Asset Management Frameworks for Outdoor Composite Insulators

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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

Manuscript received on 6 June 2012, in final form 23 July 2012.

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.

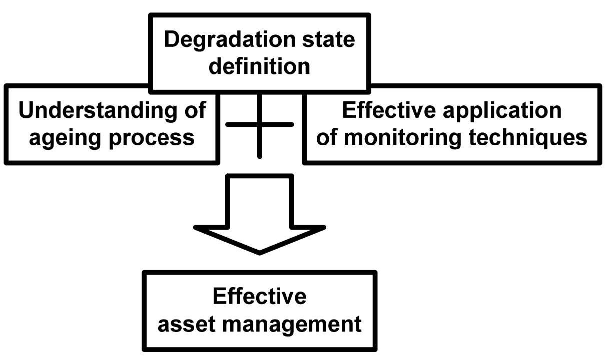


Figure 1. Illustration of effective asset management logic.

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.

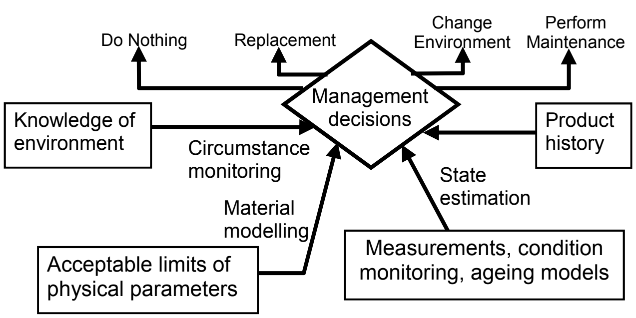


Figure 1. First layer of the asset management model adapted from [23].

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 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,

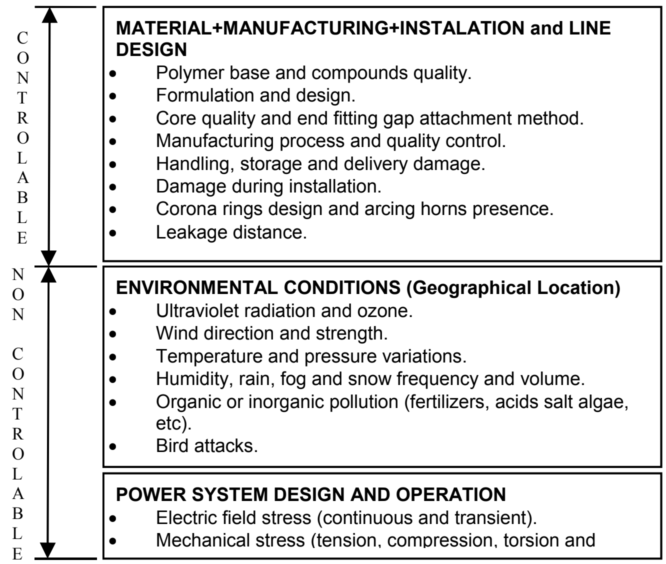


Figure 2. Factors that affect the ageing rate of composite insulators.

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 equivalent data set. Device tests are concerned with the

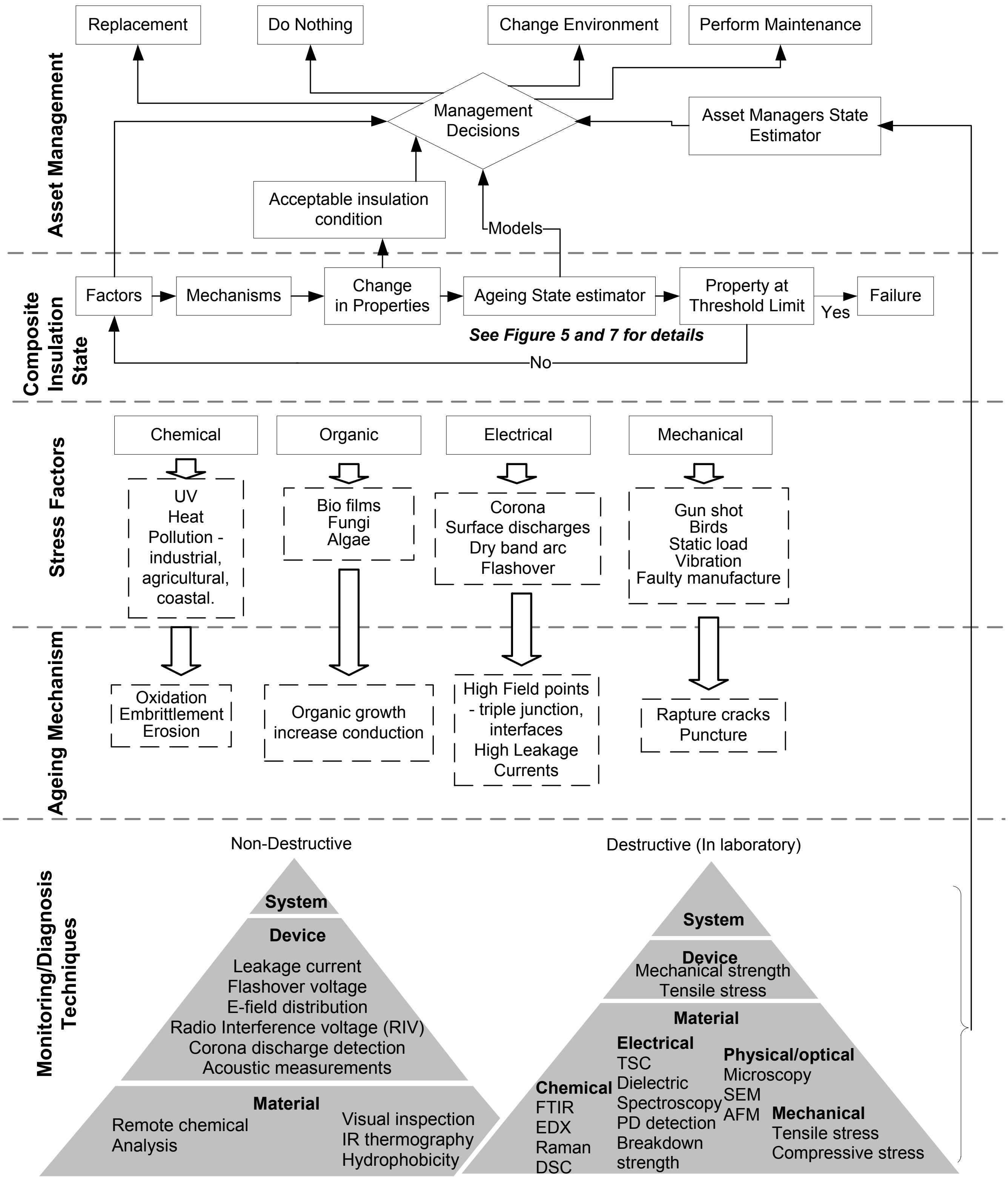


Figure 3. A multifactor framework adapted from [23] and applied on outdoor composite insulators.

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.

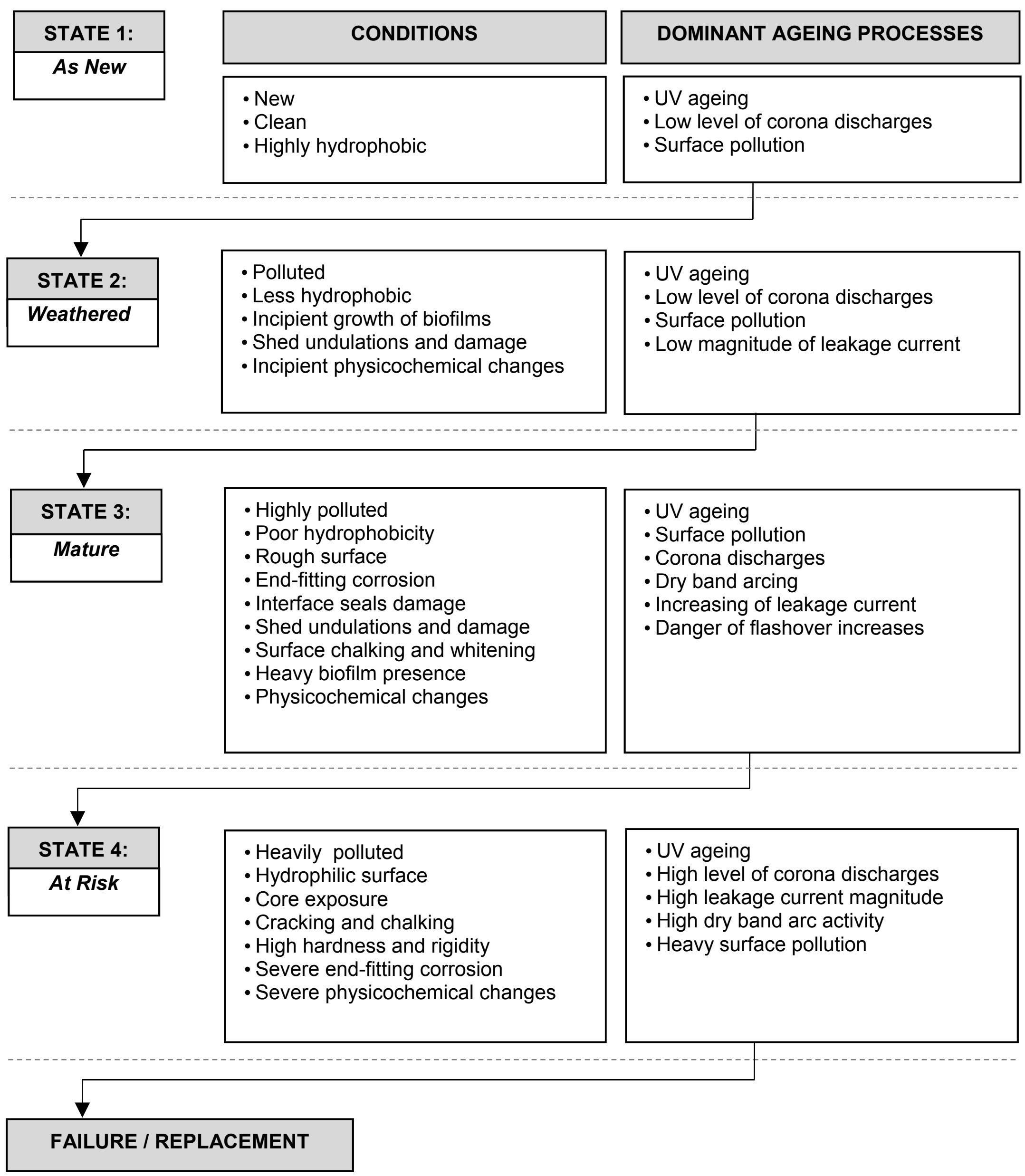


Figure 4. Ageing state estimator.

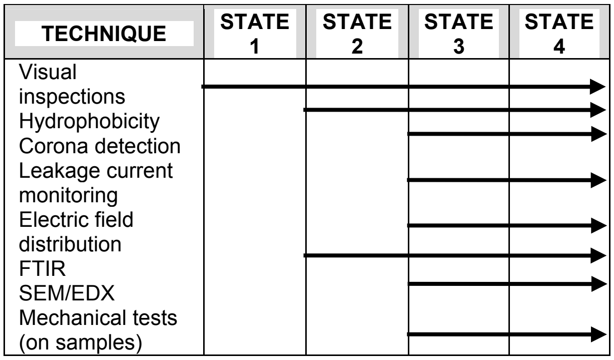


Figure 5. The arrows indicate identification of changes in states defined in Figure 5.

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

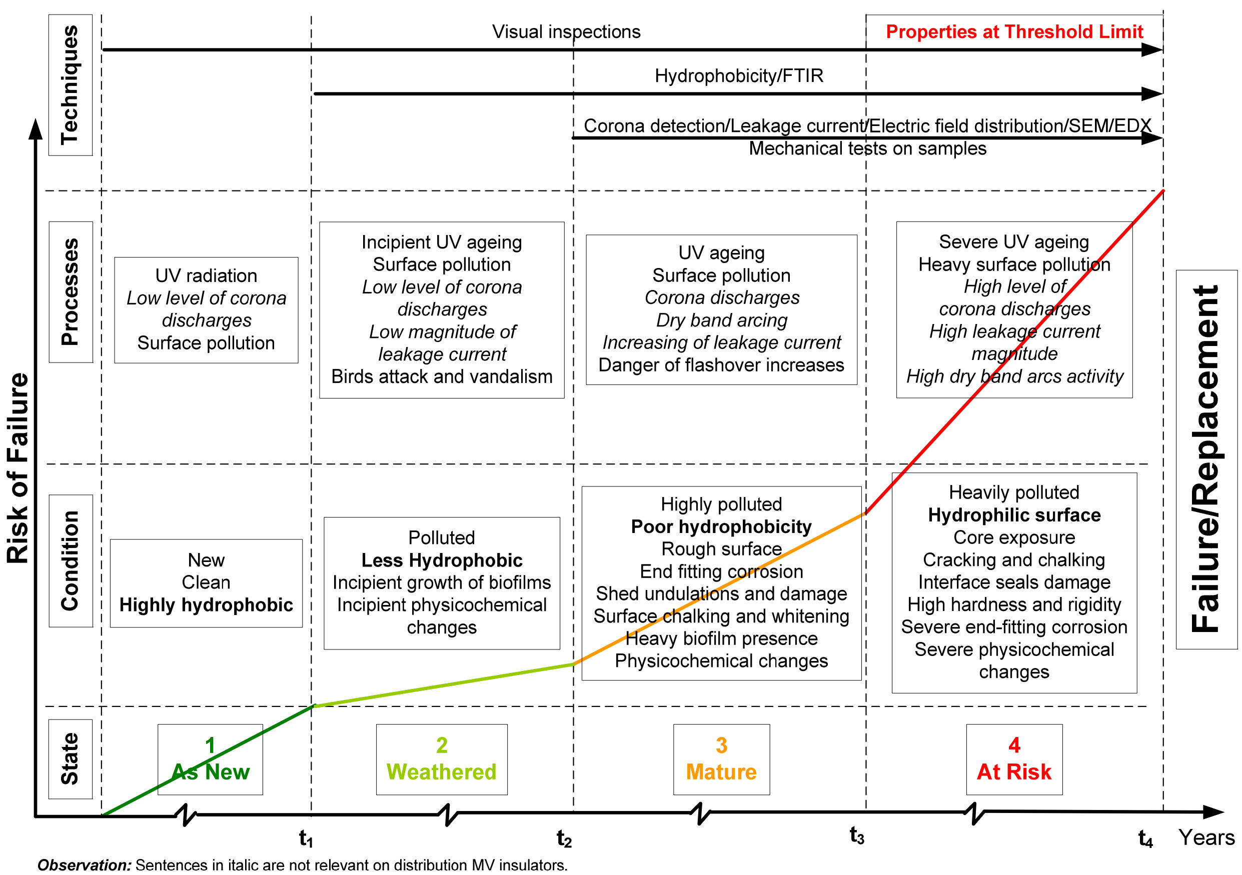


Figure 6. Ageing state estimator for composite insulators superimposed risk of failure and appropriate techniques to monitor its condition effectively at each state.

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.

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,

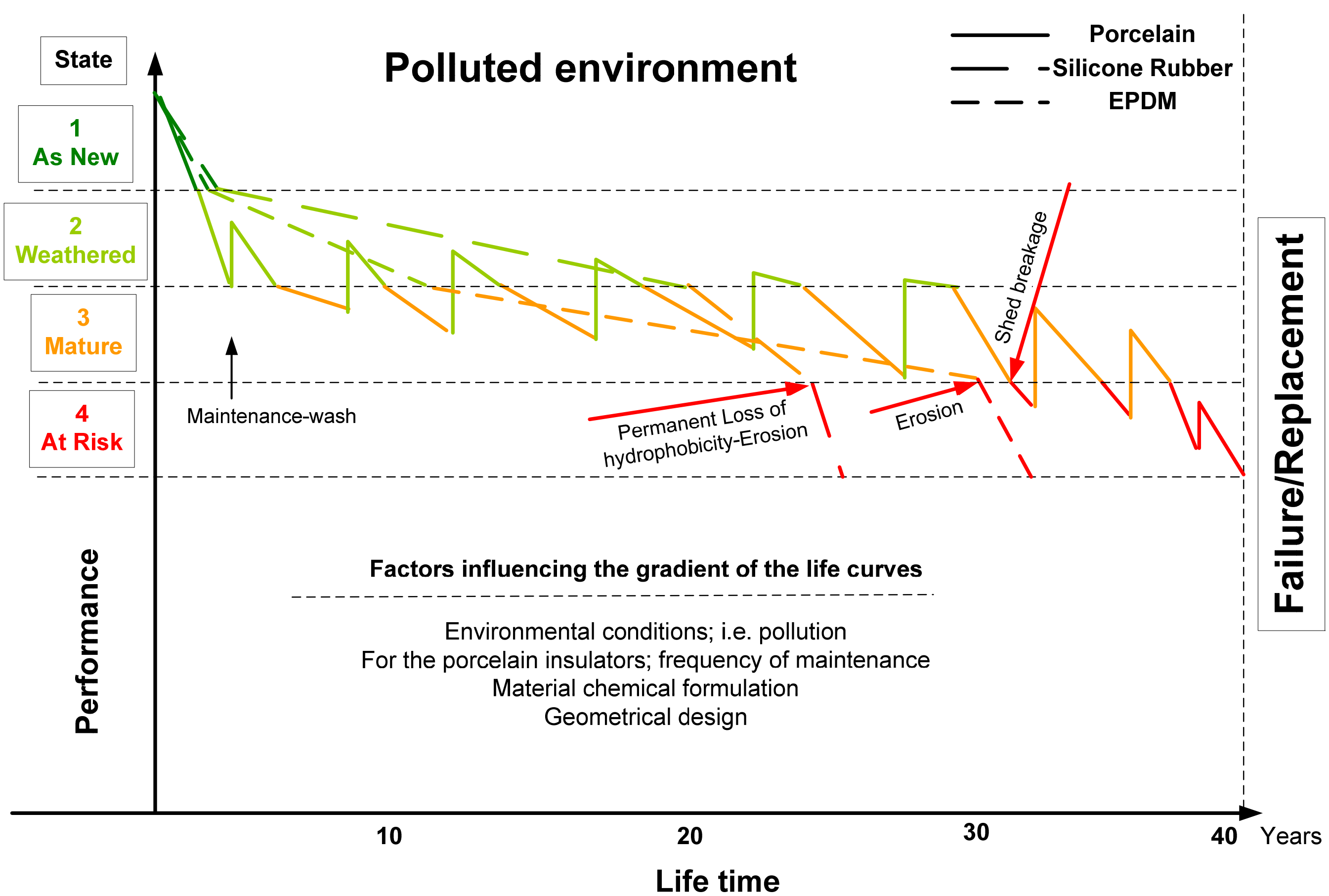


Figure 7. Suggested performance of three different insulating materials under polluted environment.

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.

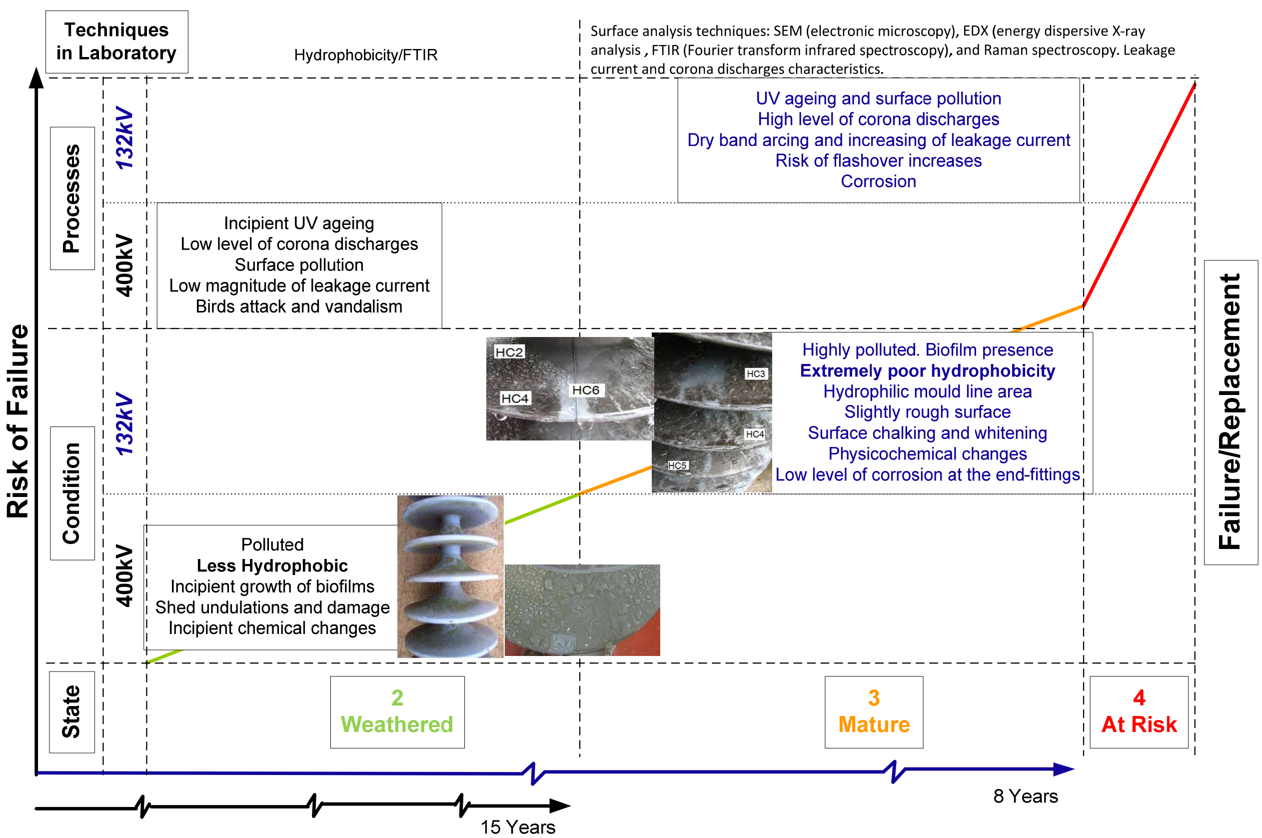
The 11 kV distribution insulators were installed in a horizontal orientation and they have been in service for six years near the UK coast, in two locations Circuit I and II, [67, 68]. Circuit I was located in farmland and Circuit II was adjacent to a farm and a residential area. They are located within 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.

5 CONCLUSIONS

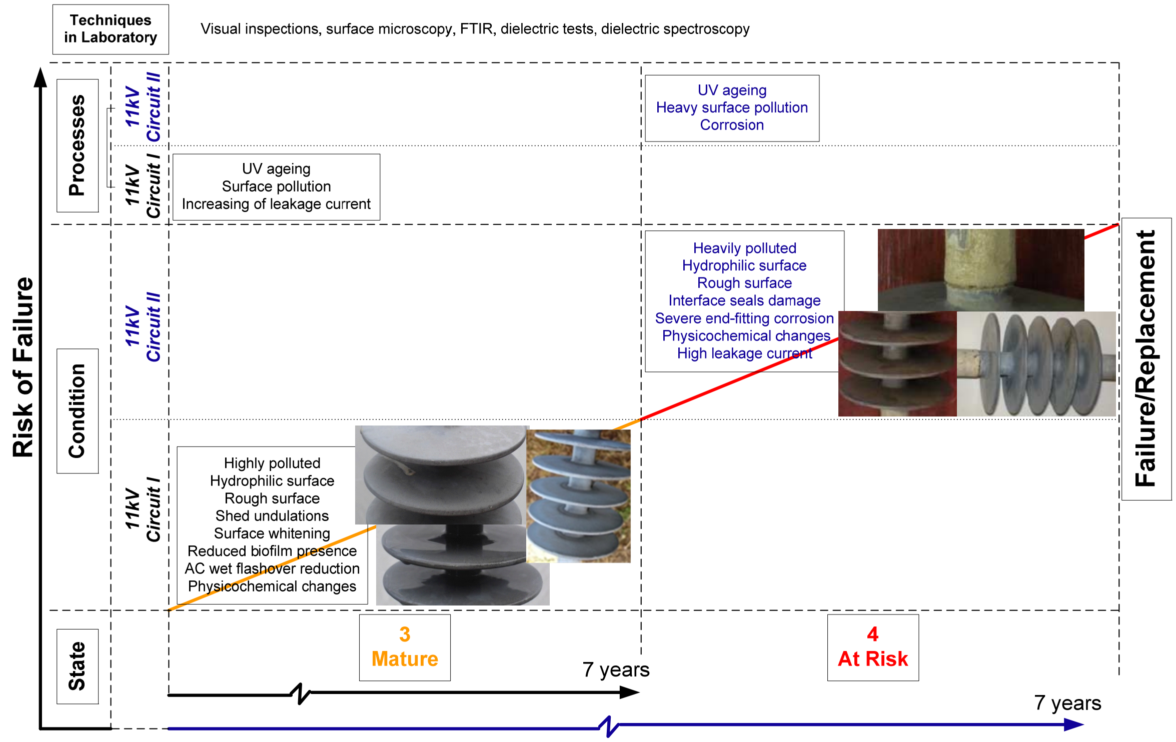
A framework to assist asset management of composite insulators has been developed from a previous generic one. An ageing state flow chart specific to composite insulators has been introduced. Each state in the flow chart defines the condition of the insulation and possible ageing processes that are taking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



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.

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