Lifetime estimation of high-temperature high-voltage polymer film capacitor based on capacitance loss

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Abstract

Under steady voltage and temperature stresses, capacitance can be considered as a reliable aging indicator since in such conditions, metallized polymer film capacitors suffer from the gradual loss of their electrode surface. Empirical laws are most often considered to predict the operating lifetime of energy storage systems under specific environmental conditions. However, expected lifetimes in this case are not able to track the capacitors degradation with time. In this paper, a special capacitance degradation model is proposed based on several experimental aging tests at different temperatures and voltage stresses. A total of 30 capacitors using a novel high-voltage high-temperature (HVHT) polymer as dielectric have been studied and compared to validate the proposed law. This novel HVHT polymer offers significant improvements upon the standard dielectric materials, providing excellent self-healing capability with an enhanced energy density.

1. Introduction

During their operating lifetime, metallized polymer film (MPF) capacitors may be subjected to variety of stresses that degrade irreversibly their performances with time. Under high temperature and voltage test conditions, capacitance degradation can be considered as a reliable aging parameter since under such stresses, MPF capacitors suffer from the gradual loss of their electrode surface due to self-healing events. Typically, for safety-critical equipment as those used in aeronautic applications, a loss of 5% of capacitance is not tolerated since catastrophic failures may occur. Therefore, aged components must be replaced before breakdown in order to guarantee and ensure the availability of the overall system. For these purposes, modeling the capacitance degradation as function of time is of great interest.

2. Metallized polymer film capacitors

2.1. Polymer as dielectric

Currently, high-reliability applications have a strong need for the development of compact and robust capacitors to operate in a variety of power conditioning applications [1–3]. Although MPF capacitors have the blend of properties that make them well suited for such critical operating systems, some limitations exist, especially upon the polymer materials forming the dielectric. Their nature and morphology has a considerable influence on the physical and electrical properties of the component.

Although polypropylene (PP) and polyethylene–terephthalate (PET) are the most used dielectrics in power electronics applications, a novel high-voltage high-temperature (HVHT) polymer film has been recently introduced by Exxelia Technologies to the capacitor market. This new polymer offers an excellent self-healing capability and an enhanced energy density making it well adapted to the severe high reliability operating conditions where size and weight are critical factors [4,5].

Like PP, HVHT polymer has very good dielectric rigidity, yet has improved properties especially in terms of temperatures (up to 155 °C). Table 1 illustrates the characteristics of “HVHT” dielectric in comparison with PP and PET.

2.2. Temperature and frequency effects

In power electronics applications, temperature and frequency are critical factors to both designers and users of metallized films capacitors since capacitance may drift from its initial rated value. Taking into account their impact within an application may limit their effects and prevent in some cases capacitors from failure. The capacitance of several MPF capacitors was measured at different frequencies and temperatures by the mean of an LCR meter and plotted in Fig. 1. As noticed, capacitance does not behave the same way depending on the dielectric material. Indeed, polymers are divided into two main categories, polar and nonpolar dielectrics. PP is a hydrocarbon polymer containing only carbon and hydrogen atoms in its chemical structure which offers a low dielectric constant slightly affected by temperature and frequency variations.

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Indeed, for nonpolar polymers, the dielectric constant along with its molecular density linearly decreases with temperature [6], which explains the slight variations of the PP observed in Fig. 1.

However, in the case of polar polymers, such as the PET and HVHT, a permanent electric dipole moment is present in their molecular chain [7–9]. Their orientations, very restrained at low temperatures, follow easier the applied electric field as the temperature increases. Typically, since the dipole orientation phenomenon is related to the dielectric relaxations, one can estimate that the capacitance increase for capacitors using polar polymers is due to an easier orientation of their dipole at a given frequency.

The contribution of electrical, thermal and combined electro-thermal stresses may also have a negative effect on the behavior of MPF capacitors and cause its degradation since chemical reactions are involved.

3. Aging of MPF capacitors

Studies and analysis have been previously carried out to examine the reliability of metallized polymers films (MPF) capacitors when subjected to thermal [10], electrical [11], and electro-thermal stresses [3], but few of them were dedicated to model the capacitor electrical parameter evolution with time when multi stresses occur. The purpose of this paper is to determine a capacitance degradation model when simultaneously subjected to a DC voltage in combination with temperatures constraints.

### 3.1. Failure mechanisms under electrical and thermal stresses

Under high electrical and thermal stresses, strengthened electric field present in some areas within the capacitors winding (due to impurities) may lead to a localized breakdown of the dielectric [12]. Although impurities are significantly reduced by thermally and electrically treating the polymer, they cannot be totally cleared. Such failure results from the sudden discharge of a localized portion of the stored electrical energy whose magnitude depends on the voltage, capacitance value, metallization thickness and the internal air pressure of the component. This energy, within the order of milli-joules, is sufficient to sublime the thin metallization layer around the defected zone and becomes electrically isolated. Metallized film capacitors can, through its exclusive property, endure a large number of discharges with as only visible impact a slight decrease of their capacitance.

Such event, known as “self-healing” or “clearing” is generally characterized by the discharge energy $E_d$, and is represented by the following equation:

\[ E_d = \frac{k U^b C}{R_s \alpha(P)} = a U^b \]

with, $U$ representing the operating voltage, $C$ the capacitance, $R_s$, the metallization resistance, $\alpha(P)$ a function connecting the inter-layer pressure to the discharged energy $E_d$, and $a, b, c$, and $k$ constants depending on the geometry and dimensions of the component [13].

Polymers by their chemical structures also contribute in the efficiency of such phenomenon [13]. In fact, during breakdown, de-metallization is often accompanied by a superficial decomposition of the dielectric layer, manifesting itself by a gaseous phase formation (mainly constituted of carbon and hydrogen atoms). When the “self-healing” event extinguishes and the temperature near the defect site decreases, the previously formed, gaseous phase condenses and gives rise to carbon particles that settle down in the cleared area, creating a graphite layer. Since carbon is electrically a conductive material, it appears that, for a safe regeneration, graphite layer primarily likewise contained in the gas phase formed by decomposition of the dielectric layer, must remain very thin [14].

Moreover, under high temperature test conditions, polymer degradation can result from an excess of energy supply to the macromolecular chain. When this energy is concentrated on a chemical bond and that exceeds its activation energy, breakdowns occur.

The involved chemical reaction follows most often the “free radical” process. This term is generally used to refer to a molecule that has lost one or more electrons from its outer layer, leading to a high instability to the molecule. Thus to restore the octet rule, several chemical reactions can take place with the surrounding compounds (such as oxygen, moisture, …). This process leads, in a part, to divisions or cross-linking within the polymer macromolecular chains causing the irreversible degradation of its properties with time. These chemical reactions may also give rise to micro bubbles and gas molecule, themselves responsible for the initiation of further “self-healing” events.

In order to identify the aging law of metallized film capacitor by considering the upper mentioned stresses, three floating aging tests at different constant temperatures and voltages were performed. A set of 30 samples provided from three different manufacturers with different electrical characteristics were studied, this way the temperature and voltage accelerating factors can be identified.

### 3.2. Aging model

Electro-thermal lifetime modeling problem have been extensively studied based on the Eyring law or on modifications of thermal and electrical endurance models [15,16]. The key to electro-thermal model formulation was thorough understanding of model parameters based...
on two independently changing degradation factors: electric field and temperature.

However, the major drawback of these empirical laws relies on the non-description of the capacitors parameters evolution through aging time. For this purpose, a novel aging law is needed.

In fact, since self-healing phenomena are random events related to the number of impurities present in the dielectric film, the capacitance decrease over time can be attributed to a probabilistic distribution which depends on the number of defects located in the metallized film. These random defects are directly associated with the manufacturing process and manifest themselves most frequently in the beginning of the component aging. Indeed, due to the presence of a large number of impurities at the beginning of the test, at first the capacitance loss increases rapidly and then slows progressively with time. Thus, an exponential probabilistic law would best describe this phenomenon.

Two hypotheses should be considered:

— $S(t)$ is the number of self-healing events occurring at time $t \geq 0$. Assuming that the self-healing process is a non-homogeneous phenomenon that follows an exponential probabilistic law, its probability density, with a constant $\lambda$, can be given by the equation:

$$f(t) = \lambda \cdot \exp(-\lambda \cdot t) \quad (2)$$

— $D_j$ ($j = 1, 2, 3, \ldots$) being a portion of the capacitance decrease when the $i$th self-healing occurs. Considering $C(t)$ the capacitance value at time $t$, and $C_0$ the capacitance initial value at time $t = 0$, capacitance loss with time would be of the form:

$$C(t) = C_0 - \sum D_j \quad (3)$$

Eq. (3) is one of the most suitable functions to model natural random events such as self-healing phenomena. An exponential aging law would be of the form:

$$C(t) = A + \lambda_1 \cdot \lambda_2 \cdot \exp(-\lambda_1 \cdot t) \quad (4)$$
where A is a parameter which depends on $C_0$ and $\lambda_1$ ($s^{-1}$), and $\lambda_2$ ($F/s$) depend on the component characteristics and the applied stresses.

This law is able to track the decrease of the capacitance $C$; however, it shows some limitations regarding the capacitance increase at the beginning of use for some tested components [17]. Actually, by applying high electrical fields ($\bar{E}$) across the capacitor terminals a strong electrostatic pressure ($\bar{F}$) will be generated causing a slight decrease in the dielectric thickness ($dl$) leading to a small rise of $C$ (i.e. Fig. 4).

By taking into account the participation of this phenomenon in the evolution of the capacitance, the $C(t)$ aging law takes the following form:

$$C(t) = A \exp(-(\lambda_1 \cdot t) \cdot (\lambda_2 - \lambda_3 \cdot \exp(-\lambda_4 \cdot t))$$  \hspace{1cm} (5)

with $\lambda_3$ ($F$) and $\lambda_4$ ($s^{-1}$) constants depending on the applied constraints and capacitor characteristics.

The adequacy of Eq. (5) with the capacitance evolution under different electrical and thermal stresses for different metallized film capacitors is shown in Fig. 2.

For instance, $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ parameters evolution were extrapolated to different temperatures and voltages for a wider application range as shown in Fig. 3.

4. Estimated lifetime

To examine the relevance of this extrapolation, expected lifetimes resulting from Eq. (5) were compared to those using the well-known Eyring law when solicited by the same stresses.

Eyring theory generalizes Arrhenius law to many factors besides the temperature [18]. It provides an accurate study of the surrounding stresses on the operation lifetime of the component. Eq. (6) describes Eyring law when two supplementary stresses are considered:

$$\tau_{\text{Eyring}}(T, S_1, S_2) = A_2 T^{\alpha} \cdot \exp\left(\frac{E_a}{kT} + \left(\frac{B_E}{T} + \frac{C_E}{T}\right) S_1 + \left(\frac{D_E}{T} + \frac{E_E}{T}\right) S_2\right)$$ \hspace{1cm} (6)

where, $\tau_{\text{Eyring}}$ is the useful life of the component, $S_1$ and $S_2$ are the supplementary considered stresses, $A_0$, $B_E$, $C_E$, $D_E$, $E_E$ and $\alpha$ are different constants. Considering the DC voltage as the only additional constraint ($S_1 = U_c$) and as independent of temperature ($C_E = \alpha = 0$), a simplified form of Eyring theory can be given.

By considering the curves of Fig. 3, and by considering a loss of 5% of capacitance as the end-of-life criterion, one can identify the expected lifetime that may have a capacitor from Eq. (5) at a specific condition of use. Comparison is given in Table 2:

As it can be seen, there is good agreement between the expected lifetimes from both methods. This shows that efficiency of the proposed law is as good as Eyring law. Furthermore, the proposed aging law gives a supplemental degree of freedom, since one can choose the end-of-life criteria and have more information on the capacitance degradation phase.

5. Conclusion

In this paper, an original aging law is proposed to model the capacitance degradation of metallized film capacitors. This latter is able to track the slight capacitance increase at the beginning of use due to the electrostatic force. The impact of voltage and temperature on the degradation kinetics of high-temperature high-voltage HVHT polymer film capacitor were studied and the corresponding parameters were identified. The validity of the proposed law was tested on PP and PET film capacitors making it valuable for all MPF capacitors.

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