A Framework Linking Knowledge of Insulation Ageing to Asset Management

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A multifactor ageing framework is described which links the work of those involved in studying ageing of dielectrics to the needs of those involved in asset management and network performance

Introduction

Change is inevitable. After conception every entity embarks upon a journey of change and finite life. This journey is often curtailed by apparently unpredictable events dispersed within a relatively steady environment. Plant operating in a power system reflects this picture. Nonetheless, in power networks of the industrialised world a significant proportion of equipment is operating well beyond its design life. In urban areas, cables which are literally one hundred years old still carry power, while transformers operate well beyond the 40 years originally envisaged. These functional, ageing assets are a testament to the success of the many insulation systems employed [1]. A characteristic of any ageing asset is a reduction in reliability. Hence the need for maintenance, providing remedial action to economically sustain reliability whilst prolonging useful life and enabling planned asset replacement. Thus the practice of asset management is a growing profession within power utilities.

Asset management has been described as the evaluation of the life cycle costs of equipment and systems versus quality of supply according to requirements and regulations [2]. It has become paramount for successful and reliable network operation. However, evaluation of life cycle costs is far from a straightforward task, especially for insulation systems. Such an evaluation must incorporate damage models estimating the condition of the components, and an understanding of future operating conditions. Research has produced many insulation- and process-specific models which have limited applicability to real insulation systems. Uncertainties tend to lead to conservative decisions, leading to higher asset maintenance or replacement costs than are really necessary [3]. This illustrates the need for a tool to improve the understanding of ageing assets by modelling the operating stresses which real insulation systems experience.

The drive to increase production of renewable and distributed energy has resulted in changes in load flows on the network, while demand-side management schemes cause variation in load demands. A steady increase in the number of power electronic devices results in fluctuations of power quality due to impulse transients and harmonic content. As a result there is a gradual change in the working environment experienced by insulation systems [4-6] and as networks undergo this evolutionary process, the insulation systems will age differently. Consequently, future failure modes may deviate from the historical norm and traditional heuristics may no longer facilitate the forecasting of behaviour of in-service insulation systems.

The Challenge

Figure 1 provides an image of the interaction of the stress factors which influence the mechanisms of failure, how this relates to the asset manager and the decisions which must be taken.

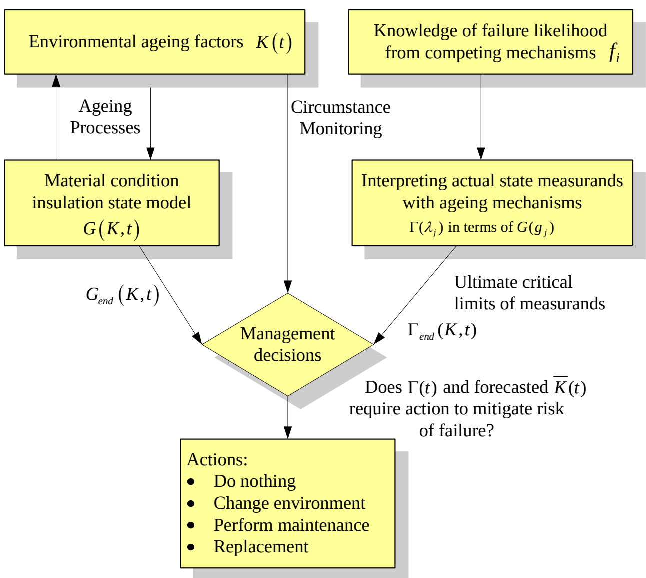

Figure 1. Multifactor framework complementing asset management

The network environment is modelled by a time-dependant vector *K(t).* This environment ages the material through a range of processes and results in a material state we describe by another vector *G(t).* The asset manager can measure the environment by what we term 'circumstance monitoring' [1], through variables such as temperature and voltage. Measurements of the plant itself can also be made through 'condition monitoring', producing a set of measurands, $\Gamma(t)$. The role of the physicist, material scientist and chemist is then to link the measurements to the real state of the materials and through models of ageing and reliability against which the asset manager can make judgements. As a result, the asset manager has tactical decisions concerning maintenance levels and loading profiles along with strategic decisions including 40-year investment plans.

The intention here is to provide a framework against which all parties can share their knowledge, and indeed identify their areas of ignorance for future development. The framework is broken into five integrated layers. The asset management layer is the first and uppermost of the model.

The way in which the stresses and materials interact as a result of ageing processes is represented in Figure 2. Densley [7] previously emphasized that to make justifiable decisions concerning ageing infrastructure, network operators must be knowledgeable concerning the operating conditions influencing the ageing factors, ageing mechanisms, rate of ageing, failure mechanisms and the criteria necessary to determine the corrective actions. There have been numerous ageing flow diagrams and conceptual models capturing the effect of single stress factors on the path of failure for any insulation system, including those in [8], and more specific combined effects of stress factors under wet and dry conditions for polymeric insulation [9]. These flow diagrams have provided the foundation for the development of a multifactor framework leading the transformation from a heuristic approach towards a scientific approach of insulation life prediction and ultimately asset management. Previous approaches have tended to be 'bottom-up', led by physicists and chemists. A framework is now required which meets the needs of asset managers more directly, but coherently links their business models with the models of ageing assets.

Consider a single component such as a cable or a transformer operating in a network. This component is subjected to 'multifactor ageing'. As time passes, these stress factors may degrade the insulation by a dominant process until, as a result of a change in the material, a different mechanism takes over. If this latter mechanism leads rapidly to failure, the critical point effectively determining the useful life of the insulation is the time at which the new mechanism is initiated, and is termed here the 'end point'. Figure 2 is a flowchart illustrating this sequence. Identifying this 'end point' is key for asset managers. Forecasting the end point enables effective asset replacement programmes. Understanding the ageing process and changes in the materials allows active management of existing assets.

The flowchart of ageing in Figure 2 is modified to make the second layer of the framework, lying underneath the asset management layer.

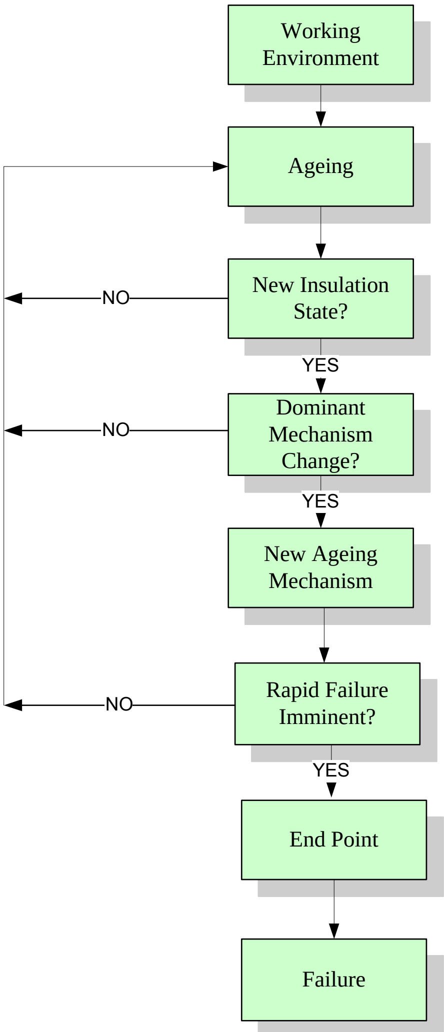

Figure 2. Insulation failure flowchart

The Role and Impact of Quality of Supply

Non power-frequency disturbances impact negatively on the quality of supply, whether they are transients, short or long-term. Figure 3 is an illustration of disturbances (outer circle) and their links to the characteristic descriptions of electrical stress factors (inner circle) [10].

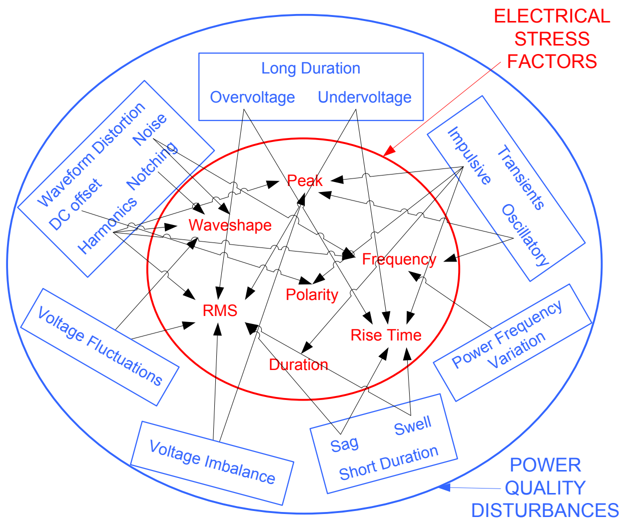

Figure 3. Links between power quality disturbances and electrical stress factors [10]

Short duration sags and swells, as well as long duration overvoltages and undervoltages, impact the rms, amplitude and rise-time factors. The rise-time denotes a rate of change of voltage which the insulation experiences, for example under fault conditions. Swells and overvoltages can represent significant increased electrical stressing depending on the peak, rms and duration of such disturbances.

An insulation component at a particular site in the network can be electrically vulnerable due to weak system impedance and so suffer from a poor quality of supply e.g. as a result of harmonics. A key question is “do we know the role the various disturbances play in ageing and failure processes of this insulation component?”

Harmonics can be described as a frequency domain representation of time domain occurrences [3] and may significantly increase the peak and rms values of an electric field within a dielectric, increasing dielectric losses whilst creating a temperature rise within the dielectric [11]. High frequency harmonics often lead to increased Joule heating and mitigation can be achieved by de-rating the equipment [12]. However, thermal stressing of the dielectric still occurs. This can be decoupled into the stress factors responsible for electrical and thermal stresses. Thermal runaway of the insulation due to high harmonic currents is prevented when protection on the network is engaged. Research conducted using the 3^{rd}, 5^{th} and 7^{th} harmonic components [13, 14] confirmed that the composite waveform may increase the voltage peak of the waveform and the likelihood of partial discharge inception depending on the phase and magnitude of the harmonic component [15, 16]. The triplen harmonics (multiples of the 3^{rd} harmonic) are usually filtered as a result of propagating across the power network but pose a serious threat by thermally overloading neutral cables. Hence, the 5^{th} and 7^{th} harmonic components would generally be the most influential to power quality and potentially to insulation system failure at the transmission level.

On real networks there may be an unacknowledged harmonic contribution. This may also be true for reported experimental laboratory work. It is therefore important to know thresholds at which power quality affects ageing. Comprehending the effect of the abnormalities in any resultant waveform experienced by the insulation is crucial to defining which time-domain wave-shape features and characteristics are most influential to insulation degradation. Only then can the harmonic combinations which most affect the insulation be identified. Under multi-stress conditions including electrical and thermal stresses, plant items suffer significant life reduction in the presence of harmonics and an equivalent reduction in reliability [11].

Harmonics are a steady-state occurrence compared to lightning and switching surges which can cause large numbers of transients on power networks. For example, SF_6 and vacuum switchgear produce hundreds of surges during switching operations with 300ns rise times and rates of 200-3000 surges per second [17]. Therefore the time-domain representation of the waveform which we describe as an electrical stress factor must be linked to the insulation performance. Network operating conditions are complex and providing a deterministic approach to insulation life prediction is significantly more difficult when considering the synergy of the many stress factors.

Multifactor Framework

Ageing factors can be represented by a matrix $K(t)$ of insulation ageing or stress factors, as illustrated in the Equation 1.

$$K(t) = \text{Stress Factors} = \begin{pmatrix} K_1(t) \\ K_2(t) \\ K_3(t) \\ K_4(t) \\ K_5(t) \\ K_6(t) \end{pmatrix} = \begin{pmatrix} \text{Mechanical} \\ \text{Physical} \\ \text{Electrical} \\ \text{Thermal} \\ \text{Environmental} \\ \text{Chemical} \end{pmatrix} \quad (1)$$

IEC 60505 [8] defines predominant stresses as electrical, thermal, environmental or mechanical. Such a clear distinction can be both useful and confining. Certainly for ‘Evaluation and Qualification of Electrical Insulating Systems’ the distinction may be of value. In service however, equipment is normally designed so no one stress is dominant. Each of these major stress factors needs to be further broken down into sub-factors which can enhance, as well as compete with, each other. The six factors described here (1) are used to assist in identifying the subfactors, and are not regarded as exclusive of each other. The factor representation has been established as a function of time, yielding some measurable form of stress on the insulation system. The electrical stress factors outlined in Figure 2 provide examples of the sub-factors which are illustrated in Figure 4. In Figure 4, the crosses denote key characteristic properties of the stress types provided. This helps define the working environment of the insulation component.

Electrical

	AC	DC	Impulse
Magnitude		x	x
Peak	x		x
RMS	x		
Wave Shape	x		
Rise Time			x
Duration	x		x
Polarity		x	x
Frequency	x		x

Figure 4. Electrical stress factors.

Failure of a given component can be regarded as a competition between a number of ageing mechanisms represented as a probability distribution function $f_i(K(t))$ which is also a function of time and of the stress factors $K(t)$. This might, for example, represent the probability of the failure of insulation through electrical tree growth, partial discharges or thermal runaway, the likelihood of each being dependent on time, and the ageing factors up to time t. In the framework proposed the stress factors present one layer (the second) of the model, and the ageing mechanisms another layer (the third).

Dominant mechanisms under electrical stress factors include spacecharge trapping, partial discharges, water treeing and electrical treeing. These ageing mechanisms can complement or compete with each other with one mechanism dictating the failure mode whilst another dictates the time to failure. For example, the key rate-determining ageing process in an XLPE cable might be water tree growth. However, water trees in themselves do not cause failure, rather they create conditions for electrical trees to initiate, which can then lead to failure. Thus these mechanisms may have a chronological sequence to their dominance. This is not always the case, as other stress factors can influence mechanism dominance in the working environment; one such example is when mechanical compressive stress leads to hot spots from thermal gradients causing insulation embrittlement and eventually compromising the mechanical strength of the cable, resulting in failure.

To provide some estimate of the degradation due to these mechanisms and thus the ageing state of the insulation, physical data capture is needed. Thus measurands are essential to the asset manager. Measurands are measurements of physical quantifiable properties, acquired either in-service or under laboratory conditions, which assist in describing the aged state of the dielectric. Again referring to electrical stress factors such as magnitude and peak which influence electrical ageing mechanisms, partial discharges occur and are a distinguishable characteristic diagnostic at higher voltage levels which can be used to characterise void formation and defect development [18, 19]. Thus partial discharge detection is one of the preferred methods of condition monitoring at high voltage. Additionally, this illustrates that mechanisms are also dependent on the operating voltage. Different mechanisms yield different measurands, some of which can be field based and some not. Consider electrical tree detection. Whilst the cable insulation is in service, this is only possible through partial discharge detection and pattern recognition. Even this method is not fully accurate but a good example is provided in [20, 21]. However, under laboratory conditions, electrical tree growth can be detected utilizing electroluminescence detection including photon counting and spectral frequency analysis [22-25]. While such tasks are bounded by physical limitations for in-service equipment, there is a need for new measurands and diagnostic tools to help cross these restrictions [10]. The measurands which allow an estimation window of material condition present another layer in the proposed model.

Techniques are well developed for the assessment of transformer oils sampled in service [26]. Dissolved gas analysis [27-29] as well as furans analysis [30] determine the state of the oil and the solid insulation of the transformer windings respectively. The end result in both scenarios is a series of measurements of insulation properties which lead to conclusions about the state of the insulation system and transformer lifetime estimates.

Through consideration of a material's state, asset managers are no longer confined to considerations of 'time to failure' or 'likelihood of failure' of the insulation. Asset managers may now consider the likelihood of the insulation reaching a specific measurable condition deemed critical. Ultimately the task is to seek the time or stress levels required to take the system to the final failure path identified in Figure 2. This is the point at which the component is no longer fit to operate in the given conditions and no longer has limited useful life. Examples of numerically defined 'end points' might include; oxidative state, void size or electrical tree length.

The associated probability distributions denoting the physical conditions are written $g_j(K(t),)$ representing the j^{th} insulation property. These distributions depend upon the insulation ageing stress factors and the history of the component. Each distribution g_j reflects the physical condition of the material and leads to an ageing state matrix $G(t)$ (Equation 2). However, the asset manager can only assemble a matrix from measurands which we term the ageing state estimation matrix $\Gamma(t)$ (Equation 3) providing a window onto the evolution of the material from the input of real measurands λ_n. This is now normally termed 'condition monitoring'.

In summary, the actual measurements, λ_n, of physical condition provide the method for assembling a 'state estimation' matrix $\Gamma(t)$. Ideally the physical measurands, λ_n, give direct information on the real physical condition $G(t)$ and the processes f_i, but identifying these links remains one of the major challenges for researchers in the area. This is why continued work on ageing models is critical to improved asset management and ultimately network reliability.

$$G(t) = \text{Actual Material State} = \begin{pmatrix} g_1(t) \\ g_2(t) \\ g_3(t) \\ g_4(t) \\ g_5(t) \\ g_6(t) \\ \cdots\cdots \\ g_k(t) \end{pmatrix} = \begin{pmatrix} \text{void size} \\ \text{oxidative state} \\ \text{mositure content} \\ \text{morphology} \\ \text{dissolved gases} \\ \text{tree length} \\ \cdots\cdots\cdots \\ \end{pmatrix} \quad (2)$$

$$\Gamma(t) = \text{State Estimation Matrix} = \begin{pmatrix} \lambda_1(t) \\ \lambda_2(t) \\ \lambda_3(t) \\ \lambda_4(t) \\ \lambda_5(t) \\ \lambda_6(t) \\ \cdots\cdots \\ \lambda_n(t) \end{pmatrix} = \begin{pmatrix} \text{dielectric loss} \\ \text{void size} \\ \text{tree length} \\ \text{mositure content} \\ \text{thermal capacity} \\ \text{pd magnitude} \\ \cdots\cdots\cdots \\ \end{pmatrix} \quad (3)$$

From previous considerations we see that the 'end-point' is better defined as the ultimate critical state $G_{end}(t)$. This state is a function of the real-time working environment and so should be written as a function of working stresses $G_{end}(K,t)$. This must be interpreted into critical values of measurands yielding an equivalent $\Gamma_{end}(K,t)$, a multidimensional critical set of measurands which also depend on the working environment. By forecasting $\Gamma(K,t)$ and identifying the likelihood of reaching any value of $\Gamma_{end}(K,t)$, a likelihood of failure can be determined in time as a function of stress $K(t)$.

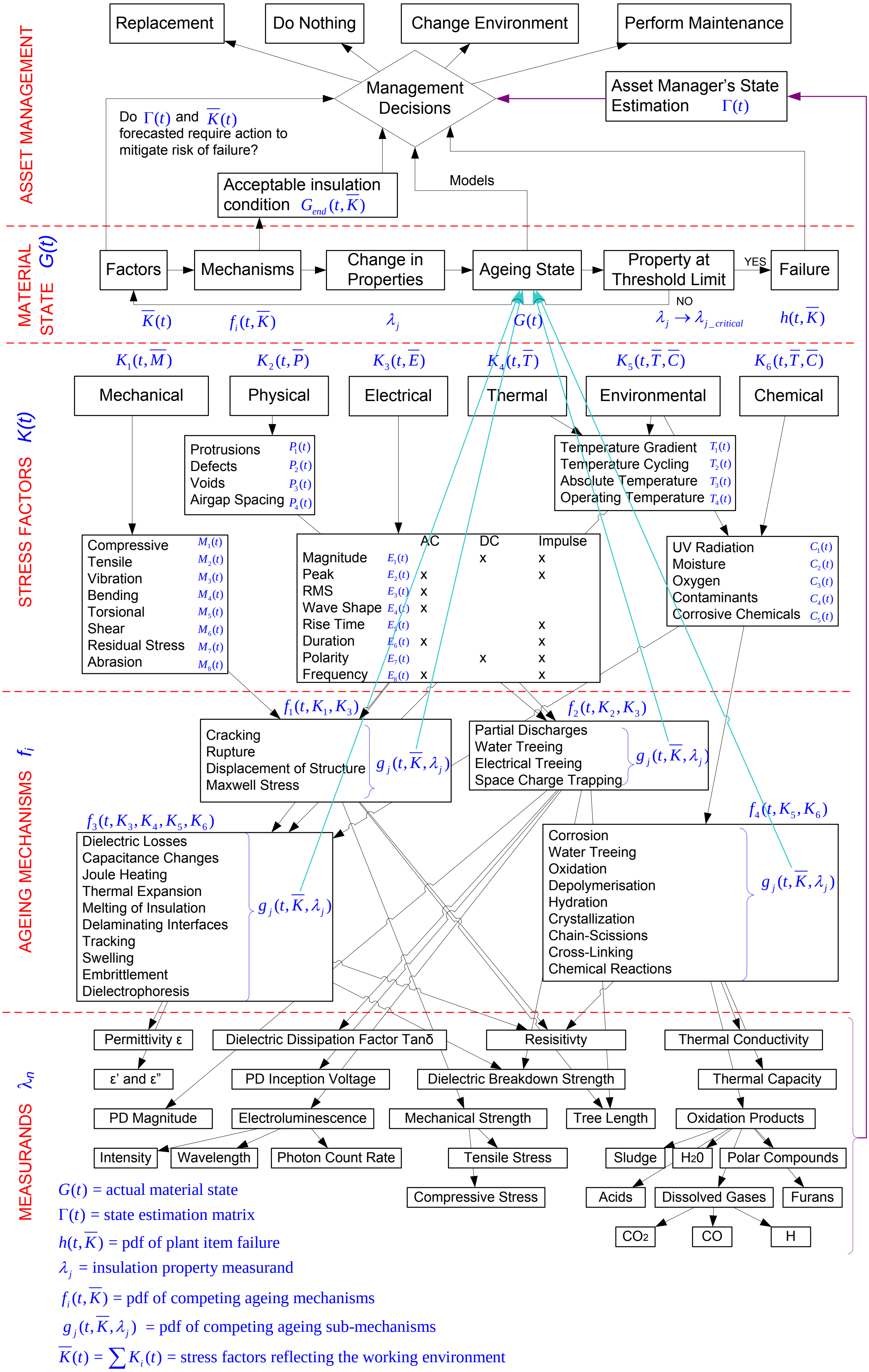

Figure 5. Multifactor framework of insulation life

The multifactor framework described in this paper consists of 5 vertically integrated layers, which are:

(i) asset management decision making
(ii) the actual material or equipment state, $G(t)$
(iii) the working environment, $K(t)$
(iv) ageing mechanisms, $f_i(t)$
(v) measurands giving an estimation material state, $\Gamma(t)$

These are summarised on a single page in Figure 5. Figure 5 identifies some of the details of ageing factors, ageing mechanisms, and measurands which might be considered by the scientist, engineer and ultimately asset manager. Although complex at first glance, the framework provides a structured approach to linking the top level of asset management, through knowledge of the material state, factors or stresses which age the dielectric, and ageing mechanisms. This is depicted in Figure 6, highlighting the movement of information to the asset manager.

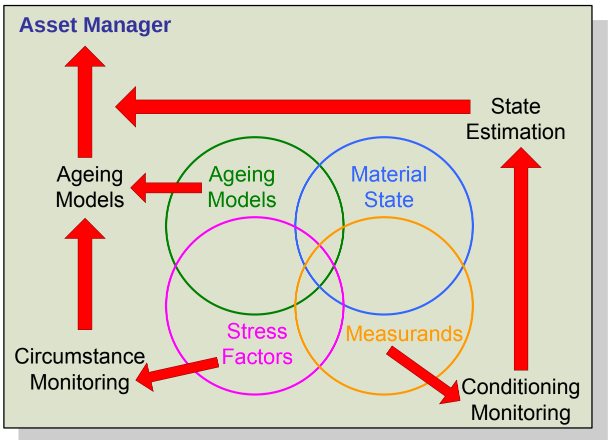

Figure 6. Flow of information to the asset manager

The stochastic nature of the failure of insulation must be taken into consideration. Once a property is at a critical limit (end-point) it is not always certain that failure will occur immediately. Thus, probabilistic representations of the working environment and material states are essential. Therefore the link between asset management and insulation ageing allows focus on specific stress factors which control insulation ageing in a given environment. Through knowledge of the physics and chemistry of ageing, a limit on the condition of the plant may be set in terms of measurands of the condition monitoring, $\Gamma_{end}(K,t)$, which can trigger actions such as maintenance or asset replacement [3]. This forms the top asset management decision-making layer of Figure 5, providing an integral link to the measurand layer via the current 'state estimation' matrix $\Gamma(t)$. These values of Γ_{end} depend upon acceptable risk to the asset manager, and the acceptable parameters depend upon the working environment $K(t)$. This has also been advocated by Montanari [31]. As an example, a higher state of oxidation of oil may be acceptable in a transformer in a lower loading situation. In reality we might form probabilistic limits within which the state estimator must lie. This last stage enables us to form probability density functions of plant life expectancy $h(t,K)$ equivalent to the life data acquired in service or in laboratory conditions. This information will undoubtedly complement current asset management strategies, decreasing the uncertainty in the decision-making process. Equally importantly the method should assist in identifying uncertainties in the decision-making process.

This framework allows a structured multidisciplinary discussion on equipment and network concerns, for example, the impact of increased thermal cycling or enhanced frequency of switching surges on real equipment, through analysis of stresses, ageing mechanisms and their impact on material condition. This may then allow an asset manager to act accordingly, to mitigate the changing stress or manage the plant differently. Given that this framework has the potential to produce a probability density function for a single plant component, the inclusion of multiple components can ultimately produce an integrated model for system reliability, enabling holistic network asset management.

Application of the framework

This framework is versatile but complex. In practice it is important to identify non-applicable factors and mechanisms so they can be omitted for a particular component operating under given environmental conditions. Thus the first step of application is to discuss existing knowledge and simplify the framework. This discussion is also expected to identify areas of ignorance. Consequently this framework provides the wherewithal for the production of life forecasting models, often radically simplified, but with a list of uncertainties.

The multifactor framework has been used to demonstrate the differences between high and low voltage ageing [7]. The major stress factors contributing to failure at both high and low voltage include chemical effects and thermal effects (oxidation, chain scission, cross-linking etc). In low voltage cables, these chemical and thermal stress factors provide the initiating mechanisms of failure, resulting in property changes to the insulation causing a reduction in the mechanical and electrical strengths [7, 32, 33], leading to eventual insulation failure. Furthermore, a high proportion of low voltage cable failures have been attributed to physical damage of the moisture barrier sheath of the cable, through excavation works or poor installation practice leading to moisture ingression and consequent chemical reactions [34]. In contrast, in high voltage cables the early stages of ageing are dependent on the local electric field conditions. Hence similarity exists in the ageing mechanisms in the final stages of failure but these have very different initiating processes [7]. In particular the electrical processes are not similar since mechanisms such as electrical treeing, tracking and dielectropheresis do not occur at low voltage. Thus chemical, physical and thermal models are transferable but electrical degradation models are not [35]. Insulation systems and diagnostic tools at high voltages are well defined and being continuously improved. The challenge, however, is at low voltages where data is mainly collected after the occurrence of a destructive event, primarily due to the financial infeasibility of online low voltage diagnostics.

It is important in application to consider the synergies which occur between mechanisms and environments. These are not explicitly drawn in Figure 5, however the framework presents an excellent template by which such interactions can be identified and discussed between experts.

Discussion

Research has yielded many diagnostic techniques and tools, suitable for use in the many insulation systems. However, these tools and techniques provide only an instant snapshot of the ageing state of the insulation from which asset managers must decide whether to undertake repair or replacement activities. The asset manager needs to forecast the reliability of plant in the future. In power networks, the changing working environment dictates changes in the stress factors which influence the ageing mechanisms, any of which might degrade the insulation. Hence it is extremely difficult to accurately predict life expectancy of equipment in service on dynamically changing networks without detailed knowledge of ageing processes. However, critical limits or end-points may be determined by performing laboratory life-estimation experiments. One approach to understanding the ageing processes is to identify the intermediate points at which key ageing processes change, since this can be used to identify a critical change in rate of deterioration. These critical limits should be developed using knowledge of both system and component perspectives. Such examples include the onset of partial discharges in a solid or the onset of water penetration into an oil-filled cable.

The asset management decisions taken within layer 1 are generally the responsibility of someone who is not specialist in ageing mechanisms. Decisions must be informed by the second layer which uses ageing models, knowledge of the working environment and an understanding of acceptable risk to allow optimal business decisions. The working environment of the equipment and materials may be known to varying degrees of accuracy, through monitoring of the service environment or time-averaged assumptions (layer 3). Moreover there may be forecasts of working environments to enable prediction of future behaviour. Similarly there may be specific knowledge of the insulation gained through direct condition monitoring (layer 5). The quality and quantity of this information is also likely to be vary varied, but can be targeted by the asset manager in an active condition monitoring regime. Knowledge of the environment and material condition are, however, only useful if a model of material ageing and material reliability is available (layer 4) to generate prediction of reliability (layer 2) in time.

Summary

The multifactor framework developed here provides a template for asset managers, plant managers and those involved in the area of network performance and material reliability to assess the available knowledge of condition of any insulation system. In order to realise maximum potential of this framework, mathematical modelling must be integrated using all existing models, tools and techniques for assessing insulation systems at the level of ageing processes. This is no simple task as the scope is extremely wide and deep, spanning all insulations systems and all modes of failure under a myriad of environmental operating conditions. A key use of the framework is to openly identify what is not known and so identify uncertainties for further evaluation.

The framework allows for stochastic modelling of the working environment, including stress factors such as electrical, thermal, mechanical, environmental, chemical and thermal. More importantly, the framework establishes links between the physics and chemistry of insulation degradation and asset management. Such a tool can complement and improve asset management strategies and provide a platform for future dielectric research.

One key issue is the need to identify ‘end-points’, or critical limits of material condition after which ageing leads to rapid failure. It is considered that understanding and identifying changes to dominant ageing processes during equipment’s life are critical to improved asset management.

Acknowledgement

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