Analysis of Electrical Tree Inception in Silicone Gels

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ABSTRACT

This work assesses the initial and crucial part of electrical treeing degradation, the inception stage, focusing on its dependence on applied voltage waveform and frequency. Tests have been performed on needle-plane configuration samples in solids and gels. A physical model has been formulated through an adaptation of an established theory for solids in which electrical tree inception is related to damage-producing injection currents. The voltage rise time appeared to be the most important parameter influencing the tree inception in the gel, while in the solid material the frequency is more relevant. The analysis leads to the conclusion that tree inception in gels is due to a single high-energy event, in contrast to what is commonly known for solids where damage accumulation takes place. A tree inception model is proposed for the gel, in which initiation is driven by a pressure wave generated by the electric field and the space charge injected into the sample. The model fits the experimental data and may be used to predict the tree initiation for different waveforms and voltage values.

Index Terms — Electrical tree, silicone gel, power module encapsulation, tree inception, electrical failure.

1 INTRODUCTION

SILICONE gel is the principal dielectric material employed in electronic power modules and it is used to encapsulate high voltage insulated gate bipolar transistors (IGBT) [1]. The transistors and the metallized substrate of IGBT are soldered onto a base plate and completely immersed in silicone gel, which provides a barrier to electrical discharge and ensures good thermal and mechanical properties [2–4]. Silicone polymer gels present some characteristic features [5]. They exhibit a very low glass transition, between -125°C and -150°C , mainly due to a high free volume in the material. After curing in-situ, silicone gels result in very soft and resilient materials capable of retaining much of the stress relief and self-healing qualities of a liquid while providing the dimensional stability of a cross-linked elastomer. Moreover, these materials are stable over a wide temperature range, between -40°C to 180°C , preserving their physical and electrical properties. The self-healing capability of silicone gels allows damage due to mechanical stresses or electrical discharge phenomena such as partial discharge (PD) to recover. Another key characteristic is a naturally tacky surface after cure. This natural adhesion allows gels to gain physical adhesion to most common surfaces without the need of primers [6]. All these characteristics make silicone gels the most cost-effective choice for IGBT encapsulation, nevertheless, alternative materials have been investigated as a possible replacement [7–10] for them.

Recent developments in power modules have increased the power density by raising the voltage employed or by miniaturization. The result is a higher stress on the IGBT insulating system. Simulations and analysis reported in the literature [11, 12], highlight the presence of significant electric field enhancements corresponding to spots on the metallization edges, which can activate PD. In these conditions, the PD can easily create an irreversible degradation of the insulating material, namely an electrical tree, which brings the dielectric to breakdown.

Silicone gels are unusual dielectrics with features reminiscent of both liquid and solid [13]. Their dielectric reliability when subject to an intense divergent electric field has been investigated by different authors, under both impulse and sinusoidal voltage. In [14, 15], the tests performed followed a classical procedure employed in liquids, with the aim to evaluate the streamer inception (streamer is a term commonly employed for the propagating breakdown structure in liquids) and to compare the behavior observed in the gels with that of silicone oil. In [16, 17], the experiments focused on lower AC voltages, highlighting the formation and growth of string of bubbles having the shape akin to an electrical tree in a solid insulator (therefore, referred to as electrical trees, indifferently from the case of solid dielectrics). The tree growth and structure were compared with that of the elastomer by means of their fractal dimension.

All the studies concluded that, regardless of the self-healing

behavior of silicone gels, a continuous voltage application leads to the formation of discharge-supporting electrical tree structures [13, 16, 17], the skeleton of which is permanent [17] (i.e. the material is irreversibly damaged). These structures propagate inside the dielectric from a needle electrode [13, 16, 17] and can eventually lead to electrical breakdown. In bulk silicone gels the propagation of the tree structure is preceded by an inception stage in which a discharge supporting cavity is formed at the needle electrode by either bond-breaking or plastic deformation or both, i.e. the material morphology is changed or ‘damaged’ at the electrode.

The inception stage can be considered as the ‘birth’ of the tree and is connected with very low energy PD in solid dielectrics, where it is a clearly discernible stage of electrical tree formation that mainly depends on the voltage applied and the time of application [18–20]. Inception therefore is clearly the key factor for the electrical reliability of the gel as an insulating material, since once a tree has initiated it will inevitably bring the insulation to eventual failure for a continuous application of the electrical stress. The aim of this work is to evaluate tree inception in silicone gels, with attention being paid to any differences between them and the well-studied ‘solid’ dielectrics that may occur as a result of the differences in physical nature of the two materials. In addition the effect of the waveform frequency and shape upon the inception process will be evaluated as this has a particular importance in view of the fact that the testing of insulation quality is often performed in ac-voltages whereas the waveform applied to IGBT insulation in operation will be that of a series of square voltages. Through the experimental and computational results obtained, a model for the inception phenomenon is proposed that has a significant difference to the ones commonly adopted in solid materials. Furthermore the results and the model allow a critical evaluation of potential test protocols to be evaluated.

2 EXPERIMENTAL

2.1 SAMPLE PREPARATION

The silicone gel used in this work was a two compound transparent silicone dielectric gel, supplied by RS Components Ltd, UK. The two liquids, labeled as part A and part B, should be mixed with a 1:1 ratio in order to obtain the correct degree of crosslinking. In previous work [21], it is shown that different ratios of the two compounds may produce either liquid, semi-elastomeric or elastomeric materials.

The two compounds were weighed separately, mixed together and manually stirred inside a beaker. The liquid mixture was degassed for 10 minutes in a vacuum oven and poured into the needle-plane cells. Each cell was manually obtained from a polystyrene cuvette of 10 mm × 10 mm × 40 mm. The cuvette base was removed and replaced with a thin copper layer which acted as the plane electrode. A sharp needle was inserted into the cuvette, leaving a 3 mm gap between the needle tip and the copper foil. The tungsten needles employed in this work had a tip radius of either 5 µm or 3 µm.

After pouring the mixture into the cells, the samples were cured in an oven at 65 °C for 4 hours and left to cool down slowly to room temperature (~20 °C) overnight. They were then

kept in an enclosed environment and tested within a few days.

The gel samples used in this work were manufactured with the compound composition specified in the datasheet, i.e. 50% part A and 50% part B. In addition some samples were prepared with 70% part A and 30% part B in order to obtain an elastomeric material with the same basic chemical composition as the gel that could be used for comparison purposes.

2.2 TEST METHOD

The main factors commonly used to characterize tree inception are the time required to initiate the process at a given voltage and applied voltage required for inception (value, frequency and shape). Preliminary experiments were carried out in order to decide the most appropriate test procedure to adopt. The time appeared not to be a crucial factor, since different voltage step lengths did not appear to influence the tree inception significantly, unlike in solids [22], [23]. Moreover, the tests required a fast and reproducible procedure, since the aim was to determine whether there was a difference in tree inception between the sinusoidal and square waveform as a function of the frequency. For these reasons, the tree inception voltage (TIV) has been adopted as the appropriate parameter for analysis. During the experiment the samples were placed under silicone oil which prevented any contact with the environment while the TIV was being measured.

The TIV was measured by increasing the applied voltage in 100 V_{pk} step per second starting from 7 kV_{pk} for the 5 µm tip needle and from 4 kV_{pk} for the 3 µm tip needle up to tree initiation, which was detected optically. At tree inception the voltage was immediately turned off and the peak voltage was recorded as the TIV. In order to avoid a possible complete instantaneous breakdown of the sample the highest voltage was arbitrarily limited to 14 kV_{pk}. The TIV was measured in this way for frequencies in the range 1 Hz to 1 kHz. In the first instance, advantage was taken of the presumed self-healing capability of the gels to make a sequence of TIV measurements at different frequency using the same sample in order to minimize the possible differences due to geometrical tolerance in each cell. In this case the TIV was obtained alternately for sinusoidal and square voltages with a rest period in between to allow the sample to recover. The results obtained in this way were then checked using a new sample for each measurement.

Figure 1 shows an example of the initial cavities taken to define the inception of an electrical tree in the silicone gel examined here. These cavities have been shown to lead to electrical tree structures in preliminary work reported in [17] (see Figure 5b of [17]). The backbone of these tree structures are permanent features and support gas discharges promoting new growth [13], though the new growth at the tree extremities is reversible for a while. In the first instance therefore we have taken the first cavity to be a recoverable entity that given a suitable recovery time allows us to use the same sample for further inception voltage measurements. Later we have made each inception voltage measurement on an unused sample.

A proper recovery time was required by the sample between each measurement to avoid the possible influence of the

Figure 1. Example of tree inception in silicone gel.

previous inception. The recovery time, ranging from few minutes to some hours, was decided after each measurement, by optically checking the condition of the area close to the needle tip. It was found that the self-healing behavior of the silicone gel is able to restore the initial conditions with no significant influence on the following measurements, but only if the structural change involved in the formation of the initial cavity is very limited. When the damage produced by tree inception exceeded this condition and gas bubbles and tree channels can be observed in the gel after the test, as in the tree structures of gels [17] the sample was not used for further inception tests, though the value obtained in its first use was retained.

All the tests were performed at room temperature and atmospheric pressure, thus, the temperature influence is not investigated in this work nor the effect of pressurization.

2.3 EXPERIMENTAL SETUP

TIV tests were carried out at different frequencies and for different waveforms. Each sample was placed inside a transparent cell with a glass window, filled with silicone oil to insulate the specimen. The cell containing the sample was placed in a Faraday cage, employed to reduce the external lighting and to ensure safety to the operator. The back-illuminated images of the needle tip and of the electrical tree projected out of the cage through a lens were recorded with a CMOS full high definition (HD) camera.

The high voltage was supplied using two different devices. For the sinusoidal waveform and for the square voltage with a maximum slew rate of 250 V/ μ s a high voltage amplifier from TREK Inc. (model 20-20C-HS) was employed. The waveform shape and frequency were controlled by an external digital waveform function generator. The higher slew rate square voltages employed in this work, about 12.5 kV/ μ s, were obtained from a push-pull MOSFET switcher supplied by Behlke, Germany. This system is able to produce a square voltage with short rise and fall time, in the range of hundreds of nanoseconds, up to a frequency of 2 kHz and a maximum voltage of 15 kV_{pk}. In this configuration, the digital waveform function generator is used only to regulate the voltage rise during the tests. In each test the voltage and the waveform shape

were double-checked with an external digital oscilloscope.

3 RESULTS

3.1 PROCESSING OF INCEPTION VOLTAGE

All the values reported and the calculations are carried out in respect of the voltage peak value, which is an appropriate value to compare square and sinusoidal voltage from the insulating system point of view. The square voltage used for comparison with the sinusoidal one had a 250 V/ μ s slew rate. Due to the limits in the maximum voltage applied during the experiments (14 kV_{pk}) some samples did not reach the TIV for all the frequencies applied. In these cases, the value recorded for the analysis was 14 kV_{pk}, even if no tree was incepted. Therefore, for some frequencies, the average of the values reported underestimates the correct values.

Since the use of multiple tree inceptions on the same sample may deteriorate the sample itself for the following measurements, thereby decreasing the TIV, several preliminary measurements using a single sample per measurement were carried out to check this possibility. In all the cases, the first TIV measurements obtained on a new sample for a given frequency and waveform had a value equal to or even slightly lower than the following ones with no significant difference.

The mechanism of electrical tree inception is a statistical process with the characteristic value in the distribution being related to the mechanism involved [18]. However variations in factors such as the needle tip radius and quality can also contribute to the spread of the TIV values for any given condition. Since measurements are performed on each of the five samples for all of the various conditions of frequency and waveform, such variations will be carried through all the measurements and may distort the characteristic values. Thus, for example, an average of TIV for the 5 μ m tip needle samples taken over all the measurement conditions gives a value for one sample of 9.77 kV_{pk} and for another of 12.7 kV_{pk}, with the others in between yielding an average over all the samples of 10.78 kV_{pk}. In order to minimize the effect these variations upon the characteristic TIV at any given condition we have adopted the following procedure. First the average TIV over all conditions is calculated for each sample, i.e. A_n with $n = 1, 2, \dots, 5$. Then the TIV for each sample at any given condition, e.g. frequency = f_x , sine wave ($a=1$) or square wave ($a=2$) is divided by its average A_n to obtain a dimensionless value given by $TIV(f_x, a)/A_n$ for the n -th sample. The characteristic average relative value of TIV, i.e. TIV-r is then determined for each condition, (f_x, a), by averaging the dimensionless fractional $TIV(f_x, a)/A_n$ over the five samples.

3.2 SILICONE GELS

The TIV-r values obtained for samples with a 5 μ m tip needle are presented in Figure 2. The 95% confidence intervals shown

Figure 2. Example of tre Average TIV-r for 5 μ m tip needle samples (TIV global average: 10.78 kV_{pk}).

in the graph are provided by the t-Student statistical probability distribution. In order to reflect the uncertainty in the estimated average due to some measurements which reached the 14 kV_{pk} limiting voltage without tree inception, the confidence intervals of the frequency values where this happened are shifted to higher TIV values.

The TIV-r decreases for the sinusoidal waveform as the frequency is increased. In contrast there is a slight increase of the TIV-r with frequency for the square waveform. Thus, the values of TIV-r obtained for sinusoidal and square waveforms tend to get closer at the higher frequencies. It should be noted that the same trends are observed in the TIV values before the scaling procedure described above.

Needle electrodes whose tip radius is 3 μ m give a higher maximum field at a given voltage than needles with a tip radius of 5 μ m. Therefore a lower TIV can be expected for such samples, which will minimize the number of tests where tree cannot be incepted at the limiting voltage of 14 kV_{pk} and hence give a better definition of the TIV trend with frequency. This reduction of TIV is confirmed by the values of A_n for the five samples, which range from 6.43 kV_{pk} to 8.63 kV_{pk}, with the global average of 7.40 kV_{pk}, in contrast to the global average of 10.78 kV_{pk} of the 5 μ m radius samples.

The average TIV-r obtained from 5 samples with a 3 μ m needle tip is shown in Figure 3.

Figure 3. Average TIV-r for 3 μ m tip needle samples (TIV global average: 7.40 kV_{pk}).

It can be seen that the difference between the sinusoidal and square value of TIV-r at lower frequencies is greater than in Figure 2, because now fewer samples have failed to initiate an electrical tree at the lower sinusoidal frequencies leading to a better definition of the TIV-r. Except for this however, no significant difference appears in the general frequency dependence of TIV between the results obtained with the 3 μ m and the 5 μ m radius needle tip. Again it should be noted that the unprocessed TIV shows the same frequency dependence for the two waveforms.

The results shown in Figures 2 and 3 demonstrate that the different frequency-dependence observed for the sinusoidal and square waveforms in gels is a feature of differences in the way that the waveform drives the tree inception mechanism. One possible difference is the length of time that a sample is exposed to the maximum voltage in the two cases. This is longer for a square wave than a sinusoidal wave of the same frequency and hence could mean that the sample was exposed to a larger amount of damaging energy in the former case than the latter, thereby leading to a lower TIV. This possibility was checked by applying a constructed pulse waveform formed by cutting the top and bottom of a sinusoidal waveform (cosrect), such that the rise time was similar to that of a 1Hz sinusoid and the width at peak voltage was equal to that of a 1Hz square voltage. Tree inception under this waveform was not observed up to 14 kV_{pk} as in the 1 Hz sinusoidal waveform. Therefore the length of time at the maximum voltage of the pulse peak does not influence the result but instead the voltage slew rate is a significant parameter for tree inception in silicone gel. In order to check the importance of the slew rate, experiments have been performed on 5 samples with 5 μ m radius needle tip under a square voltage with two different slew rates, one of about 12.5 kV/ μ s and one (already performed and shown in Figure 2) of 250 V/ μ s, and the results are given in Figure 4. Here it can be seen that the average TIV increases with frequency as for the square wave in Figure 2 and Figure 3. More importantly however the average TIV decreases by about 13 % on increasing the slew rate (decreasing the rise time) from 250 to

Figure 4. Average TIV for 5 μ m tip needle samples with 250 V/ μ s slew rate and 12.5 kV/ μ s slew rate square voltage.

Figure 5. Average TIV for elastomer.

12.5 kV/μs, consistent with the result for the constructed waveform which is equivalent to a very low slew rate.

3.3 ELASTOMER

The work on tree inception in polyethylene reported in [22] and discussed in [23] imply that the tree inception voltage decreases with increasing frequency (of a sine wave or pulse repetition). In order to check that our results are not the consequence of the very different chemical composition of the silicone gel compared to that of polyethylene, but genuinely the property of its gel nature, experiments have been carried out for elastomeric samples made from the same chemical components as the gel, but with 70% part A and 30% part B compounds and a needle tip of 5 μm radius. Figure 5 shows the results obtained.

The solid nature of the elastomer did not permit multiple tests on the same sample and so each point in the chart in Figure 5 is the average value obtained by a single measurement on three new samples. The TIV values show the same frequency dependence for both types of waveform, unlike in the case of the gel. They are slightly higher than in silicone gel at the lower frequencies, and decrease strongly as the frequency increases in line with the results obtained for polyethylene. It is therefore clear that the difference between the frequency dependence of the TIV of different waveforms in silicone gels is a consequence of their gel-nature and not of their chemical composition.

4 INCEPTION MODEL

4.1 GENERAL FEATURES OF ELECTRICAL TREE FORMATION

The electrical treeing process is commonly divided into three main stages: the tree inception, a decelerating growth, and runaway [22]. The features of tree propagation in solids are broadly understood to be related to discharge action in gas-filled tubes or charge injection from conducting tube walls [19, 22]. The tree inception process, which usually determines the time to breakdown [24] is much less clear [19, 25]. In solid materials however, and under alternating voltages stress, it is generally accepted that electrical tree inception is associated

with charge injection in and extraction from a region of high alternating electrical stress, as evidenced from the electroluminescence these currents generate [26–28]. This work associates tree inception with damaging injection and extraction currents which is consistent with the relationship of the TIV with the slew rate of the square pulses. A model for the inception of electrical trees therefore requires the contribution of two features to be brought together: (i) the injection and extraction currents, and (ii) the way that these currents produce the initial cavity that results in the formation of a propagating electrical tree.

4.2 SPACE CHARGE LIMITED INJECTION

In [22] the damaging currents were assumed to be injection currents from a needle electrode that took place in an environment where no space charge was accumulated. This restriction was lifted in [29] where injection currents from a divergent field electrode were calculated for sinusoidal applied voltages when space charge was accumulated in the polymer. Recombination between mobile charges from the injection currents and trapped charges of opposite polarity from the previous half-cycle were shown to be able to reproduce the behavior of electroluminescence during the first stage of tree inception in epoxy resin [29]. This work gives a means of calculating the injection currents, the space charge, and the electric field, around an injecting electrode in either a sinusoidal or repeated square wave applied voltage. These features yield factors than can be inputted into a theory for damage generation (i.e. bond breaking and/or polymer deformation) leading to electrical tree inception in the silicone gel and elastomer.

The details of this model are given in [29]. Its main physical features are that during an increasing applied voltage the injection current increases with electrode field until the space charge it produces is big enough to limit the field to a constant value. The approximations required to obtain an analytical solution are summarized below, and followed by the pertinent equations needed for computation.

Assumptions:

1. The geometry of the samples is approximated as a concentric sphere electrode arrangement. r_0 is the inner electrode radius equal to the needle tip radius, r_1 is the end of the space charge region and r_2 is the ground electrode position.
2. The space charge region is small compared with the sample, i.e., $r_1 \ll r_2$.
3. Space charge density, ρ , is constant between r_0 and r_1 , zero outside this region.
4. Transport and diffusion outside this region are neglected.
5. The space charge density depends on time t through $E_0(t)$, the field at the injecting electrode.

Through these assumptions, $\rho(t)$ can be obtained from the solution of Poisson's equation where $V(t)$ is the potential between the injecting electrode and the ground electrode.

$$E_o(t) = \frac{V(t)}{L_0} - \frac{\rho(t)}{\epsilon_0 \epsilon_r} K(r_0, r_1, r_2) \quad (1)$$

In equation (1), ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of silicone gel, L_0 is a scale length which depends on the electrode geometry. For the concentric sphere electrode geometry:

$$L_0 = (r_0)^2 \left(\frac{1}{r_2} - \frac{1}{r_0} \right) \quad (2)$$

$K(r_0, r_1, r_2)$ is a function of the electrode geometry and space charge region thickness and has dimensions of length. This function can be derived as follows. Equation (1) relates the electric field at the injecting electrode to the field in the absence of space charge (Laplacian field), and its modification due to a space charge region adjacent to the injecting electrode. Using the continuity equation, the charge density flowing across the surface area of the injecting electrode S_i into the space charge volume V_{sc} is related to the rate of increase of charge density in volume v as follows:

$$\int_{S_i} j(t) ds = \int_{V_{sc}} \dot{\rho}(t) dv \quad (3)$$

By differentiating equation (1) with respect to time and introducing the injection current j described in equation (3) it is possible to obtain:

$$\dot{E}_o(t) = \frac{\dot{V}(t)}{L_0} - \frac{k j(t)}{\epsilon_0 \epsilon_r} \quad (4)$$

where k is a dimensionless constant and in this work geometry is equal to:

$$k = \frac{3r_0^2}{r_1^3 - r_0^3} \left(\frac{r_1^3}{3} - \frac{r_1^2 r_2}{2} - \frac{r_0^3}{3} + \frac{r_0^2 r_2}{2} \right) / (r_0^2 - r_0 r_2) \quad (5)$$

In order to use equation (4) it is necessary to have an expression relating the injection current to the electrode field at any given time. In [29] equation (6) was adopted because it fits to the regime of fields and temperatures commonly occurring for which neither the Schottky-Richardson (low field – room temperature) nor the Fowler-Nordheim, (high field – low temperature) approximations apply [30, 31]. This equation introduces two constants α and β , which depend on the temperature and potential barrier height. Since it was shown in [29] that because of the field limiting nature of the space charge generated the actual injection current is independent of the details of the injection current expression, equation (6) will be used here.

$$j(E, t) = \alpha e^{\beta E_o(t)} \quad (6)$$

Numerical integration of equation (4) using equation (6) for the injection current has allowed the electrode field and injection current to be calculated for the two voltage waveforms. The integration was carried out over two full waveform cycles taking $\dot{V}$ as a boundary condition which

depends on the voltage waveform. The values of α and β have been chosen equal to the ones adopted in [29], hence, α was set equal to $1 \times 10^{-5} \text{ Am}^{-2}$ and β to $8 \times 10^{-8} \text{ V}^{-1}\text{m}$. Though these values applied to epoxy resin and not silicone gel, this choice should be sufficient to allow general trends of behavior to be identified, especially as α and β relate to the electrode-polymer interface and will take different values for different materials. In this concentric sphere model, the electrode radius, r_0 , was set to $3 \mu\text{m}$, the space charge radius, r_1 , was set to $6 \mu\text{m}$ and the outer radius, r_2 , was set equal to 3mm (the same as the pin-plane spacing used in the experiments). The thickness of the space charge region, equal to the difference between r_1 and r_0 , was set to $3 \mu\text{m}$, but this choice does not influence significantly the overall trend. The relative permittivity of the silicone gel, ϵ_r , was assumed equal to 2.8.

The space charge injected in the proximity of the needle tip is calculated through the integration over time of:

$$\rho(t) = j(t) \Delta t \frac{S_i}{V_{sc}} \quad (7)$$

Figure 6 shows the behavior of the E_o , j and ρ for a 50 Hz sinusoidal waveform at different peak voltages applied, while in Figure 7 the behavior of the three quantities is shown for a 50 Hz square waveform at the same voltages.

From Figures 6 and 7 it can be seen that the field limiting effect of the space charge results in an electrode field that saturates at a maximum value that is not dependent upon the peak value of the applied voltage and which is almost independent of the waveform. The only effect upon the electrode field of increasing the applied voltage is a change of rise time in the sinusoidal waveform, which increases the rate of change of electric field curve during polarity reversal.

The major parameter affecting the injection current is the rate of change of voltage, $\dot{V}$, in equation (4). In the case of the square waveform the injection current reaches a very large maximum during rise and fall times, but falls close to zero in between

Figure 6. E_o , j and ρ behavior for 50 Hz square waveform at 6 kV_{pk} (dashed blue), 9 kV_{pk} (dotted green) and 12 kV_{pk} (continuous red)

Figure 7. E_0 , j and ρ behavior for 50 Hz square waveform at 6 kV_{pk} (dashed blue), 9 kV_{pk} (dotted green) and 12 kV_{pk} (continuous red).

where $E(t)$ saturates at a constant value and $\dot{V}$, is zero. This is very different to the sinusoidal waveform for which $\dot{V}$, continues to change even when $E(t)$ saturates. This results in an injection current that continues throughout most of the ac-cycle but is orders of magnitude lower than that found for the square waveform.

As a result of the differences in the injection current there are differences in the space charge. In the square waveform all the space charge is accumulated during the rise and fall times and it remains constant during the period of constant voltage. In the case of an ac applied voltage, the space charge roughly lags the voltage by 90° but has a similar waveform because the injection current continues throughout the ac-cycle. The maximum amount of space charge accumulated is however very similar.

These calculations show that there are significant differences in the time dependencies of the electrode field, injection current, and space charge, for the two waveforms, which may have some relationship with the differences observed for the TIV under the two waveforms. As a step towards establishing the relationship the frequency dependence of, E , j , and, ρ , have been calculated for a voltage of 9 kV_{pk} and the results are given in Figure 8. It can be seen that there are significant differences between the outcomes for the two waveforms.

For the sinusoidal waveform, the maximum electric field and injection current increases in proportion to the logarithmic increase of the frequency, similar to the reciprocal of the TIV. In contrast the same quantities for the square waveform show hardly any change, whereas the TIV increases slightly with increasing frequency. On the other hand the space charge in both cases decreases with increasing frequency with the amount accumulated under square wave excitation being very slightly higher than that for a sinusoidal voltage. It would therefore appear that the space charge and the electrode field are the quantities that result in the differences in TIV between the two waveforms, however it is necessary to connect them with a physical model to determine exactly how they influence the TIV behavior.

Figure 8. Maximum values of E , j and ρ as a function of frequency, calculated at 9 kV_{pk}

4.3 INCEPTION MODEL FOR GELS

The model for tree inception developed here is adapted from that of Tanaka and Greenwood [22, 23], which was chosen because it is expressed in terms of general quantities that can be given simple physical meanings. The physics of this inception mechanism is described below:

- Each pulse or sine wave half-period produces an event (or a set of events) which delivers an energy G_n to the dielectric.
- When G_n is greater than a dielectric specific value G_{th} (temperature dependent) the excess energy causes material changes either by bond-breaking or plastic

deformation or both. If G_{th} is greater than G_n the event cannot produce such damage.

- c. The material alterations (damage) produced on each pulse are accumulated until they reaches a critical quantity C_t at which level a tree is initiated, through the formation of the first cavity.

These postulates lead to an equation connecting the time to initiation t_i and the event frequency f (pulse or polarity reversal):

$$f t_i (G_n - G_{th}) = C_t \quad (8)$$

The damage accumulation concept in this model is appropriate for solids because they have no ability to self-heal., and equation (8) has been used successfully to describe the time to initiation in polyethylene at different voltages where G_n was taken to be proportional to the injection-extraction currents [22, 23]. In this case the time to inception would reduce with increasing frequency, and since the voltage on a tree-initiating ramp is proportional to the time it can be expected that the TIV would reduce with increasing frequency as observed for the elastomer. However, such a frequency dependence is not consistent with the behavior of the silicone gels under a square waveform, where their semi-liquid nature and self-healing capability make such damage accumulation unlikely. Therefore we should assume that damage is not accumulated during tree inception in silicone gels i.e. $C_t = 0$, instead an electrical tree is initiated following a single event with an energy $G_n \geq G_{th}$, i.e. the inception condition for silicone gels that is equivalent to equation (8) is:

$$G_n = G_{th} \quad (9)$$

The factors involved in determining G_{th} for silicone gels can be determined by noting that the trees are initiated by the formation of a bubble-like feature in contact with the needle tip, see Figure1. Bubble formation requires the presence of gases, which may have originated with the gel cross-linking or be generated by vaporization of a small amount of liquid component by joule heating from the injection/extraction currents. A pressure difference across the gas-fluid interface is also needed to expand the region into a gas filled bubble and the equilibrium condition is given by the Young-Laplace equation [32]:

$$\Delta p = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (10)$$

Here Δp is the pressure difference across the fluid interface, γ is the surface tension and R_1 and R_2 are the principal radii of curvature.

During inception, injection and extraction must supply the energy to produce the pressure difference required for the formation of the bubble. In the model, the space charge ρ produced by charge injection is assumed to be spatially uniform over the space charge volume, V_{sc} , hence, ρV_{sc} is the total charge accumulated close to the high voltage electrode. Figures 6 and

7 show its behavior as a function of time. Denoting the external surface of this space charge layer as S_{sc} , it is possible to define a parameter u that can be regarded as the pressure produced by the region of charged silicone gel upon the surrounding material when acted on by the electrode field E , with:

$$u = E \rho \frac{V_{sc}}{S_{sc}} \quad (11)$$

This pressure (force per unit surface area) has maximum absolute values during the polarity reversal, when the accumulated space charge, ρ , and the field, E , have opposite sign. Under these circumstances the pressure, u , acts to first compress the space charge region and expand the silicone gel abutting the contracting boundary and then to compress the gel and expand the space charge region and hence can be thought of as acting to induce cavitation at the boundary of the injection region. Therefore it is reasonable to consider G_n approximately directly proportional to u , which can also be thought of as the stored energy density available for the formation of the cavity.

It should be noted that the cavitation in the model would occur at the boundary of the spherical space charge region due to the assumptions that the size of the region is always the same and that the charge distribution is homogeneous. This will probably not be the case in the real situation of a pin-plane electrode configuration where the pressure difference required for the initiation would occur in the region where the space charge and electric field difference inside the gel are higher, that is, along the pin axis direction and extremely close to the pin electrode within the gel matrix.

The parameter u depends on temperature, T , by the physical properties of the material since is connected with the parameters controlling the injection current (here α and β), the applied voltage, V , and its derivative with respect to time. As a first approximation, it is possible to consider $G_n(0)$ and u_0 equal to zero, and write:

$$G_n(u) = Au \quad (12)$$

Here A is a proportionality factor that should take into account the influence on the inception mechanism of operating pressure (which should have an important role in the tree inception), moisture, and other physical and geometrical quantities not studied in this work. Since all of them should not change during the tests performed, A can be considered to be simply a constant for the model analysis.

For a small variation of the voltage applied, u is proportional to the peak voltage applied V_{pk} , thus, it is possible to normalize u , through dividing it by a fixed value of peak voltage V_t , to obtain u_t . Now equation (9) can be written in a form that determines the inception voltage:

$$u_t V_t A = G_n = G_{th} \quad (13)$$

Here $u = u_t V_t$ and V_t is the peak value of inception voltage, i.e. the TIV. Since the same sized bubble cavity defines inception in all cases, G_{th} will be independent of the TIV value

Figure 9. TIV for 5 μm tip samples and ϕ trends.

and therefore the measured TIV should be inversely proportional to the value of u . The calculated values of u have been used to validate this result. For clarity, the value ϕ is introduced:

$$\phi = 1/Au_t \quad (14)$$

For the inception model proposed, the calculated value of ϕ should be proportional to the TIV-r.

Figure 9 shows the fit between the TIV-r values of Figure 2 and the trends of ϕ , calculated for 9 kV_{pk} voltage with a high-voltage electrode radius of 5 μm .

The small increase with the frequency of ϕ calculated for the square voltage waveform (red curve) shown in Figure 9 follows the measured TIV for the square voltage. Moreover, the ratio between square and sine TIV seems to be approximatively the same as the one between ϕ calculated for the square and sinusoidal voltage.

Figure 10 shows the behavior of TIV-r for the 3 μm tip samples and ϕ calculated for 6 kV_{pk} applied to a 3 μm radius electrode.

For this second series of data, the correspondence between the experimental results and the model is even more evident. A small discrepancy is present for the lower frequencies in the sinusoidal voltage: in this case, probably, some of the assumptions made in the model are not completely true. For instance, the proportionality between u and V may not be valid for a wide range of u (and consequently TIV) values.

It was shown in Figure 4 that the slew rate influences the TIV for the square waveform, with a higher slew rate reducing the TIV. The same behavior was obtained from calculations of u for varying slew rate, i.e. u increases and ϕ decreases when the slew rate is higher and vice versa. For example the average increase in TIV measured for the 250 V/ μs slew rate with respect to the 12.5 kV/ μs slew rate was 13% while the average ϕ increase calculated is about 18%. This good agreement was found even though at the high slew rate the effective time where u is at its maximum value is extremely short and it may be possible for the direct proportionality between TIV and ϕ to be lost.

Figure 10. TIV for 3 μm tip samples and ϕ trends

The proposed model has a practical importance as it permits the comparison of a potential qualification test voltage with the operating one, allowing it to be determined: a) if it is acceptable; b) whether it requires an enhancement factor; c) or if it is even conservative compared with the working condition of the device. For example, for a square voltage, using a lower frequency is conservative as long as the rise times are the same (and as long as tree inception is considered the qualifying criterion), while a test with a 50 Hz sinusoidal voltage is not suitable to qualify a device working at high frequencies.

CONCLUSION

Electrical tree initiation in silicone gel has been studied for sinusoidal and square voltages as a function of the frequency applied. It was found that the square waveform exhibited a much lower tree inception voltage than the sinusoidal waveform at low frequencies (1Hz). However, the tree inception voltages at 1 kHz were almost the same for both sinusoidal and square waveforms due to a slight increase in the TIV for the square waveform and a strong decrease in TIV for the sinusoidal waveform. It was also shown that the reduction of the TIV for the square waveform with respect to the sinusoidal waveform was not due to the longer time spent at the maximum voltage, but to the shorter rise time of the voltage.

A computational model has been presented based on the concept of inception damage (bond breaking and plastic deformation) brought about by injection/extraction currents. In order to reproduce the experimental results it is necessary to assume that instead of accumulating damage from one injection/extraction event to another, as is the case for electrical tree inception in solid (visco-elastic and elastic) dielectric materials, initiation in the gel occurs as the result of a single event whose magnitude is greater than the critical level required to form a gas-filled cavity such as occurs in liquids where the cavity that is produced is able to support partial discharges and expand. This physical process relates to the self-healing ability of the silicone gel which behaves more as a liquid than a solid.

The model proposed has been shown to successfully reproduce the different frequency dependences of the TIV of

the sinusoidal and square wave excitation, their relative magnitudes, their dependence upon the radius of curvature of the needle electrode, and the dependence of the TIV upon pulse slew rate that are experimentally observed. The ability of the model to predict tree inception in silicone gel could become crucial for the future use of this material in high voltage power systems.

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