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Metallized polymer film capacitors ageing law based on capacitance degradation

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ABSTRACT

Passive components, particularly capacitors, are very used devices in power electronics applications providing key function on board. Nevertheless, capacitors breakdowns can have catastrophic consequences on the financial and human scale; a good acquaintance of their deterioration over time would contribute in the improvement of the availability of the whole system by performing a predictive maintenance on the component. This operation requires the knowledge of the capacitor ageing law and their failure mechanisms associated to the application. Capacitance loss can be mainly attributed to the self-healing process occurring in metallized film capacitors when used under high steady electrical and thermal stresses. In this paper, a capacitance ageing law is proposed based on the identification of voltage and temperature degradation kinetics from three experimental floating ageing tests performed at different voltage and temperature constraints. A total of 34 capacitors provided from different manufacturers using polyester film as dielectric have been studied and compared to validate the proposed law.

1. Introduction

Reliability and maintainability are two basic requirements for a proper operation of a system and is mainly related to the technological characteristics of the components composing it [1]. Previous studies showed that one of the most frequent causes of the power electronics equipment breakdowns results from the failure of capacitors [2]. Even though metallized films capacitors are very reliable components due to their capabilities to self-heal, they are not free of failures either [3]. These failures can be attributed to adverse operating conditions, such as high temperatures, voltages and current spikes. A better understanding of their ageing laws and of the different factors accelerating them would prevent capacitors from failures and thus enhance the availability of the system. In this paper, an original ageing law is proposed considering voltage and temperature as the only encountered operating stresses. After a brief introduction to metallized film capacitors technology, DC voltage and temperature effects are investigated and presented hereafter in Section 3, while Section 4 is dedicated to present the experimental ageing results in comparison to the proposed ageing law.

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2. Metallized film capacitors

Capacitors using a plastic film as dielectric are widespread in literature and their characteristics depend on the material used. This technology, coveted for its ability to self-heal [4–6], is constituted of two plastic films, themselves coated with zinc or aluminum alloys of a few nanometers thickness to constitute the electrode (see Fig. 1). Metalized films are then rolled together around a cylindrical insulated base called mandrel. To assure connections with an external circuit, a sprayed metal technique known as "Schoopage" is used on both ends of the winding.

Polymer films are the preferred materials for capacitive energy-storage applications due to their high dielectric breakdown strengths, low dissipation factors and good stability over a wide range of frequencies and temperatures [7]. The most commonly plastics used as dielectric are the polypropylene (PP) and the polyethylene terephthalate (PET) also known as polyester.

In this paper, we will be particularly interested in the study of metallized film capacitors using PET as dielectric.

3. Ageing of metallized film capacitors

During their operating lifetime, capacitors may be subject to a variety of stresses that can irreversibly degrade their properties with time and cause their so-called "ageing". Among the numerous

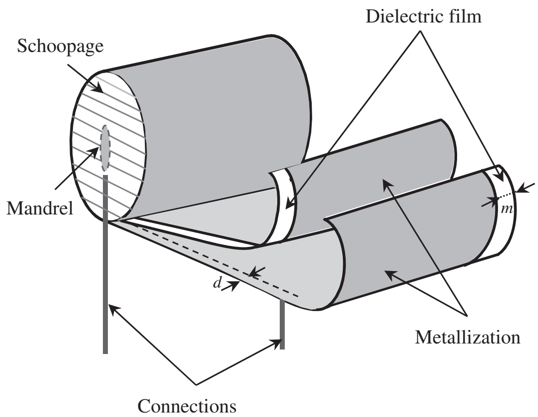

Fig. 1. General structure of metalized film capacitors.

encountered ageing factors, voltage and temperature are the most prevalent stresses.

3.1. Temperature effect

Under high thermal stresses, polymer plastic films forming the capacitor dielectric are the most affected parts of the component by the encountered stress. Their behavior determines most often the maximal operating temperature that a capacitor can endure. Ensuring their correct operation requires maintaining the temperature constraint below the one at which the polymer loses all its physical and dielectric properties. Indeed, increasing the temperature may cause changes in the chemical structure of the polymer that may results from the thermal activation of some inactive chemical reactions at low temperatures. Polymer degradation can result from an excess of energy supply to the macromolecules chains; when such energy is concentrated on a chemical bond and that exceeds its activation energy, breakdown occurs [8]. Most often, the involved chemical reactions follow the "free radical" process. This term generally refers to a molecule that has lost one or more electrons from its outer layers due to a chemical reaction. Various constraints may be at the origin of the initiation of such phenomena such as, high temperatures, ionic radiation, ultraviolet radiations or even impurities that can act as chemical triggers. In fact the presence of a free radical or single electron confers a high instability to the molecule. Such state involves, to restore the octet rule, a large probability to initiate chemical reactions with the surrounding compounds such as absorbed oxygen (oxidation), moisture (hydrolysis) [9], or even reactions between different polymer chains (de-polymerization creating new products, most often monomers). These chemical reactions may cause divisions or cross-linking in its main chain [10], leading to the progressive degradation of the polymers macromolecules.

3.2. Voltage effect

Under high electrical test conditions, defects in the dielectric material can lead to a localized breakdown of the dielectric film. Such breakdown events result from a sudden and localized discharge of a portion of the stored charge under the influence of temperature and pressure [11]. Dielectric breakdown occurs when the applied electric field is much higher than the one that can be handled by the dielectric due to the presence of impurities or gas inclusions among the dielectric. These impurities lead to local reinforcement of the applied field [12]. In fact when in certain areas of the dielectric, the electric field becomes important, many phenomena can occur within the polymer film or even at the dielectric/electrode interface, such as the release of dissolved gas, electric shock accompanied by the destruction of certain molecular bonds, or the formation of micro-bubbles [13].

During these intense discharges, punctures are developed in the dielectric material and the thin metallization layer near the defected site will be vaporized and blown away and the site becomes electrically isolated [14]. This phenomenon called self-healing (*i.e.* Fig. 2) leads to a slight loss of the capacitance due to the vaporization of a small portion of the metallization forming the electrode [6].

3.3. Accelerated ageing tests

Thermal and electrical stresses may, under some specific operating conditions, be alone or combined together to create in this case a "multi-stress" situation over the component. According to [15], the "multi-stress" situation involves different failure mechanisms from those determined under separated constrains. In order to identify the ageing law of metallized film capacitor by considering the upper mentioned stresses, three floating ageing tests at different constant temperatures and voltages were performed. A set of 34 samples provided from three different manufacturers with different electrical characteristics were studied. The realized accelerated tests are listed below:

- Floating ageing test #1: at 85 °C – 1.1 U_R.
- Floating ageing test #2: at 100 °C – 1.1 U_R.
- Floating ageing test #3: at 85 °C – 1.3 U_R.

where U_R is the capacitor rated voltage.

By comparing the degradation kinetics between the floating ageing tests #1 and #3, we would be able to determine the accelerating voltage factor, whereas from the floating ageing tests #1 and #2, temperature accelerating factor can be identified.

4. Ageing law

4.1. Existing ageing laws

Very often, for energy storage components including capacitors, it is well recognized that failure process is equivalent to a chemical reaction. Its rate constant, according to Arrhenius law (*i.e.* Eq. (1)), is function of the absolute temperature T [16]. This law gives a good approximation about the operating life of a component, but as seen in equation it is limited to a temperature effect.

$$v = v' \exp\left[-\frac{E_a}{kT}\right] \tag{1}$$

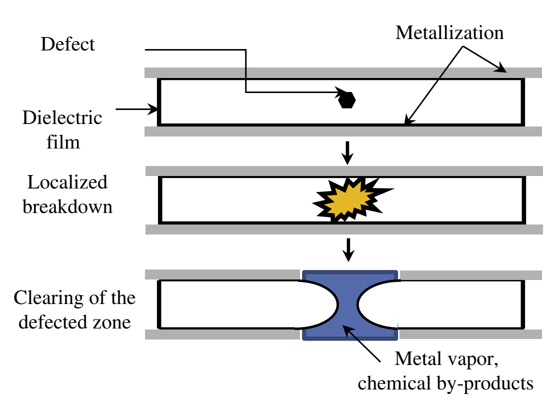

Fig. 2. Self-healing process in metallized film capacitors.

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