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Ageing of aeronautical cables exposed to partial discharges: the effects of voltage frequency

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Abstract— In this work, the behavior of the electrical insulation system of an aeronautical tape wound PTFE power cable in presence of partial discharges (PDs) was investigated in terms of time to failure as a function of the characteristics of an AC applied voltage. The electrical insulation of specimens was submitted to an intense electric field by applying voltage to the conductor, while a grounded metallic braid covered the outer surface of the insulation. An AC mean frequency (14-56 kHz) voltage was set above partial discharge inception voltage (PDIV) of the cable. Aging with PDs was carried out at constant voltage amplitude. For each voltage frequency, seven specimens were tested. Time to failure (dielectric breakdown) for each specimen was recorded and different parameters such as surface temperature and dissipated discharge power were measured during the ageing.

Keywords— Partial discharges, power cable, insulation system, aeronautics, ageing

I. INTRODUCTION

With increasing electrification of aircraft, new risks and challenges arise. One is the potential occurrence of partial discharges (PDs) due to increased on-board network voltage. Can cables withstand these phenomena without failure, and for how long? Which conditions can increase or decrease the effect of partial discharges on cables' insulation?

The potential implementation of PWM systems at high voltages onboard aircraft makes the effect of applied frequency on the order of tens of kHz particularly interesting in addition to the applied voltage amplitude. Previous work has studied the effect of frequency on PD behavior [1] [2] [3] exhibiting differences in PDEV (Partial Discharge Extinction Voltage), discharge current amplitude and PD patterns in the range of 0.1 Hz to 1000 Hz. Other studies with higher frequency ranges have also been made showing an influence of the supply frequency on PD activity [4] [5]. These results suggest that applied voltage frequency could also influence delay to failure of cables submitted to partial discharges.

Following on from work [6] focused on the effect of voltage level at fixed frequency (30 kHz), a more detailed analysis of the effects of applied frequency at a given voltage level was carried out. External insulation surface temperature and mean discharge dissipated power were measured during the treatments. Three sinusoidal frequencies were considered: 14 kHz, 32 kHz, and 56 kHz. Even though these sinusoidal voltages have a much higher risetime than PWM waveforms, the frequencies are comparable to commonly used carrier frequencies [7] and thus, the physical (ion sputtering),

chemical (short-lived radicals and atoms) and local thermal effects of discharges could be comparable assuming that the number of partial discharge events per cycle is the main difference that results from different risetimes [8]. So, the lifetimes found in this study cannot be directly applied to a PWM system, but the general results can be applied to analyze the effects of carrier frequency.

II. EXPERIMENTAL SETUP

A. Ageing chamber

An air-tight ageing chamber was used to contain the cable samples whose solid insulation was subjected to partial discharges in air at atmospheric pressure. A 1 L/min constant air flow (RH < 5% Vol. at room temperature) was imposed at atmospheric pressure through the chamber to prevent the accumulation of air discharge products such as ozone and nitrogen oxides. This chamber was fitted with a high-voltage feedthrough and a ground connection that enabled an electric field to be imposed on the cable insulation (Fig.1).

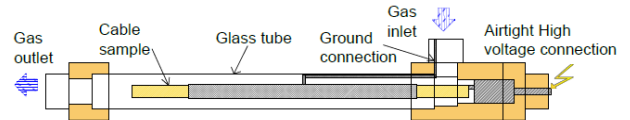


Fig. 1 Diagram and photograph of the air-tight ageing chamber containing a cable sample.

B. Sample description

The samples were prepared according to the following procedure: each sample was a 30 cm section of cable (tape wound DH gauge 2 with PTFE insulation) with a connector fitted to one of the conducting ends allowing voltage to be imposed to the cable conductor. The insulation (925 μm thick) was partially covered with grounded shielding braid over a length of 20 cm. It should be noted that this is a realistic configuration, since power cables are often mechanically protected in aeronautical installations with such metallic braids. The braid was adjusted over the insulating surface to keep the air gap to a minimum. The ends of the braid were retracted, and the triple junction (metallic braid/solid

insulation/air) was coated with insulating silicone grease to prevent surface discharges in this area. When a high voltage amplitude exceeding PDIV was applied to the cable conductor, partial discharges appeared in the spaces between the metallic strands of the braid and the external surface of the cable insulation. The PDIV of the samples at a frequency of 50 Hz, room temperature and atmospheric pressure was measured obtaining an average value of 4 kV peak.

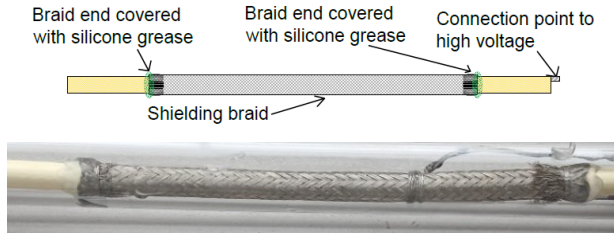


Fig. 2 Diagram and picture of a cable sample.

III. EXPERIMENTAL PROCEDURE

For each test, a newly prepared sample was introduced into the ageing chamber and a fixed frequency sinusoidal voltage was applied to the cable conductor with the metallic braid grounded. Discharge current was detected and measured with a Tektronix CT2 probe (1 mV/mA ratio, 1.2 kHz-200 MHz bandwidth) placed on the grounding conductor of the braid. Voltage was measured at the high-voltage feedthrough of the enclosure using a Tektronix P6015 A probe (1:1000 ratio, 75 MHz bandwidth). Current and voltage signals were acquired using a digital oscilloscope (Tektronix MSO54, 500 MHz, 6.25 GS/s). The average value (calculated over an integer number of periods of the voltage signal) of the instantaneous product of the voltage and current signals corresponds to the mean dissipated discharge power.

Constant voltage and frequency levels were maintained until the insulation system failed. The time between voltage application and failure was measured. For each frequency level, 7 specimens were tested.

Insulation external surface temperature was measured using a type K thermocouple. More precisely, the thermocouple extremity was placed between the metallic braid and the surface of the cable insulator, roughly in the middle of the sample. However, there was no way to know if this point of measurement would be in a region of partial discharges or not. It should be noted that during the tests, the dielectric breakdown of the insulation never occurred in proximity to the extremity of the thermocouple.

IV. RESULTS

In a previous study, the delay to failure of cable samples subjected to PDs with a 30 kHz AC peak voltage ranging from 4.4 kV to 6.5 kV was measured and analyzed [6]. The main results were that increasing voltage amplitude strongly decreased delay to failure and reduced the dispersion of time-to-failure values. In addition, the mean power dissipated in the discharge was seen to increase almost linearly with applied voltage. We concluded that the time to failure was heavily influenced by stochastic factors such as random differences in the insulation between different segments of cable or metallic braid fabrication and exact position. These stochastic factors produce “weak points” and “strong points” and whether the discharges take place in weaker or stronger points can drastically change the delay to failure.

For the present study, we measured the delay to failure for three different frequencies of the AC applied voltage with a 5.5 kV peak value. Obtained time-to-failure values are given in Fig. 3.

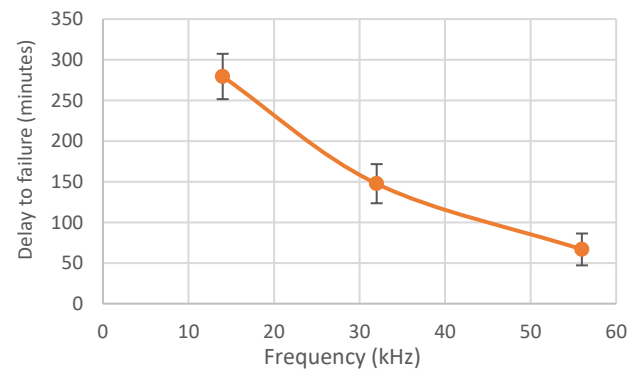


Fig. 3 Delays to failure at three different frequencies with a voltage of 5.5 kV peak. Each point is the average of 7 samples and error bars are the standard deviation of those 7 specimens. PTFE taped DH gauge 2 cable.

First, delay to failure decreases with an increase in voltage frequency. Given the dispersion in the measurements, it is difficult to establish if this decrease follows a linear or exponential trend. Second, dispersion in time-to-failure (standard deviation) is weakly affected by voltage frequency; on the other hand, average delay to failure is strongly affected (see Table 1). This means that the standard deviation is rather stable in the three frequencies we investigated, and it is not proportional to the delay to failure values.

Table 1 Standard deviation and average of the delays to failure for the three cases at 5.5 kV peak with different frequencies - PTFE taped DH gauge 2 cable.

Frequency (kHz)	14	32	56
Standard deviation (minutes)	27.9	24.1	19.6
Average (minutes)	326	148	67

The insulator temperature is shown in Fig. 4. Even though there is a large dispersion in the measured values, the higher frequency shows a noticeable increase in temperature compared to the other ones.

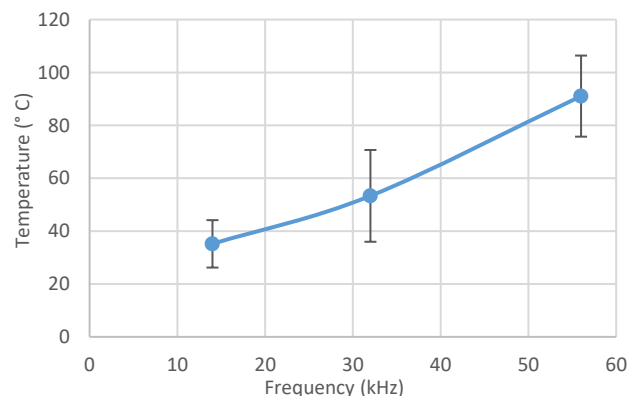


Fig. 4 Insulation surface temperature at three different frequencies with a voltage of 5.5 kV peak. Each point is the average of 7 samples and error bars are the standard deviation of those 7 samples. PTFE tape wound DH gauge 2 cable.

Mean dissipated power, shown in Fig. 5, increases linearly with the voltage frequency. Although the spread of values is increasing too, this means that the energy deposited in the discharge per cycle is constant in this frequency range. Finally, the relation between dissipated power and delay to failure is shown in Fig. 6; and between dissipated power and temperature, in Fig. 7.

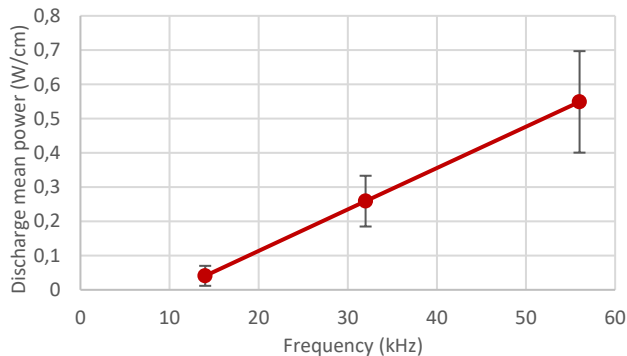


Fig. 5 Mean discharge power at three different frequencies with a voltage of 5.5 kV peak. Each point is the average of 7 samples and error bars are the standard deviation of those 7 samples. PTFE tape wound DH gauge 2 cable.

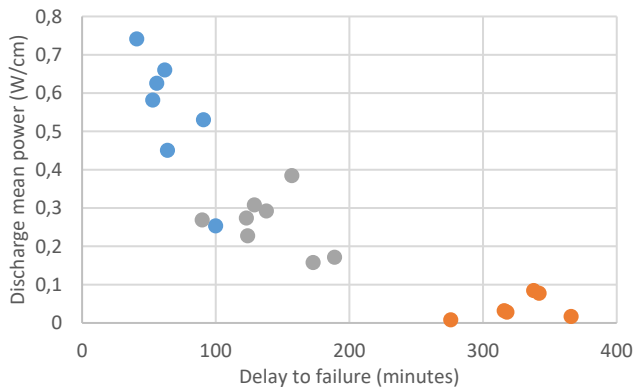


Fig. 6 Discharge mean power as a function of delay to failure for the three frequencies studied (56 kHz in blue, 32 kHz in gray and 14 kHz in orange). Each point is a sample.

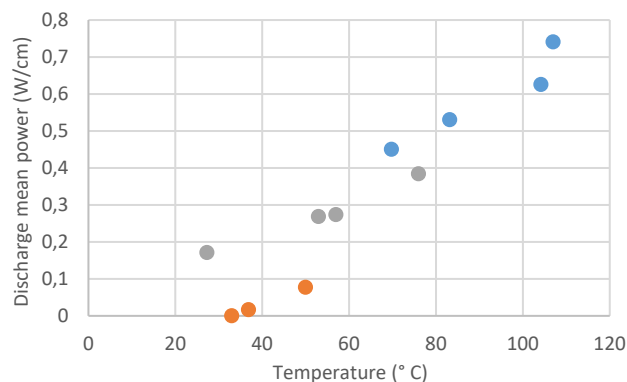


Fig. 7 Discharge mean power as a function of temperature for the three frequencies studied (56 kHz in blue, 32 kHz in gray and 14 kHz in orange). Each point is a sample.

V. CONCLUDING REMARKS

The effect of AC voltage frequency (from 14 kHz to 56 kHz) on partial discharge accelerated ageing of cable samples was experimentally studied. The three frequency values were chosen to be on the same order of magnitude as PWM systems and to be sufficiently different from each other to paint a clear

picture. Tests were carried out for the same voltage amplitude, waveform and type of sample (PTFE tape wound DH gauge 2 cables). Mean discharge dissipated power, insulator surface temperature and time-to-failure were measured for each ageing test. Although this study was made with power cables used for aeronautics and in the perspective of the more/all electric Aircraft, all tests were conducted at room temperature and atmospheric pressure to limit the number of variables to be controlled.

Frequency having little influence on the dispersion of the time-to-failure measured values is remarkable especially seeing how it has a big effect on the average (see Table 1). Considering that voltage frequency does not have a large effect on partial discharge inception (in the frequency range under study) [4] and the metallic braid geometry is the same for all samples, we can assume that the surface area actually submitted to partial discharges is not meaningfully affected by frequency. This suggests that dispersion is heavily dependent on the particular locations on the surface most affected by partial discharges as we had suggested in our previous work [6].

Finally, regarding the discharge power, its linear increase with frequency suggests that it depends mostly on the number of cycles per second and thus, for our system and frequency range, the average discharge amplitude and number of discharges per cycle are not affected by supply frequency. Temperature increases linearly with discharge power as well while the trend of the relationship between discharge power and delay to failure seems less linear. If delay to failure depends solely on the number of discharges affecting the cable, a very linear relationship is expected between delay to failure and dissipated power, which is actually not the case (see Fig. 6). However, given the large spread of measured data, it is difficult to formulate an accurate analytical model. In any case, what is clear is that the number of cycles per second (and thus number of discharges per second) are the main factor driving the delays to failure, which suggests that in the given range of frequency, the lifetime of the cable might be approximated simply as “a number of cycles” or “a number of discharges”, which finally result in mean discharge power. An accelerating effect of temperature is a possible explanation for the lack of clear linearity, and an Arrhenius type mechanism could be added as well to improve the model. Nevertheless, more concrete data about the effect of temperature on the delays to failure would be needed to confirm this theory and establish to which degree the lifetime of a cable under partial discharges can be modeled as an exponential function of discharge power/cm.

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