

# The Role of Power Quality in Electrical Treeing of Epoxy Resin

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**Abstract-** The impact of power network changes on one ageing mechanism in one simple insulation system is considered. The effects of non-power frequency events on electrical treeing in epoxy resins are critically reviewed. These non-power frequency events include 3<sup>rd</sup>, 5<sup>th</sup> and 7<sup>th</sup> odd harmonics and various impulses superposed upon the power frequency. A framework under development is tailored for the stochastic modeling and assessment of electrical treeing, emphasizing the influence of electrical stress factors related to power quality. The impact of network changes on ageing of insulation through electrical trees is discussed in the context of this framework.

## I. INTRODUCTION

Voltage waveform distortion levels from harmonic phenomena and transient disturbances observed on the transmission and distribution networks are an important problem. This distortion is a direct consequence of power electronic devices such as adjustable speed drives, personal computers, electronic ballasts, power converters and other high-speed switching devices. This distortion often leads to a reduction in power quality supplied to end users resulting in malfunctioning of electronic devices, unexpected opening of circuit breakers due to high harmonic currents, loss of reliability and accelerated ageing of insulation systems reducing functional life of electrical components [1]. Thus harmonics on the network have resulted in new working environments to which the ageing insulation systems are subjected. At the same time, many of the world's established electricity supply networks are ageing beyond their installed design-life, thus the traditional approach to asset life prediction and the use of established heuristics must be challenged.

## II. POWER QUALITY FACTORS

Harmonics are a frequency-domain representation of time domain occurrences [2]. At the distribution level the dominant, odd harmonic components, namely 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> exist in descending order of magnitude respectively. Harmonic voltages may significantly increase the peak and rms values of an electric field within the dielectric, increasing dielectric losses and insulation operating temperatures [3]. The triplen harmonics (multiples of the 3<sup>rd</sup> harmonic) are usually filtered as a result of propagating across the power network but pose a serious threat through thermally overloading neutral cables. Hence, the 5<sup>th</sup> and 7<sup>th</sup> harmonic components would generally be the most influential to power quality and potentially to insulation system failure at the transmission level.

Research using the odd harmonics (3<sup>rd</sup>, 5<sup>th</sup> and 7<sup>th</sup>) confirms that the combination of one harmonic component and the fundamental can influence the voltage peak at constant rms to reduce the fundamental voltage required for the inception of partial discharges (pd), thus decreasing insulation life [4,5]. The dielectrics used in these life tests were polyethylene terephthalate (PET) and cross-linked polyethylene (XLPE) respectively. Treeing tests in XLPE [5] do not readily facilitate the capture of the visible aspect of tree growth or any measurement of tree length within the dielectric unlike transparent unfilled epoxy resins [6,7]. However, pd measurements may be used as a monitoring mechanism in either case [5]. Investigations into the effect of harmonic content on the insulation life [8-10] lead to three parameters to describe any waveform emphasizing its degree of distortion. These were the peak, rms and wave shape parameters. The peak parameter was identified as the most influential to insulation life even as the rms of the resultant waveform remained constant. The wave shape parameter was concluded to be less dominant than the rms parameter but both were less important than the peak parameter. One of the remaining challenges is to further develop this work to include the waveform distortion analysis for electrical treeing in epoxy resins. In order to determine the critical conditions for electrical tree initiation where the power quality has been compromised, experiments require small increments of phase and magnitude of harmonic components interacting with the fundamental. Only then can the critical harmonic levels for electrical treeing be identified.

Many transients occur on power networks particularly switching surges and lightning impulses. Experiments superimposing impulses and the fundamental on XLPE samples concluded that once the fundamental ac voltage exceeds a threshold level, the tree inception voltage is decreased [11, 12]. Additionally the role of space charge has been identified as important in electrical tree inception at the instant of the peak voltage [12], particularly under positive impulses [11]. It is suggested that the cumulative effect of impulses leads to injection and accumulation of space charge and charge transfer, forming low density areas which facilitated tree initiation [12]. Delays in tree initiation were attributed to space charge trapping [12], particularly under negative impulses [11]. Research on epoxy resin [7] confirmed that polarity, decreases in time between surges (increase of repetition rate) and voltage magnitude all result in a reduction of the tree inception time. The voltage magnitude being the

most influential factor and the repetition rate the least. However when more than one factor is varied, they can collectively negate the influences of each other, which can lead to longer inception times [7].

### III. IMPACT OF POWER QUALITY

Disturbances on the power network impact the quality of supply whether they are transient, short or long term. Fig. 1 is an illustration of disturbances (outer circle) and characteristic links to the electrical stress factors (inner circle) previously outlined in the multifactor framework [13].

Short duration sags and swells and long duration overvoltages and undervoltages are linked to the rms amplitude and rise-time. The rise-time denotes a rate of change of voltage which the insulation experiences under fault conditions. Swells and overvoltages can represent significant electrical stressing depending on the peak, rms and duration of such disturbances. An insulation component located at some site in the network can be electrically vulnerable due to weak system impedance and so suffer from a poor quality of supply as outlined in the outer circle of Fig. 1. A key question is “do we know the role the various disturbances play in ageing and failure processes of this insulation component?”

High frequency harmonics lead to increased Joule heating and mitigation against such an occurrence is achieved by de-rating the equipment [14]. However this still thermally stresses the dielectric. Referring to the developed framework [13] this occurrence can be decoupled into the stress vectors 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. The transients introduced with the switching of the protection further pollute the network. For example SF<sub>6</sub> and vacuum switchgear produce hundreds of surges during switching operations with 300ns rise times and rates of 200-3000 surges per second [7]. As the fundamental ac frequency is increased pd magnitude has been shown to

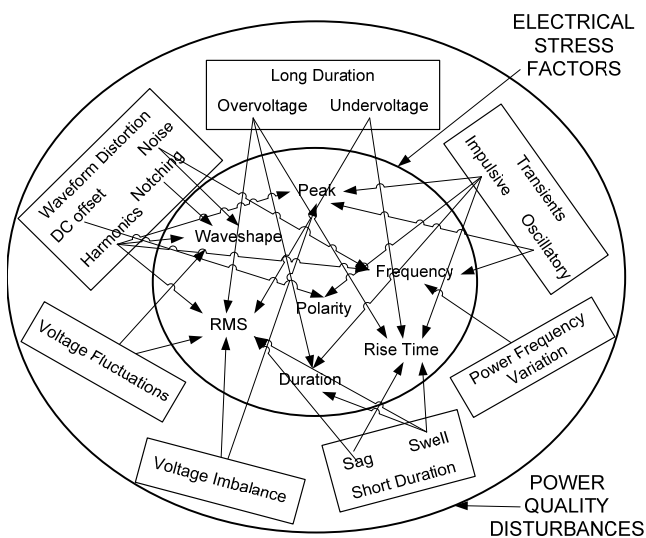


Fig. 1. Links between power quality disturbances and electrical stress factors

decrease [15-17] although the minimum pd magnitude was found to be frequency independent [15]. Frequency is an electrical stress vector while pd is modeled as a competing failure mechanism whose characteristic probability density function is a function of the electrical stress factors, and time. Partial discharge has measurable properties including magnitude and inception voltage [13]. Pd is also a predecessor for electrical treeing and, as frequency increases, tree growth changes from a branched to a bushy structure [18]. However the question remains whether such findings assist in forecasting of the insulation integrity should the harmonic frequency component be increase by a given factor? Some transients are oscillatory ranging from kHz to MHz with magnitudes typically less than 0.8pu [14] and their effect upon the insulation might be regarded as insignificant. This may be true but in a working environment, with a host of stressing factors and interdependent mechanisms, the task of life prediction is further complicated.

A myriad of harmonic and fundamental combinations may be digitally generated for observation of the resultant wave shape. Fig. 2 is an example of one such waveform and shows the combination of the 5<sup>th</sup> and 7<sup>th</sup> harmonic orders both with 180° phase shift and 40% magnitude relative to the fundamental. This waveform is characterized by double peaks at least 20% greater than the fundamental and increased voltage gradients which quickly reverse direction around the zero crossing regions of the fundamental. The time-domain analysis highlights that the rate of change of applied field, including oscillating ripples and multiple peaks, will have an impact on the rate of loss of trapped charges affecting pd and tree inception voltages [2]. This is another level of complexity in comparison to the one harmonic component combined with the fundamental previously reported [4, 5].

Fig. 3, is developed from the multifactor framework [13], tailored to electrical treeing. This figure demonstrates the impact of the power quality factors on electrical treeing and the available measurands. Void formation has been linked to cumulative degradation due to electrical stress [19] and manufacturing defects which also produce protrusions. These physical factors enhance the electrical fields at sites in the insulation facilitating space-charge trapping leading to

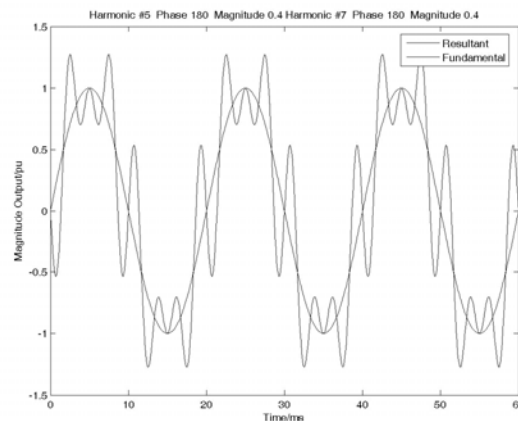


Fig. 2. Fundamental combined with 5<sup>th</sup> and 7<sup>th</sup> harmonic components.

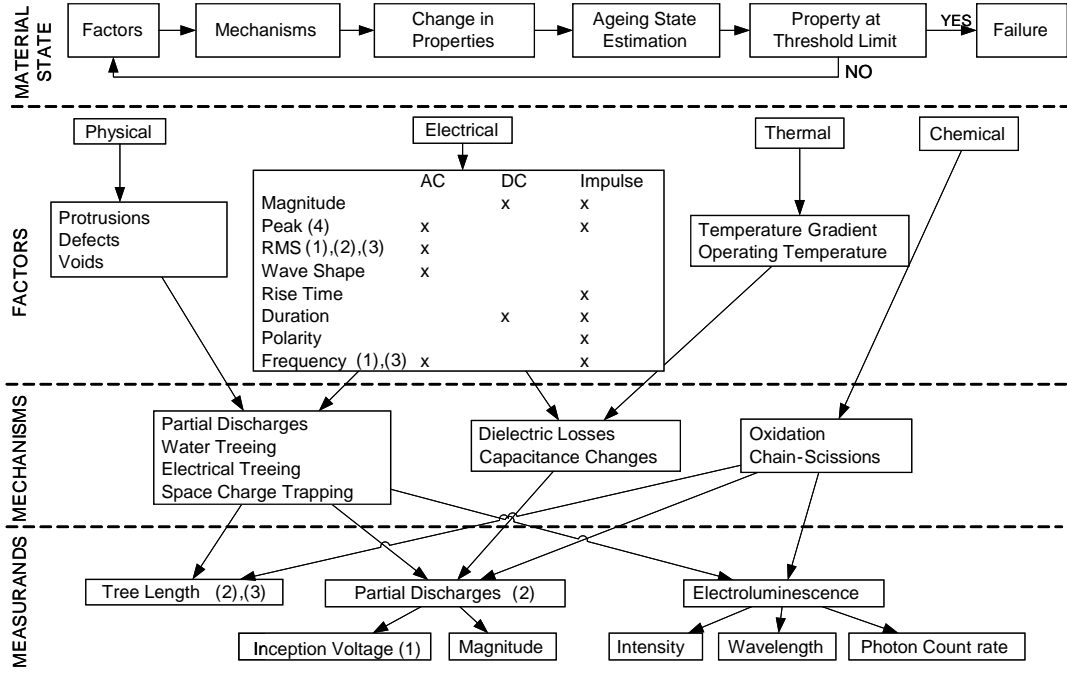


Fig. 3. Multifactor framework for electrical treeing. Numbers in brackets refer to equations in the text below.

electroluminescence, pd inception and treeing. Electrical tree inception has been attributed to chemical mechanisms (oxidation and chain-scissions) after prolonged electrical stressing [19]. This framework allows asset managers and dielectric experts to link the effect of any stress factor (e.g. wave shape or thermal cycling) to any mechanism (e.g. electrical treeing) and so to asset ageing. To facilitate this, life estimation models must be available to process the raw data captured from the measurands, whether they be photon counts, pd magnitude or tree length. More importantly the critical levels must be determined to quantify the threshold limits. Critical levels are values of the measurands which indicate the system is changing state or close to failure. As an example, the model developed for tree growth by Bahder et al [20] assumed once a local threshold field was exceeded due to imperfections, pd can occur, and time to failure is given by:

$$t_G = \frac{1}{a_1 f \{ \exp a_2 (E - E_t) - 1 \} \{ \exp a_3 E + a_4 \}} \quad (1)$$

where,  $E_t$  represents a threshold of electrical field for electrical treeing,  $E$  is the local electric field at the initiation site,  $f$  is the supply frequency and the constants  $a_i$  are dependent on the material, geometry, temperature, shape and the form of applied voltage. Montanari [21] modelled the failure time of insulation by setting a predefined limiting value of the charge due to pd activity which correlated with tree length:

$$t_G = b_1 \frac{[\ln((Q/b_2) + 1)]^d}{(E - E_t)^n} \quad (2)$$

where  $Q$  is related to an integrated measured partial discharge,  $b_i$  are constants,  $n$  is a voltage endurance coefficient,  $E_t$  represents a field threshold for the process, and  $d$  is the fractal dimension of the tree.

Water trees can exist in polyethylene without causing failure until an electrical tree is initiated. An electro-thermo-mechanical phenomena has been suggested as the mechanism causing the transition from water tree to electrical tree [22]. It is suggested that an impulse voltage induced transient current causes the water in the tree channel to boil leaving a void which supports pd activity and electrical tree initiation. Another model proposes tree initiation from voids and consideration of evolving new branches from an existing tree to yield a time to failure of:

$$t_G = \frac{1}{c_1 f \{ \exp(\alpha L_b E) - 1 \}} \quad (3)$$

where  $L_b$  is a unit of tree branch length,  $\alpha$  is the Townsend ionization coefficient and  $c_1$  is a material constant. This model inherently accounts for the fractal dimension index.

Lightning surges are often considered a severe threat. There are many other transients with rise times from nanoseconds to milliseconds which can exist on the power network [14]. High rates of change of voltage often result in increased temperature gradients and increased momentary operating temperatures. Significant oxidation may occur in water trees at high temperatures leading to an increase in water absorption, higher conductivity and eventual thermal runaway [27]. This suggests such transients are key to tree inception if not growth characteristics. A theoretical expression for tree initiation time due to energy from injected pulses is given by [25, 26]:

$$\log(t_i) = A/E + B - \log\left(\frac{1}{E_t} - \frac{1}{E}\right) \quad (4)$$

Where  $t_i$  is the time to initiation,  $E_t$  is a threshold field for damaging electron avalanches and the constants  $A$  and  $B$  are determined by geometry.

#### IV. DISCUSSION

Harmonics are a steady state occurrence compared to lightning and switching surges. On real networks there maybe 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 effects ageing in general, and in particular the propagation of an electrical tree. In a working environment, the growth and fractal dimension of trees cannot be accurately forecast. 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. It is clear that the quality of supply can decrease the inception time of an electrical tree and reduce pd and tree inception voltages, resulting from superposition of disturbances and steady state events.

Research has yielded many diagnostic techniques and tools, suitable for use in the many insulation systems. These advances must be acknowledged as remarkable and significant progress in life estimation of insulation. However these tools and techniques provide an instant snapshot of the ageing state of the insulation from which asset managers can decide to undertake repair or replacement activities. The changing working environment dictates the combination of the stress factors influencing the future ageing mechanisms. It is extremely difficult if not impossible to accurately predict the effect of changing conditions on equipment in service. However critical limits are often determined by scientists and physicists who frequently perform simplified laboratory life-estimation experiments. These critical limits should be set by asset managers whose in-service equipment is exposed to the numerous stress factors and has both a system and component perspective. An improved knowledge base of the multifactor ageing of insulation systems is required to comprehend the competing failure factors and mechanisms while accurately forecasting insulation life.

#### V. CONCLUSION

The literature reviewed provides a strong basis of research into the impact of harmonics and transients on the simplest of insulation systems, the point-plane geometry. In particular, models can identify critical electrical stress conditions which provide transition from one ageing state to another, identifying operating conditions which may accelerate or initiate insulation degradation. However the situations modeled fall short of the complexities expected in real power networks and knowledge of the influence of power quality on electrical ageing falls short of the needs of asset managers. A multifactor ageing framework is proposed as a tool to assist identifying the questions which need answering in the future.

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