The Challenges of Reliable Dielectrics in Modern Aerospace Applications: The Hazard of Corona Resistant Materials

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***Abstract*— The development of more electrical transportation systems requires rotating machines having higher efficiency and specific power. To date, this is achieved by feeding them with rising supply voltages with higher frequencies. This generalized strategy is introducing several challenges in the correct design of the insulation that is necessary for a reliable system. A major issue to be dealt with are partial discharges (PDs), an aging mechanism that can bring insulation to failure in short times. A solution often proposed by manufacturers involves the use of the so-called corona resistant (CR) materials, which supposedly can withstand PD activity. This article investigates the possibility of using CR magnet wires for electrical machines operating at reduced pressures, such as the actuators for primary control surfaces in more electric aircraft. The results show that CR insulations are characterized by an improved behavior at ground level but are not a viable option at reduced pressures.**

***Index Terms*— Aging, life estimation, materials reliability, partial discharge (PD), pulse width modulated (PWM) inverters.**

I. Introduction

THE green transition is changing our lives and expectations. Generalist media outlets are often spreading the idea that fully electrical airplanes are just around the corner [1]–[3], probably supposing an outlook matching the boom of the electric vehicle market. Yet, meeting these expectations proves to be challenging. One obvious issue is that of batteries. However, more subtle problems are yet to be solved. As more power will be handled by electrical devices (see Fig. 1 from [4]), higher voltage levels will be required to keep the weight of the conductors to an acceptable level. For electrical machines, another parameter that is usually increased to enhance power density is frequency.

Wide-bandgap power semiconductors characterized by high nominal input voltages, high ampacity, and fast rise times [5] enable the development of electrical machines with higher power densities. In electrical vehicles, dc bus voltages of 800 V and modulation frequencies higher than 20 kHz are becoming a standard [6]–[10].

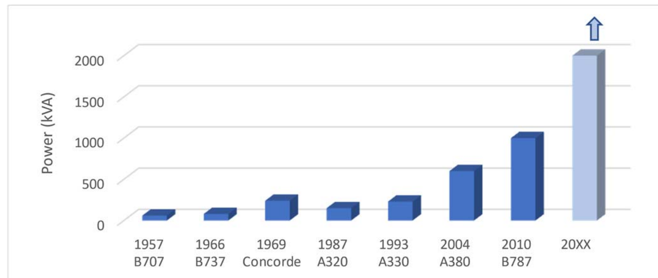

Fig. 1. Trend of the electrical power need in aircraft.

Aircraft manufacturers have recently begun implementing high voltage dc (HVDC) buses. Constant 400 Hz or more recent variable frequency (also called "wild") 115/200 V ac systems used to be the only options. Today, modern aircraft like the Boeing 787 integrate a 540-V dc bus [8], [9]. Next-generation planes, pursuing the more electric aircraft philosophy, are thought to be introducing electrical systems with a dc bus rating up to 1 kV. Considering the overvoltages induced by a fast-switching power supply, those voltage levels can translate into a peak voltage of up to 2 kV on the terminals of the actuators. These rather challenging conditions are known to be the cause of the premature failure of insulation systems.

A lot has been written on the detrimental effect of PWM inverter repetitive voltage impulses on the life of the insulation of rotating machines [11], [12]. This is due to 1) an increase in the peak voltage at the machine terminals due to reflections (the surge impedance of the machine is larger than that of the cable) and 2) an increase in the turn-to-turn voltage in the proximity of the line terminals due to the inductive/capacitive nature of the stator windings [13], [14].

There is no doubt that those aspects should be considered during the design of a drive when a machine and an inverter must be integrated. To help the designer, standards have been issued regarding qualification tests for rotating machines insulation [15]–[24], operating with pulsed supplies.

Due to the ongoing trend toward systems at higher voltage levels operating at reduced pressures, the risk of triggering

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partial discharge (PD) activity is high. Insulation systems able to withstand PD activity (the so-called Type II insulations) are typically employed in systems with low design fields, thus large volumes.

A valid option for the insulation of land and marine electrical transportation systems is corona-resistant (CR) materials (e.g., polymeric materials filled with inorganic micro- or nanoparticles). Those are presented as a promising solution, but there is still significant research work to be done to support such speculation for low-pressure working conditions [25], [26]. Indeed, for a fixed voltage supply, the reduced working pressure is not only promoting the inception of PD, but is also enhancing their energetic content [17], thus their destructive potential [18]. This means that insulation materials perfectly capable of withstanding moderate PD activity at ground level might be insufficient at cruising altitudes.

This will be the main topic and drive for this work, which aims to assess the possibility to employ CR insulation for modern aerospace applications while determining the severity of insulation life reduction due to operation at reduced pressure. The theoretical background, experimental results, and life behavior for enameled wire insulation will be discussed in this work.

II. Materials and Methods

A test setup was realized for testing insulation models (twisted pairs) of the turn-to-turn insulation subsystem subjected to the output of a two-level inverter capable of producing pulses with either low or high slew rates (up to 140 kV/μs). Tests were conducted in a low-pressure environment (0.1 bar) corresponding to a cruising altitude of 16 km.

A silicone carbide (SiC) inverter to be used for the tests was designed and assembled by the University of Modena. The inverter is based on Wolfspeed C2M1000170D SiC MOSFETs. These MOSFETs have a blocking voltage of 1700 V. The lowest rise time of the MOSFETs is 7 ns corresponding to a gate resistance of 27 Ω. To test with different slew rates, gate resistances of 53 and 500 Ω were used to achieve rise times of 12 and 237 ns, respectively. Tests were carried out at switching frequencies of 100 kHz with variable rise times. The two waveforms have different overshoot factors, as can be observed in Fig. 2. In the low slew rate configuration, the overshoot is around 2%, while in the high slew rate, it is around 18%. Due to the overshot presence, each result can be expressed by resorting to either the peak value or the steady part of the wave (referred to as "dc" in the following). In this article, the peak value is used, unless otherwise specified.

A vacuum cell able to reach pressures down to 1 mbar was used to simulate the low-pressure atmospheric condition. Samples were connected inside the cell and fed by means of 20 kV pass-throughs. The voltage applied was measured by a Tektronix MDO3054D oscilloscope (500-MHz bandwidth, 2.5 GS/s sampling rate) using a Tektronix THDP0100 differential probe (100-MHz bandwidth).

Grade 2 round enameled winding wires having a diameter of 0.56 mm were used as test samples. The insulation is

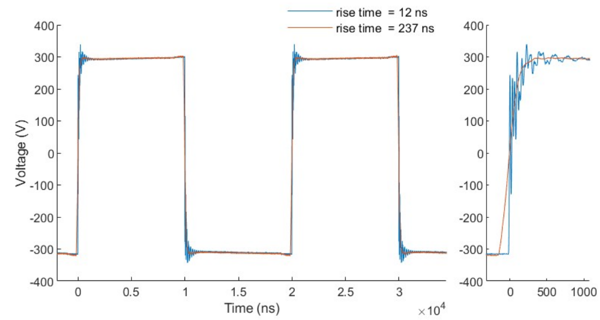

Fig. 2. SiC Inverter waveforms for a rise time of 12 ns (blue line) and 237 ns (red line) for a dc bus voltage of 300 V, with different time scales (left: 36 μs, right: 1 μs, highlighting overshoots).

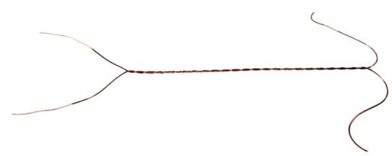

Fig. 3. Picture of a twisted pair manufactured out of NCR wire.

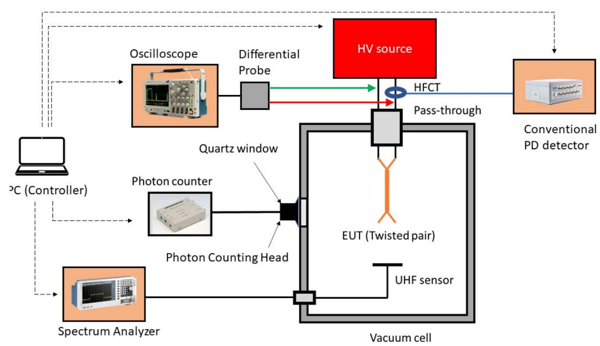

Fig. 4. Schematic of the test cell equipped with a PD detection system.

in thermal class 200, and it features a tris-(2-hydroxyethyl) isocyanurate (THEIC)-modified polyester-imide basecoat and a polyamide-imide overcoat. Two different typologies of wire were tested: one with an inorganic nano-filler (CR) and one neat alternative (N-CR, non-CR). According to [19], the wires were twisted 12 times applying a load of 7 N. For each test condition, seven freshly manufactured twisted pairs were used. A picture showing the sample is in Fig. 3.

In the setup, both PD inception voltage (PDIV) and endurance time under voltage tests were performed, and its schematic drawing is shown in Fig. 4. During the tests, the temperature and humidity were monitored constantly and set at the desired level of 25 °C and 8.1 g/m^3 (corresponding to 35% relative humidity (RH) at 25 °C, 1 bar).

A. Measurement of PDIV

Measurements of PDIV were performed under ac and SiC converter waveforms. Each measurement was performed by increasing the peak voltage in steps of 10 V every 30 s and the PDIV was recorded as the first voltage level where

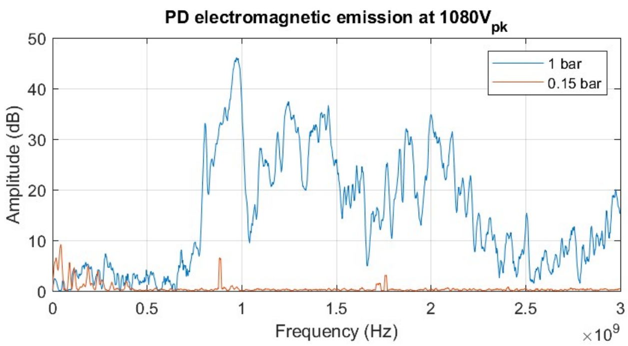

Fig. 5. Spectrum of PD emitted signal, recorded with an antenna for different pressure levels.

PD activity occurred. PDIV levels were determined for each test condition by testing seven samples and fitting the data with a two-parameter Weibull distribution using the median ranks method, calculated by the inverse of the incomplete beta function. The tenth percentile (B10) of the Weibull distribution obtained is used to summarize the measured PDIV values.

For measurements in ac, a step-up 220/3000 V transformer controlled on the primary side by a variable autotransformer, manually controlled and fed by the grid, was used to produce the voltage. A conventional ferrite-core high-frequency current transformer (HFCT) was used to sense PD signals. An external capacitor (1 nF) was connected in parallel to the twisted pairs to improve the detection sensitivity, down to 3 pC. A commercial PD detector was connected to the sensing HFCT (Techimp PDBaseII, with a bandwidth of 40 MHz, and a sampling rate of 200 MSa/s). For measurements under converter waveforms, an optical system was used, together with a more conventional high bandwidth instrument due to difficulties to differentiate between signals belonging to PDs and noise from positive and negative flanks of the inverter. The optical PD detection is achieved using a photon-counting system by Hamamatsu Photonics: an H11870-09 photon-counting head, and a C8855-1 photon-counting unit. This device can detect the emission of photons mostly due to the de-excitation of nitrogen molecules excited by the discharge occurring on test samples in the air. The technique proved to be equivalent to a classical electromagnetic detection system with a sensitivity of less than 5 pC for ac PD testing. Technical details and relative sensitivities of this can be found in [20]. Also, the maximum number of photons per second recorded by the system was collected.

High-bandwidth PD activity detection with fast pulsed voltage supplies has been performed in the frequency domain, by means of a Rohde Schwarz FPC1500 spectrum analyzer and a log-periodic antenna (750 MHz–6 GHz) placed at 20 cm from the sample. This was necessary due to the unfeasibility of time-domain detection caused by high-frequency converter noise overlapping with PD signals.

PD spectra at 1 and 0.1 bar are displayed in Fig. 5. The figure is obtained from frequency-domain measurements subtracting the signal in the absence of PD, just before their inception (where only the converter noise is captured) from the one in the presence of PDs. The presence of PDs was known from the optical detection. Results show that the average amplitude of the discharge decreases with pressure, and their detection becomes almost impossible with conventional electromagnetic methods, confirming what was observed for discharges in ac in previous studies [17]. For this reason, optical detection was the only viable option for the PDIV measurements at low pressure.

B. Measurement of Wires Endurance Times

Endurance tests were performed monitoring the peak voltage applied to the sample and recording the time endured under voltage. A constant voltage was applied to the sample and when a short circuit was detected the time elapsed from the switching on of the voltage was saved. The sensitivity for the measure of the endurance time is 1 s.

Three different voltage levels have been selected: 1120, 840, and 700 V, corresponding to the turn-to-turn stress appearing on a machine fed by a bipolar two-level inverter with a dc bus level of 800 V, where the overshoot at the terminals is, respectively, 100%, 50%, and 25% higher than the nominal voltage. These tests will consider the worst case for a bipolar two-level converter, where all the jump voltage (two-thirds of the phase-ground voltage) [13] drops on the first turn of the insulation. Such dc bus voltage has been selected to represent a next-generation drive system, or even present 540-V drive systems that allow for bus transients. Indeed, the bus system of an aircraft is often designed to operate at higher voltage levels for a fraction of its operation time.

Experimental results obtained at fixed voltage were fit to a two-parameter Weibull distribution (with α as scale parameter and β as shape parameter) using the same methods described for the PDIV tests. The tenth percentile of the life distribution (B10) is used to summarize the life values.

III. Influence of Pressure on PDIV and Its Energetic Content

A. PD Inception Voltage

PD occurs when the electric field exceeds a value large enough to trigger streamer discharges in cavities or defects embedded in the insulation or at insulation surfaces [27]. A rough expression for the inception field in a cavity, E_i, is given by [29]

$$E_i = 25.2p\left(1 + \frac{8.6}{\sqrt{pl}}\right)\left[\frac{V}{m}\right] \quad (1)$$

where l is the cavity diameter, or the thickness of delamination or, in general, of a defect; and p is the gas pressure inside the defect.

The voltage at which PD incept steadily into insulation, that is, PDIV, is therefore associated with the defect thickness, as well as the working pressure.

Magnet wires twisted together (twisted pairs) are representative insulation models for random wound machine insulation since, even with vacuum pressure impregnation (VPI), cavities at the contact point between wires can exist. Previous work [20] was done to derive an analytical model to predict PDIV as a function of pressure on enameled wires.

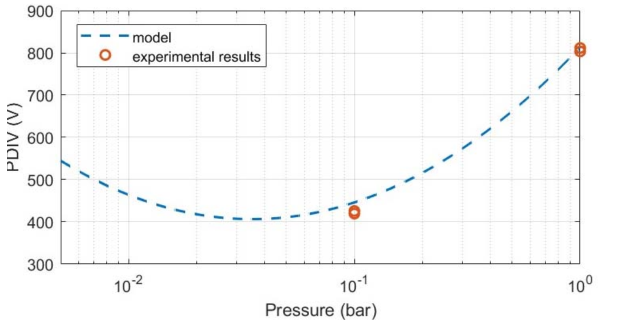

Fig. 6. Trend of PDIV as a function of the pressure, model (dashed line), and ac experimental results (markers) for the N-CR samples.

TABLE I

PDIV (PEAK AND DC) OF CR AND N-CR WIRES SUBJECTED TO BIPOLAR SiC CONVERTER WAVEFORM (100-kHz SWITCHING FREQUENCY), FOR WORKING PRESSURES OF 1 AND 0.1 bar

Material	Pressure $[bar]$	Rise time $[ns]$	$PDIV_{pk}$ $[V]$	$PDIV_{DC}$ $[V]$	Photons per second $[s^{-1}]$
N-CR	1	12	880	732	$(1-2)\cdot 10^5$
N-CR	0.1	12	555	424	$> 10^6$
CR	1	12	881	731	$(1-2)\cdot 10^5$
CR	0.1	12	558	426	$> 10^6$

An empirical model based on the logarithm of the pressure (in bar) was obtained under ac 50-Hz sinusoidal voltages, valid in the range $5 \cdot 10^{-3} - 1$ bar

$$\frac{\mathrm{PDIV}(p)}{\mathrm{PDIV}(1\ \mathrm{bar})} = 1 + 0.3 \cdot \ln(p) + 0.044 \cdot \ln(p)^2 \qquad (2)$$

where p is the pressure expressed in bar. As can be noticed from Fig. 6, representing (2) for a 0.56-mm grade 2 wires (PDIV(1 bar) $=$ 813 V), PDIV trend is nonmonotone with pressure, featuring a minimum in the range 0.050.07 bar.

In the case of the actuators for the primary control surfaces of an aircraft, considering a worst-case scenario cruising altitude of 16 km, a pressure of 0.1 bar, the expected PDIV is 59% of its value at $p = 1$ bar, that is, 482 V for the wires used in the following. Thus, considering the effect of thermal stress and possible overvoltages, the likelihood that PD may incept is very high if modern 540 V dc bus levels will be employed, and this option can become a certainty when considering the overvoltages induced in electrical systems by pulsed supplies (see Section IV). Hence, materials capable of withstanding such activity are necessary.

PDIV tests performed on the magnet wires used in this article fully support previous findings [17]. Table I and Fig. 7 show the values of PDIV (as the dc bus voltage), for twisted pairs with different insulation materials and at different pressures. Table I also reports the photon emission rates at PDIV. Fig. 6 shows the measured values compared with the predictions obtained from (2).

As can be observed, PDIV levels are strongly affected by the reduction of working pressure, going from 880 and 881 V to 555 and 558 V when pressure is reduced from 1 to 0.1 bar, for N-CR and CR materials, respectively.

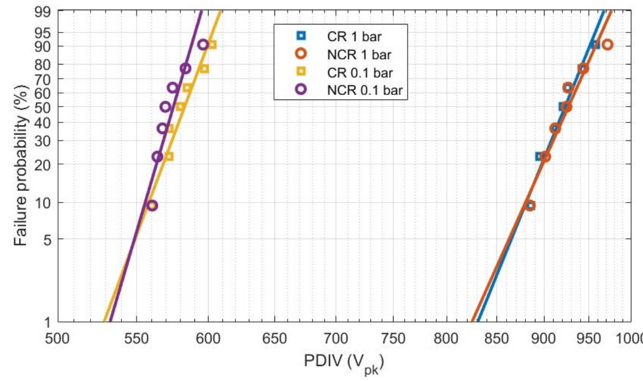

Fig. 7. Weibull chart of PDIV (peak voltage) levels for working pressures of 1 and 0.1 bar, for N-CR and CR samples.

The severity of a pressure reduction on insulation life is going to be investigated later in this section, but it can be immediately noticed that an insulation system could very well be able to operate at ground level at, for example, 600 V, even without CR insulations. When at cruising altitudes, however, the same voltage would surely incept strong PD activity, quickly bringing non-CR insulation to failure.

Additionally, at the same pressure, wires having the same diameter but insulated with different materials have comparable PDIV levels. This can be expected since the most important factor that determines the PDIV is the insulation thickness (that depends on the diameter [21]), whereas the sensitivity of PDIV on permittivity is lower and the limited range of variation of permittivity across different materials [22].

B. Electron Energy Density

An important element that should be considered when operating electrical systems at low pressure is the enhanced destructive potential of the PD.

The damage that a discharge induces on insulation is mostly (but not exclusively) due to the so-called dissociative electron attachment (DEA) degradation process, involving the disruption of polymer bonds and growth of local degradation. If, for example, a minimum dissociative energy of 4 eV is considered (as it is often the case for C-H bonds) to be necessary to trigger a DEA event, a PD devoid of electrons featuring energies higher than such level is not going to be capable of any damage to the insulation.

Unfortunately, the energetic levels, w, of the electrons forming the discharge of a single PD, which is effectively a nonequilibrium cold atmospheric plasma, is approximately fitting to a Druyvesteyn distribution function [23]

$$f(w) = 1.23 \cdot \left(\frac{w}{\langle w\rangle^3}\right)^{\frac{1}{2}} \exp\left(-0.55 \cdot \left(\frac{w}{\langle w\rangle}\right)^2\right) \qquad (3)$$

where $\langle w\rangle$ is the mean energy of the population.

This means that even a population characterized by a value of $\langle w\rangle$ much lower than the minimum energy necessary for DEA degradation is capable of inducing some damage, since a fraction of its population is going to have a sufficient energetic content to trigger DEA (see Fig. 8).

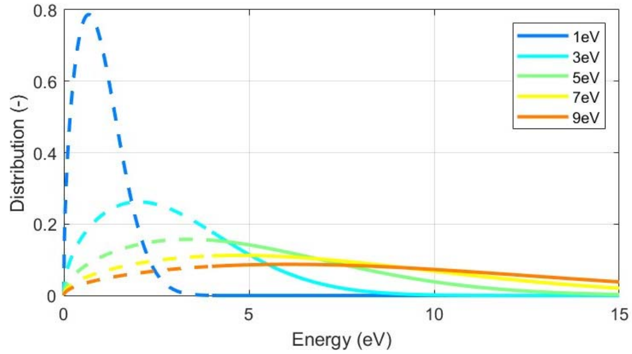

Fig. 8. Distribution of the electrons' energetic content, for different mean energies. The lines are solid in regions where the energy is enough to start DEA events, dashed elsewhere.

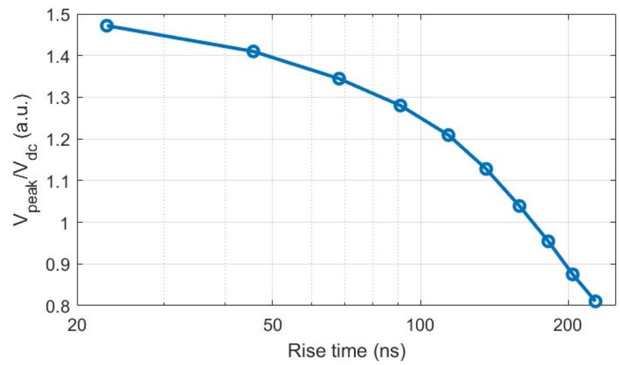

Fig. 9. Turn-to-turn worst-case voltage difference as a function of rise time, for a cable length of 2 m.

TABLE II
ENDURANCE OF CR AND N-CR WIRES SUBJECTED TO BIPOLAR SiC CONVERTER WAVEFORM (100-kHz SWITCHING FREQUENCY), AT GROUND AND FLIGHT PRESSURE LEVELS (1 AND 0.1 bar)

Material	Pressure $[bar]$	Applied Voltage $[V_{pk}]$	Rise time $[ns]$	Life 10th $[s]$	Life	
					α $[s]$	β
N-CR	1	1120	12	390	446	17
N-CR	0.1	1120	12	1	1	∞
CR	1	1120	12	10577	12987	11
CR	0.1	1120	12	5	6	14

During a discharge process, electrons gather their energy by accelerating through their mean free path, which is the average distance that an electron can travel without collisions with neutral particles. When a discharge occurs at reduced pressure, the mean free path is increased, due to the lower density of the medium. This implies an increase in the mean energy of electrons and the fraction capable of DEA degradation (see Fig. 8).

Indeed, results in Table I show that the production of photons detected at a fixed rise time increases with the reduction of pressure, going from an order of magnitude of 10^5 to complete saturation of the detection system (more than 10^6) photons per second, suggesting a higher fraction of electrons is able to trigger the excitation of nitrogen molecules in the air.

As a result, even when PD intensity is reduced (i.e., a lower amount of electrons are involved), it is possible that low-pressure conditions might eventually result in being much harsher and more damaging than stronger PD activity under atmospheric pressure [17]. This means that materials rated as "CR" that are proved to be effective at ground level might be unsuccessful if operated at reduced pressures.

Results of endurance tests on N-CR and CR materials can be found in Table II. On one side, the life reduction on the same kind of material and stressing voltage is dramatically evident. Life of N-CR specimens is always lower than for CR, as expected, going from 446 to 12987 s and from 1 to 6 s, respectively, for N-CR and CR materials, at 1 and 0.1 bar, respectively. However, at reduced pressure, even when CR materials are considered, failure is almost immediate.

IV. INFLUENCE OF VOLTAGE WAVEFORM RISE TIME ON STRESS DISTRIBUTION AND PD DYNAMICS

Short rise times and high dc bus voltages combine to produce voltage stress levels that can often be challenging for the insulation system. Short rise times can increase the stress on the turn-to-turn insulation by increasing the overshoot factor at the machine terminals and by enhancing the inhomogeneity of the voltage drop in coils and turns [13], [14].

The worst-case scenario can be found with random-wound windings fed by high slew rate converters, where there is the chance of the first and last turns of the coil to be adjacent. This means that the entire coil voltage drop could appear between the two turns, causing high localized stress on the insulation system.

As an example, the turn-to-turn voltage stresses appearing in a permanent magnet motor rated 5.7 kW, fed by a 2-m cable with voltage waveforms with variable rise times were simulated with tools detailed in [30] and are illustrated in Fig. 9. If a 24-ns rise time is opted, with a dc bus voltage of 540 V, the stress generated in the turn-to-turn results be 794 V_{pk}, which is well above the PDIV measured for lower pressures, but not at atmospheric pressure, ensuring a probably PD-free system at ground level, with practically certain PD inception once at cruising altitude.

Under converter voltage impulses, the PD pulse magnitude increases as the voltage pulses get steeper, and their frequency content is shifted to higher frequency ranges [31], increasing the degradation rate of the insulation system. Besides, it is possible that the large frequency content has an influence on the PDIV itself.

Experimental results of PDIV measurements with different rise times on N-CR and CR samples can be found in Table III for 1 and 0.1 bar, and in Fig. 10 for tests at a pressure of 0.1 bar. Table III also reports the photon repetition rate.

As before, when the rise time of voltage flanks is fixed, PDIV levels of specimens insulated with different materials are generally similar. On the other hand, at 1 bar, when the rise time is decreased from 237 to 12 ns, PDIV levels increase from about 790 to 880 V_{pk} for both N-CR and CR materials. This encouraging finding can, however, be mostly explained considering that two requirements have to be met

TABLE III
IMPACT OF RISE TIME ON PDIV (PEAK AND DC) OF CR AND N-CR WIRES SUBJECTED TO BIPOLAR SiC CONVERTER WAVEFORM (100-kHz SWITCHING FREQUENCY), FOR WORKING PRESSURES OF 1 AND 0.1 bar

Wire type	Pressure $[bar]$	Rise time $[ns]$	$PDIV_{pk}$ $[V]$	$PDIV_{DC}$ $[V]$	Photons per second $[s^{-1}]$
N-CR	1	12	880	732	$(1-2)\cdot 10^5$
N-CR	1	237	797	780	$(1-3)\cdot 10^4$
CR	1	12	881	731	$(1-2)\cdot 10^5$
CR	1	237	787	770	$(1-3)\cdot 10^4$
N-CR	0.1	12	555	424	$> 10^6$
N-CR	0.1	237	421	411	$> 10^6$
CR	0.1	12	558	426	$> 10^6$
CR	0.1	237	433	422	$> 10^6$

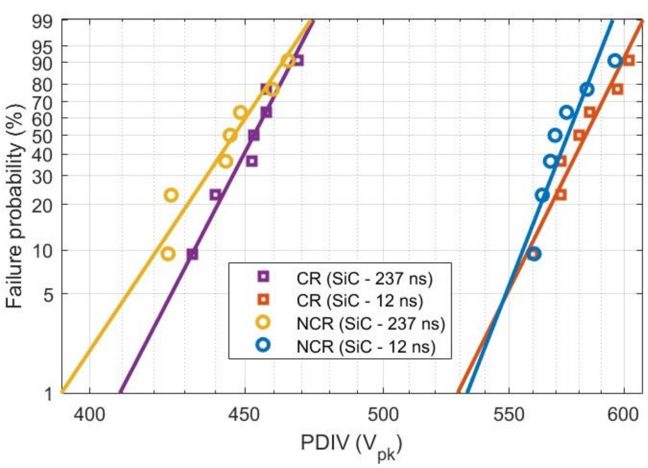

Fig. 10. Weibull chart of PDIV (peak voltage) levels obtained under a pressure of 0.1 bar for different rise times, for N-CR and CR samples.

to incept PD: 1) a minimum voltage able to produce a field exceeding the ionization field in the medium has to be applied and 2) a starting electron becomes available. A higher peak value of the PDIV could be due to a negligible duration of the portion of the waveform exceeding the minimum voltage for PD inception, during which the probability of having a starting electron is reduced. By increasing the dc bus voltage, the duration of such period also increases, together with the probability of having a free carrier to start the electronic avalanche.

On the other hand, it is worthwhile noting that, at atmospheric pressure, the photon count rate is lower for tests with larger rise time, going from an order of magnitude of 10^5 to 10^4 photons per second, suggesting that the measured PDIV at short rise times is higher than the actual PDIV.

Another conflicting indication arises observing the dc bus voltage observed at PD inception. At atmospheric pressure, the dc bus voltage at PDIV goes from about 770 to 730 V_{DC} for both materials, when the rise time is reduced from 237 to 12 ns. At reduced pressure, the same trends of PDIV at different rise times are observed, with reduced voltage levels.

Those trends are entirely opposing the results suggested by the observation of peak values, which were indicating a benefit from the usage of fast rise times.

Similar results were also obtained previously [32], and they seem to indicate that the increasing peak value of PDIV obtained with short rise times is most probably due to the insufficient time spent under a voltage level sufficient to trigger a discharge (only a few ns), which is not enough to statistically guarantee the presence of a free carrier.

Let us see in the following sections whether those materials would be able to pass the tests required by the current standard and the results of endurance tests, letting us understand which is the most appropriate indicator for PDIV.

V. DESIGN INDICATIONS FROM THE IEC 60034-18-41

The IEC 60034-18-41 is the most recent standard dealing with design qualification, type, and quality control tests of insulation systems used in rotating machines fed from voltage converters. Definitions of PDIV and repetitive PDIV (RPDIV) are provided by this standard in relation to PD testing under sinusoidal and repetitive impulse voltage, respectively.

As the investigated materials belong to Type I insulation systems (i.e., organic dielectrics, intended for use in the absence of PD activity throughout their lifetime), the pass criterion is that the insulation system does not incept PD up to a voltage level defined on the basis of the peak voltage at the motor terminals. To simulate aging and other factors that tend to reduce the PDIV, safety factors are proposed in the standard. However, no clear information is given on testing pressure and slew rates (the standard only considers a rise time of 300 ± 200 ns, longer than rise times from wide bandgap converters), which are clearly factors to be considered when dealing with PD inception.

For sinewave testing, PDIV is recognized when there is at least one pulse detected per cycle, while for impulse testing, the equivalent test is for there to be at least one pulse detected during all the impulses which occur in one fundamental operating cycle. It must be noted that in the presence of two-level inverters, PDIV and RPDIV values are practically overlapping [33]. For this reason and being PD repetition rate measurements are extremely challenging at low pressure (due to the difficulties described in Section II) PDIV will only be considered here.

For example, if a dc bus voltage of 540 V and an overshoot factor of 1.1 are considered, a peak voltage of $540 \times 1.1 \times 0.66 = 392$ V_{pk} is found for a turn-to-turn insulation system. However, to ensure a reliable operation over time, this value should be multiplied by safety factors to define the test voltage. The combined effect of these safety factors is to multiply by 1.25–1.95 the peak voltage to derive the peak test voltage. Taking an average value of 1.6, a test voltage of 627 V_{pk} is obtained. As can be seen from Tables I and III, the considered materials would pass this kind of test, if evaluated under atmospheric pressure, but would fail at lower pressure.

Considering the same overshoot factor as above, and the PDIV results obtained at low pressure with fast rise times, the highest dc bus allowed by this standard would be 353 and 363 V, respectively, for NCR and CR materials. Those values are well below the voltage targets expected for the More Electric Aircraft.

TABLE IV

ENDURANCE OF CR AND N-CR WIRES SUBJECTED TO 840 V_{pk} BIPOLAR SiC CONVERTER WAVEFORM (100-kHz SWITCHING FREQUENCY), WITH DIFFERENT RISE TIMES

Material	Pressure $[bar]$	Applied Voltage $[V_{pk}]$	Rise time $[ns]$	Life 10th $[s]$	Life	
					α $[s]$	β
N-CR	0.1	840	12	15	16	23
N-CR	0.1	840	237	23	25	24
CR	0.1	840	12	17	19	24
CR	0.1	840	237	27	30	28

TABLE V

ENDURANCE OF N-CR AND CR WIRES AT 0.1 bar FOR DIFFERENT VOLTAGE APPLIED (VALUE IN PEAK). ALL VOLTAGE WAVEFORMS APPLIED WITH A RISE TIME OF 12 ns

Material	Pressure $[bar]$	Applied Voltage $[V_{pk}]$	Rise time $[ns]$	Life 10th $[s]$	Life	
					α $[s]$	β
N-CR	0.1	1120	12	1	1	∞
N-CR	0.1	840	12	15	16	23
N-CR	0.1	700	12	131	155	13
CR	0.1	1120	12	5	6	14
CR	0.1	840	12	17	19	24
CR	0.1	700	12	165	192	15

However, the main aim of this standard is to prevent PD inception in a machine designed with insulations incapable of withstanding any PD activity. Being CR materials literally "CR," it is possible that the threshold set by the International Electrotechnical Commission (IEC) standard results be too conservative. Therefore, the following section will investigate this possibility, addressing the endurance of the tested insulations in the presence of PD activity.

VI. LIFE

Since the turn-to-turn electrical stresses are directly related to the peak voltage of the applied waveform, and technical standards often refer to such level [15], the stress levels considered during endurance tests were based on the peak of the applied voltages. This means that specimens tested with fast rise times were stressed using a lower dc bus voltage, since the applied waveform was characterized by a larger overshoot.

The effects of fast switching on life can be seen in the following results of endurance tests reported in Table IV. The result shows how the usage of modern wide-bandgap semiconductors, such as SiC power MOSFETs reduces life by about 50% (despite testing at a reduced dc bus voltage), introducing a potentially important unreliability factor on the insulation system, especially with N-CR insulations.

Tests were also run at different peak voltage levels. Results are summarized in Table V. The inverse power model (IPM) is often used to model the life of insulation [34]

$$L = A \cdot V^{-n} \tag{4}$$

where L represents the time to failure (the life of the material), V the applied voltage, n the voltage endurance coefficient (VEC), and A is a proportionality factor. Equation (3) can be used to fit results in Table V, as shown in Fig. 11. As the

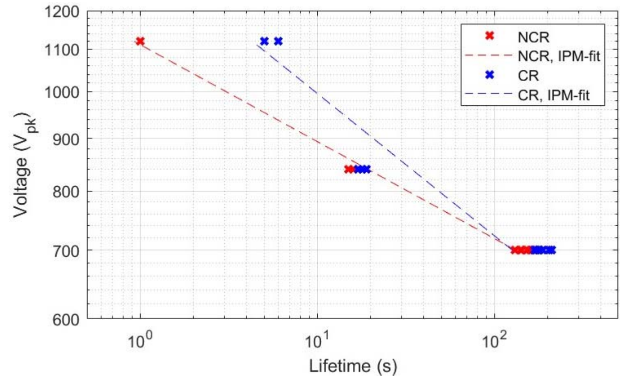

Fig. 11. Life curves for CR and N-CR wires at low pressure (0.1 bar) under SiC converter waveform stresses. Experimental results (markers) and their fitting line to (4).

stressing voltage peak increases, the higher electric field in the air causes a higher number of ionization and excitation events, generating larger electron avalanches and higher PD magnitude. Consequently, the damage per unit time increases, and the erosive power due to the mentioned DEA process is enhanced accordingly. The CR and NCR wires share very similar values of endurance time within the voltage range explored, which are too short to guarantee operation in presence of PD activity. This result may come from the speculated shift of the electron energy distribution to higher values, with a single electron capable of breaking multiple bonds or capable of breaking chemical bonds previously inaccessible [35].

As can be seen, even neglecting the enhancement factor (thus, the impact of aging and increased temperatures), the design voltages required for operation at low pressure are very limited, so much that feasibility with modern dc bus levels is practically prevented even suppressing voltage overshoots, having a predicted life in the order of thousands of seconds, for both N-CR and CR materials at 540 V.

VII. CONCLUSION

The harmfulness of PD in organic insulation is known and so is the fact that power inverters electrically stress the insulation possibly leading to PD inception. On the other hand, a solution that can be adopted when insulations need to cope with PD activity is resorting to CR materials. This article adds a significant information for the design and operation of the whole insulation system in aerospace, that is, the overwhelming energetic content of discharges at reduced pressure.

Tests on N-CR and CR insulating materials at different pressures and slew rates have clearly shown that CR insulations are insufficient to design a reliable insulating system operating above the PDIV. Thus, the voltage and frequency increase required by manufacturers for transportation in aerospace must be pursued with the target of operating at voltages safely below the PDIV (even during anomalous operating conditions) by matching the inverter voltage stress with the stator insulation.

A leap forward in solid insulations seems to be necessary to reach the desired power densities, either developing novel materials capable of sustaining a prolonged amount of strong PD activity at cruising altitude or implementing insulation systems characterized by higher PDIV levels, able to prevent discharges in the first place.

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