The Relationship Between Insulation Ageing and Power Network Performance

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Abstract: A framework has been developed which links the reliability of insulation and plant to changes in their operating environment. These changes include non-power frequency events such as harmonics and the occurrence of impulses. This work is driven by the new demands put on real networks as a result of changing loads and renewable and distributed generation. The framework presented allows a coherent view of the interaction between models of failure mechanisms and network performance. Such a framework allows a clear interface between system analysts and plant engineers. It provides a platform for integrated asset management using existing knowledge of dielectric ageing mechanisms and condition monitoring. It will also provide a framework for future research in the area.

INTRODUCTION

The issue of ageing of insulation has been at the heart of high voltage engineering since its inception. The success of the various forms of insulation used is verified by the age of much of the plant in the energy supply networks around the world today. In urban areas cables which are literally one hundred years old still carry power. Similarly transformers continue to operate well beyond their design life.

Plant insulation systems are undergoing a change in environment as a consequence of the drive toward distributed generation, active participation in demand-side management schemes, and the use of power-electronic devices in the network. As a result, load flows are changing and fluctuations in power quality occur due to increased impulse transients and harmonic content. For polymeric insulation 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 major role in determining ageing and failure mechanisms. A key question is then ‘what is the influence of non-power frequency parameters on the life of the already aged infrastructure?’. It is clear that heuristics developed in previous network arrangements may no longer apply.

This paper reviews a holistic model which, in principle, allows the impact of network management on insulation reliability to be examined. Initially the model will be used to identify the key questions which material reliability experts need to answer to provide data for asset managers. First, a review of literature on non-power frequency ageing factors is provided.

IMPACT OF POWER QUALITY ON INSULATION AGEING

Frequency Related Review

Harmonics are a frequency domain representation of time domain occurrences. Harmonic voltages may significantly increase the peak and rms values of an electric field within the dielectric increasing dielectric losses. Both these effects result in an insulation temperature rise [1]. The presence of odd harmonics particularly the 3rd, 5th and 7th orders significantly influence the resultant wave shape of the power signal. Research has been conducted using these specific harmonic components [2,3] to confirm that the composite waveform, depending on the phase and magnitude of the harmonic component may increase the voltage peak of the waveform and the likelihood of partial discharge inception [4,5]. Whilst partial discharge is the first sign of electrical ageing in most electrical systems, the voltage peak was identified as the factor most detrimental to insulation life even in absence of discharges [5]. When partial discharges did occur the wave shape parameter was more influential than the rms parameter [5]. This is attributed to the rate of decay of charge which is influenced by frequency [6]. Additionally the research in [2-5] investigated phase increments and magnitudes inversely proportional to the harmonic order but with large phase increments. In order to determine the critical conditions for degradation, the tests require smaller increments of phase and magnitude. Consideration of composite waveforms in the time-domain highlights that the rates of change of applied field, including oscillating ripples, should have an impact on the rate of loss of trapped charges. Understanding the effect of the abnormalities in any resultant waveform which the insulation experiences is crucial to defining which time domain wave-shape features and characteristics are most influential. Only then can the harmonic combinations which most affect the insulation be identified. Under multi-stress conditions plant items suffer significant life reduction in the presence of harmonics and an equivalent reduction in reliability [1].

Impulse Related Review

Results from tests on polyethylene cables suggest that ac and impulse breakdown values may not be significantly affected by exposure to periodic surges [7,8]. This is provided that the level of underlying ac stress is not great enough to influence breakdown. Additionally, there were no visual differences observed in samples of cable cross sections as a result of the impulses [7,8]. However, the cumulative effect of these impulses was responsible for reducing life expectancy [8]. It has been suggested that the cumulative effect leads to injection and accumulation of space charge creating conditions to facilitate tree inception and that higher stresses create a shorter inception periods [9]. 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 having the most detrimental impact and the repetition rate the least [10]. However when more than one factor is changed, they can collectively negate the influences of each other, which can lead to longer insulation life [10]. An increase in the impulse voltage magnitude results in the pd inception voltage being exceeded, initiating pd activity and tree inception [9]. Accompanying the increase in voltage magnitude is a corresponding increase in current which constitutes a rise in thermal stress. Positive polarity surges have been found to be more damaging than negative, irrespective of the level of moisture present. However only the negative surges produced electroluminescence [10]. There has been no link yet established with insulation life or the number of impulses to failure. The rise time of an impulse has been identified as promoting space charge accumulation [11].

Space charge accumulation is the first stage to initiating pd activity which develops into electrical treeing leading to eventual failure of the insulation. Faster rise times and higher the frequencies of impulses lead to increased stress on the insulation [11]. This in turn generates local dielectric heating which contributes to ageing and has been suggested as the mechanism which provides the conversion from water trees to electrical trees [12]. Hence lightning impulses which have fast rise times and high magnitudes are associated with the production of electrical trees. If the repetition rate is high enough this may prevent dielectric relaxation and the dielectric losses would increase thus causing thermal runaway and failure. The end result is a reduction in insulation life. Similar to the frequency related review, the time domain representation of the waveform must be linked to the insulation performance.

MULTIFACTOR FRAMEWORK

A single plant component operating in a network is subjected to multifactor ageing which involves mechanical, physical, electrical, thermal, environmental and chemical factors. With the passage of time these factors may degrade the insulation until, as a result of a failure mechanism, electrical breakdown occurs. Figure 1 is a flowchart illustrating this sequence. These ageing factors can be represented by a matrix $K(t)$ of insulation ageing or stress factors, as illustrated in the equation below:

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

Each of these major stress factors can be further broken down into sub-factors which can enhance, as well as compete with, each other. The factor representation has been established as a function of time yielding some measurable form of stress on the insulation system. Examples of the measurable ageing sub-factors include temperature, mechanical strain, pressure, oxygen levels, moisture levels, morphology, thermal history, radiation and electrical treeing.

Traditionally, the failure density function which is a function of time is represented as *f(t)*. It is clear that this is also a function of the various ageing factors, their histories and how they combine to influence the ageing mechanisms. Thus we can represent the failure density function as

$$f(t) = f(K(t)) \qquad (2)$$

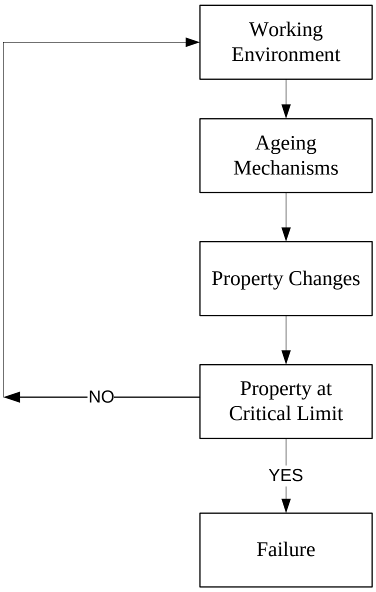

Figure 1: Insulation failure flowchart

f(t) depends on the insulation ageing factors through physical mechanisms changing the material and the values of stress at time *t*. Failure of a given component is often thought of as a competition between a number of failure mechanisms (such as chemical ageing or moisture penetration). We might then consider each mechanism to be represented as a probability distribution function $f_i(K(t))$ which is also a function of time. This might, for example, represent the probability of the failure of insulation through tree growth, partial discharge or thermal runaway, the likelihood of each being dependent on time, and the ageing factors up to, and including, time *t*. Each mechanism may consist of many sub-mechanisms or ageing stages which define the state of the insulation. For example an electrical tree might have a number of stages including inception, propagation and runaway [13]. At this level we are no longer concerned with the likelihood of failure of the insulation, but the likelihood of the material reaching a specified measurable condition. Examples might be oxidative state, void size or tree length. Again the associated probability distributions of physical condition are written $g_j(K(t))$ and depend upon the insulation ageing stress factors and their history. Each distribution g_i reflects the likelihood of the physical condition of the material and leads to a state estimation matrix *G(t)* similar to equation (1), producing the following equations.

$$G(t) = \text{State} = \begin{pmatrix} g_1(t) \\ g_2(t) \\ g_3(t) \\ g_4(t) \\ g_5(t) \\ g_6(t) \\ \ldots\ldots\ldots \\ g_k(t) \end{pmatrix} = \begin{pmatrix} \text{Void Size} \\ \text{Oxidative State} \\ \text{Mositure Content} \\ \text{Morphology} \\ \text{Dissolved Gases} \\ \text{Tree Length} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \end{pmatrix} \qquad (3)$$

$$g_j(t) = fn\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \ldots. \\ \lambda_n \end{pmatrix} = fn\begin{pmatrix} \text{dielectric loss} \\ \text{void size} \\ \text{tree length} \\ \text{mositure content} \\ \text{thermal capacity} \\ \text{pd magnitude} \\ \ldots\ldots\ldots\ldots\ldots \\ \end{pmatrix} \qquad (4)$$

G(t) may be defined as describing the ageing state of the material, which depends directly on the stress factors *K(t)*. Thus we have the state estimation providing a probabilistic evolution of the material with a set of potential measurands λ_n. Previously the competing and ultimate failure mechanisms were described in terms of a probability density function *f(t)*, dependent on *K(t)*. It can also be described using the material state at any time using *G(t)*.

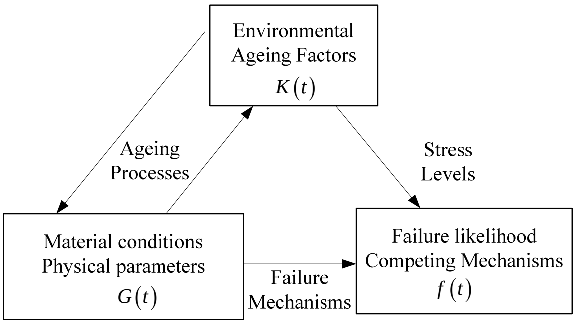

Figure: 2 Link between ageing and failure processes

In this way the ageing environment, the state of the material and the likelihood of failure are linked by the ageing and failure processes, shown schematically in Figure 2. In this schematic the concept is presented that the environment and the material condition are continually linked and changing until the failure mechanism starts irreversibly and dominates the remaining process.

THE USE OF CRITICAL LIMITS

Insulation failure can be defined as that instant a threshold limit of a critical insulation measurand, $\lambda_{n\_critical}$, is exceeded. Typically for insulation failure we might consider an irreversible increase in current magnitude to identify failure.

However in the context of asset management, a critical parameter threshold before such catastrophic failure will allow operational, maintenance or replacement decisions to be made. Thus Figure 2 can be amended to include explicit threshold values. This is shown in Figure 3. This matrix of acceptable material conditions is described by a state limitation matrix G_{limits}.

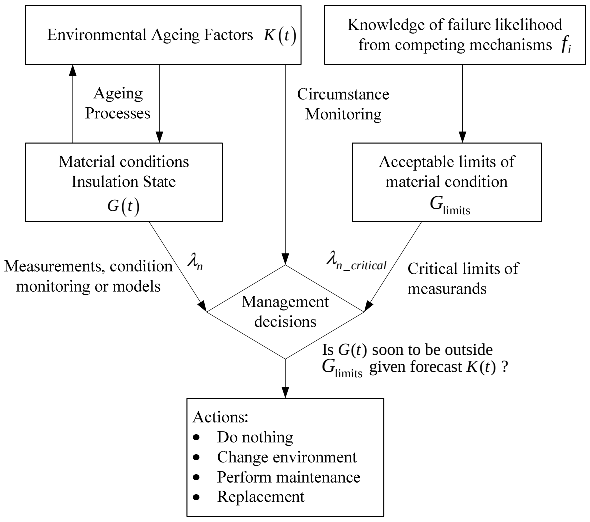

Figure 3: Multifactor framework complementing Asset Management Systems

The likelihood of specified variables exceeding given limits might then trigger action. In general G_{limits} will not vary in time and will be a function of the measurands, λ_n. However the values in G_{limits} will depend upon acceptable risk to the asset manager, because the acceptable parameters may depend upon the working environment (for example a higher state of oxidation of oil insulation may be acceptable in a transformer in a lower loading situation). Thus G_{limits} may also be chosen to be dependent upon $K(t)$. In reality we might form probabilistic limits within which the state estimator must lie. Decisions and actions on these limits becomes the art of network and asset management. The requirement is then clear for an understanding of the chemistry and physics of the materials and their ageing and failure processes.

DISCUSSION

The analysis proposed provides a structure on which to base models of plant reliability. This allows for a direct relationship to be built between the working environment of the equipment and the ageing and failure processes within the material. With further work it is hoped that both stochastic and deterministic models can be incorporated as appropriate. The model will also assist asset managers to determine appropriate use of condition monitoring. Once the analysis can produce a probability density function for a single plant component, the inclusion of multiple components can produce an integrated model for system reliability enabling holistic network asset management. One key issue remains the interaction of ageing mechanisms, and this highlights the underlying importance of understanding the nature of the ageing mechanisms and the failure processes. It is hoped in the short term that this approach will allow a dialogue between the various disciplines working in this field, resulting in new questions being asked and generating a new focus on ageing models.

CONCLUSIONS

A review of frequency and impulse related literature is provided, to highlight the significance of investigating the electrical stress factors due to non-power frequency events influencing insulation life. A framework has been developed which allows a holistic model of insulation ageing. The general nature of the framework permits simple adaptation to any insulation system. The model allows consideration to be given to what is meant by failure, options for condition assessment, and the implications of ageing mechanisms for practical long term asset management. Key to this is enabling the implications of changes to the working environment of plant to be considered.

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