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Material Performance

Short-term and long-term breakdown analysis of electroactive polymer with and without nanofillers

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A B S T R A C T

Electroactive polymers have drawn widespread interest in the electric engineering community primarily due to the large shape deformations that can be obtained under the application of an electric field. The energy storage for a linear dielectric elastomer is determined by its relative permittivity and the applied electric field (magnitude squared), and is maximized by operating the electroactive polymer at high electric fields and large stretches. In a previous study, it was shown that the relative permittivity of a silicone elastomer can be increased by adding titania nanoparticles without sacrificing the electrical characteristics such as the electrical conductivity and space charge dynamics. It was demonstrated that the threshold for space charge accumulation is about 20 kV/mm and the absence of deep traps in the titania-filler modified elastomer leads to fast space charge depletion. In the present work, the short-term and long-term breakdown characteristics of neat and nano-titania silicone elastomer films are discussed.

1. Introduction

Electroactive polymers are soft dielectric elastomers (DE) that can be used as actuators. DE are provided with compliant external electrodes, usually sputtered, in order for voltage, and thus for an external electric field, to be applied. DE themselves and the interfaces between the DE and the external sputtered electrodes exhibit electromechanical instability [1–3]. When an external field is applied to DE, they respond with shape or dimensional changes [4,5]. If DE are pre-stretched and pre-charged, a reduction of the tensile force lets the elastomer revert to its original form and increases the electrical potential. The energy storage for a linear dielectric polymer is determined by its relative permittivity and the applied electric field. DE can be used as generators for harvesting energy from the movement of the ocean waves.

From an energy-conservation point of view, the increase of the relative permittivity without sacrificing the breakdown strength of the material can be a solution [6,7]. The generated energy is related to the relative permittivity and the applied electric field squared, and is maximized by operating the DE at high voltage and stretching the film to large strains. In order to be more effective for energy harvesting, DE should be employed at high electric fields close to the breakdown strength. In this case, the operating lifetime will be reduced due to electrical ageing and space charge accumulation.

Electrical conductivity, dielectric response and space charge dynamics were discussed in a previous publication by the same authors [8]. The aim of the present study is to investigate the short-term DC breakdown and the electrical ageing lifetime (long-term DC breakdown) of neat and nanoreinforced silicone elastomer films with different thicknesses.

2. Experimental

2.1. Materials

The electroactive polymer materials provided by Danfoss PolyPower for investigation were silicone elastomer films designated as V3 and V4. The former is an unfilled (neat) elastomer film, which consists of two batches of samples, i.e., one with a thickness of (50 ± 4) μm and a second one with a thickness of (90 ± 4) μm. The other elastomer film, V4, is of the same type as V3 but reinforced with titania nanoparticles. V4 consists of two batches of samples with a thickness of (57 ± 3) μm and (119 ± 7) μm. One of the surfaces of the elastomer films is corrugated, while the other one is flat [9]. The films were not treated prior to testing and were tested at ambient conditions (temperature of ≈20 °C and relative humidity of ≈65%).

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2.2. Measurement details

A Heinzinger HNC 20000–10 and Heinzinger PNC 6000–30 were used as voltage supplies for the short-term and long-term breakdown (BD) tests, respectively. Two types of short-term DC BD tests were performed, namely ramp and step-up voltage tests. The rate of rise for the ramp voltage tests was 2 kV/min with a starting point at zero volts, according to IEC standard 60243-2. The rate of rise for the step-up tests was 0.2 kV/20 s with a starting point at 40% of the average breakdown voltage of the ramp voltage tests (based on EIC standard 60243-2).

Fig. 1 shows an illustration of the setup constructed for the tests to determine the short-term DC BD strength and the voltage life of the DE. The base metal plate was connected to earth potential and the toroid, which was suspended in air, was put at high voltage potential. The samples were connected to the HV torus via rods made from stainless steel. Between the rods and the DE, hemispherical electrodes made from stainless steel were used. The diameter of the hemispherical electrodes was 4 mm. The function of the toroid shape of the HV electrode was to suppress corona phenomena.

Short-term ramp and step-up tests were performed on the 4 different films without sputtered external electrodes. The electrical accelerated ageing tests were performed only on V4 film. Five different voltage levels were chosen, namely 1.0 kV, 2.5 kV, 3.0 kV, 3.5 kV, and 4.5 kV. The thickness of the film was measured as 57 μm on average with metal sputtered electrodes on both sides. The sputtered electrodes were of circular shape, 11 mm in diameter, which resulted in a stressed area of about 95 mm^2.

2.3. Breakdown data analysis by means of the Weibull distribution

The Weibull distribution (WD) is a general-purpose reliability distribution used to model material strength, time to failure of electronic and mechanical components, equipment or systems [10]. It is the most common failure distribution for electrical breakdown because it models a distribution based on the weakest link of a sample [11–13]. The WD can be described in terms of two or three parameters. The best distribution relies on the number of data points and the distances between the points. The cumulative density function (CDF) of the 2-parameter WD is given by equation (1).

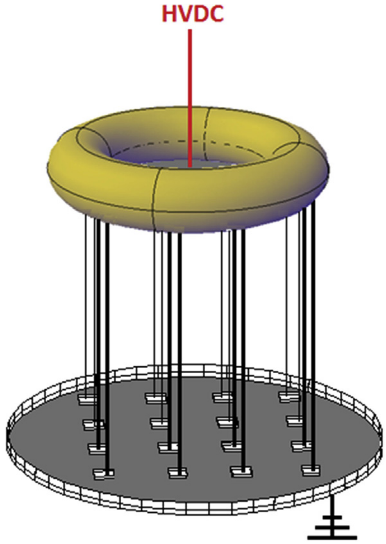

Fig. 1. A schematic illustration of the setup used for the long- and short-term breakdown tests. Sputtered electrodes were used only for the long-term breakdown tests.

$$F(x) = 1 - \exp\left[-\left({}^{x}\!/_{\alpha}\right)^{\beta}\right] \tag{1}$$

where:

x is the measured or random variable, e.g., time-to-breakdown or the breakdown voltage,
$F(x)$ is the cumulative probability of failure at a voltage or time less than or equal to x,
α is the scale parameter and must be positive, and
β is the shape parameter and must also be positive.

The scale parameter α is the time or voltage (same unit as the measured variable, x) where the failure probability reaches 63.2%. The shape parameter β is a value that describes the scatter of the failure times or voltage values. The larger β, the smaller is the scatter of breakdown voltages or times-to-breakdown. Also, it can be stated that the steeper the slope of F(x) (the larger the value of β), the smaller the scatter in the times-to-breakdown or breakdown voltage values. Different values of β can indicate different failure mechanisms [14].

2.4. Ageing tests

Accelerated life tests are commonly used to stimulate the product to fail in a life test. This is accomplished by applying stresses that exceed the nominal operational stresses. The times-to-failure data obtained under these conditions are then used to extrapolate the results to operating conditions. Usually, an inverse power law relationship is used to relate life and stress level.

$$L = \frac{C}{E^n} \tag{2}$$

where L is the mean-time-to-failure (MTTF) at the electrical stress E, n is the life exponent and C is a constant. A minimum of two stress levels are required for properly mapping the function to an operating stress level. In the accelerated life testing analysis software package (ALTA) the following assumptions are implemented [15,16]:

- The lifetime at any single stress level satisfies a two-parameter WD;
- The Weibull shape parameter at different stress levels is the same;
- The MTTF has an inverse power relationship with the applied stress.

2.5. Size effect

The size of specimens during the development phase of a product is smaller than the real high-voltage component. Also, when prototypes are considered, full scale products do not exist. Therefore, the effect of the size difference on the insulation life has to be taken into account. Due to the inherent inhomogeneities of polymeric dielectric materials, a smaller number of weak points occur in small-size than in large-size insulating material samples, thereby implying that breakdown times and voltages are longer and higher, respectively, in the former than the latter.

It can be considered that, if the area under stress of a dielectric is increased y times, equation (3) is also valid, as long as the field strengths in the dielectric are maintained at the same level and the shape parameter β retains its value. In equation (3), μ is the scale