Effective asset management, Figure, of outdoor composite insulators means a good understanding of the ageing process in combination with accurate, focused and cost effective application of monitoring techniques.

Figure 1. Illustration of effective asset management logic.

2 AGEING OF COMPOSITE INSULATORS

2.1 FAILURE MODES OF COMPOSITE INSULATORS

Outdoor composite insulators are susceptible to two major failure modes. These are:

- Mechanical failure;
- Electrical failure;

Early catastrophic mechanical failure soon after installation is normally attributed to a manufacturing defect. Much improved methods of fitting metal-work to the insulator strength member have reduced such incidences to an acceptable level. In the longer term, mechanical failure can also occur because of severe erosion of the insulation surface, resulting in exposure and stress corrosion cracking of the glass

fiber reinforced core. In the latter case, the mechanisms that lead to severe erosion, are normally due to electrical and environmental stresses, i.e. dry-band arcing, or discharge activity.

Less catastrophic but equally important to the electrical system is electrical failure. In practice this means that the likelihood of flashover of an insulator becomes too high, and so interferes with the reliability of the power network. This occurs as a result of increased leakage current, often after a loss of hydrophobicity, with a resultant high occurrence of flashover. Another method of electrical failure is when internal tracking occurs in the interface of the insulation material and the GFR core due to erosion and moisture ingress. This is ultimately seen as a mechanical failure.

Ageing occurs throughout the insulations' service life [10], nevertheless it is not always possible to detect changes in the insulation state. We consider the ageing of composite insulators to occur in two stages [25]. The first stage is when the material ages mainly chemically and the insulation still performs "As New". The first stage is defined from the period from installation and while the insulation retains its initial hydrophobic properties. During the first stage the insulation may age chemically, for example through surface oxidation and migration of the low molecular weight chains from the bulk to the surface that help to retain its hydrophobic properties [6]. The second stage is defined from the time the insulation's hydrophobic properties start to decrease until the failure of the insulation. Historically it has been difficult to identify any quantifiable properties that alter during the early stages of ageing. In this work we introduce the idea of identifying four states of ageing, and argue that it is key for asset managers to identify transitions between these states.

Failure of any insulation which has been type approved for installation, i.e. passed the various short-term electrical and mechanical tests, is unlikely during the first stage. If any such failures are likely to be associated with manufacturing or installation quality issues [7]. Hence the focus of this work lies on the second ageing stage, where observable changes on the properties of the insulation begin to occur and could affect its overall performance. These are outlined below showing how they may progress in time:

- UV Ageing + weathering
- *Decrease of the hydrophobicity*
- Increase of local fields as water droplets grow/merge
- Corona and surface discharges
- Further chemical damage
- Increase of conductivity/ leakage current
- Dry-band arcing
- Increased likelihood of flashover
- Insulation erosion
- Core strength-member exposure
- Mechanical failure

The italicized font line show where the two stages described above are separated. It should be noted that the above stresses and ageing features are generic to composite insulators and variations to chemical compositions of the materials as well as the addition of nano-filler could improve considerably their ageing resistance to the aforementioned ageing processes [15], [26-29].

3 ASSET MANAGEMENT FRAMEWORK

This treatment follows the form of the five-layer framework [23] that links insulation ageing to asset management. The following layers can be defined for composite insulators.

3.1 ASSET MANAGEMENT - 1ST LAYER OF THE FRAMEWORK

The first two generic layers that describe the asset management decision process and the material state remain almost the same as the generic case for outdoor composite insulation. For instance in Figure 2, where the first layer of asset management is presented, the knowledge of environment, circumstance monitoring and material state is focused on learning the environment in which composite insulators operate, identifying what is their normal and hence abnormal behavior. This behavior for composite insulators can be determined by identifying thresholds of operation modes with respect to leakage current, frequency of flashover [30-34] and changes in their visual aspect. In [33] the leakage current thresholds that are identified are also linked with the hydrophobicity classification [35] a widely used method to diagnose the insulation's condition. Further methods of diagnosing the insulations state are discussed later.

Figure 1. First layer of the asset management model adapted from [23].

3.2 COMPOSITE MATERIAL STATE – 2ND LAYER OF THE FRAMEWORK

The second layer of the model describes the on-going ageing processes experienced by the insulator in terms of a flow chart. Key to the model in this case is the changing state, and changing environment of operation leading to many processes and cycles seen in the insulator's lifetime. This process underpins the asset management decisions.

3.3 STRESS FACTORS - 3RD LAYER OF THE FRAMEWORK

There are four main stresses that contribute significantly toward the ageing, degradation and failure of the outdoor

Figure 2. Factors that affect the ageing rate of composite insulators.

composite insulators. These do not act separately but often interact with synergy. As it is illustrated in Figure 4 in the third layer of the framework, these are chemical, organic, electrical and mechanical. The susceptibility of the outdoor composite insulators to these stresses is strongly dependent on the environment or circumstance of the insulator as shown in Figure 3. These factors are the ones that affect the ageing rate of the material. One clear distinction between distribution and transmission line insulators is that greater electrical and mechanical stresses are acting on the transmission line insulators as the rated voltage and physical size increases.

3.4 AGEING MECHANISMS - 4TH LAYER OF THE FRAMEWORK

The fourth layer of the model, seen in Figure 4 shows the ageing mechanisms that are initiated because of the stress factors that act on the composite insulators. Under chemical stress these are; oxidation, consumption of low molecular weight chains, embrittlement and erosion of the insulation. Under organic stresses there is organic attack and growth that can lead to increase surface conduction over the surface of the insulation [36, 37]. Regarding electrical stress: there are high field points at interfaces that could initiate corona and high leakage currents that could initiate surface discharges, dry band arcing and flashover. Finally under mechanical stress; rupture cracks can be formed from static loads and vibrations while puncture may occur from gunshot and birds.

It is the modelling of, and forecasting the implications of, these ageing processes which forms the core of much work on composite insulators [38-40].

3.5 MONITORING/DIAGNOSIS - 5TH LAYER OF THE FRAMEWORK

The fifth layer of the framework consists of the monitoring and diagnostic techniques that can be applied to the composite insulators in order to characterize their state as shown in Figure 4. These techniques are divided between the non-

destructive that could be applied in service (either with the system energized or with an outage) [41, 42] and destructive ones that can only be applied in a laboratory [43]. Each pyramid or category is divided into three types of test. These are: system, device and material tests. The system tests are the

ones that test the whole transmission or distribution line or network. System tests are appropriate for some devices, but not for these insulators. Statistics of on-going insulator fault rates, determined from system performance, are however an

Figure 3. A multifactor framework adapted from [23] and applied on outdoor composite insulators.

equivalent data set. Device tests are concerned with the electrical and mechanical properties of the insulation string as an individual whole. Material tests are for samples of the insulation material.

The techniques that are included in each pyramid can be categorized further as techniques used for chemical, electrical, physical/optical and mechanical tests. Under chemical there are techniques which determine the materials' chemical composition and concentration. Chemical analysis can for example detect the methyl group concentrations that are responsible for the hydrophobic properties of silicone rubber based insulators [4].

Techniques that are widely used for chemical analysis are [20, 21, 44]:

- Fourier transform infrared reflection, (FTIR) [45];

- Energy dispersive X-ray, (EDX);
- Raman spectroscopy;
- Differential scanning calorimetry;

Techniques that are widely used for electrical measurements are:

- Leakage current magnitudes [46];
- Flashover voltage inception and frequency [46, 47];
- Electrical field distribution [49–52];
- Radio interference voltage, (RIV);
- Corona discharge detection;
- Acoustic measurements;
- Thermal stimulated currents, (TSC) [53];
- Dielectric spectroscopy [54, 55];
- Partial discharge detection [42, 56];
- Breakdown strength.

Figure 4. Ageing state estimator.

TECHNIQUE	STATE 1	STATE 2	STATE 3	STATE 4
Visual inspections				
Hydrophobicity				
Corona detection				
Leakage current monitoring				
Electric field distribution				
FTIR				
SEM/EDX				
Mechanical tests (on samples)				

Figure 5. The arrows indicate identification of changes in states defined in Figure 5.

Techniques that are used for physical/optical analysis are:

- Visual inspections;
- Hydrophobicity [35];
- Optical microscopy;
- Infrared Reflection (IR) thermography;
- Scanning Electron Microscopy (SEM);
- Atomic-Force-Microscopy (AFM).

Techniques that are used for mechanical tests include:

- Tensile stress measurements;
- Compressive stress;
- Tear strength.

The layered framework adapted for composite insulators is shown in Figure 4. Figure 5 illustrates how the conditions and

ageing processes are linked. In this model, four states are identified; 'As new', 'weathered', 'mature' and 'at risk'. The dominant ageing processes are different in each case. This figure essentially provides the detail of the second layer of the framework.

Figure 6 shows some of the chemical, physical/optical, electrical and mechanical properties of the material that determine changes between ageing states 1, 2, 3 and 4. The arrows indicate when it is most suited to monitoring according to the composite insulation states defined in Figure 5.

4 AGEING STATE ESTIMATOR FRAMEWORK

The second framework is the outcome of combining Figures 5 and 6 together and integrating them over the risk of failure in the lifetime of the outdoor composite insulators, see Figure 6. Times t_1 , t_2 , t_3 and t_4 , i.e. the duration that a group of insulators will belong to a state, is dependent upon the environmental stresses acting at site as well as the material's resistance to the environmental stresses [25]. Figure 7 illustrates how the performance of a silicone rubber insulator, an EPDM insulator and a porcelain insulator would change under a polluted

Figure 6. Ageing state estimator for composite insulators superimposed risk of failure and appropriate techniques to monitor its condition effectively at each state.

environment. The following characteristics of the three materials are reflected in Figure 7 according to literature [1, 4, 6, 8–12, 16, 18, 33, 34, 57–64]:

- porcelain:
 - good resistance to discharges;
 - poor hydrophobicity;
 - frequent maintenance-wash in polluted environments;
 - shed breakage;
- silicone rubber:
 - excellent hydrophobic properties;
 - poor resistance to tracking and erosion;
 - no need for maintenance;

- EPDM:
 - loss of hydrophobicity;
 - excellent resistance to tracking and erosion;
 - no need for maintenance.

It should be noted that the suggested life lines in Figure 8 are for illustration purposes only and they may change drastically depending on the factors that influence the gradient of the life lines, see Figure 8. For example the severity of the pollution at site, the frequency of maintenance washing for porcelain insulators, material chemical formulation for composite insulators [26, 65] as well as the geometrical design [66] would play a driving role on the performance and life time of the insulators in service.

Figure 7. Suggested performance of three different insulating materials under polluted environment.

4.1 EXAMPLES FROM SERVICE

The ageing estimator is applied to insulators that have been removed from transmission and distribution networks to establish the state of the assets in each system. Figures 8 and 9 present the diagnosis of the transmission and distribution insulators respectively, following the proposed general framework of Figure 6.

The first example from service is applied to transmission network insulators; silicone rubber insulators removed after fifteen years in service from a 400 kV line located on the South coast of England and EPDM insulators removed after eight years in service on a 132 kV line located on the west

coast of Scotland. The silicone rubber insulators from the 400kV line have been found to be described best by the state 2 characteristics according to Figure 5. On the other hand the 132kV EPDM insulators have been found to be described best by the State 3 characteristic. Nevertheless, the fact that the silicone rubber insulators belong to State 2 it does not always mean that they would last longer than the EPDM insulators that belong to State 3. As it is pointed out in Figure 8, EPDM insulators may lose their hydrophobicity faster than the silicone rubber ones under the same environmental conditions but EPDM insulators have a better resistance to discharges and erosion. The presence of a mold line in the EPDM insulators

forms a continuous hydrophilic path that increases, consequently, the leakage current magnitude and corona discharge activity. This means that the mold line is a weak point on the performance of these insulators. Solar radiation, humidity level, pollution type and corona discharges acting in a synergistic way determine biofilm growth characteristics and type. The impact of biofilms on these transmission insulators is still not fully understood.

The 11 kV distribution insulators were installed in a horizontal orientation and they have been in service for six years near the UK coast, in two locations Circuit I and II, [67, 68]. Circuit I was located in farmland and Circuit II was adjacent to a farm and a residential area. They are located within 3 km of each other. Circuit I and II are exhibiting “Mature” and “At risk” states, respectively. Despite the fact that Circuit I insulators are in state 3 (‘mature’), there are no indications to infer that they are going to change shortly to state 4 (‘at risk’). This incipient mature state of Circuit I

insulators is mainly defined by physicochemical changes, roughness, and the level of hydrophobicity but at the same time the insulator presents a very good electrical performance. Circuit II insulators are defined as being in the ‘At risk’ state because of the severe damage to interface polymer/metal end-fittings, corrosion levels, high roughness, hydrophilic surfaces and physicochemical changes. In spite of the fact that their electrical performance is still very good, the damage on the seals compromises the insulators robustness. Nevertheless, the fact that the Circuit II insulators are in the “at risk” state means that the inspection intervals should be frequent to monitor their progress but they may last for many more years to come.

The ageing state estimator described in Figure 6, when taking into account the material properties that are suggested in Figure 8, could provide a useful tool to asset managers for choosing insulators that best fit their asset management policies according to the service environment.

Observation: The arrows with the year in service are extended along the state to indicate a possible advance along it of each group of insulators. In this case, even so the 132kV insulators have been shorter time in service, there are more deteriorated.

Figure 8. Application of the ageing state estimator for 132kV and 400kV composite insulators.

5 CONCLUSIONS

A framework to assist asset management of composite insulators has been developed from a previous generic one. An ageing state flow chart specific to composite insulators has been introduced. Each state in the flow chart defines the condition of the insulation and possible ageing processes that

are taking place. Identifying the transition between such states could be a tool to assist asset management decision making.

Despite the striking differences in environmental and electrical stressing conditions, common ageing mechanisms can be identified between insulators under study. UV radiation is a common stress factor over distribution and transmission insulators producing physicochemical reactions, reducing the

Observation: The arrows with the year in service are extended along the state to indicate a possible advance along it of each group of insulators. In this case, even so both groups of insulators have been the same time in service, Circuit II is more deteriorated.

Figure 9. Application of the ageing state estimator for the 11kV composite insulators (Circuit I and II).

hydrophobicity, increasing the roughness, favoring in many cases biofilm growth, creating a damaging cycle. Non-uniform ageing along all the evaluated insulators is consequence of the environmental factors including natural UV radiation and prevailing wind direction, and the resultant pattern of growth of organic species.

On the other hand, differences between the frameworks application on transmission and distribution assets is an important consideration. Even though all the diagnosis techniques can also be applied on both system levels, their application could be not justified on medium voltage lines considering their cost/benefit impact.

New composite insulators are mainly made with SiR but still there are many lines around the world with EPDM insulators installed. This means that techniques to diagnosed them and understand the main ageing processes that have been occurring under specific environmental conditions is key for their classification.

The ageing state estimator described in Figure 7, when taking into account the material properties that are suggested in Figure 8, could provide a useful tool for asset managers concerning choice of insulators that best fits their asset management policies according to the service environment.

ACKNOWLEDGMENT

E. Da Silva, A. Tzimas and S.M. Rowland thank National Grid and UK power networks for supporting the work reported here.

REFERENCES:

- [1] J. Kim, M. Chaudhury, and M. Owen, "Hydrophobicity loss and recovery of silicone HV insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 695–702, 1999.
- [2] S. Wang, X. Liang, Z. Cheng, X. Wang, Z. Li, Y. Zhou, Y. Yin, L. Wang, and Z. Guan, "Hydrophobicity changing of silicone rubber insulators in service", CIGRE session, 2002.
- [3] S. H. Kim, E. A. Cherney, and R. Hackam, "The loss and recovery of hydrophobicity of RTV silicone rubber insulator coatings", IEEE Trans. Power Delivery, Vol. 5, pp. 1491–1500, 1990.
- [4] T. Tokoro and R. Hackam, "Loss and recovery of hydrophobicity and surface energy of HTV silicone rubber", IEEE Trans. Dielectr. Electr. Insul., Vol. 8, pp. 1088–1097, 2001.
- [5] 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, pp. 628–631, 2001.
- [6] D. A. Swift, C. Spellman, and A. Haddad, "Hydrophobicity transfer from silicone rubber to adhering pollutants and its effect on insulator performance", IEEE Trans. Dielectr. Electr. Insul., Vol. 13, pp. 820–829, 2006.
- [7] T. Kikuchi, S. Nishimura, and M. Nagao, "Survey on the use of non-ceramic composite insulators", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 548–556, 1999.
- [8] J. Mackevich and S. Minesh, "Polymer outdoor insulating materials. Part I: Comparison of porcelain and polymer electrical insulation", IEEE Electr. Insul. Mag., Vol. 13, No. 3, pp. 5–12, 1997.
- [9] C. Spellman, H. Young, A. Haddad, A. Rowlands, and R. Waters, "Survey of polymeric insulator ageing factors", 11th Int'l. Sympos. High Voltage Engineering, (Conf. Publ. No. 467), Vol. 4, pp. 160–163, 1999.
- [10] J. P. Reynders, I. R. Jandrell, and S. M. Reynders, "Review of aging and recovery of silicone rubber insulation for outdoor use", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 620–631, 1999.
- [11] T. Tokoro, Y. Katayama, M. Kosaki, and R. Hackam, "Aging and recovery of HTV silicone and EPDM rubbers due to continuous

- wetting", Int'l. Sympos. Electr. Insulating Materials (ISEIM), pp. 51-54, 2001.
- [12] R. Sundararajan, A. Mohammed, N. Chaipanit, and T. Karcher, "In-service aging and degradation of 345 kV EPDM transmission line insulators in a coastal environment", IEEE Trans. Dielectr. Electr. Insul., Vol. 11, pp. 348-361, 2004.
 - [13] R. S. Gorur, G. G. Karady, a. Jagota, M. Shah, and a. M. Yates, "Aging in silicone rubber used for outdoor insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp. 525-538, 1992.
 - [14] I. Ramirez, S. Jayaram, and E. A. Cherney, "Aging evaluation of silicone rubber nanocomposites", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 270-273, 2009.
 - [15] A. Naderian Jahromi, E. A. Cherney, S. H. Jayaram, and E. C. Simon, "Aging characteristics of RTV silicone rubber insulator coatings", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, pp. 444-451, 2008.
 - [16] S. Rowland, Y. Xiong, J. Robertson, and S. Hoffmann, "Aging of silicone rubber composite insulators on 400 kV transmission lines", IEEE Trans. Dielectr. Electr. Insul., Vol. 14, pp. 130-136, 2007.
 - [17] T. Yanming, "Approaches to aging of composite insulators", Int'l. Conf. Properties and Applications of Dielectric Materials, pp. 5-8, 2000.
 - [18] Y. Xu, Y. He, F. Zeng, and R. Zhang, "Aging in EPDM used for outdoor insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 60-65, 1999.
 - [19] T. Tanaka, "Aging of polymeric and composite insulating materials. Aspects of interfacial performance in aging", IEEE Trans. Dielectr. Electr. Insul., Vol. 9, pp. 704-716, 2002.
 - [20] D. Birtwhistle, G. Cash, G. A. George, and D. Hinde, "New Techniques for Estimating the Condition of High Voltage Polymeric Insulators", Proceedings of the 1st World Congress on Engineering Asset Management (WCEAM), Paper No. 169, pp. 949-956, 2006.
 - [21] S. M. Gubanski, A. Dernfalk, J. Andersson, and H. Hillborg, "Diagnostic Methods for Outdoor Polymeric Insulators", IEEE Trans. Dielectr. Electr. Insul., Vol. 14, pp. 1065-1080, 2007.
 - [22] P. D. Blackmore, G. A. Cash, G. A. George, and D. Birtwhistle, "New condition monitoring techniques for composite insulators", J. Electrical and Electronics Eng., Australia, Vol. 18, No. 2, pp. 91-99, 1998.
 - [23] S. Bahadoorsingh and S. Rowland, "A Framework Linking Knowledge of Insulation Aging to Asset Management", IEEE Electr. Insul. Mag., Vol. 24, No. 3, pp. 38-46, 2008.
 - [24] S. M. Rowland and S. Bahadoorsingh, "A Framework Linking Insulation Ageing and Power Network Asset Management", IEEE Int'l. Sympos. Electr. Insul., (ISEI), pp. 732-736, 2008.
 - [25] A. Tzimas and S. M. Rowland, "Risk Estimation of Ageing Outdoor Composite Insulators with Markov Models", IET Trans. Generation, Transmission and Distribution, pp. 1-8, doi: 10.1049/iet-gtd.2011.0858, 2012.
 - [26] E. A. Cherney, "Silicone rubber dielectrics modified by inorganic fillers for outdoor high voltage insulation applications", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, pp. 1108-1115, 2005.
 - [27] L. H. Meyer, S. H. Jayaram, and E. A. Cherney, "A novel technique to evaluate the erosion resistance of silicone rubber composites for high voltage outdoor insulation using infrared laser erosion", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, pp. 1201-1208, 2005.
 - [28] L. Meyer, S. Jayaram, and E. A. Cherney, "Thermal conductivity of filled silicone rubber and its relationship to erosion resistance in the inclined plane test", IEEE Trans. Dielectr. Electr. Insul., Vol. 11, pp. 620-630, 2004.
 - [29] I. Ramirez, E. A. Cherney, S. Jayaram, and M. Gauthier, "Nanofilled silicone dielectrics prepared with surfactant for outdoor insulation applications", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, pp. 228-235, 2008.
 - [30] M. a. R. M. Fernando and S. M. Gubanski, "Leakage current patterns on contaminated polymeric surfaces", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 688-694, 1999.
 - [31] M. a. R. M. Fernando and S. M. Gubanski, "Leakage currents on non-ceramic insulators and materials", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 660-667, 1999.
 - [32] T. Sorqvist and S. M. Gubanski, "Leakage current and flashover of field-aged polymeric insulators", IEEE Trans. Dielectr. Electr. Insul., Vol. 6, pp. 744-753, 1999.
 - [33] T. Sorqvist and A. E. Vlastos, "Performance and ageing of polymeric insulators", IEEE Trans. Power Delivery, Vol. 12, pp. 1657-1665, 1997.
 - [34] T. G. Gustavsson, S. M. Gubanski, H. Hillborg, S. Karlsson, and U. Gedde, "Aging of Silicone Rubber under ac or dc Voltages in a Coastal Environment", IEEE Trans. Dielectr. Electr. Insul., Vol. 8, pp. 1029-1039, 2001.
 - [35] STRI, STRI Guide 1/92 Hydrophobicity Classification.
 - [36] Z. Cheng, X. Liang, Y. Wang, X. Wang, Y. Zhou, and Z. Li, "Investigation on composite insulators in contaminated areas", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 327-331, 2002.
 - [37] R. S. Gorur, J. Montesinos, R. Roberson, J. Burnham, and R. Hill, "Mold growth on nonceramic insulators and its impact on electrical performance", IEEE Trans. Power Delivery, Vol. 18, pp. 559-563, 2003.
 - [38] L. Lan and R. S. Gorur, "Computation of AC wet flashover voltage of ceramic and composite insulators", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, pp. 1346-1352, 2008.
 - [39] R. Boudissa, S. Djafri, A. Haddad, R. Belaicha, and R. Bearsch, "Effect of insulator shape on surface discharges and flashover under polluted conditions", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, pp. 429-437, 2005.
 - [40] S. Venkataraman and R. S. Gorur, "Prediction of flashover voltage of non-ceramic insulators under contaminated conditions", IEEE Trans. Dielectr. Electr. Insul., Vol. 13, pp. 862-869, 2006.
 - [41] M. Matthieu, "Moving Towards a Complete 'On-line Condition Monitoring' Solution", Int'l. Conf. Electricity Distribution, Paper No. 81, pp. 12-15, 2003.
 - [42] M. Matthieu, "Innovative Asset Management and targeted investments using on-Line partial discharge monitoring & mapping techniques", Int'l. Conf. Electricity distribution, Paper No. 0551, pp. 21-24, 2007.
 - [43] WG-B2.21, "Guide for the Assessment of Composite Insulators in the Laboratory after their Removal from Service", CIGRE Technical Brochure No. 481, p. 63, 2011.
 - [44] P. J. Baird, H. Herman, and G. C. Stevens, "Non-destructive Condition Assessment of Insulating Materials in Power Transformers", Int'l. Sympos. Electr. Insulating Materials, pp. 425-428, 2005.
 - [45] P. D. Blackmore, D. Birtwhistle, G. a. Cash, and G. a. George, "Condition assessment of EPDM composite insulators using FTIR spectroscopy", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 132-141, 1998.
 - [46] A. H. El-Hag, S. H. Jayaram, and E. A. Cherney, "Calculation of leakage current density of silicone rubber insulators under accelerated aging conditions", J. of Electrostatics, Vol. 67, pp. 48-53, 2009.
 - [47] J. Montesinos, R. S. Gorur, and J. Burnham, "Estimation of Flashover Probability of Aged Nonceramic Insulators in Service", IEEE Trans. Power Delivery, Vol. 15, pp. 820-826, 2000.
 - [48] C. S. Engelbrecht, R. Hartings, and J. Lundquist, "Statistical dimensioning of insulators with respect to polluted conditions", IEE Proc.-Gener. Transm. Distrib., Vol. 151, pp. 321-326, 2004.
 - [49] I. Ramirez-Vazquez, R. Hernandez-Corona, and G. Montoya-Tena, "Diagnostic of nonceramic insulators aged in a salt fog chamber by using electric field sensor", IEEE Int'l. Sympos. Electr. Insul., pp. 471-474, 2004.
 - [50] Y. C. Chen, C. R. Li, X. Liang, and S. Wang, "The influence of water and pollution on diagnosing defective composite insulator by electric field mapping", Int'l. Sympos. High Voltage Eng., pp. 345-348, 1999.
 - [51] G. H. Vaillancourt, S. Carignan, and C. Jean, "Experience with the detection of faulty composite insulators on high-voltage power lines by the electric field measurement method", IEEE Trans. Power Delivery, Vol. 13, pp. 661-666, 1998.
 - [52] R. Hartings, "Electric fields along a post insulator: ac-measurements and calculations", IEEE Trans. Power Delivery, Vol. 9, pp. 912-918, 1994.
 - [53] Y. Liang, L. Ding, C. R. Li, K. Yang, and A. T. Samples, "The TSC Characteristics of HTV Composite Insulators", IEEE Int'l. Sympos. Electr. Insul., pp. 190-192, 2006.
 - [54] M. Ehsani, G. R. Bakhshandeh, J. Morshedian, H. Borsi, E. Gockenbach, and A. A. Shayegeani, "The dielectric behavior of outdoor high-voltage polymeric insulation due to environmental aging", European Trans. Electr. Power, Vol. 17, pp. 47-59, 2007.
 - [55] M. Ehsani, H. Borsi, E. Gockenbach, J. Morshedian, G. R. R. Bakhshandeh, and A. a. A. Shayegeani, "Effect of aging on dielectric behavior of outdoor polymeric insulators", IEEE Int'l. Conf. Solid Dielectrics, Vol. 1, pp. 312-15, 2004.
 - [56] I. A. D. Giriantari, "Condition Monitoring of Composite Insulators Using Partial Discharge Analysis", IEEE 8th Int'l. Conf. Properties and Applications of Dielectric Materials, 2006, pp. 52-56.

- [57] 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.
- [58] R. Hackam, "Outdoor high voltage polymeric insulators", Int'l. Sympos. Electr. Insulating Materials, pp. 1–16, 1998.
- [59] R. Hartings, "The AC-behavior of a hydrophilic and hydrophobic post insulator during rain", IEEE Trans. Power Delivery, Vol. 9, pp. 1584–1592, 1994.
- [60] T. Tanaka, T. Okamoto, K. Nakanishi, and T. Miyamoto, "Aging and related phenomena in modern electric power systems," IEEE Trans. Electr. Insul., Vol. 28, pp. 826–844, 1993.
- [61] J. Mackevich and S. Simmons, "Polymer outdoor insulating materials. II. Material considerations", IEEE Electr. Insul. Mag., Vol. 13, No. 5, pp. 10–16, 1997.
- [62] J. Goudie, M. Owen, and T. Orbeck, "A review of possible degradation mechanisms of silicone elastomers in high voltage insulation applications", IEEE Conf. Electr. Insul. Dielectr. Phenomena, Vol. 1, pp. 120–127, 1998.
- [63] T. G. Gustavsson, S. Gubanski, H. Hillborg, and U. Gedde, "Aging of silicone rubber materials in marine environment", IEEE Int'l. Sympos. Electr. Insul., pp. 188–192, 2000.
- [64] S. Gubanski, "Modern outdoor insulation-concerns and challenges", IEEE Electr. Insul. Mag., Vol. 21, No. 6, pp. 5–11, 2005.
- [65] I. Ramirez, S. Jarayam, and E. A. Cherney, "Performance of silicone rubber nanocomposites in salt-fog, inclined plane, and laser ablation tests", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, pp. 206–213, 2010.
- [66] A. H. El-Hag, S. H. Jayaram, and E. A. Cherney, "Influence of shed parameters on the aging performance of silicone rubber insulators in salt-fog", IEEE Trans. Dielectr. Electr. Insul., Vol. 10, pp. 655–664, 2003.
- [67] E. da Silva and S. M. Rowland, "Natural, Rotationally Asymmetric Ageing of Composite Insulators", IEEE Int'l. Sympos. Electr. Insul., pp. 530–534, 2008.
- [68] E. Da Silva and S. M. Rowland, "In-Service Surface Degradation of MV Composite Insulators under Severe Environmental Conditions and Low Electric Stress", IEEE Conf. Electr. Insul. Dielectr. Phenomena, pp. 224–227, 2008.

Antonios Tzimas (M'08) was born in Volos, Greece in 1979. He received the B.Eng. (2001) and M.Sc. (2003) degrees in electrical and electronic engineering from the University of Leicester where after completing his national service duties in Greece he returned to study for the Ph.D. degree on ageing properties of cross linked polyethylene. He received the degree in 2008. He then joined the National Grid High Voltage laboratory at the University of Manchester as Post-Doctoral researcher. Currently he is working on the ageing properties of outdoor composite insulators as well as cable insulation. In 2011 he became the chair of IEEE Dielectrics and Electrical Insulation Society GOLD membership and part of the society's membership committee. He is also board member of an annual Conference on Electrical Insulation and Dielectric Phenomena (CEIDP).

Elizabeth Da Silva (SM'05) was born in Caracas, Venezuela. She graduated in electrical engineering in 1991 and obtained the MSc. degree in 1995 from the Simon Bolivar University (USB), Venezuela, with honors in both theses. She received the Ph.D. degree from the University of Manchester, UK, in 2012. She worked as academic of the Conversion and Transportation of Energy Department and a research member of the HV and Insulation Research Group at the USB (1991–2011). She lectured on high voltage and power systems and was a consultant for utilities, oil companies and manufacturing industries. Her research activities mainly bear on solid dielectric degradation under multi-stress (cables, organic chains, epoxy resins, etc.). She has been an IEEE DEIS member since 2001 and a DEIS representative in the IEEE-WIE affinity group. She is currently working as High Voltage Technical Lead in TE Connectivity UK at the Rail Department.

Simon M. Rowland (SM'07) was born in London, England. He completed the B.Sc. degree in physics at The University of East Anglia and the Ph.D. degree at London University. He was awarded the IEE Duddell Premium in 1994 and became a FIEE in 2000. He has worked for many years on dielectrics and their applications and has also been Operations and Technical Director within multinational manufacturing companies. He joined The School of Electrical and Electronic Engineering in The University of Manchester as a Senior Lecturer in 2003, and was appointed Professor of Electrical Materials in 2009. He is currently President of the IEEE Dielectric and Electrical Insulation Society.

Martin Queen was born in Glasgow, Scotland in 1984. He received the B.Eng (Hons) (2007) degree in electrical and electronic engineering from the University of Strathclyde. He joined Scottish Hydro Electric Transmission in 2007 and subsequently went on to manage the Transmission Research and Development portfolio including projects investigating the ageing effects on composite insulators. In 2012 he moved to TNEI Services Ltd where he currently works as a Senior Electrical Engineer working on Front End Engineering Design and Low Carbon Networks Projects.