A Framework Linking Insulation Ageing and Power Network Asset Management

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Abstract- **Power network operators in developed countries are faced with the challenge of effectively managing network performance with an ageing asset population. Some of these ageing assets have been in service well beyond their design-life. As these networks grow and undergo operational changes, load magnitudes, load cycles, and power quality are all deviating from the historical norm. Hence, it is likely that traditional heuristics no longer facilitate forecasting reliability behaviour of the insulation systems. A key challenge is now to manage existing assets and put in place economic and viable asset maintenance and replacement plans. A structured framework is presented through which knowledge of the physics and chemistry of ageing phenomena in dielectrics can be used to inform asset managers' plans. This framework will assist asset managers in identifying appropriate condition monitoring regimes whilst providing a transparent process for rule-setting decision making.**

I. INTRODUCTION

In the early twenty-first century, electrical energy networks might be classified on a linear scale between two extremes. At one end of the scale are those networks which are being built to meet the demands of rapidly expanding economies. At the other extreme are networks which have been in operation for many years and require refurbishment. Clearly many networks have aspects of both conditions. In this paper we consider the needs of operators of mature transmission and distribution networks.

Features of these mature networks are that a large proportion of the asset base is approaching or has exceeded the original design-life. Similarly the network designs which determine load and network dependence on individual assets are essentially those of 40 or 50 years ago. Thus we see large-scale capital intensive assets such as transformers, overhead lines, and buried cable, 40, 50 or more years old, still in operation. It is a result of excellence in engineering that such equipment is still operational. Previous experience of high reliability has led to the situation whereby there is insufficient capability and capital available to replace the plant such that all equipment remains less than, say, 40 years old.

In addition to the concerns over ageing plant, network managers have other new issues with which to be concerned. These include: connection of renewable generation, introduction of new non-linear loads which degrade power quality, requirements to minimize energy loss, optimizing environmental performance, changing weather patterns and minimizing health and safety risks. In a deregulated market such considerations must be balanced for optimal returns to shareholders [1].

As an example of network evolution, we might consider a part of the network which was previously subjected to a steady low level of loading. The network equipment might be old, but not considered as aged since it has not been highly thermally stressed. In addition the plant may be in a location where reliability was not critical and so maintenance may not have been a priority. If, however, that location is now in the route of a wind-farm connection, there may be a need to have high reliability so that whenever wind is available, renewable energy can be connected to the network. By its nature, therefore, the plant may be highly loaded at given intervals. Consequently, we might expect more extreme and more regular thermal excursions than previously experienced. Similarly, connection of non-linear loads may lead to locations of high harmonic content and reduced power quality not experienced previously.

It is therefore sensible for the Network Manager to ask of the Asset Manager questions such as:

'What is the impact of increased load on failure likelihood?'

'What is the impact of increased load cycling on maintenance requirements?'

'What is the impact of power quality on life expectancy?'

Figure 1 shows some of the considerations [2]. The problem clearly must be addressed at the network level. This requires managing the following three perspectives:

- ⇒ Plant/Asset Management
- ⇒ Network Design
- ⇒ Network Management

In this paper, however, we are only concerned with the reliability level of individual plant items. Nonetheless even then the environment in which the item functions is linked to network management [3-5].

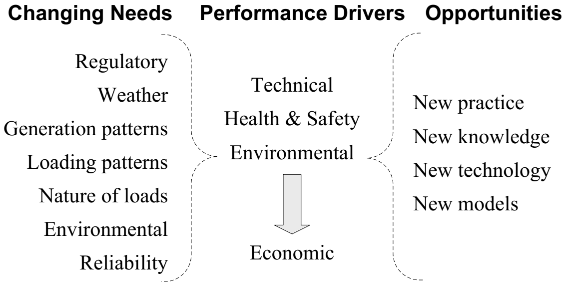

Fig. 1. Considerations for business managers. This may be viewed at either the plant-item or network-system levels.

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For many decades researchers have been studying ageing of dielectrics and a great deal of material is found in the literature. However, the importance of asset management has increased only recently. At the date of writing, if ‘asset management’ is the search term in abstracts on the search engine of *IEEE Xplore* only 225 papers are identified out of 1,733,971. If, however, ‘electric tree’ or ‘partial discharge’ are the search terms, 3141 papers are identified [6]. Thus the challenge is to make available the information on ageing which already exists in a form to assist the Network and Asset Manager [7-9].

II. THE FIVE LAYERS OF THE FRAMEWORK

The five layers of the framework [2, 14] are:

- Asset management
  Decision making processes
- Material state
  The actual condition of the insulation
- Circumstance monitoring
  Monitoring the working environment to determine the stresses at a microscopic level
- Ageing mechanisms
  Physics and chemistry controlling microscopic material changes resulting in macroscopic properties
- Condition monitoring
  Measurements which enable an understanding of material state.

These are now considered in more detail:

A. *Asset management decision making*

The top layer concerns the decision processes of the asset manager. The overall flow of information is captured in Figure 2. The Asset Manager has to decide on a combination of actions which reflect plant loading and stress levels, maintenance schedules, and replacement timetabling. These things are generally interdependent and also depend upon the system requirements of the equipment. It is possible that one route to asset husbandry involves changing the working environment of the item to extend life or reduce immediate failure likelihood.

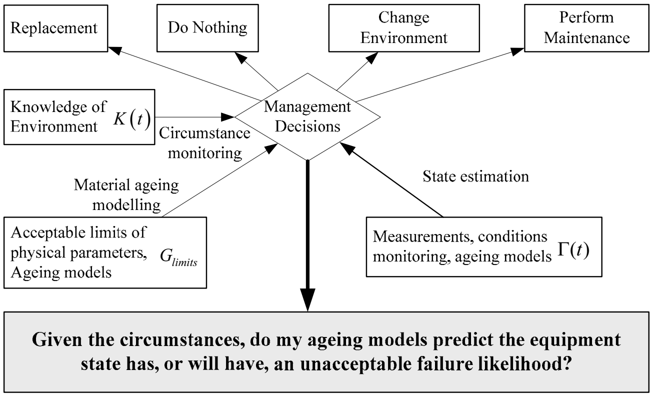


Fig. 2. Asset management layer of the model.

B. *Actual material or equipment state*

The decisions explicitly identified in Figure 2 should be informed by a number of knowledge or data streams. The most important of these is knowledge of how the equipment functions and fails. At a component level the concern is whether the plant functions correctly and a forecast of future reliability. At the system level it is important to understand the implication of plant failure. Two issues arise from the consequence of the failure of an individual item. Firstly whether the system will continue to perform satisfactorily and secondly whether there are consequences of failure (i.e. is other plant then put at unacceptable risk). These system considerations are beyond the scope of this paper but should be the true drivers of asset management [10].

In terms of the impact of dielectric reliability, we consider a set of acceptable limits of physical parameters which describe the state of each insulation component. Here we generate a vector *G(t)* to represents the physical parameters as a function of time. Given that *G(t)* represents the state of the material at a microscopic level we may consider an envelope of properties which are acceptable, and a range of properties which require some form of action (asset maintenance or replacement). We notate a range of properties not requiring intervention as G_{limit}. Equation (1) summarises an example of *G(t)* and its constituents.

$$G(t) = \text{Actual Material State} = \begin{pmatrix} g_1(t) \\ g_2(t) \\ g_3(t) \\ g_4(t) \\ g_5(t) \\ g_6(t) \\ \text{.........} \\ g_k(t) \end{pmatrix} = \begin{pmatrix} \text{void size} \\ \text{oxidative state} \\ \text{mositure content} \\ \text{morphology} \\ \text{dissolved gases} \\ \text{tree length} \\ \text{..........................} \\ \end{pmatrix} \tag{1}$$

For an oil-impregnated-paper insulated cable the moisture content might be a key parameter. As for most large scale insulation systems, this will normally require a probability density function $g_i(t,)$ to describe spatial or temporal variations throughout the insulation [11].

An example of a system which already works on this basis is the sampling of oil from a transformer for dissolved gas analysis. Limits of acceptable gas levels are set and responses pre-determined in maintenance procedures [12].

C. *The working environment*

The second core knowledge stream feeding into the Asset Managers’ decision is the existing and future working environment. This environment controls the stresses which the equipment and in particular any dielectric is subjected. The asset manager may be in the position to regard this as uncontrollable. However, in some cases it is possible to load plant differently to alter the system reliability. This does not necessarily mean reducing the load. It may mean instead maintaining a more steady loading level, or reducing transient impulse stresses (mechanical or electrical).

The working environment is described by a second time-dependent vector *K(t)*, known as the stress vector. The vector consists of many factors and similar to the material state vector, may be distributed spatially and change in time. Generally these factors are segregated into the six categories shown in (2).

$$K(t) = \text{Stress Factors} = \begin{pmatrix} K_1(t) \\ K_2(t) \\ K_3(t) \\ K_4(t) \\ K_5(t) \\ K_6(t) \end{pmatrix} = \begin{pmatrix} \text{Mechanical} \\ \text{Physical} \\ \text{Electrical} \\ \text{Thermal} \\ \text{Environmental} \\ \text{Chemical} \end{pmatrix} \tag{2}$$

Quite often there is some uncertainty about the future working environment. Presently this is a particularly dynamic part of the framework as a result of changing generation and loading patterns on many networks. Thus knowledge of a particular network is critical to this part of the model.

It should be emphasized that for this framework, the relationship between macroscopic stresses created by the external network (such as applied voltages and temperatures) must be used to determine the local microscopic stresses which control physical (ageing/degradation) processes.

Frequently models assume steady-state external stresses. However, key to the study of reliability of real systems is the impact of short-term events such as switching surges or lightning strikes. These may be considered separately but are an essential part of any integrated model.

D. Ageing mechanisms

Changes in the likelihood of failure occur because either the working environment (stress factors) changes or the material changes. These changes may be described variously as degradation, ageing or failure mechanisms. In reality a continuous change in a material will change the local stress factors. Additionally, it is important to consider the physical chemistry of the processes at a local level.

The modelling of physical processes allows definition of the limits of the acceptable material state G_{limit} at a microscopic level. These limits might then be associated with gradually degrading material such as oxidative state, degree of polymerization or might be seen as the change required in a material necessary for a change in ageing mechanisms. Two examples of such transitions include the growth of electron mean free path eventually allowing partial discharges, and the growth of a water-tree enabling transformation to an electrical tree.

Figure 3 shows a schematic of the continuous cycle of ageing processes changing the local stresses (say through space-charge accumulation) and changing material properties. The loop shown will change radically if the main ageing process changes. Ultimately, a lack of a stable state indicates rapid decline into failure.

The response of a dielectric to short-term events as identified previously must also be considered. In particular, the role of impulse voltages and resultant transient mechanical and electric stresses on initiation of ageing mechanisms, such as electrical tree growth is important. For an asset manager, identifying the appropriate protection levels for a device against transient and infrequent events is a key economic decision for which reliability data should be essential.

E. Measurands giving an estimation material state

In practical systems, knowledge of the state of a material is limited. In plant equipment, direct measurement of a material is difficult. There is clearly less restriction in laboratory experiments, particularly on model samples, where destructive testing and model stresses allow detailed investigation. The measurements available can be used to derive an understanding of the material condition. The measurands used, λ_n, are then useful only in as much as they allow an estimation of the actual physical state of the material. We call this estimate the State Estimation Matrix, $\Gamma(t)$.

The content of the state estimation matrix depends upon the condition monitoring being undertaken at the time and the interpretation available. Examples of potential measurands for cables are:

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

III. USING THE FRAMEWORK

Much of the description given in the previous section has assumed that factors are independent. This is clearly not necessarily the case. Identifying inter-relating stresses and the relationship between the material state, local stresses and ageing mechanisms is a critical part of any discussion. That this leads to extreme complexities is not a reason to ignore the fact. Indeed this makes the use of this framework more meaningful rather than less.

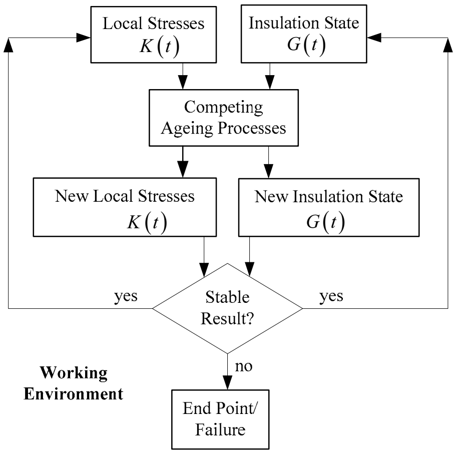
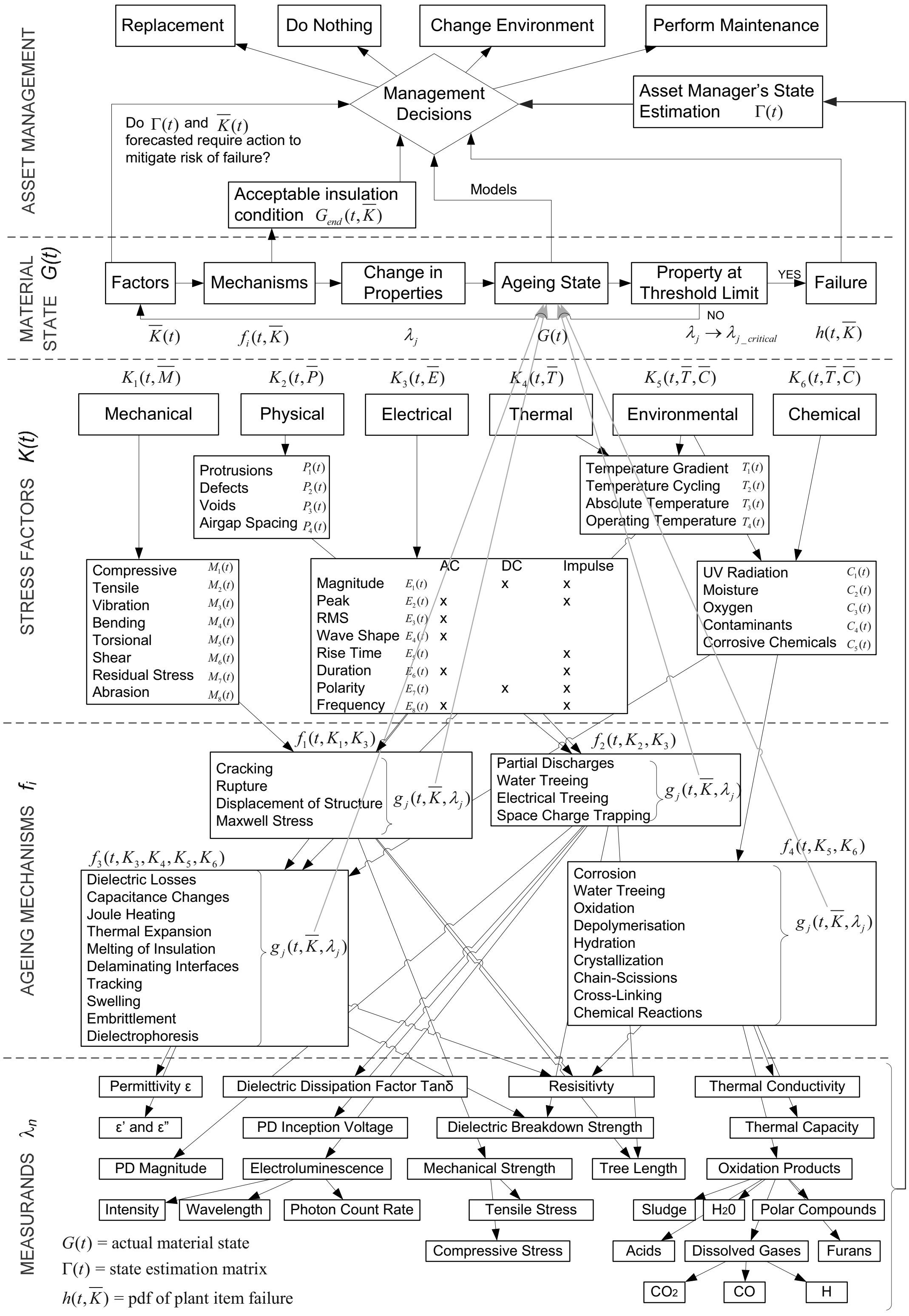


Fig. 3. The ageing mechanisms are dynamic and may change in time as the material and local stresses change.



$G(t)$ = actual material state
$\Gamma(t)$ = state estimation matrix
$h(t,\overline{K})$ = pdf of plant item failure
λ_j = insulation property measurand
$f_i(t,\overline{K})$ = pdf of competing ageing mechanisms
$g_j(t,\overline{K},\lambda_j)$ = pdf of competing ageing sub-mechanisms
$\overline{K}(t) = \sum K_i(t)$ = stress factors reflecting the working environment

Fig. 4. The five-layer multifactor framework [2, 13]

The complete framework illustrated in Figure 4 is not a model of failure, but provides a platform from which to build a coherent model from expert knowledge. If the first stage of its use involves trying to agree which complexities can be removed from the model, one of the end points may well be the identification of uncertainties and ignorance. This is in itself a useful function since experts tend to describe their knowledge with much more openness than they do their ignorance.

Hence key issues for the Asset Manager may be:

⇒ Identification of what can be measured, and how that can be interpreted

⇒ Knowledge of how to identify the times when dominant ageing mechanisms change

⇒ How to identify rates of change of key material properties

⇒ Interpretation of ageing processes

One example of a coherent approach to this problem is the use of a knowledge-based approach to interpretation of partial discharge data intelligent [14].

In practical applications, the first issue is to try to identify factors which do not apply in a given situation and so simplify the discussion. Often ageing takes several stages and in this case each stage may need to be treated as a separate problem. For example a breakdown scenario might be considered in three stages; void growth, electrical treeing, and breakdown:- one model will not cover all. In this way more detailed specific models [2] can be incorporated into the more general picture.

It is clear, however, that an Asset Manager will not have the skills in general to understand the physics and chemistry of ageing. The framework provides a powerful diagnostic tool to enable expert understanding of the working environment (using circumstance monitoring), plant condition (through interpretation of condition monitoring) and ageing models to define risks. This is illustrated in Figure 5.

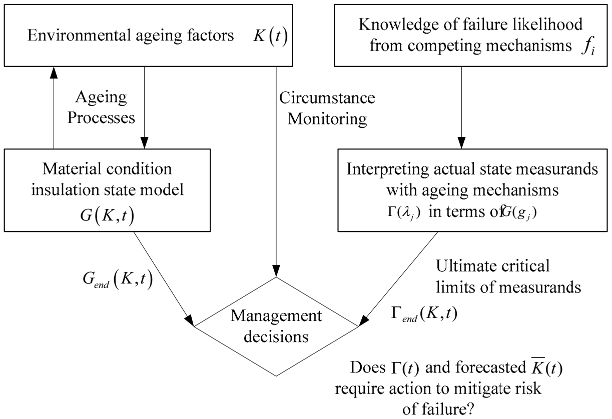


Fig. 5. A view of the model as seen from the asset managers' view-point [2].

IV. CONCLUSION

A framework has been presented which links the requirements of asset managers to scientific knowledge of insulation ageing. The framework provides a platform on which to base models of plant reliability, identifying direct relationships between the working environment of the equipment and the ageing and failure processes of the dielectric systems.

Condition monitoring is a powerful tool for asset managers only if a true understanding of the working environment of the dielectrics enables stresses to be determined at a microscopic level and models of the physics and chemistry of ageing exist. One approach to use of condition monitoring data is to identify changes in the dominant ageing processes.

The five-layer framework will assist asset managers in identifying appropriate condition monitoring regimes, and provides a transparent process for rule-setting for decision making. This framework will engage the various technical disciplines needed for asset management, generating new questions and a new focus for ageing-model research.

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