A Multifactor Framework Linking Insulation Ageing and Power Network Environments

S. Bahadoorsingh and S. M. Rowland
The University of Manchester, School of Electronic and Electrical Engineering,
PO Box 88, Manchester, M60 1QD, United Kingdom
E-mail: s.rowland@manchester.ac.uk

***Abstract-* The development of a multifactor framework which links ageing of insulation systems to power network performance is described. The framework provides a platform on which to develop models of plant reliability, identifying direct relationships between the working environment of the equipment and the ageing and failure processes of the insulation system. The evolution of the working environment is far from trivial and requires a stochastic modeling approach. The framework establishes links between the physics and chemistry of insulation degradation, the management of power quality and load flows in the network, thus linking plant reliability to asset management. In this paper, as an example of its use, the framework is used to provide a qualitative analysis and contrast of ageing and failure of insulation systems in high and low voltage networks. Finally, it is also shown to provide a platform for future research in the area.**

I. INTRODUCTION

In the power energy sector, asset management is paramount for successful and reliable network operation. Sustaining the life of, and predicting end of life for in-service plant is a problem confronted by network operators. A significant percentage of this in-service plant may be beyond the design-life but operating without any significant complications. Propelled by the growth of renewable and distributed generation, the adjustment of power flows and variation of load demands, there is now a change in the working environment experienced by these insulation systems. The frequent occurrence of switching transients and injection of harmonic waveforms into the network at the low voltage levels by a host of power electronic devices result in a reduction of power quality which can propagate to higher voltage levels.

The potentially important non-power frequency electrical stress factors which affect electrical ageing mechanisms (such as partial discharges, water treeing, electrical treeing and space charge injection) include the peak, rms, wave-shape, polarity and frequency. In addition, greater loads and load cycling will change thermal stress conditions. Intrinsic contaminants, imperfections, protrusions and voids remain in these insulation systems and will continue to play a potential role in determining ageing and failure mechanisms. As the network undergoes this evolutionary process, the plant is changing through ageing, and the failure modes may deviate from the perceived historical norm. Hence traditional heuristics no longer facilitate the forecasting of behaviour of in-service insulation systems. Consequently, key questions arise which include ‘what is the influence of non-power frequency parameters on the life of the ageing infrastructure? And ‘what are the critical levels of such parameters influencing ageing?’.

II. THE ROLE OF POWER QUALITY

The role of power quality can be broadly captured and described as an electrical stress factor. The power quality categorizes those non-power frequency occurrences. This research focuses primarily on harmonics and impulse-related events.

Harmonics are a frequency domain representation of time domain occurrences [1] and may significantly increase the peak and rms values of an electric field within a dielectric, increasing dielectric losses and creating a temperature rise within the dielectric [2]. Research conducted using the 3rd, 5th and 7th harmonic components [3, 4] 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 [5, 6].

The cumulative effect of impulses leads to injection and accumulation of space charge, creating conditions to facilitate partial discharges and electrical tree inception [7], accompanied by an overall reduction in life expectancy [8]. Impulse polarity and increases in major factors such as repetition rate and voltage magnitude all result in a decrease in the life of the insulation, with the voltage magnitude being the most influential and the repetition rate the least [9]. Notably, when more than one factor is changed, they can collectively negate the influences of each other, which can lead to longer insulation life [9]. Faster rise times and higher frequencies of impulses lead to increased stress on the insulation [10] generating dielectric heating contributing to ageing.

Given the complexity of the situation, and the need to run power networks with minimal risk, it is to be expected that incomplete or inappropriate models may therefore be too conservative, leading to higher asset maintenance or replacement costs than are really necessary. Understanding and correctly interpreting the effect of irregularities of composite waveforms in the time-domain is crucial to defining the wave-shape features and characteristics most influential to initiating and developing ageing of any insulation system. This will then facilitate the link from the system level which determines power quality to the component level which can model the life expectancy of the insulation system.

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III. ASSET MANAGEMENT AND THE MULTIFACTOR FRAMEWORK OF INSULATION AGEING

Densely [11] 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 exists a vast amount of literature on insulation ageing aiding comprehension of the ageing mechanisms and factors, including [12, 13].

Any plant component operating in a network is subjected to multifactor ageing which involves mechanical, physical, electrical, thermal, environmental and chemical factors. These ageing factors can be represented by a matrix $K(t)$ of insulation ageing or stress factors. These major stress factors can be further broken down into sub-factors which enhance, as well as compete with, each other in the failure process.

Failure of a given component is regarded as a competition between a number of failure mechanisms represented as a probability distribution function $f_i(K(t))$ which is also a function of time and importantly a function of the stress factors $K(t)$. Each mechanism may consist of many sub-mechanisms or ageing stages which define the state of the insulation. From an asset management perspective, we are no longer confined to considerations of 'time to failure' or 'likelihood of failure' of the insulation. We may now consider the likelihood of the insulation reaching a specific measurable condition deemed critical. The associated probability distributions denoting the physical condition are written $g_j(K(t))$ representing the *jth* property. These depend upon the insulation ageing stress factors and their history. Each distribution g_j reflects the likelihood of a physical condition of the material and leads to an ageing state estimation matrix $G(t)$ describing the aged state of the material. The onset of any critical condition will lead to management decisions on possible options and courses of action which can be taken, denoted in Fig. 1. Thus we have the ageing state estimation providing a probabilistic evolution of the material from the input of real measurands λ_n. These measurands are measurements determined by the physical condition of items of plant either in-service or under laboratory conditions.

Asset managers may use the framework outlined in Fig. 1 to model the network environment $K(t)$, identify a set of measurands for each plant item and determine its state $G(t)$. We have termed establishing the real working environment of plant 'circumstance monitoring' [1], to distinguish these measurements from 'condition monitoring' which reflects that state of the plant. Thus 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 physics and chemistry of ageing, a limit on the condition of the plant may be set in terms of measurands of the condition monitoring, G_{limits}, which can trigger actions such as maintenance or asset replacement.

Fig. 2 shows a schematic of the framework. Although complex to the first glance, it provides a structured approach to linking the top level of asset management, though knowledge of the material state, factors or stresses which age the dielectric, and ageing mechanisms. The final layer (at the base of Fig. 2 identifies the measurands open to the scientist, engineer and ultimately asset manager. Such a framework allows a structured multidisciplinary discussion to be had concerning, 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.

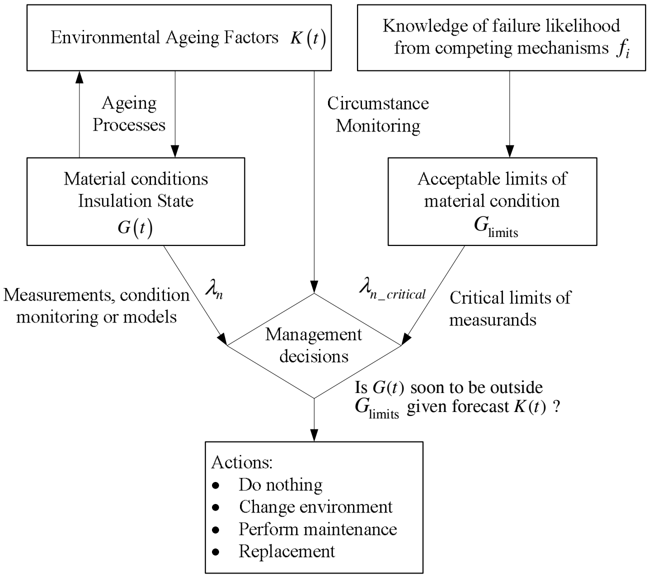
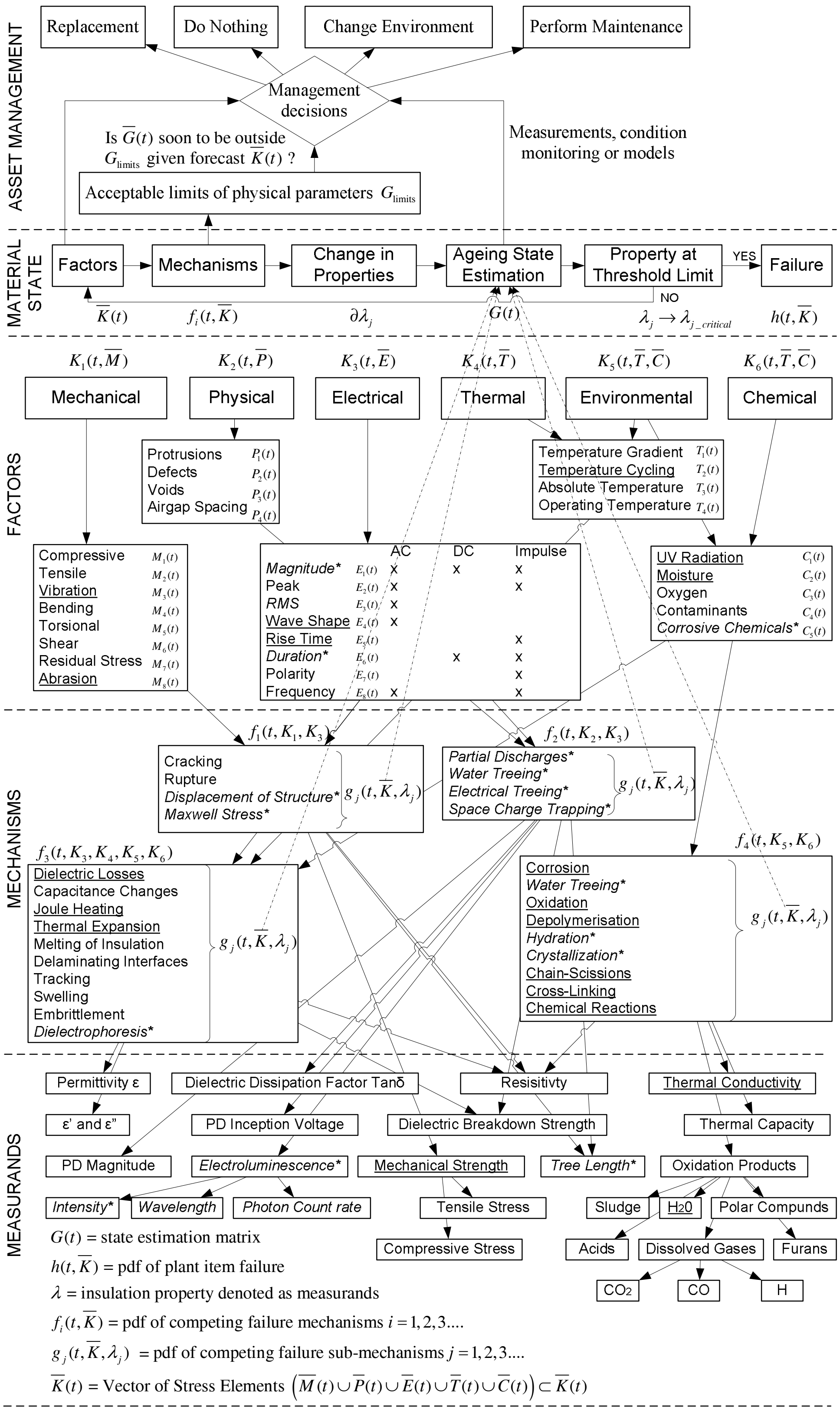


Fig 1. Multifactor framework complementing Asset Management Systems [1]

IV. HIGH VOLTAGE AND LOW VOLTAGE AGEING

As an example of its use, the multifactor framework in Fig. 2 has been used to demonstrate the differences between high and low voltage ageing. The key ageing parameters relevant in each application are distinguished in this figure, by highlighting those absent in low voltage insulation with an '*', and underlining those which dominate in the LV case. The major stress factors contributing to failure at both high-voltage 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 [11, 14, 15], 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



$G(t)$ = state estimation matrix

$h(t,\overline{K})$ = pdf of plant item failure

λ = insulation property denoted as measurands

$f_i(t,\overline{K})$ = pdf of competing failure mechanisms $i = 1,2,3....$

$g_j(t,\overline{K},\lambda_j)$ = pdf of competing failure sub-mechanisms $j = 1,2,3....$

$\overline{K}(t)$ = Vector of Stress Elements $\left(\overline{M}(t) \cup \overline{P}(t) \cup \overline{E}(t) \cup \overline{T}(t) \cup \overline{C}(t)\right) \subset \overline{K}(t)$

Fig. 2. Multifactor Framework of Insulation Life. (*) denotes absent at LV while underlining denotes Dominant at LV

consequent chemical reactions [16]. In contrast, in high voltage cables the early stages of ageing are completely different being critically dependant on the local electric field conditions. Hence there is some similarity in the ageing mechanisms in the final stages of failure but these have very different initiating processes [11]. 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 [17].

V. CONCLUSION

The multifactor framework developed here provides a template for asset managers and plant managers to assess the condition of any insulation system. In order to realize maximum potential of this framework, mathematical modeling must be integrated using all existing models where applicable. This is no simple task and will be dependent on the data available. Insulation systems at high voltages are well defined and being continuously improved, allowing condition monitoring data to be collected in abundance. The challenge however, is at the low voltages where data is mainly collected after the occurrence of a destructive event, primarily due to the financial infeasibility of on-line low voltage diagnostics.

The framework developed has enabled engagement of those involved in the area of plant monitoring, asset management, network performance and reliability in discussions about further developing the models, tools and techniques for assessing insulation systems at the level of ageing processes. This in turn will ask new questions of those working on the physics, chemistry and reliability of dielectrics, and in particular focus on the changes being witnessed in power system networks.

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