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Numerically Established Correlation in Electrical Responses of Polymer Film Capacitors to ac and Pulsed Voltages

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ABSTRACT

In this paper, an equivalent circuit model is used to simulate electrical responses of metalized polymer film capacitors to either ac voltage or pulsed voltage stresses, in particular electric field induced on the electrode coating surface and power dissipation within the film capacitor. Electrode segmentation patterns are taken into consideration by means of arrays of interconnected lumped surface resistors, and the film capacitance is modeled by a set of shunt capacitors distributed across the length of the capacitor film. Voltage magnitude and waveform characteristics are studied in great detail for their effects on surface electric field and power dissipation. Through numerical examples, surface electric field and dissipated power induced by one type of external stresses (ac or pulsed) at one frequency are shown to correlate to that at a different frequency. Further correlation is also established to relate surface field and dissipated power induced by one type stress (e.g. ac) to those by the other (pulsed), provided the waveform characteristics of the two different stresses are specifically related. These numerically established correlations can permit significant reduction in development time of metalized film capacitors.

1 INTRODUCTION

METALIZED polymer film capacitors have been used in a wide range of industrial applications including power electronics, power factor correction, power distribution, traction drives, pulsed power drives, laser energization, and space based applications [1–3]. Over the past 20 years, there has been a considerable amount of research and development work on the properties of polymeric films and their degradation under mechanical [4] and electrical stresses (dc, ac, and pulsed) [4–6], and at high temperatures [7]. Accelerated life tests also have been employed extensively to assess and predict the performance of complete capacitor units. These predominately experimental efforts are largely responsible for some 30-fold increase in energy density achieved in HV polymer film capacitors [7].

With new capacitors being designed and prototyped to achieve higher and higher energy density, their performance in practical applications needs to be assessed first by means of accelerated life tests under elevated temperature and electrical stress of various wave forms (dc, ac, and pulsed). These accelerated life tests are very time consuming. dc life tests of a well-designed capacitor can easily last >4 months at one temperature point, and additional aging tests at ac and pulsed voltage stresses will increase further the duration of a full evaluation of capacitor performance. It is therefore advantageous if some theoretical model of film capacitors can be established to aid a preliminary but

rapid assessment of capacitor performance. This would not only permit selection of fewer new capacitor designs for accelerated life tests, but also allow a more creditable comparison of their test results with those performed previously for comparable capacitor designs. The intelligence enabled by viable theoretical models in capacitor design and in the subsequent selection of prototype capacitors for accelerated life tests can lead to considerable reduction of development time as well as substantial saving in materials and consumables incurred inevitably in any accelerated life test.

Degradation of polymer film capacitors is however very complex, influenced strongly by physical, chemical, mechanical, and discharge related processes. As a result, it is particularly difficult to develop a viable capacitor model to include all relevant processes. It is therefore more appropriate and beneficial to develop first simpler capacitor models to address one constituent process of capacitor aging [8]. However it is worth noting that most aging mechanisms are enhanced predominantly by, while not necessarily originated from, a high electric field and the power dissipation induced heat generation within a metalized polymer film capacitor. For instance, HV and large power dissipation accelerate rapidly capacitor aging processes via many known degradation mechanisms including those resulting from electrode corrosion, breakdown discharges, thermal and physical aging of the polymer film, and electrode contact assisted charge injection [2]. This implies that electric field and dissipated power may be used as an indicator of the

relative extent of subsequent aging processes in all aforementioned degradation mechanisms. As a result, it may be sufficiently adequate to model film capacitors with simple field models, for calculation of electric field and dissipated electrical power only, without taking into account of detailed effects of main aging mechanisms (electrode corrosion, discharges, etc.). This consideration has led to the development of equivalent circuit based field models recently proposed for film capacitors [9, 10]. It should be emphasized that electric field and dissipated power on the electrode surface influence significantly, but do not determine, the capacitor life, because there are many other influencing factors. Thus results of our present simulation of surface electric field and power dissipation are a relative indicator of capacitor life, most appropriate when other factors remain common in comparison cases.

In addition to their generic guidance to capacitor design and to eliminate less well-designed capacitors from time consuming accelerated life tests, equivalent circuit models of film capacitors can reveal economically similarities and differences in performance of different capacitor designs that may not be readily or/and economically identifiable experimentally. This capability can further shorten the development time by bridging life test performance of past capacitor designs to the evaluation of new designs. Given that ac and pulsed life tests are performed routinely on film capacitors for many common applications [5, 6, 11, 12], it is of great interest to note the similarity in waveform between ac and pulsed signals. If this similarity in externally applied voltage signals results in a correlation in electrical responses of film capacitors to these two different voltage stresses, it will be potentially possible to relate the results of accelerated life tests under ac stresses to that under pulsed stresses. This correlation can then be used to evaluate the possible removal of the need to conduct pulsed life tests if ac life tests have been conducted for the same capacitor, and *vice versa*.

The aim of this paper is to establish whether there exists a correlation in peak electric field and dissipated power in a film capacitor when subjected separately to ac and pulsed voltage stresses, based on a recently proposed equivalent circuit model of film capacitors [10]. After its basic characteristics are briefly introduced in Section 2, the equivalent circuit model will be used in Section 3 to calculate electric field and dissipated power in a simple film capacitor under an ac voltage stress. The numerical relationship between peak dissipated power during the transient phase and that in the steady state will be established. This calculation is repeated in Section 4 for the pulsed stress case. Then in Section 5, numerical results obtained for ac and pulsed cases will be analyzed to examine whether or not there exists any correlation in electrical responses of film capacitors. Finally, conclusions reached will be summarized in Section 6.

2 AN EQUIVALENT CIRCUIT MODEL OF FILM CAPACITORS

A power film capacitor typically consists of a few thousand flattened polymer layers stacked together and immersed in an impregnation medium (silicon oil or insulating gas) [2, 3]. To bring out the underlying fundamentals of capacitor performance with minimum computational complication, a simplified capacitor model consisting of a single polymeric layer was suggested to facilitate a one-dimensional simulation of

metalized film capacitors with segmented electrodes [10]. This is illustrated in Figure 1(a) where the presence of the impregnation medium is ignored. The polymeric film is assumed to be deposited on both of its two sides a thin metallic coating and the latter is then connected to an external voltage source. Thus the top and bottom metallic coatings act as the electrodes for the single-layer film capacitor. The electrode materials are however assumed to be resistive rather than perfectly conductive. This allows them to be described by means of surface resistors in equivalent lumped circuit models of film capacitors [10].

Figure 1. (a) A simplified model film capacitor with its patterned electrode coating and side margins; and (b) an equivalent circuit model for a single layer film capacitor having four electrode segments.

Electrode coatings in power capacitors usually are segmented and their segmentation can usually be decomposed into interconnected square segments each having the same mosaic design as shown in Figure 1(a) [4, 13]. This allows us to describe each one of them with a lumped surface resistor of identical resistance. Thus a horizontal stripe of the capacitor electrode coating with a width equal to the size of one electrode segment can be represented by an array of identical resistors. Since there are two electrode coatings, each on one side of the polymeric film, they are modeled by two parallel arrays of series-connected identical resistors, each having the same surface resistance R_s , as shown in Figure 1(b). To account for the presence of the polymeric film, a series of shunt capacitors are also added to connect the two arrays of lumped resistors. R_{end} in Figure 1(b) represents the resistance from the electrode edge to the external voltage source. Resistance of the capacitor's external connection is usually much lower than R_s . Hence if the surface resistances of the first and the last mosaic elements are absorbed into the two end resistors in Figure 1(b), respectively, R_{end} may be approximated by R_s . It should be mentioned that the equivalent circuit in Figure 1(b) only models one stripe of a single-layer film capacitor. Nevertheless the remaining part of the single-layer film capacitor of many stripes deep may be considered as being charged up by separate but identical voltage sources. Their behavior should therefore be at least very similar to that of the single-layer film capacitor, especially the electric field distribution.

For numerical examples discussed here, the length of the capacitor stripe is fixed to $L=15$ cm and divided by m divisions to form an array of m square segments. Thus every lumped resistor used in Figure 1(b) takes the value of the surface resistance of one segment. Depending on the mosaic pattern used, the surface resistance is between 50 and

200 Ω . Note that large surface resistance may lead to large electric energy dissipation on the electrode coatings. Thus a small nominal surface resistance of $R_s = 50 \Omega$ is assumed, although the effects of different surface resistance will be assessed through numerical examples in Section 5. On the other hand, the capacitance of each shunt capacitor depends on the number of segments in the length L . Assuming all individual shunt capacitors have the same capacitance

$$C_m = \epsilon_o \epsilon_r \frac{L^2}{m^2 d} \quad (1)$$

where d is the film thickness and ϵ_r is its relative permittivity. For all cases studied here, $d=10 \mu\text{m}$ and $\epsilon_r=2.3$. Thus $C_m=4.58 \times 10^{-8}/\text{m}^2$.

3 SURFACE FIELD AND DISSIPATED POWER INDUCED BY AN AC VOLTAGE

Suppose that at $t=0$ the equivalent circuit in Figure 1(b) of the single layer capacitor of Figure 1(a) is switched on to an external ac voltage source

$$V_a = V_0 \sin \omega t \quad (2)$$

where ω is the angular frequency. For numerical examples considered here, the peak voltage V_0 is fixed at 1.25 kV and the number of electrode segments is fixed at 17. When the film capacitor is switched to the ac voltage source, current starts to flow along the two arrays of surface resistors and this induces a surface electric field on the capacitor electrodes. Such an electric field can trigger and enhance many important physical processes on electrode surfaces from evaporation of current gates in the film self-healing process, to that of electrode segments induced by surface flashover. Thus the level of the peak surface electric field indicates the likely onset of surface-dependent aging processes in metalized film capacitors, particularly surface breakdowns, and as such it may be used to assess the reliability of film capacitors against internal breakdown. The electric field induced across the polymer film should, on the other hand, represent a much lesser problem because polypropylene used in film capacitors is an excellent insulator. As a result, this work concentrates on the evaluation of surface electric field.

Figure 2. Spatial-temporal distribution of surface electric field for the first four cycles of an externally applied ac voltage at 200 kHz.

Circuit equations are developed for the film capacitor of Figure 1 and their subsequent discretization has been used to develop a com-

puter code to simulate metalized film capacitors [10]. Using this computer code, electrical responses of the film capacitor in Figure 1 to an external ac voltage are numerically simulated. Figure 2 shows surface electric field induced across the length of the top capacitor electrode for the first four cycles of an external ac voltage signal at 200 kHz. The alternating nature of the surface electric field is evident, reflecting that of the applied ac signal. Furthermore, it is clear that surface field at one film edge (the left hand side edge in Figure 1) is the highest. While the current flows on the top electrode coating from the left hand edge of the capacitor ($x=0$), part of it will distributively leak to shunt capacitors and so its value decreases progressively towards the right hand edge of the electrode coating ($x=L$). This explains the smaller surface electric field at $x=L$. It should be mentioned that the spatial distribution of surface electric field on the bottom electrode is reversed spatially to that in Figure 2.

Figure 3. Peak surface electric field as a function of frequency induced by an ac electrical stress.

The peak value of the surface electric field is found to be dependent on signal frequency. Figure 3 shows the peak surface electric field as a function of signal frequency, and it is seen that it increases when the signal frequency increases. At higher frequencies, individual shunt capacitors in Figure 1(b) are charged up faster and their induced capacitor current is therefore higher. This leads to a more significant contribution to the current flowing through surface resistors and so a larger surface electric field. At 500 kHz, the highest frequency shown in Figure 3, the surface electric field is $\approx 120 \text{ V/cm}$. This level of surface electric field should not normally, at room temperature, trigger drastic and rapid aging events, such as flashover, on electrode surfaces since it is well below the breakdown field in air [14].

In addition to surface electric field, current flowing on the electrode surface results in power dissipation and the latter contributes to accumulative heat generation within film capacitors. The resulting temperature rise within a capacitor unit can accelerate significantly the aging of its polymer film, electrode coating, and impregnating medium [2]. The elevated capacitor temperature also may induce surface discharges at a surface electric field of 120 V/cm, as observed in the case of outdoor insulators [15], even though such level of surface field is not problematic at room temperature. Dissipated power is therefore a useful indicator

of the likely speed of aging processes of film capacitors and hence their lifetime [2, 13].

Figure 4. Temporal evolution of the normalized dissipated power at different frequencies of an ac voltage stress.

In Figure 4, the instantaneous dissipated power, normalized to the peak steady-state dissipated power, is plotted *vs.* time from switching of the circuit at four different frequencies, namely 5, 10, 50, and 100 kHz. It is evident that there is a transient phase before the steady state is reached and the duration of the transient phase increases with frequency. This is reasonable, because at high frequencies it is less possible to fully charge a capacitor during the first period of the applied signal and as such it will take longer for the capacitor to reach its steady state. It can be shown that the equivalent circuit in Figure 1(b) may be described approximately by a simple lumped RC circuit with circuit resistance [10]

$$R_t = \left(2 + \frac{m-1}{2}\right) R_s \quad (3)$$

$$C_t = mC_m$$

Thus the time constant of the circuit in Figure 1(b) may be assumed to be in the region of $\tau_0 = R_t C_t = 1.35 \mu s$. It is known that above $5\tau_0$, a lumped dc capacitor will be charged from initially uncharged to >99% of its eventual voltage. Thus for a capacitor to be charged sufficiently fully around the mid-point on the ramp-up of the first half cycle of an applied ac voltage signal, the signal period needs to be $> 8 \times 5\tau_0 = 40\tau_0$. In other words, the signal frequency needs to be much less than $1/40\tau_0 = 18.5 \text{ kHz}$ for the capacitor to reach steady state in the first half cycle and this is reasonably consistent with the findings in Figure 4.

It is interesting to note that the first peak of dissipated power is always lower than the peak dissipated power in the steady state. When the film capacitor of Figure 1 is switched to the external voltage source, current will flow through the surface resistors and individual shunt capacitors also will be charged up gradually. The charging of shunt capacitors induces initially an additional but transient current component to oppose the initial current flow on the electrode surface. Consequently the instantaneous power dissipated on the electrode coatings is reduced. However as the current induced by the initial capacitor charging is a transient component, its contribution is diminishing with

the steady state being gradually reached. Hence the dissipated power at the steady state becomes larger and this explains the lower first peak of dissipated power in Figure 4.

When the signal frequency increases, the capacitor charging process persists beyond the first signal period after which the applied voltage alternates its polarity. As a result, both the externally induced current component and the capacitor induced current component evolve to the same priority in the second half cycle of the applied voltage signal, and their combination then leads to the second peak of the dissipated power being higher than its steady-state value. This is true for the 100 and 500 kHz cases in Figure 4. In subsequent half cycles of the applied voltage, the peak dissipated power becomes closer and closer to its steady-state value until the steady-state is reached. Therefore the first two peaks of the dissipated power are its lower and upper bounds for the entire duration of the application of the external electrical stress. This is an important finding, since it permits us to use the values of the first two peak dissipated powers to define the limits of power dissipation and hence the range of dissipated power likely to be induced in an ac capacitor.

Figure 5. Peak dissipated power densities during the transient phase and at the steady-state induced by an ac voltage stress.

Figure 5 shows the absolute dissipated power density, at its first peak (the minimum peak), second peak (the maximum peak), and steady state peak, as a function of frequency. It is shown that the three values of the peak dissipated power tend to be similar to each other at low frequencies (<10 kHz) but different from one another at high frequencies (>50 kHz). Their difference at frequencies >50 kHz is a result of a more persistent transient phase at high frequencies observed in Figure 4. The numerical relationship among the three peak power values is however fixed at any given frequency for a given film capacitor configuration, because repeated numerical computation at $V_0 = 2.5 \text{ kV}$ found an identical normalized relationship. Therefore for a specific capacitor design with given segmentation and surface resistance, their power dissipation at different frequencies can be correlated uniquely, and this correlation may then be translated into a unique correlation in the temperature rise at different frequencies. In practice, this correlation in estimated temperature allows the life tests obtained for one frequency to be extrapolated to predict the likely outcome of life tests

at a different frequency. Similar extrapolation also may be attempted to predict capacitor performance when stressed at an ac voltage of different magnitude. It should be noted that capacitor aging is typically complex, involving interacting phenomena, and as such simple extrapolation must be performed with caution. However these extrapolations should be reasonably accurate when used to eliminate capacitor designs deemed, by the aforementioned correlation, to result in too high temperature rise at a signal frequency of interest.

Apart from the benefit of using the calculated dissipated power to evaluate the level of resulting temperature rise within a film capacitor [13, 16], its frequency dependence and its numerical range shown in Figure 5 can be used to compare to that induced under pulsed electrical stress. This will be discussed in the next Section.

4. SURFACE FIELD AND DISSIPATED POWER INDUCED BY A PULSED VOLTAGE

As a generic example of pulsed voltage stresses applied to film capacitors, the following Gaussian voltage signal is used to stress the film capacitor in Figure 1(a)

$$V = V_p \exp[-(t/\tau)^2] \quad (4)$$

where the applied pulse voltage lasts from $t = -3\tau$ to $t = 3\tau$ for all numerical examples. To correlate the above pulsed signal to the ac signal in Equation (2), we need to set $V_p = V_0 = 1.25$ kV and relate the pulse width to the signal frequency of the ac signal. To this end, we consider the point at which both pulsed and ac voltages drop from their peak value to $V_p/\sqrt{2}$ (the half-power point). If we let τ_1 and τ_2 to be the time for the pulsed and ac signal, respectively, to drop from their corresponding peak value to their half-power point, it can be shown easily that $\tau_1 = 1.1774\tau$ and $\tau_2 = 0.25/f$. Thus $\tau_1 = \tau_2$ requires

$$\tau = \frac{0.2123}{f} \quad (5)$$

This relation correlates a pulsed voltage to its corresponding ac signal. Electrical responses of the film capacitor in Figure 1 to a pulsed voltage stress exhibit typically a temporal characteristic consisting of a charging event and a discharging event. The latter occurs when the applied voltage stress tails off and the charged shunt capacitors start to discharge to the surface resistors. Thus the charging event depends on characteristics of both the applied voltage stress and the film capacitor system, while the discharging event is dominated by characteristics of the film capacitor. Figure 6 is an illustration of the spatial-temporal distribution of surface electric field along the top electrode surface of the single-layer film capacitor when the pulse width is equivalent to 200 kHz. Similar to the case of the ac voltage stress discussed in the previous Section, the surface electric field induced by a pulsed signal is at its highest at the left hand edge of the top electrode coating. Its reduction from the left hand edge of the capacitor film to the right hand edge also follows an approximately linear fashion.

The peak electric field induced on the electrode surface depends on the pulse width in a very similar manner to that observed for the ac case in Figure 3. For short pulse width, shunt capacitors in Figure 1(b) are charged up much faster and as such their induced current makes a larger contribution to the surface current on electrode coatings. In other

Figure 6. Spatial-temporal distribution of surface electric field induced by a pulsed voltage stress having an equivalent frequency of 200 kHz.

Figure 7. Peak surface electric field induced by a pulse voltage stress vs. the equivalent frequency.

words, surface electric field should be higher at short pulse widths. Figure 7 is a plot of the peak surface electric field reached as a function of the equivalent frequency calculated from the pulse width τ , in Equation (5). This field-frequency dependence follows a very similar trend to that observed for the ac case in Figure 3. The absolute value of the surface electric field in the pulsed stress case is however lower than that in the ac stress case, even though they are within the same order of magnitude. One possible cause responsible for the lower surface field reached in the pulsed case is perhaps the very gentle ramp-up phase of the pulsed signal giving the film capacitor much longer time to react. It is conceivable that the relative strength of surface field for the pulsed and ac cases can be reverse if the pulse voltage has a much shorter rise time than that of the Gaussian signal.

Similar to surface electric field, power dissipation on the electrode coatings also exhibits both the charging and the discharging events. Figure 8 shows the normalized dissipated power vs. the normalized time for four different equivalent frequencies 10, 50, 100, and 500 kHz. In units of the corresponding period of the equivalent frequency, the charging event at short pulse widths (high equivalent frequencies) appears to be slower, because the dissipated power reaches its peak at

Figure 8. Temporal evolution of the normalized dissipated power induced by a pulsed voltage stress at four different equivalent frequencies.

a later time. This is consistent with that observed for the ac case in Figure 4. Because a sufficiently narrow pulse signal may not allow a capacitor to be fully charged, the capacitor voltage can exhibit a lower rate to climb to its peak value. To support such an explanation, we note that for the capacitor to be sufficiently charged up during the ramp-up of the pulse signal, the pulse width should be $\gg 0.5\tau$. From the discussion for the ac case, the time constant of the film capacitor in Figure 1 is likely to be in the region of $1.35 \mu\text{s}$ and this requires the equivalent frequency of the pulse signal to be $\ll 1/0.5\tau = 148 \text{ kHz}$. This is reasonably consistent with that observed in Figure 8, where the delay in reaching the peak power from 100 to 500 kHz is longer than that from 10 to 50 kHz.

The second hump in Figure 8 represents the power dissipation during the discharging process and it is seen to be of small peak value and wide duration when the pulse duration is short (high equivalent frequency). Since the discharging event is determined largely by the characteristics of the film capacitor itself, the duration of the second hump in Figure 8 is indicative of the time constant of the capacitor circuit in Figure 1(b). Normalized to short pulse width, the time constant of the film capacitor gives an impression of a wider duration of the second hump in Figure 8. On the other hand, the smaller magnitude of the second hump at high equivalent frequencies in Figure 8 does not necessarily mean a less intense discharge event since the dissipated power in Figure 8 is normalized. It will be shown below that the peak dissipated power at high equivalent frequencies is larger. Finally, integration of the second hump is found numerically to be the same as that of the first hump for all cases, confirming the conservation of energy.

Figure 9 shows the dependence of the peak dissipated power density on the equivalent frequency. The monotonic dependence of the maximum peak power on frequency is very similar to the ac case albeit the absolute value of the peak power in the pulsed case is smaller. This suggests that both the charging process in the pulse case and the entire process of the ac case are influenced very strongly by the characteristics of the applied voltage. Therefore the rapid changing nature of high frequency signals results consistently in a larger surface current, and

hence higher power dissipation. The minimum peak power in Figure 9

Figure 9. Peak dissipated power during the charging and discharging processes vs. equivalent frequency.

demonstrates, on the other hand, a reversed dependence on frequency when the equivalent frequency becomes $>200 \text{ kHz}$. We note that, from earlier discussion with Figure 8, the capacitor may not be fully charged during the ramp-up of the pulsed voltage stress if its equivalent frequency is $>148 \text{ kHz}$. It is therefore conceivable that for $f > 148 \text{ kHz}$ the film capacitor is reasonably away from being fully charged and so its discharging involves less electrical energy. This is believed to be responsible for the reversed dependence of power dissipation on equivalent frequency for $f \geq 200 \text{ kHz}$.

In terms of the absolute value of the dissipated power, the pulsed case leads to less power dissipation than the ac case as shown in Figures 5 and 9, although they are in the same order of magnitude. Similar to the explanation given to the surface field, the above observation may be a result of the slow ramp-up nature of the pulsed signal. Also similar to the ac case, there is a unique relationship of power dissipation at different equivalent frequencies of the pulsed voltage stress, independent of the peak value of the applied voltage. This may be used to perform careful extrapolation to eliminate capacitor designs deemed to cause too large heat generation at a pulse width of interest.

5 COMPARISON BETWEEN THE AC AND PULSED VOLTAGE CASES

Electrical response of the single-layer film capacitor to ac and pulsed voltage stresses is compared in terms of the peak surface electric field and the maximum peak dissipated power. The minimum and the steady state values of the peak power are not considered here, because they do not represent the worst scenario in accelerated life tests and so are not appropriate as an indicator of the probable extent of relevant aging processes. As shown in Figures 3 and 7, the peak surface electric field depends on the signal frequency (or the equivalent frequency in pulsed stress cases) in a very similar manner for both the ac and pulsed cases. This similarity is observed also for the frequency dependence of the dissipated power illustrated in Figures 5 and 9. These observations highlight a close correlation in frequency dependence for the ac and pulsed cases, and this makes it possible to predict electrical responses of

a film capacitor to an ac voltage stress from the knowledge of its electrical responses to a pulsed voltage stress, and *vice versa*. To examine this correlation more quantitatively, we note that the absolute values of both the surface electric field and the dissipated power in the pulsed case are always less than their counterparts in the ac case. Figure 10 shows the value of a pulsed stress induced response (surface field and dissipated power) in units of its corresponding ac stress induced response. It is particularly interesting to note that for frequencies <10 kHz, both relative surface field and relative dissipated power are approximately constant at 0.63 and 0.4, respectively. Therefore for these low frequencies we can deduce a straightforward and quantitative correlation that the peak surface field and the maximum peak dissipated power reached in a pulsed voltage stress are 63% and 40% respectively, of that induced by a corresponding ac voltage stress of the same magnitude. Also within the frequency range (<10 kHz), this simple proportionality is valid regardless signal frequency. Further numerical computations suggest that it is also possible to achieve simultaneously the same peak surface electric field and the same maximum peak dissipated power for the ac and pulsed cases if the voltage magnitude of the pulsed stress is made $\approx 58\%$ higher than that of the ac stress. Similarly, this can be used to deduce a straightforward correlation for ac and pulsed signals having correlated frequencies, via Equation (5), but different voltage magnitudes.

Figure 10. Peak dissipated power and peak surface electric field calculated for the pulsed case divided by their corresponding values for the ac case, respectively.

At higher frequencies, especially >100 kHz, the frequency dependence of surface electric field and dissipated power becomes more sensitive and as such can no longer be approximated by a constant. As suggested in the previous two Sections, this sensitive frequency dependence is likely to be caused by the film capacitor not being fully charged within the first half cycle of the ac signal or the pulse duration in the pulsed case. As shown in Figure 10, the onset of this more sensitive frequency dependence occurs between 100 and 200 kHz. This is consistent with our previously estimated maximum frequency of 148 kHz for sufficient capacitor charging. As the proportionality between the pulsed and ac quantities becomes frequency dependent sensitively at frequencies >100 kHz, the numerical correlation between them needs to be assessed at each of these high frequencies of interest. However, although the

resulting relationship becomes less straightforward numerically, it still represents a close and quantitative correlation in electrical responses between the ac and the pulsed cases. As a result, electrical responses under one type of electrical stress can still be extrapolated to estimate that under the other type, albeit by means of a graphic relationship or a look-up table rather than a simple proportionality constant.

It is worth mentioning that both the peak surface electric field and the maximum peak dissipated power are instantaneous quantities measured at specific instants of time. However the peak surface field occurs at one particular spatial point on the electrode surface, whereas the dissipated power is in fact averaged across the entire electrode coating area. Therefore they are not necessarily quantitatively related. However when the peak surface electric field in Figure 10 is squared, the resulting new frequency dependence demonstrates an excellent agreement with the dissipated power curve for frequencies <100 kHz, reflecting the simple relationship of $P \propto E^2$. This is a useful correlation, for it allows calorimetric measurement of film capacitors [16] to be used to estimate surface electric field, which is very difficult to measure non-intrusively. Nevertheless for frequencies >100 kHz, this simple relationship is no longer valid, highlighting again the impact of the capacitor not being fully charged during the first half cycle.

Figure 11. Comparison of the peak dissipated power and peak surface electric field calculated for $R_s=50\ \Omega$ and $R_s=100\ \Omega$.

Numerically established correlation in electrical responses shown in Figure 10 is found to be independent of voltage magnitude of the applied electrical stress. Thus as long as the frequency of an ac stress is related to the pulse width of its corresponding pulsed stress, the simple proportionality exhibited in Figure 10 may be used to extrapolate the electrical responses at different stress levels. However, if a characteristic of the film capacitor, e.g. surface resistance or segment number, changes, the results in Figure 10 should not in principle be applicable. One important design parameter for film capacitors is the electrode segmentation pattern which can be used to improve reliability of film capacitors. Since different electrode patterns result in different values of surface resistance, it is useful for capacitor designers to know the implication of different segmentation patterns on the peak surface electric field and maximum peak dissipated power. To this end, we consider a second single-layer film capacitor with $R_s=100\ \Omega$ and the correlation between the ac and pulsed stress again is investigated numerically.

The results are summarized in Figure 11 together with the correlation curves for the $R_s=50\ \Omega$ case. Significantly, the correlation at low frequencies remains more or less unchanged when the surface resistance is increased from 50 to 100 Ω . The more frequency dependent correlation in the $R_s=100\ \Omega$ case starts however at a lower frequency, $\sim 5\ \text{kHz}$, a result of the increased time constant for the new film capacitor. It is therefore evident that provided the maximum frequency for the simple proportional relationship is identified for a film capacitor configuration of interest, the numerically established correlation in Figure 10 can be applied to assess a wide range of film capacitors for their electrical responses to ac and pulsed responses.

While correlations in electrical responses are established numerically in this study without taking into account the evolution of properties of capacitor components during relevant aging processes, they may very well be reflected in similar correlations in life test results between different types of voltage stresses. Given that they are very simple and unique, and that electric field and dissipation induced heat generation predominately are responsible for acceleration of many known aging mechanisms, the suggested correlation in life test results is realistically probable. This of course requires confirmation based on systematic and specifically designed life tests. However the confirmation work is outside the limits of this study, and will be addressed by a future paper.

6 CONCLUSIONS

BASED on an equivalent circuit model developed for metalized polymer film capacitors, a single-layer film capacitor was studied numerically for its electrical responses to an external voltage stress of either ac or pulsed waveform. In particular, essential characteristics of externally applied stresses, such as signal frequency for the ac case and pulse width for the pulsed case, were investigated in detail for their effects on surface electric field and power dissipation induced within the film capacitor.

Although the equivalent circuit of the film capacitor is a relatively sophisticated network consisting of multiple interconnected RC sub-networks, its surface electric field and dissipated power were found to relate to the signal frequency (or the pulse width) in a simple manner. It was shown that this frequency dependence was specific to the characteristics of the film capacitor but independent of the magnitude of the applied voltage stress. Thus for a given electrical stress, surface electric field and power dissipation induced at one signal frequency (or pulse width in pulsed stress cases) can be correlated to that at a different frequency. In addition a further correlation was established for surface electric field and dissipated power induced by an ac signal and those by a pulsed signal, provided that the frequency of the ac signal is related to the pulse width of the pulsed signal in a specific manner (see Equation (5)). These correlated relationships are simple and straightforward, reflecting perhaps an underlying generic trend in the penetration of an external voltage signal into the film capacitor and its subsequent interaction with the capacitor structure. They should be useful for assessment of different capacitor designs by comparing the surface field and dissipated power induced in a new capacitor to that induced in a reference capacitor (preferably a present industry standard capacitor of appropriate grading), both estimated numerically. If the numerical assessment of a new capacitor design predicts a much

higher surface electric field and/or dissipated power than that in the reference capacitor, this new capacitor can then be justifiably eliminated from subsequent life tests. In the case that much lower surface electric field and dissipated power are predicted for a new capacitor design, its further accelerated life tests can then be seriously considered and convincingly justified. These findings should enable useful information to reduce development time of new metalized film capacitors.

In the event that future and specifically designed accelerated life tests reveal a correlation in life tests for ac and pulsed stresses, now anticipated from our numerically established correlations in surface field and dissipated power, development time of film capacitors may be reduced considerably. It would then be possible to extrapolate and predict the results of one type of life tests (for instance pulsed stress) from those obtained experimentally in the other type of life tests. This projected correlation in life test results is a highly realistic prospect, given the very close correlation observed for surface field and dissipated power under different electrical stresses. However even in the absence of the aforementioned confirmation from future accelerated life tests, the numerically established correlations are likely to aid significant reduction in development time of polymer film capacitors.

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