Insulation Materials and Systems for More- and All-Electric Aircraft: A Review Identifying Challenges and Future Research Needs

Moein Borghei, *Graduate Student Member, IEEE*, and Mona Ghassemi, *Senior Member, IEEE*

***Abstract*— In recent decades, extensive research has been conducted on the electrification of commercial aircraft to reduce the dependence on mechanical, hydraulic, and pneumatic systems and replace them with electrical systems. A primary goal of this path is to make the power density of the more-/all-electric aircraft (MEA/AEA) closer to that of conventional aircraft. While current commercial aircraft operate at voltages below 1 kV, it is widely accepted that higher operating voltage is necessary for MEA/AEA. NASA has envisaged a voltage level of at least 6 kV for MEA. In the language of electrical insulation technology, higher voltage levels translate into higher electric tension on the insulation system. A serious challenge stems from the fact that, at high altitudes, high-voltage insulation design strategies are not necessarily as efficient as at sea level due to differences in environmental conditions, including lower pressure, higher moisture level, microgravity, and plasma radiation. In this article, challenges associated with the electrical insulation design of future aircraft are reviewed. These challenges extend to almost any part of the electric power system in an aircraft, such as electric machines, power converters, cables, and printed circuit boards (PCBs). An overview of the aging factors, such as internal discharges, arc tracking, and thermal degradation, is accompanied by a discussion of the potential of novel insulating material and the ways to reinforce the current commercial dielectric materials. Finally, considerations for testing at simulated high-altitude conditions and the existing standards and their deficits are investigated.**

***Index Terms*— Cryogenic systems, insulation system, more-electric aircraft (MEA), partial discharge (PD), surface flashover, tracking, wide bandgap (WBG) semiconductors.**

I. Introduction

The failure of electrical equipment had a long tie with the accelerated aging of insulation systems. In 1971, a study performed by Grumman Aerospace Company showed that the polyimide (PI) films that are exposed to water and humidity are prone to an accelerated deterioration rate [1]. Later in 1988, Campbell *et al.* [2] showed that the lifetime of the wiring system used in naval aircraft is lower than the expected lifespan by 8–11 years. Kapton PI that was used as the insulating material was chosen due to its good dielectric and mechanical strength. However, the chemical reaction of water with the daily used chemical cleaners led to tracking and the breakage of the polymer chain (hydrolytic scission) and subsequently weakened mechanical and dielectric strength [3]. Later, on July 17, 1996, Trans World Airlines Flight 800 crashed only 12 min after taking off from New York to Paris. After years of investigation, the National Transportation Safety Board (NTSB) specified the explosion of the fuel tank in the center wing as the cause of the accident for the Boeing 747-100 [4]. The reason behind the detonation was most likely due to insulation failure and a short circuit of electrical wires [5]. Now that electrified aircraft is visualized as the future paradigm, how can we move forward if the reliable operation of the insulation system is not ensured? As a result, NASA considers the electrical insulation system, a core technology for future electrified aircraft.

The notion of more-electric aircraft (MEA) can be traced back to the late 19th century [6]. However, in recent decades, this concept has been promoted extensively to address the need for emission reduction and to lower fossil-fuel dependence [7]. The electrification trend in the aviation industry is also favorable due to its potential for improved reliability and sustainability. Nevertheless, the state-of-the-art electrical propulsion systems are still not viable compared to conventional aircraft due to lower specific power [8]. According to [9], the required power density for future propulsion systems is approximately 40 kVA/kg. Since the electrical distribution and protection system stands for nearly 30% of the entire system's mass, great potential resides in the optimization of electrical systems [10]. Therefore, to achieve the advantages of electrified transportation, the most important task of researchers in this area is to develop an electrical system with high power delivery and low system mass. Taking into account the efficiency and reliability of an aircraft, electrical systems can substitute hydraulic, mechanical, and pneumatic systems either entirely or partially, leading to fuel saving, reduced emissions, and lower noise levels [11]–[14].

The electrification trend has provided interest in the transportation sector to electrify cars, ships, and aircraft. Although all these vehicles share the objective of efficiency, weight, and cost optimization, the pathways to achieve these goals have major differences for each type of vehicle. The MEA is quite different from electric cars in the way they meet their power requirements; while batteries are being commonly adopted for

Manuscript received September 22, 2020; revised December 1, 2020 and January 1, 2021; accepted January 5, 2021. Date of publication January 8, 2021; date of current version August 24, 2021. This work was supported in part by the Air Force Office of Scientific Research under Award FA9550-20-1-033. *(Corresponding author: Mona Ghassemi.)*

The authors are with the Bradley Department of Electrical and Computer Engineering, Blacksburg, VA 24061 USA (e-mail: moeinrb@vt.edu; monag@vt.edu).

Digital Object Identifier 10.1109/TTE.2021.3050269

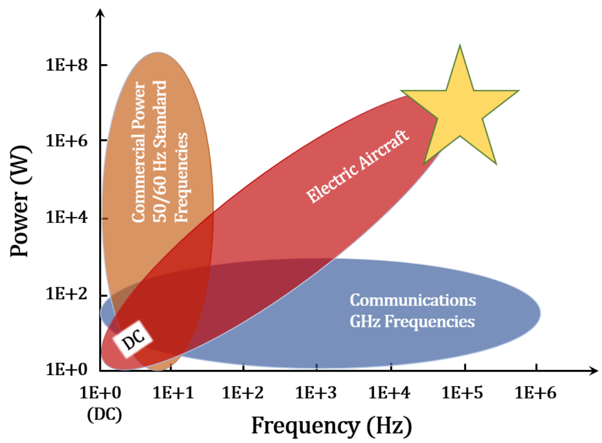


Fig. 1. Power and frequency combination in electric aircraft [17].

electric cars, this option cannot satisfy the power requirements of the MEA/AEA because of the much higher power need. In terms of insulation systems, the harsh environmental conditions that an aircraft undergoes introduce many challenges to the design of insulation systems.

Electric ships, on the other hand, have more similarities with electric aircraft in terms of electrical equipment design. Even the standards developed for electric ships are, sometimes, used in the design of electric aircraft. However, major differences exist between the power requirements and environmental conditions of these transportation systems. In terms of power requirements, MEA demands stricter design criteria; for instance, the mid-term goal of electric ships for the power density of generator and propulsion motor is less than 2 and 1 kW/kg, respectively [15]. On the other hand, the target for the power density of electric machinery in MEA is more than 10 kW/kg [16]. Besides, the insulation in these two systems undergoes different challenges that demand different remedy actions. In naval applications, for example, the pressure level does not change significantly; however, the tracking due to salt deposition and humid environment is a severe challenge. On the other hand, in aeronautical applications, the pressure varies over a wide range, and the resistance of insulation against PD falls dramatically at low pressures. Also, due to the higher power density, the operating voltage in electric aircraft needs to be higher than conventional systems that impose more tension on the design of cables and wires.

NASA estimates that the future electric aircraft would need to distribute 10–20 MW of power having an ac, three-phase voltage with variable frequency (400 Hz–4 kHz). The maximum voltage is estimated to be 20 kV, and the insulation system must be able to withstand up to ~41 kV [17]. The combination of high-frequency and high-power applications in high-altitude environments makes the design a complex and difficult process that is not compatible with conventional terrestrial insulation system designs (see Fig. 1). According to [18], the PD inception voltage (PDIV) is directly proportional to the pressure ($U_{\text{inc}} \propto p(1 + \alpha/\sqrt{p})$). This means that, at high altitudes where the pressure drops, the resistivity of insulation to PD also drops. The insulation should not only be suitable for low-pressure conditions but also needs to withstand a wide range of pressure levels that an aircraft might undergo during ascent/descent. Also, at high altitudes, high voltage leads to different insulation aging patterns compared to terrestrial applications, usually at an accelerated rate due to the different environmental conditions, such as low-pressure [19]. The crucial parameters in the design of insulation systems in electric aircraft include dielectric breakdown, thermal conductivity, and mass/volume [19].

NASA also adopted a dc network for the design of the N3-X conceptual aircraft, which is based on turboelectric distributed propulsion. In this design, a high-temperature superconducting (HTS) dc network is introduced as the feasible option [20]. DC networks are more favorable as they impose lower losses than ac architecture. If one can develop dc machines for operating at higher voltages, even more mass savings could be achieved. Based on a NASA study performed to design a turboelectric system in which the rotating machines are all made of superconducting material and all components operate in a cryogenic environment, it is expected that converters contribute to more than 50% of the system's mass. Therefore, if high-voltage dc machines with high-speed commutators could be developed, a significant mass reduction could be achieved through the removal of ac/dc and dc/ac converters. However, at higher voltages, it would be much harder to prevent electrical arcs from occurring between commutator sections [10].

The technologies for the electric power system in MEA are reviewed in [21]–[23]. In this study, the authors target the insulation system as a key element in every electrical equipment. Some of the major factors in the premature failure of electrical insulation are partial discharges (PDs) and poor thermal management [11]. PDs are local discharges that do not completely bridge between the electrodes but cause progressive aging of the insulating material, also known as "silent killers" [24]. Paschen curves have long been used to guide the design of insulation systems and demonstrate the variation of electrical breakdown with pressure and/or gap distance. However, Paschen curves cannot solely address all the challenges, such as those associated with low-pressure environments, as these curves are usually derived based on homogeneous electric fields and are limited to dc voltage or 400-Hz ac voltage [25].

The PD turns into a major issue in the electric aviation industry as its likelihood increases by three main factors: 1) the higher operating voltage that is required to achieve high specific power; 2) the fast-rise, high-frequency voltage pulses generated by wide bandgap (WBG) power converters; and 3) the harsh environmental conditions (e.g., pressure and humidity) that weaken the insulation resistance to PD. In the rest of this article, these factors will be discussed in detail.

Cryogenic systems provide the opportunity to benefit from HTS cables and transmit electric power with nearly zero losses at high current density (up to 100 times higher than conventional cables) [26]. Although it can be generally stated that cryogenic systems can provide a more PD-resistant environment, the long-term reliability of these systems is still poorly addressed [27]. Many terrestrial insulating materials show different (and sometimes weaker) insulating properties at cryogenic temperatures. For instance, pure polymers offer lower mechanical and thermal strength at low temperatures. Also, the formation of bubbles due to operation at the quenching state can significantly reduce the dielectric's expected lifetime [28]. Another great opportunity is to use superconducting technology for the design of the electric machine. Although the research in this area has not led to a commercial application yet, the very high current density that can be produced by superconducting machines motivates further research in this field.

The components in the scope of this article are listed in Table I. The motivations of studying insulation systems for each equipment/technology are brought, and the research problems are highlighted.

The rest of this article is organized as follows. In Section II, the challenges associated with the insulation system in MEA/AEA are reviewed. The state-of-the-art electric machines and the potential candidates for their replacement are discussed in Section III. In this section, the various pathways to approach the desired power density for electric machines are discussed, and challenges are highlighted. In Section IV, the challenges associated with the cables in terms of discharges, thermal stress, and environmental conditions are discussed, and the potential candidates with superior dielectric properties are introduced and analyzed. The challenges associated with the insulation design of printed circuit boards (PCBs) and power converters are discussed in terms of internal discharges, surface discharges, corona, and thermoelectrical stresses in Section V. In Section VI, the idea of using superconducting equipment (such as cables and electric machines) is evaluated with addressing the challenges and future needs. The current standards and the gaps requiring the development of standards along with the testing considerations are discussed in Section VII. The final remarks are made in Section VIII.

II. Overview of Insulation System Challenges in MEA/AEA

NASA has proposed a minimum of 6 kV for the voltage level for the N3-X design [29]. A power system sizing study on a 2.6-MW single-aisle turboelectric aircraft design showed that 1.4 tons of cable conductor mass can be saved when elevating the voltage level from 540 V to 4.8 kV [30]. As the operating voltage of an electrical system increases, accelerated aging of the insulation system due to PDs becomes a much more severe issue. Discharges can occur at the surface (tracking) or inside the voids and protrusions of dielectric material; it can also occur in the gases where the inhomogeneous electric field is sufficiently high. Factors affecting PD characteristics in gaseous environments are gas pressure and composition, type, magnitude, frequency, the rise time of the applied voltage, electrode configuration and geometry, and conditions and properties of insulating material [24]. Employing WBG technology in power converters can impose high-frequency, fast-rise voltage pulses that can accelerate aging due to PDs. Employment of WBG-based devices using superconducting machines in a cryogenic environment and developing dc and ac breakers with lower power density are among the promising solutions that have been paid attention to in recent years.

Since thicker insulating layers are not favorable due to limitations on the system mass, developing materials with higher dielectric strength seems necessary; however, the industry has not sufficiently progressed in terms of developing materials with high dielectrics suitable for high-altitude conditions [31]. As a first approximation, Paschen's law gives the breakdown voltage (V_b) between two electrodes in gas, forming a uniform electric field as a function of the product of the gas pressure (p) and the gap length (d), $V_b = f(pd)$. The breakdown voltage goes through a minimum value $(V)_{b\,\min}$ at a particular value of the product $(pd)_{\min}$; for air, the experimental values are, $V_{b\,\min} = 320$–352 V_{pk} [32]–[36]. This means that no breakdown is possible in the air gap for an applied voltage of less than 320 V_{pk} (226 V_{rms}). However, moving to higher voltages, such as 230 V_{rms} and 540 V_{dc} for Boeing commercial aircraft and 1–3 kV for NASA's EAP designs, brings an increased risk of PD. Furthermore, to have the same V_b at an altitude of 40 000 ft with an approximate pressure of 18 750 Pa (p_1) at a temperature of 23 °C, compared to ground level with a pressure of approximately 100 000 Pa (p_2) at a temperature of 23 °C, the gap length should increase to $p_1 d_1 = p_2 d_2 \Rightarrow d_1 = 5.34 d_2$. In [37], a sphere-sphere electrode system is used to examine internal discharges under partial vacuum conditions. It was shown through the finite-element analysis (FEA) that microvoids that do not lead to PDs at sea level can be a source of harm at higher altitudes. Besides, the intensity of discharges increases under low-pressure conditions. From the above results, one can easily infer that high-altitude applications need specific PD testing and standards to ensure reliable operation of the MEA/AEA power system.

The insulation system challenges for the electrification of the aviation industry are not limited to higher voltage levels. The harsh environmental conditions that commercial aircraft undergo can also escalate the electrical tension on insulation systems. The challenges of an insulation system at high altitudes include low pressure, microgravity, and plasma radiation [38]. Furthermore, the medium that the insulation system works in has a substantial impact on the characteristics of aging mechanisms, such as PD occurrence. Okubo *et al.* [39] measured the PDIV in He, Ar, and air in a vacuum and under nonuniform dc electric field distribution. Using an image processing technique, they classified the discharge profiles and concluded that the critical value of E_i/p is independent of the nonuniformity of the electric field and relies on the type of gas.

Note that the insulation performance under dc voltage differs from that under ac voltage. In [40], the PDIV under these two types of applied voltage is compared. The results indicate that, depending on the operating temperature, the PDIV in these two cases can be almost similar (at full load), or the PDIV under dc voltage can considerably larger than ac voltage at room temperature. In [41], the breakdown voltage of nitrogen gas under partial vacuum was evaluated when a square wave voltage with a frequency ranging from 50 to 200 kHz (rise time < 25 ns) was applied. Fig. 2 shows a constant decrease in the breakdown as frequency increases. Also, the

TABLE I
MOTIVATIONS AND RESEARCH GAPS FOR THE COMPONENTS/TECHNOLOGIES IN THE SCOPE OF THIS ARTICLE

	Motivations	Research Problems
Electric Machine	- Wide range of applications in MEA/AEA (Generators, motors, drives, actuators) - The profound impact on the power density of the entire system	- Design of machines with the targeted power density - Design of winding insulation at high altitudes - Thermal issues of insulation systems
Cable	- Design of a more reliable power transmission system - Reduction in the weight of cables	- Overvoltage at cable terminations - Tracking at the surface of the insulation - Design of insulation system that suits high-altitudes - Evaluating the performance of proposed candidates
PCBs and Power Converters	- The great potential of converters for power density enhancement - The utmost importance of PCBs in the reliable operation of actuators	- Mitigation of potential damage by WBG-based converters - Preventing the *in-situ* discharges in encapsulating material - Preventing tracking and surface flashover - Managing thermo-electrical stresses in the power modules
Superconducting Equipment	- The ability of superconducting equipment to offer very high current magnitudes - The potential to have a lightweight machine and PD-free insulation systems	- Design of feasible superconducting machinery - Developing a reliable, cost-efficient cryogenic system - Developing circuit-breakers to interrupt very high currents - The long-term reliability and lifetime

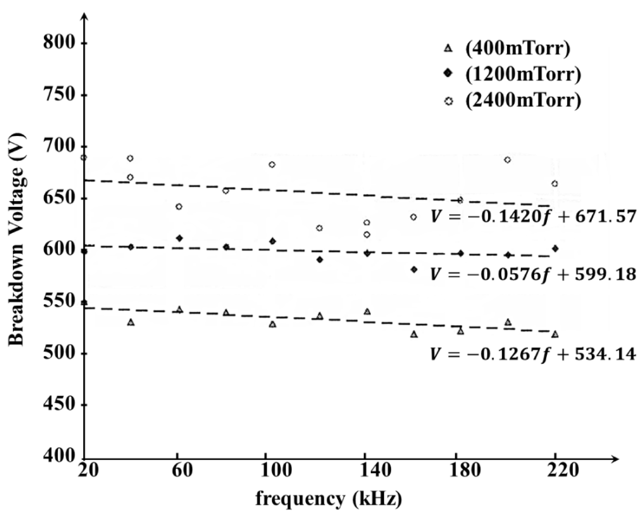


Fig. 2. Impact of frequency on the breakdown voltage (linear fit) [41].

lowest pressure introduces the lowest breakdown strength, among others. Compared to helium gas, the decreased rate in breakdown voltage in nitrogen is much slower [42], [25]. Also, in [43], it is reported that the electrical breakdown of oil at 60 Hz for a gap distance of 2.5 mm is 17 kV/mm, which decreases almost to half of this magnitude when operating at 90 kHz. In a more recent study, the breakdown of mineral oil is investigated for the Rogowski profile electrodes [44]; this study shows that, at a frequency range of 100–140 kHz, the breakdown voltage for a 2.5-mm gap is ~20 kV, which is ~36 kV lower than the breakdown voltage at 50 Hz with the same gap distance. Mason [45] show that the decline in the electric breakdown of air starts at a frequency of 300 kHz for gap distances longer than 2 mm, and in the range of MHz, the breakdown voltage is about 20% lower than that at 50 Hz frequency for a 5-mm gap.

In [42], the electrical breakdown of helium gas at 20 kHz under partial vacuum was assessed when undergoing an inhomogeneous electric field. Note that the pressure under consideration is under 500 Pa, and the gap distance is 1 cm. Therefore, it locates on the left-hand side of the Paschen curve minimum, and the lower the pressure is, the higher the breakdown voltage will be. It is inferred that the current magnitude has a direct relationship with gas pressure. On the other hand, the optical light emission inversely changes with the pressure increase.

Moreover, the fast-rise, high-frequency pulsewidth modulation (PWM) pulses generated by WBG-based power converters are another potential threat to insulation systems. In [46]–[55], the detrimental impacts of applied voltage characteristics, such as rise time, amplitude, frequency, and cavity properties, were presented and discussed. In [56], a series of studies were conducted on various types of dielectrics (polytetrafluoroethylene (PTFE), polypropylene, and paper) for capacitors at high frequencies. The results showed that, at a frequency of 90 kHz, the breakdown voltage is 25%–50% lower than the dc breakdown voltage.

To improve the thermal conductivity of polymer insulation, the incorporation of conductive fillers has been proposed [11]. However, this compromises the dielectric strength and flexibility of polymers. Besides, with the existence of conductive fillers, the charge build-up and interfacial polarization would be more probable [11]. Polyphenylsulfone with added boron nitride (PPSU-BN) composite ribbon has a thermal conductivity five times higher than neat polymer and 16% improvement in dielectric strength [11].

In an aircraft, wires are stressed by different factors, including environmental conditions, such as changes in temperature, pressure, and moisture, and vibration and chafing [57]. Outgassing has also been enumerated as an influential factor in electric breakdown [58]. The impact of these factors should be assessed on the aging mechanisms. One of these mechanisms is arc tracking, which occurs when an arc initiates between

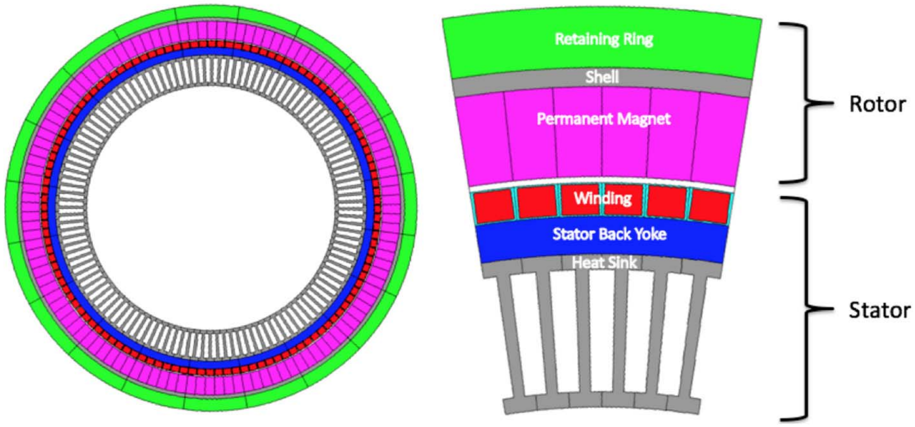


Fig. 3. Axial view of the PM motor proposed by Haran's group [70].

two or more wires and sustains through a conductive path, deteriorating the insulation through the bombardment of the defect with electrons and, ultimately, resulting in chemical transformation and formation of carbonized conducting paths [59]. Since this phenomenon can lead to inflammation and intoxication, it is crucial to consider the safety and reliability issues in the aircraft design associated with wiring [59]. The severe stochastic nature of arc tracking has been an obstacle to defining this failure mechanism and classifying its various types [59]. In this phenomenon, large leakage currents on a wet insulation surface can vaporize the moisture and lead to the formation of dry spots. The voltage across this dry region results in the occurrence of small surface discharges producing highly localized temperatures on the order of 1000 °C. High temperature causes thermal degradation of the insulation material used and, in the case of PI, forms a conductive carbon path [60].

In the following, arc tracking characteristics in various materials are examined. The insulation system's challenges and solutions for various equipment used within the electrical system of MEA/AEA are also reviewed.

III. Electric Machines

In MEA/AEA, the application of electric machines spans from generators to electric drives and electromechanical actuators (EMAs). While enhancing the specific power is the main goal of all these efforts, it is also crucial to ensure the safety and reliability of these machines. Key enabling technology for the turboelectric propulsion system highlighted by NASA is the development of electric motors with quadrupled power density compared to the state-of-the-art motors [61]. In this regard, there have been several efforts that will be discussed later. Also, throughout electrification, hydraulic actuators are envisaged to be replaced with EMAs in which an electric motor substitutes the control knob or handle. EMAs provide more flexibility and are less intricate. An advanced fault diagnosis and recovery system are crucial for EMAs as it can reduce the cost and weight associated with redundancy [62]. To make EMAs viable versus hydraulic actuators, the motor's torque density must increase. The torque density can be improved through higher winding currents, but this might endanger the reliability of the machine by thermally overloading it [63]. According to [64], the insulation lifetime is cut in half for every 8 °C–10 °C temperature increase [64]. Madonna *et al.* [63] and Madonna *et al.* [65] experimentally explored the thermal aging of low-voltage random wound coils in a permanent magnet (PM) synchronous machine (PMSM) with a low duty cycle. Using the proposed model and tests, turn-to-turn insulation was determined to be the weakest part of the insulation, and for every 7 °C of temperature rise, insulation lifetime was reduced by 50%. Motors in EMAs suffer from insulation deterioration and wire chafing (manifests itself via reduced or intermittent current through stator coil or intermittent shorts) [62].

A. Types of Machines

So far, wound-field synchronous generators (WFSGs) have been the main choice in commercial aircraft. However, the advances in power electronics have made PM and switched reluctance (SR) machines competitors for WFSGs [66].

The features of WGSGs, such as direct control of field options and the small number of components, have been incentives compared to other candidates. WFSG operates at a lower speed range and, generally, has a lower efficiency than PM and SR generators. The most recent and efficient design of WFSG was performed by Honeywell that could achieve a power density of 7.9 kW/kg [67]. On the other hand, the PM machine has received significant popularity over the previous years due to its higher power density and efficiency.

To date, NASA's efforts toward the development of electric motors for MEA has led to two proposed motors: 1) a 1.46-MW motor proposed by an internal NASA research team, which achieves a power density of 16 kW/kg and 2) an ~1-MW motor proposed by a NASA-funded external team that achieves more than 13 kW/kg of power density and 96% efficiency for enabling hybrid-electric aircraft propulsion. Both teams proposed Litz wire for the machines with form-wound winding type [68]. A Litz wire is comprised of bundles of thousands of very fine wires that are twisted; therefore, the very thin insulated wires are minimally impacted by skin

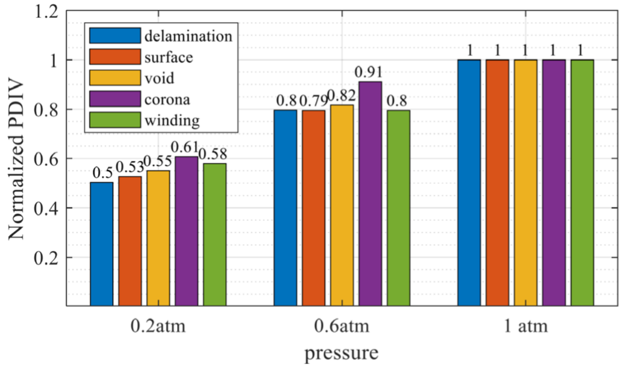


Fig. 4. Normalized PDIV variation with pressure for stator winding in form-wound machines (room temperature) [71].

effect, and losses are reduced due to decreased eddy currents [68]. The development and design details of this winding presented in [69] consider electric losses, dielectric capabilities, heat dissipation, and mechanical forces. PI, Nomex, and Glass Fiber were used and designed to insulate the strands, the bundles, and the turns with a breakdown voltage of more than 3 kV.

The 1-MW PMSM designed by the external NASA team has: 1) thinner stator and rotor yoke due to higher pole numbers; 2) air-gap winding that removes the need for stator teeth; and 3) Halbach arrays that eliminate rotor back yoke. These factors help reduce the heavy iron alloy in the machine's structure and increase the power density (see Fig. 3). Moreover, Litz wire enables the machine to operate at higher speeds (ratio of frequency to the number of poles) to increase the power output [70].

Wang *et al.* [71] probed the PD characteristics of the stator winding in a form-wound electric machine for electric aircraft propulsion. Similar to earlier studies, it was reported that PDIV drastically declines with pressure reduction (see Fig. 4), and PD magnitude tends to increase. To achieve a PD-free stator winding, the authors further optimized the design using a genetic algorithm [72]. It should be noted that the design is PD free against sinusoidal voltage. Therefore, further developments are necessary when the motor is energized by a PWM waveform. The FEA and experimental tests were coupled to assess PD criterion due to voids and delamination. In [68], FEM was employed to ensure the reliable operation of insulation between phases in the stator slot and between the conductor and back iron.

B. Stator Structure

Typically, the stator slots in an electric machine house the conductors. These conductors are surrounded by insulating materials that prevent a short circuit between adjacent conductors. Also, potting materials are utilized to reduce the vibration of wires. In a machine, the majority of faults stem from the failure of either stator or rotor winding. Therefore, high-quality design of winding structure and insulation can play a pivotal role in the reliability of motors [14]. The stator insulation failure is a gradual process and begins with the degradation of turn-turn insulation. As the degradation process continues, it further extends to phase–phase and phase–ground insulations. Among the two types of winding structures (random wound and form wound), form wound is preferable as, in its design, each coil turn is wound in a way that the smallest voltage difference occurs between two adjacent turns and the insulation undergoes less electrical tension [14]. However, the threat of PD occurrence goes up as the voltage level and frequency increase, and the environmental conditions lower the dielectric strength. An efficient monitoring system is, therefore, necessary to detect any alteration of the insulation state. This provides the chance to take action for diagnosing any fault and plan for mitigating strategies before the ultimate breakdown of insulation [14].

In the designs proposed by both NASA teams, Litz wires that constitute twisted bundles of wires are used in the form wound. This type of wire offers higher power densities through a reduction in eddy current losses [68]. Fig. 5 demonstrates a fully epoxy impregnated Litz wire with five bundles. In these bundles, each individual wire is insulated by epoxy.

C. Design Aspects and Limitations

The general considerations regarding the design, testing, and monitoring of the performance of electric machines have been extensively studied in [73]. PD tests performed in [74] showed that this phenomenon drastically degrades the insulation of the twisted pairs of winding coils at low pressure. This conveys the fact that there is no guarantee that the magnet wires, which can properly operate at sea level, operate flawlessly at higher altitudes. In [75], it was shown that PD occurs at a much lower voltage and was several times more severe under partial vacuum than at sea level. In this regard, an experimental study was performed to assess the impact of voltage, pressure, and temperature on the PD behavior of different types of machine winding insulation in a more-electric engine (MEE) concept [76], [77]. Fang *et al.* [76] examined the PD phenomenon for PI film (Kapton FCR) insulated twisted pair winding wires. In this study, when applying a 50-/60-Hz sine voltage, PDIV showed a linear relationship with pressure. The PDIV value has dropped by 50% for all samples when pressure decreased from 1000 to 100 mbar. The performance of ceramic, mica, and composites (made of organic and inorganic materials) as insulating materials for high conductivity windings made of nickel-plated copper was also examined. When applying a 50-Hz sine voltage, ceramic showed the worst performance among the others by having a global breakdown voltage of 234.1 V before and 233.3 V after thermal aging. On the other hand, mica showed the best performance in terms of breakdown voltage (648.4 and 502.7 V before and after thermal aging, respectively), and PDIV was only observed after thermal aging at a voltage magnitude of 430 V. This shows that the lifetime of PI films with varying temperatures and pressure seems to increase as the dissipated energy decreases [78].

In [79], the PD characteristics of a twisted pair of insulated conductors were investigated using FEA and visual tests under low-pressure conditions. In a twisted pair of conductors with circular cross sections, the spots at which the two insulated conductors meet are of the highest electric field intensity.

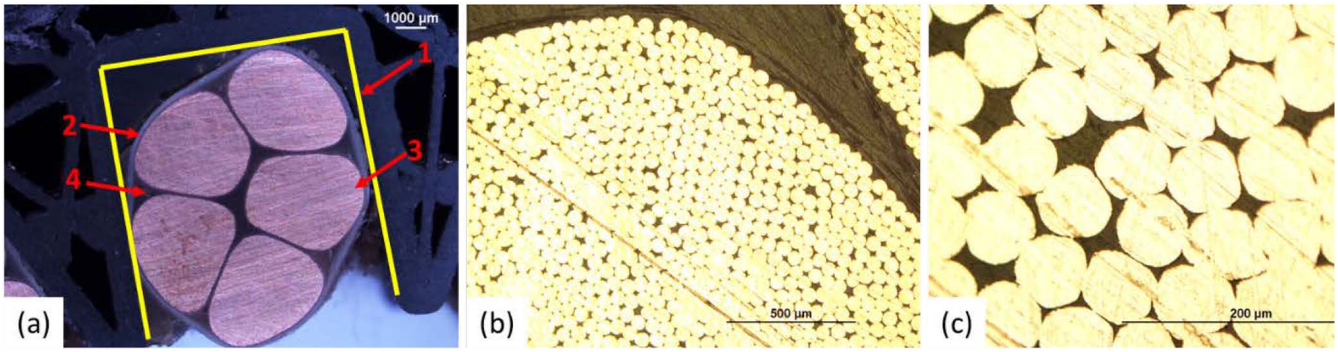


Fig. 5. Optical image of a Litz wire with five bundles. (a) Entire wire (1: slot edge; 2: HV insulating material; 3: bundle of very fine wires; and 4: potting material). (b) Impregnated bundle. (3) Individual wires in a bundle [68].

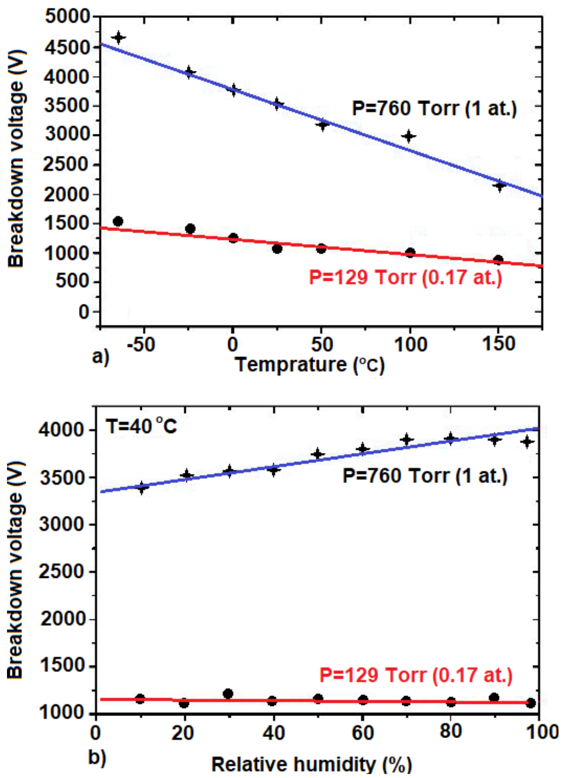


Fig. 6. Impact of (a) temperature and (b) relative humidity variations on the breakdown voltage [80].

At low pressures, the electron avalanche takes longer to occur since the electron mean free path is longer. Due to the longer electron travel duration, at low pressures, mostly single peak transient discharges were observed [79].

The influence of environmental conditions, including temperature from −60 °C to +180 °C, pressure from atmospheric to 125 mbar, and relative humidity ranging from nearly zero to 100% on the breakdown voltage of an air gap between two spherical electrodes, was studied [80]. It was found that the greatest electric stress conditions are low pressure and high temperature, as shown in Fig. 6. Also, in [81] and [82], the investigation of PD characteristics in a pressure range of 2–7 Torr under a 60-Hz ac voltage for a twisted pair of insulated conductors in air, argon, and helium showed longer PD duration in low-pressure air than those at the sea level. The research focus in [74] and [75] was on PD testing of cables located in various configurations in a low-pressure aerospace environment where the lack of standards for test methods was highlighted. In [83], the impact of ambient humidity on the PDIV in magnet wire (Type I motor) imposed by pulsed voltage was investigated. At a rise time of 0.5 μs, the PDIV decreases by 5% when humidity increases from 39% to 86%. Therefore, the impact of humidity, in this case, did not make a deep impact. However, condensation by 100% relative humidity considerably affects the PDIV.

Under low-pressure and harsh thermal, mechanical, and environmental conditions, operating at higher voltage levels leads to accelerated aging and failure of insulation systems. In [84], this technical gap is highlighted, and a preliminary method to specify safe clearances in aerospace systems was suggested. The impact of low-pressure conditions on PD patterns under sinusoidal and impulse waveforms was also experimentally investigated in [85] and [86].

Motors fed by fast-rise, high-frequency power electronics inverters have reliability issues. In [87], the increase in the overvoltage due to the use of silicon carbide (SiC) inverters enhanced the PD probability in Type II form-wound motors. Few studies have been conducted on the impact of fast-rise, high-frequency square wave voltages on insulation systems under harsh environmental conditions. In [88], the effects of fast, repetitive voltage pulses of 5–200 kHz at pressure levels of 20–100 kPa on the repetitive PDIV (RPDIV) of a solid insulation system (a twisted wire pair) are discussed; the most important finding in [88] is shown in Fig. 4. This figure reveals the peak-to-peak RPDIV as a function of supply frequency for three pressure levels (20, 65, and 100 kPa). Based on Fig. 7, RPDIV monotonically decreases with pressure at all frequencies. According to Paschen's law, the electrons' mean free path declines with pressure reduction. However, some researchers hold that Paschen's law is not appropriate to predict PDIV since the feedback from the electrodes (secondary electrons extracted from the cathode) is likely negligible, and streamer inception criteria should be used [89]. Also, at all pressure levels, RPDIV decreases with frequency until it nearly saturates at frequencies above 100 kHz and is a function of

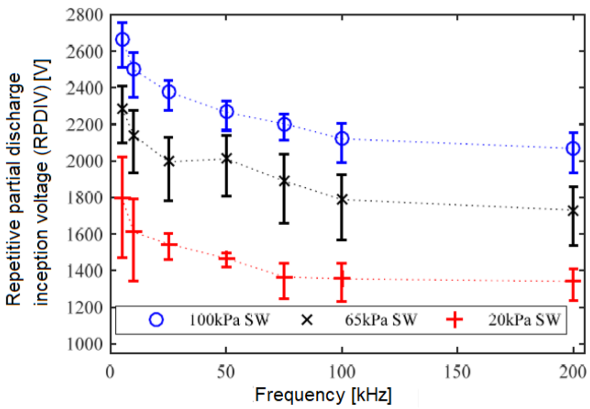


Fig. 7. RPDIV ($V_{\mathrm{pk-pk}}$) as a function of frequency and pressure [88].

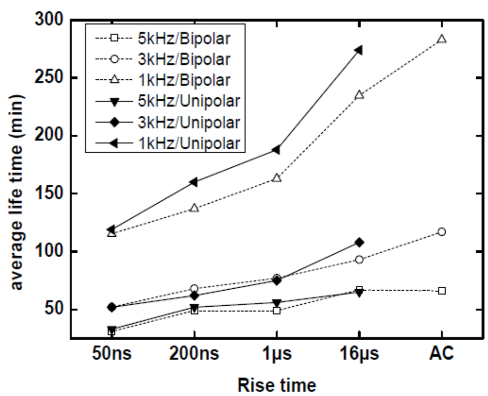


Fig. 8. Average lifetime of single-contact point crossed enameled wire pairs as a function of frequency and rise time [51].

pressure [88]. As another corroboration, Fig. 8 shows that, with increasing frequency, the average lifetime of single-contact point crossed enameled wire pairs in atmospheric pressure approaches a plateau [51]. An important point is that the critical frequency for internal PDs may decrease in a few tens of kHz with decreasing air pressure (close to 75 kHz at 20 kPa, as shown in Fig. 7), making this solution (increasing the switching frequency of power electronics above the critical frequency) feasible for aeronautical applications.

While electrical insulation must be lightweight to meet the power density requirement, it should also be thermally conductive to optimize the electric motor performance [90]. Thermal deterioration is the major cause of winding failure and usually, during the design phase, limits the machine's torque. Therefore, the handling of thermal issues plays a pivotal role in the efficiency and reliability of machines [91]. Materials with high thermal conductivity can enhance heat transfer in the system and decrease the hot spots [21]. It is specifically vital for end-windings since the operation at high temperatures provides the opportunity to bring the machines closer to the engine, which subsequently leads to reduce the system weight. In recent efforts, ceramic materials depicted a promising outlook due to their high thermal conductivity and high dielectric strength [92]. Polymer matrix composites (PMCs) have also been proposed as a potential material due to their lightweight, moldability, and high strength [90].

In the 1960s, a technique was introduced to the rotating machine industry to improve the quality of stator windings, called vacuum pressure impregnation (VPI) technology [93]. Through the VPI process, the windings of the stator core are filled with a fluid, such as resin, to obtain a void-free insulation system. The process of VPI can be performed through one of the mechanisms of: 1) flood filling; 2) closed tool within a vacuum chamber; or 3) vacuum sealed tool without a vacuum chamber. The details of each process are discussed in [94]. The VPI process requires significant considerations on aspects, such as the resin viscosity or flow path [95]. Also, the process is strongly dependent upon temperature; in a humid environment, the preheating of the winding and the resin can help to remove any bubbles or moisture. On the other hand, overheating of resin beyond the manufacturer's recommendations could potentially weaken the material properties. Therefore, it can be stated that the VPI process is useful only when it is performed at high quality; otherwise, it may damage the insulation tape, create wrinkles or sharp edges, cause delamination, or produce unwanted voids [96].

To conclude, electrical, thermal, mechanical, and ambient factors play major roles in the lifetime modeling of stator insulation. While evaluating the impact of each factor on the insulation health can provide insights into the mechanism behind these factors, the lifespan of the machine can only be discussed when the effect of an aggregation of the aging factors is studied. In this regard, a test rig is proposed in [14] which models the lifespan under various aging factors and the coupled stress factors. This test setup includes a thermal vacuum chamber, a WBG-based power inverter, an embedded brake system, and a data acquisition system.

IV. Cable

Cables are necessary to transmit power from one node to another. To make the MEA/AEA financially viable, it is important to reduce the weight of the power transmission system while keeping it as efficient as possible. The efficiency of a cable can be defined as

$$\eta = \frac{P_{\mathrm{Del}}}{P_{\mathrm{Del}} + P_{\mathrm{Loss}}} \tag{1}$$

where P_{Del} is the power delivered by the cable at its receiving end and P_{Loss} stands for the ohmic loss. To enhance the power transmission capability of a cable, one can increase either current or voltage. Increasing current demands heavier conductors, which adversely affects system mass and also increases voltage drop [97]–[99]. Therefore, the voltage level increment is the feasible option. A study performed by NASA showed that a maximum saving of mass occurs at a 6-kV voltage level presuming that the entire electrical system operates in a pressurized cryogen at a pressure level equal or above 1 atm [10].

However, one should bear in mind that the system mass and voltage level does not have a monotonic relationship [100]. On the other hand, a higher voltage level requires thicker insulation to prevent discharges. Thicker insulation also increases system weight (but is accepted over the current increase).

Therefore, it is of great significance to find workarounds, such as developing new dielectric materials to efficiently design cables.

A. Design Considerations

Although, in the range of frequencies generated by inverters, the cables with polymer- or rubber-based insulation do not usually show substantial changes over time, the cables' termination remains the most critical point in cables where surges' amplitude could be doubled, and the grading system might be affected by their frequency content [101]. An important issue arises when a WBG-based power converter is used; the PWM voltages, which have a high frequency and slew rate, can travel on cables. When a surge traveling on a cable faces an abrupt change in the characteristic impedance of the system, the surge impedance of the cables is approximately in the range of a few tens of ohms, while this quantity is hundreds of ohms for the machines. Due to the impedance mismatch, once these traveling pulses reach the motor's terminals, they reflect back to the converter causing overvoltage on the order of two to three times the dc bus voltage [102]. The reflection at the terminals is one of the main design challenges of the cables and wires. This can initiate the PDs that, in turn, accelerates the insulation aging process.

Hot spots created by high electric field magnitudes are located in the overlap area, which, subsequently, leads to temperature rise stress due to the power loss [103]. In [104], it is reported that frequency can further increase the temperature. When working at 10 kV, the temperature increase at 4 kHz is about 5.3 °C, while this is around 3.5 °C for 2-kHz frequency. Since a variable frequency ac synchronous generator is envisaged for many MEA/AEA electrical systems, the temperature variations at the terminal should be considered accordingly.

Moreover, with the thinness of wire insulation, which is in the range of micrometers, PDs can occur over the surface of wire insulations. Trees usually initiate from the protrusions on the surface. When the electric field is very high, the treeing initiates in these protrusions by the injection and extraction of electrons from the polymer matrix [103]. Note that only the insulating material properties influence the treeing phenomenon but also the characteristics of applied voltage affect it: 1) the higher magnitude of applied voltage decreases the lifespan by an inverse power law; 2) the higher frequency of applied voltage leads to more frequent trees; and 3) positive pulses have a more detrimental impact on the lifetime of the cable.

When a cable with polymeric insulation is exposed to humidity for a sufficiently long period, a tree-like (also in a bow-tie or human's hand shape) degradation path forms across the insulation. This degradation path called "water tree" has long been one of the major causes of failure in power cables. In an actual long power cable, the generation of water trees is localized according to the surrounding conditions [105]. It is well-established that the length of a water tree depends on the number of voltage zero-crossings [106]. The degradation by humid environments adds another factor to the improper choice of PI-insulated wires. According to [107], PI insulation is at a higher risk of degradation under humidity than polymers, such as PTFE.

When the cable is left unshielded in proximity to the ground plane (aircraft metallic structure), the characteristics of the cable can considerably change due to the electromagnetic interactions between the cable and the ground [108]. The lack of standards for this is discussed in Section VII. These uncertainties in cable characteristics (resistance, capacitance, and so on) can hinder the proper design of a cable and increase the mass.

In [109], the PDIVs of three coaxial cables were characterized in low/medium vacuum conditions in an argon and nitrogen environment. The test results were compared to the PDIV values derived from the Paschen curve with the aid of the cross section analysis of cables. Despite the assumption of an inhomogeneous electric field for the Paschen curve and its probable uncertainties due to differences in the electrode material, geometry, and gap length, good agreement was observed between the estimated PDIV and the measured one.

For a cable, a primary way to mitigate PD is by using field-grading materials in the conductor shield and insulation layer. Conventionally, the insulation material can be a single layer made of PTFE, ethylene tetrafluoroethylene (ETFE), PI, or even materials used in cross-linked polyethylene (XLPE) [110].

B. State-of-the-Art and New Technologies

PI has been considered as one of the main options for cable and wire insulation. Despite its promising thermal stability and dielectric properties, it suffers from moisture absorbance and potential electrical fires [111]. The state-of-the-art cable manufactured by GORE, which uses PTFE-PTFE composite insulation with 1.36-mm thickness, would normally have a breakdown voltage of 39 kV. However, when a PTFE jacket encloses the cable, the breakdown voltage drops to 29 kV [17].

Recently, a new technology called the micromultilayer multifunctional electrical insulation (MMEI) system was developed to meet the high-voltage, high-power, and high-temperature needs while decreasing the weight of insulation systems. Fig. 9 shows a typical design of the MMEI structure. The primary incentive for the development of MMEI was to achieve higher breakdown voltages. Moreover, the multi-functionality that MMEI structure brings is another merit; an MMEI structure has corona and moisture barriers, an EMI shield, heat dissipator layer, and mechanical strength [112].

A recent improvement has resulted in a 91% higher dielectric breakdown compared to Kapton PI insulation (see Fig. 10), which translates into an approximately 50% reduction in insulation thickness [112]. It also outperforms the commercially employed insulation systems, such as Teflon–Kapton–Teflon (TKT). For an insulation thickness of 0.38 mm, single layers of Kapton PI and PFA results in a breakdown voltage of 29 and 27 kV, respectively. On the other hand, the breakdown voltage of an MMEI with three layers (5∗KBF/5∗PFA/5∗KBF) and 19 layers ($[0.5{*}\mathrm{HPP}/1{*}\mathrm{PFA}\text{-}]_9$ /0.5∗HPP) would be 38 and 46 kV, respectively [113].

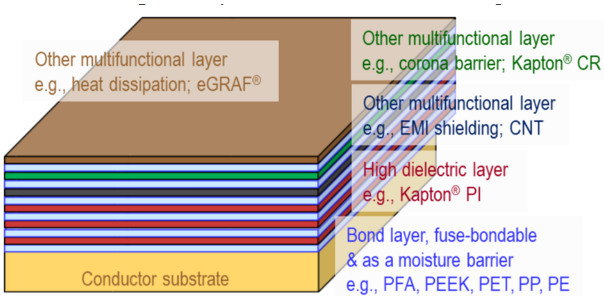


Fig. 9. Example of the MMEI structure [112].

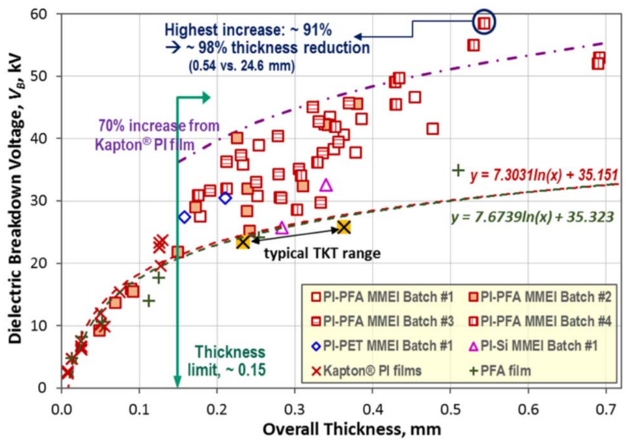


Fig. 10. Comparison of dielectric breakdown voltage for different state-of-the-art MMEI structures [112].

Investigations have shown that, to maximize improvement, the structure thickness should be at least 0.15 mm, while a greater number of thinner layers form the overall structure [114]. The applications of these systems can range from power cables and wiring to busbars and PCBs up to 40 kV [114]. Superior bonding quality is necessary for the performance of the MMEI structure. The bonding layer is fused by heat to reduce the number and size of voids. This helps to have higher PD resistivity. However, more research is required to optimize the configuration of the MMEI structure and guarantee a good quality of bonding.

Also, to enhance the safety and longevity of electrical insulation, self-healable insulating materials, such as PI siloxane and polyethylene-co-methacrylic acid (Surlyn), have been introduced [111]. There are significant challenges to overcome, such as the improvement of dielectric strength. For instance, Surlyn can potentially repair itself after a puncture at high velocity, but its average dielectric strength is more than 10% lower than that of PI [115], [116]. The self-healing property is most effective when the puncture causes a local melt [116]. Also, no healing is observed after thermal degradation, and healing after charring damage is limited [111].

V. Power Converters and PCBs

Power converters are inseparable parts of any architecture for aircraft electrical systems. There is great potential in the power density enhancement of power electronic devices due to the emergence of WBG semiconductors. WBG-based devices are advantageous due to their higher switching frequency and efficiency, higher blocking voltage, and smaller form factor. Therefore, they can enhance the aircraft actuator power density [117].

A. Internal Discharges

However, high-frequency and high-slew-rate surges generated by these devices endanger the reliable operation of their insulation system especially at high altitudes where the low-pressure condition weakens the breakdown strength even more. In [118], a drastic drop in the breakdown voltage of gases was reported at high frequencies (above 10 kHz). The breakdown voltage at high frequency can go as low as the dc breakdown voltage and, in some cases, even lower [41].

The two main applications of insulating materials in a power electronic module are: 1) to electrically insulate between active components and the grounded baseplate and 2) to encapsulate the power modules and prevent *in situ* discharges and protect the substrate, semiconductors, and connections. Ceramics are used for the former goal and silicone gel for the latter. Silicone gel is more prone to PDs due to its lower dielectric strength. In [37] and [119]–[121], an FEA model is proposed to model the PD phenomenon in silicone gel under low-pressure conditions based on experimental data. In [119], an IGBT module geometry was investigated to assess the impact of voids in silicone gel (encapsulating material). The results imply that true and apparent PD charge magnitudes at 0.5 atm drop to almost 50% of their initial values at 1 atm. A way to enhance the resistance to PD is through field mitigation at the most crucial parts of the module. In this regard, geometrical techniques, applying nonlinear field-dependent conductivity coatings and fillers, can be adopted [122]–[125].

In the case of working at cryogenic temperature, silicone gel would no longer be an option as its breakdown voltage significantly declines at temperatures below 215 K [126]. The fact that the change in breakdown voltage is irreversible makes silicone gel a completely improper choice for power modules that are going to work under cryogenic conditions [127]. On the other hand, many epoxy-based encapsulants can properly work at low temperatures.

PCBs are used to energize the electrical actuator systems. To slow down the electrical degradation of PCBs, conformal polymer coatings are applied. However, there is a concern about the performance of coatings at higher altitudes. A 58% decrease in the PDIV of silicone conformal coating applied to PCBs was reported when air pressure was decreased from 1000 (atmospheric pressure) to 116 mbar (equivalent to an altitude of 50 000 feet) [128], [129]. The influence of the type of coating materials and their thicknesses were also studied [128], [129]. It was shown that a conductive surface pollution layer with conductivities of 2,500 μS/cm or greater on silicone conformal coated boards provided a desirable breakdown route where the track separation (d) was comparable to the coating thickness (t) ($t \approx d$). This led to much lower breakdown voltages that than were expected between tracks through the bulk polymer coating [130]. The influence of temperature was also studied, and it was shown that damage to the silicone coatings occurred in the form of surface cracks, which accelerated at high temperatures (+70 °C), low air pressure (116 mbar), and for coating thicknesses less than 100 μm [131], [132]. Including internal and corona discharge criterion based on Paschen law, a preliminary methodology was developed to obtain the optimal ac or dc operating voltage of unscreened insulated wires within an aircraft, leading to a maximum power transfer-to-weight ratio within a fixed volume system, such as a cylindrical duct [32], [33], [133].

B. Surface Discharges

In the interface of solid/liquid dielectrics with a gaseous medium, there is a possibility of PD on the surface of the dielectric. When there is contamination on the surface of a dielectric, the leakage current can flow over the surface along a path with more contamination (which has higher conductivity) [134]. This phenomenon is known as "arc tracking." The contamination can be in various types, such as dust, salt, or cellulose fiber deposits. Moisture has also been known as a factor that can lead to wet arc tracking. During the ascents and descents of an aircraft, the rapid pressure variations can result in condensation. Tests have shown that aging has a significant impact on arc tracking, making them more vulnerable to the reignition of arcs compared to newer cables [135].

Tracking occurs when a high tangential electric field exists along with the interface between the gaseous phase and solid insulation. The process strongly depends on the material properties. However, the existence of contamination (conducting film) is necessary to have a creepage current flow through it [136]. The current magnitude is directly related to the extent of the contamination. Besides, the current flowing through the surface of dielectric produces heating causes a dried region over the surface on which the arc occurs. Therefore, for the tracking to happen, the availability of a wet and contaminated medium is required.

The tracking phenomenon is inherently a nonlinear process with high uncertainty levels. Despite the long history of work performed on arc tracking, modeling of this phenomenon is not a trivial task, and major progress is still needed to ensure reliable operation of insulation systems under harsh environmental and electrical conditions of an aircraft. In [134], two nonlinear methods (fractal dimension and recurrence plots) were proposed to model the tracking failure at low pressures. At low pressure, the fractal dimension of the tracking pattern declined, while the recurrence plot of discharge current indicators went up. Thus, the two methods correlated with the mechanism behind the tracking and the surface morphology.

First, one should know that the bulk and surface insulation of material is quite different. The dielectric strength of the surface is affected by its shape, roughness, residual stress, resistivity, and many other parameters [137]. At high altitudes, new challenges, such as spatial contamination and space plasmas, are introduced [138].

In wires, if part of the insulation material is removed by either accident or aging, arcing can initiate from this region. Also, if the current is high enough, this would lead to an arc. If an arc intensity is high enough, it can also carbonize the other wires as in the case of bundled wires. Therefore, the damage can extend to the entire bundle and disrupt the operation [57].

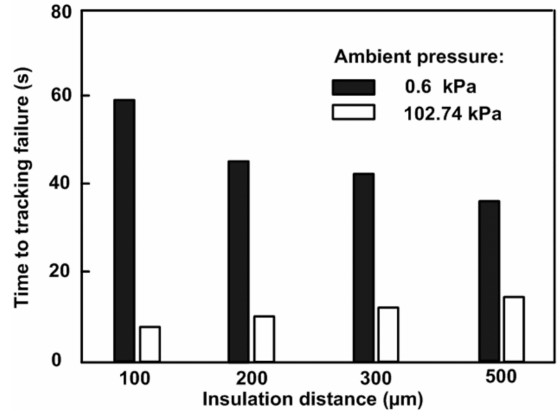


Fig. 11. Tracking failure time versus different insulation distances and different pressures [134].

Arc tracking behavior is strongly dependent upon the type of applied voltage, environmental conditions, and the conductor and dielectric materials [59]. The difference between ac and dc is at the extinguishing criterion. For the ac voltage, an arc may be extinguished at each current zero; however, when the arc is stabilized under the dc voltage, only protection devices can quench the arc [59]. Organic insulating materials, such as pure polymeric insulation, are usually more prone to arc tracking, and the addition of nanocomposite fillers has been reported to enhance the resistance of polymeric insulation [139], [140]. The surface treatment is also employed as an efficient way to improve the resistance of polymers against arc tracking [57].

In [141], the impact of low-pressure conditions was investigated on PCBs when a train of voltage pulses was applied. In contradiction to other studies, the results of this study showed enhanced endurance of PCB to tracking under low-pressure conditions although the cumulative charge increased. The high oxygen content can lead to a quicker occurrence of tracking failure [141]. In [141], it was claimed that, since, at high altitudes, the supply of oxygen is lower, pressure has little effect on time-to-failure, and temperature dominates the occurrence of tracking with little effect by cumulative charge. Fig. 11 shows the variation of tracking time to failure with pressure and insulation distance.

The impact of vacuum conditions on arc occurrence in space applications was assessed in [142]. The behavior of the arc is dominantly attributed to the type of material, cable design, and environmental conditions. In this work, it was shown that the consequences of arc propagation were more severe under vacuum conditions, and in some cases, vacuum conditions imposed the worst case scenario [143]. On the other hand, the ambient temperature was less significant since the arc temperature itself is an extremely high temperature (>400 °C) [59], [144].

As mentioned earlier, arcs are accompanied by high-temperature rise, which can adversely impact the chemical bonds of the material. This can be followed by carbonization, graphitization, or the release of gases. All these consequences can severely damage the insulation and ultimately lead to complete failure of the wiring [59].

In [145], the impact of microgravity (μg $<$ 0.04 g) was investigated on the arc characteristics. The findings show that, in any kind of arc, the damage degree would increase under microgravity conditions. The reason for this is that, under normal conditions, the overheated cables cool down with the aid of heat convection processes, but, under microgravity conditions, heated air molecules remain inert; therefore, the heat cannot be cooled down efficiently resulting in more severe damage.

The arc pattern in ETFE and PI insulated cables are different. For ETFE, the arc duration is short, extinguishes by itself, and does not reappear after reapplying the stress. On the other hand, for PI, the arc reignites after reapplying the voltage, which can lead to a stronger arc [142]. According to [142], the mean arc propagation velocity was almost independent of environmental conditions; however, environmental conditions can have an impact on the severity of arcs (damages to conductor and insulation).

Surface flashover is often one of the limiting factors of high-voltage systems, which occurs when the electric field exceeds an inception value and triggers the emission of electrons from the triple-junction (interface of cathode, insulator, and vacuum) [146], [147]. After the initiation stage comes the growth stage where there are many debates on the mechanisms of discharge development. In the final stage, surface flashover terminates through plasma breakdown in the desorbed surface gas [148].

The dielectric surface condition plays an important role in the surface flashover voltage [149], [150]. In [137], the bottlenecks in surface flashover investigations in vacuum were discussed, and the main contributing factors were divided into three aspects: electrode–dielectric interface, dielectric surface, and other external factors. To modify the surface, one can perform sanding, coating, fluorination/oxidation, electron beam irradiation, and so on [151]. Also, the surface flashover can be increased through the elongation of insulator surface distance.

Similar to the tracking phenomenon, the voltage waveform can significantly affect the surface flashover [152], [153]. The duration of surface flashover at 20 kHz is longer than the dc flashover [154]. Temperature is another factor that can potentially influence surface flashover [155], [156].

Kirkici *et al.* [154] report the experimental results of epoxy resin surface flashover in nitrogen under partial vacuum. They used the optical method employing a video camera and a photomultiplier tube. Similar to [149], light emission was observed before the collapse of voltage across the gap and flow of the flashover current in the case of the ac voltage. Therefore, compared to the electrical method, the optical method is advantageous in terms of detection speed. However, under dc voltage, this seems not to be valid, and the transient current coincides with the light emission [154].

Al-Taie *et al.* [157] tested the surface flashover in a gaseous helium (GHe) environment. It was demonstrated that temperature does not affect the dielectric breakdown of GHe and its interaction with a solid dielectric. However, the mass density (the thermophysical property merging temperature and pressure) is impactful on the breakdown strength of GHe [157]. Assuming the operation of the system at a temperature of 77 K, the dependence of the surface flashover strength on the pressure of GHe is shown in Fig. 12.

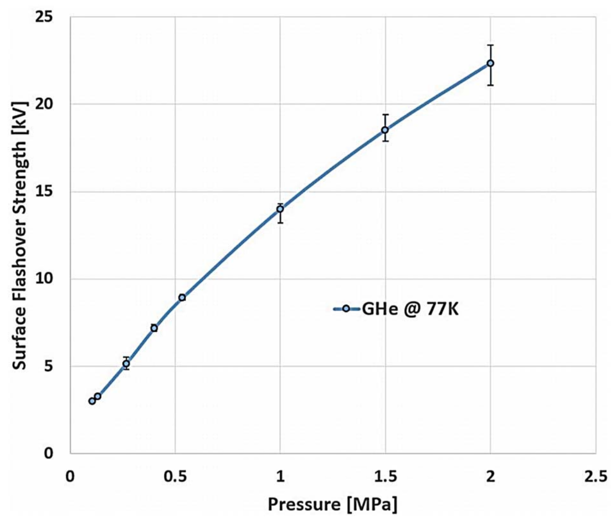


Fig. 12. Surface flashover voltage measurement on PTFE in the GHe environment at 77 K [157].

Two ways to improve surface flashover are to: 1) optimize the electric field distribution through insulation design (especially at the triple-junction) and 2) material surface modification [151].

The use of inorganic fillers to enhance the resistance against tracking and erosion has been considered an effective method. In [158], to improve the resistance of the silicon rubber surface against tracking, its surface is fluorinated by F_2/N_2 mixture. Then, the increased hydrophobicity leads to higher surface flashover voltage. In [154], by casting epoxy resin with nano/micro Al_2O_3 powder, the surface flashover voltage could be enhanced by up to 20% for both dc and ac voltages. To further improve the surface condition of the composite, plasma etching can be used. In [154], after only 2 h of plasma etching, a 10%–20% improvement was observed in the flashover voltage. Moreover, the contact angles of the material surface can greatly influence the flashover performance [151]. Researchers have agreed that, in a vacuum, a 45° contact angle can provide optimal flashover performance [159].

As the trap parameters of dielectric material have a profound impact on surface flashover, the modification of the crystallization behavior of a polymeric matrix can improve the trap parameters and, thus, enhance the surface flashover voltage, especially in low-pressure environments. In [160], the crystallization of low-density polyethylene (LDPE) is modified by phenolphthalein, and this enhances impulse and dc flashover voltages by about 31% and 48%, respectively.

C. Corona

Corona has been recognized as an important aging factor of circuit boards. The ozone that is formed during corona discharge can cause the rapid oxidation of dielectric materials [161], [162] and increases the conductivity of insulating materials [163], [164]. According to [165], the corona discharge under low-pressure conditions can significantly degrade the electric circuit boards; after 100 h of being exposed to the 60-Hz ac voltage, an irreversible dark brown discoloration was observed over the board surface caused by corona, and thereafter, it increased.

D. Thermoelectrical Problem

There has been an incentive for the miniaturization of power electronic modules, and this has led to a complicated problem to manage the heat losses in switches, such as an IGBT module [166]. The proper handling of thermal and thermoelectrical stress is critical for a power module. The mismatch between the coefficient of thermal expansion (CTE) of different layers in a power module reduces the power module's lifespan. Besides, WBG semiconductors have much higher temperature tolerability that can only be utilized if these mismatches are handled efficiently [167]. If the bonding between the semiconductor layer between the conductive substrates and the semiconductive layer fails to deform, the high shear stress results in the breakage of joints or chips [168].

There are various ways to tackle this challenge. One is the cooling of power modules spanning from a low-cost option, such as air cooling, to more sophisticated cooling options, such as direct liquid cooling, microchannel heat sinks, forced convection cooling, and jet impingement cooling [166]. In [169], a thermal controller is developed for power semiconductor devices to protect them against thermal aging. The gate voltage and fundamental frequency are controlled to lower the temperature variation at the junction and, thus, enhance the reliability of the device. In [168], a chemical reaction between indium (In) and silver (Ag) is performed to create a flux-less bonding layer of $AgIn_2$. Also, the Cu substrate is cladded with Ag to benefit from its superior properties, such as ductility and high electrical and thermal conductivity. Using this method, the joint melting can be increased to 850 °C.

VI. High-Temperature Superconducting Equipment

The design of superconducting equipment should be such that it avoids breakdown and PDs especially at high altitudes where lower air pressure leads to lower PDIV according to Paschen's law. In this regard, if the cryogenic system could be designed such that it operates at the sea-level pressure or higher, the risk of breakdown and discharges would be significantly lower. Moreover, cryogenic liquids, such as liquid nitrogen (LN_2), have been shown to have promising characteristics as insulating materials [170]. LN_2 for HTS applications can act as both cryogenic liquid and insulation [171]. However, one should note that the properties of gaseous nitrogen are different from its liquid form; for instance, in the liquid form, $\epsilon_r = 1.44$, while, in the gaseous state, $\epsilon_r = 1$ [172]. In [171], LN_2 was investigated under lightning surge voltage in a homogenous electric field. The results showed that pressurizing LN_2 can enhance the dielectric strength by 15% for any voltage waveform. An economical incentive for the adoption of cryogenic systems is due to the lower insurance cost as the hazard of fire is nearly zero in these systems [170].

Next, the HTS cables and superconducting electric machines will be examined.

A. Superconducting Machines

To turn the idea of a large and commercial AEA into reality, the power density of the electric machine should be increased massively. One promising technology for this purpose is the HTS electric machines. The superconducting machines can offer very high current density, thus very high specific power, through much higher air-gap flux density (five to ten times more than conventional machines). Also, the efficiency of these machines can surpass 99% as a result of removing the core and ohmic losses. In [173], the study compared PM, wound rotor (WR), and HTS superconducting generators with the rating of 5, 10, and 14 MW driven at 16 000, 7000, and 7000 rpm, respectively. The results showed that the PM generator is the lightest at 5 MW, while the WR and HTS machines were preferable at 10 and 14 MW. At 14 MW, the HTS generator was lighter than WR and PM generators by 22% and 30%, respectively.

An important superiority of operating at cryogenic temperature is the compression of voids, which helps to lower PD intensity and number [100]. A supercritical cryogen does not allow the formation of bubbles and air-filled voids [10]. A lower number of voids with smaller sizes can reduce the probability of PD occurrence, which, in turn, increases the lifetime of the insulation system. Also, since these machines can transfer megawatts of power at much lower voltage levels, the risk of PD is almost fully suppressed [174]. A typical ac synchronous machine is shown in Fig. 13. This machine uses the dc superconducting field winding to generate the magnetic field at the armature winding. As shown, the rotor has no iron or magnetic material. Similarly, the stator is free of iron. As a result, a longer air-gap can exist without a saturation problem [175]. These machines can be either partially or fully superconducting. In the latter, the field and armature windings are both made of superconductors. This makes the fully superconducting machine a better choice due to the significant reduction that can be achieved in armature Ohmic losses [174].

A major challenge is the development of an energy-efficient and cost-effective cryocooler to regulate temperature, which is not commercially available yet. All the great features, as mentioned earlier, come at the price of cryo-cooling; on the other hand, the heat-load decreases to 10%–20% of conventional systems [174]. The same as the case of HTS cables, the choice of proper cooling agent is the most important matter. While cryocoolers are reliable for airborne applications, the state-of-the-art technology of cryocoolers does not lead to lighter HTS machines compared to the conventional machines. As another option, LH_2 can be used both as fuel and as a cooling liquid. However, more research needs to be done on that [176]. The fully superconducting machine created by the Moscow

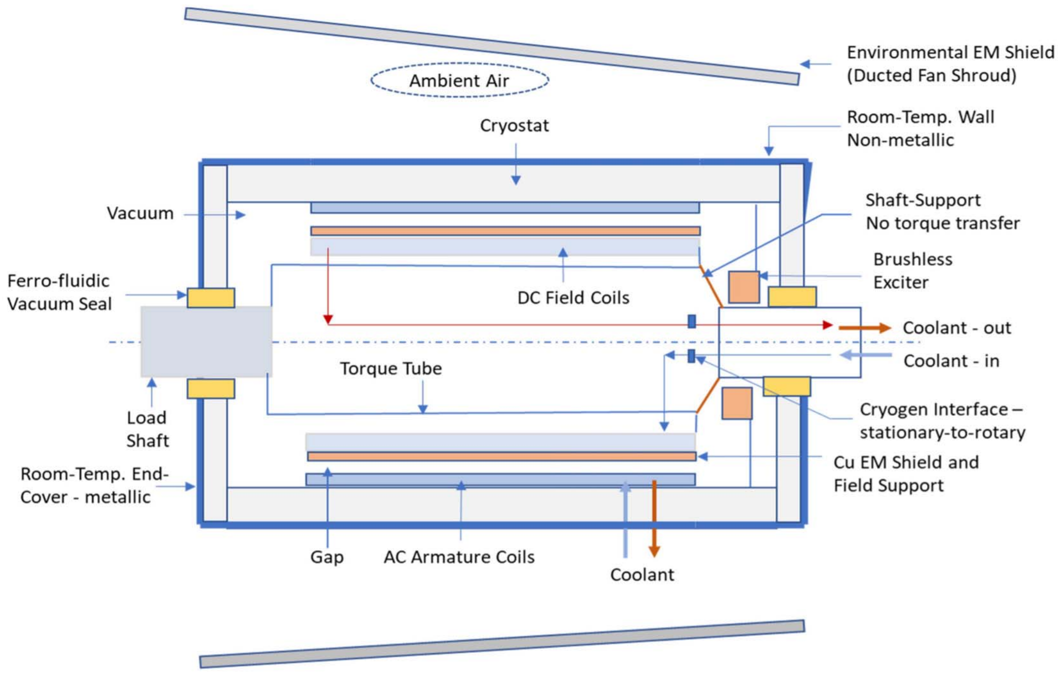


Fig. 13. Configuration of a typical superconducting rotating machine [175].

Aviation Institute uses LH2 to achieve a power density of greater than 20 kW/kg [177].

The properties of LN_2 as an insulating material have been addressed in the literature, which showed that its dielectric strength is comparable to insulation oil (19.6 kV/mm in a homogenous electric field [178]) [170], [179], [180]. In the case of impregnation of other insulating material with LN_2, the ac breakdown of the entire system would be dependent upon LN_2 pressure [27]. The higher the pressure of LN_2, the higher the PDIV would be.

Pressurizing the cooling liquid is an effective method to lower the chances of PD; for instance, in LN2, increasing the pressure from 0.1 to 0.25 MPa increases the PD inception electric field threefold [181]. To improve the breakdown strength of GHe, the addition of a small amount of nitrogen or hydrogen is proposed in [182] and [183].

Assuming the availability of efficient cryogenic systems, it is important to ensure the reliable performance of MEA/AEA components that are envisaged to work under cryogenic conditions. Insulation systems in cryogenic environments should withstand the cooling/heating cycles without substantial compromise [181]. Due to the small reactances of these machines, a large short-circuit current may be produced, which needs a circuit-breaker that can interrupt this high current.

The main challenge is still the cooling of high-temperature equipment. The cooling mechanism ought to work consistently under all operational conditions. Also, to make superconducting electric machinery a feasible option for commercial aircraft, not only the cost of cooling systems but also the superconducting wires should reduce [175].

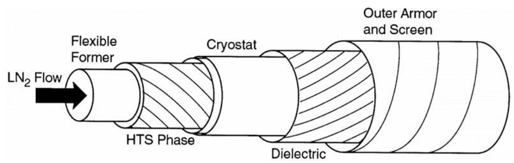
Finally, there has not much work on the long-term reliability of the superconducting machine and its expected lifetime so far. This should be addressed in future studies.

B. HTS Cables

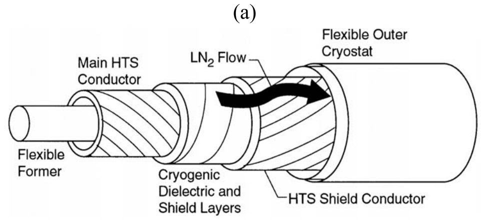
As a fruit of superconducting materials, HTS cables have emerged with the superior capability of nonresistive current flow, nearly negligible thermal interaction with infrastructures, and very low external magnetic field designs [27]. Besides, HTS cables can offer up to five times more power density, which can considerably lower the mass of the equipment and reduce emissions [26], [184]. Unlike conventional cables, where voltage level enhancement directly leads to cable mass reduction, in HTS cables, higher voltage levels do not translate to a lower cable mass but need a more complex taping [185]. However, finding insulating materials that can properly work in cryogenic environments is a challenge toward the development of HTS technology [186]. Also, due to the cryogenic temperature, the chemical degradation of HTS cables is very slow [187]. The use of the vacuum impregnation technique and/or semiconductive layers can lower the voids and cracks, which are the PD igniting points [109], [188]. Also, it was shown that, in an HTS cable, the increasing number of insulation layers can harm insulation strength [189].

There are two main design strategies for dielectrics in HTS cables: warm dielectric and cold dielectric [190] (see Fig. 14). Each strategy can be advantageous depending upon the application. Since the aircraft industry is seeking to enhance power density, the cold dielectric design is preferred as its power density is approximately twice the power density of cables with warm dielectric [190].

However, if the system is not entirely working in a cryogenic system, the cable terminations can be significantly vulnerable to aging due to the difference between room and cryogenic temperatures, which can lead to cracks and mechanical damage. In [192], using auxiliary crosslinking agents, an ethylene propylene diene monomer (EPDM) material was



(a)



(b)

Fig. 14. Basic structure of HTS cable with (a) warm dielectric and (b) cold dielectric [191].

used for cable terminations by a UV-initiation crosslinking technique. The novel material would have better thermal conductivity while maintaining the insulating properties at an acceptable level.

Choosing LN_2 as the coolant is also motivated by its higher safety of use compared to liquid hydrogen (LH_2), as well as its simplicity to obtain [185]. A common design for HTS cables is to use LN_2 as the coolant and lapped tape insulation for conductors [193]. However, the lower critical current of LN_2 compared to LH_2 makes it less promising in cases where high current magnitudes are needed [185]. GHe is another coolant option. Although it has lower dielectric strength (4 kV/mm in a 60-Hz uniform field [194]), it has a wider operating temperature range (6 K–80 K) compared to LN_2 (63 K–80 K). This is the incentive behind choosing GHe for HTS devices by the U.S. Navy [195]. If a superconducting network is going to be found that comprises superconducting motors, superconducting generators, and superconducting cables, LN_2 is not a promising option for coolant. Also, when a temperature of lower than 65 K is demanded, GHe is preferred over LN_2 [157]. For instance, motors may require operating in the temperature range of 20 K–30 K, which is not possible to achieve through LN_2 [186]. Therefore, to merge the wide operating temperature range with good dielectric properties, a mixture of helium with other components has been addressed in the literature [182], [183], [196]. LN_2 offers much better dielectric strength compared to helium and can also be used as a fuel source [197]. However, the safety concerns that are raised when using LN_2 hinder its wide employment.

In [27] and [181], the accelerated lifetime modeling of HTS cables is proposed through a power law

$$t_0 = \left(\frac{E_{\text{test}}}{E_0}\right)^p \times t_{\text{test}} \tag{2}$$

where the known parameters are the rated stress (E_0), testing electric field magnitude (E_{test}), the corresponding time to breakdown (t_{test}), and the exponent of the power-law (p). The estimated lifetime (t_0) is greatly dependent upon the accuracy of the p-value. For example, in a PD-free polypropylene-laminated paper (PPLP) insulated HTS cable, the p-value is about 50 [198]. Then, for the PD-inducing case, the p-value can drop to a value as low as 4 [199].

Solid dielectric is not a proper choice for the cryogenic environment as it may crack during the cooling process [200], therefore, composite dielectrics entailing insulating tapes immersed in a cooling liquid is the feasible option [201]. In the case of composite insulations, the butt gaps of tapes filled with cryogenic liquid are the weak point. The sharp edges of electrodes are also potential locations for discharge propagation due to the high electric field intensity. In a superconducting coil, an important role in the dielectric strength of the equipment is played by the butt gaps filled by liquids [170]. In the quenching state—in which a sudden transition from the superconducting state to nonsuperconducting occurs—the resistive zone in the superconducting wire expands and leads to the formation of a hotspot [28]. The bubbles formed after vaporization undergo a high electric field and give rise to PDs. PDs then exacerbate the situation through further vaporization of the liquid and produce even more bubbles [28], [201], [202]. Therefore, the worst case scenario can be the full vaporization of the cryogenic liquid [172]. With the generation of bubbles, the dielectric strength can go as low as 32% of the dielectric strength when there is no bubble [203]. In [109], it was noted that the cross section of cables can be a good indicator of threatful regions and cavities. Also, the formation of white power on the surface of some polymeric insulation films has been reported because of PD [181].

While polymeric dielectrics in their pure form may suffer from low thermal conductivity and loss of mechanical strength at cryogenic temperatures, the polymeric composites and nanodielectric present promising properties for operating in cryogenic environments [204]–[207]. Nanodielectrics have been shown to have promising behavior, such as dielectric strength stability in cryogenic environments [208]. In [208], several thin layers of nanodielectrics, all of which had a polymeric matrix modified by nanoscale fillers, were tested. These materials showed little to no degradation under cryogenic conditions. For instance, the mean breakdown field of polymethyl methacrylate (PMMA) modified with barium fluoride (BaF_2) nanoparticles (5% wt) is roughly 161 kV/mm [208]. At cryogenic temperatures, the dielectric strength of epoxy bound nanoparticles went as high as 25–40 kV/mm [209]. The refrigerant liquid, e.g., liquid nitrogen, can provide even more electrical insulation, resulting in an overall increase of five to ten times for polymeric insulation at a cryogenic temperature over room temperature. Compared to room temperature, PD occurrence is 100 times lower in LN_2 for PPLP and PI [117]. Moreover, no significant decay in PDIV was found during thermal cycles in the cryogenic environment [201].

In [210] and [211], a novel superconducting gas-insulated transmission line (S-GIL) was proposed in which the coolant also acts as an insulation material, and the tape insulation is omitted. This prevents PD occurrence in butt joints and the interface of layers [197]. As this technology conductor should be concentric to the cryostat to operate at an optimal voltage level, insulator spacers should be used that can introduce new challenges for the insulation system. In [197], 3-D-printed spacers were designed, which showed favorable characteristics to be adopted in S-GIL.

Another problem with cryogenic systems is that the behavior of dielectrics might change under these conditions. SiC-based devices, which are envisaged to be widely used in power converters, do not properly work under cryogenic conditions [212], [213]. However, this is not the case for silicone, which even indicates improved behavior in terms of faster switching speed and lower switching loss [214]. Similarly, tantalum shows a higher dissipation factor, while polypropylene, polycarbonate, and mica show even better properties in terms of the dissipation factor [215].

VII. Consideration for Testing and Standards

Multiple aging factors threaten the insulation system's health in an electrified aircraft. These factors include electrical, ambient, thermal, and thermomechanical aging [14]. An efficient experimental test of the insulation system must not only investigate the impact of each aging factor but should also address the coupling of these factors when they occur together.

A rigid experimentation procedure requires the simulation of the inflight environment to test the electric power distribution network [17]. This includes simulation of pressure, temperature, vibration, ionizing radiation, and ground plane (fixed and movable), the same as those that a commercial aircraft might undergo [17].

Moreover, with the prevalence of WBG-based power converters that operate at much higher frequencies, the switching noises will have higher frequencies, resulting in it being harder to discriminate PD signal from noise [87]. Conventional PD detection methods are well-suited for 50–60-Hz ac voltage and may not be able to discriminate the high-frequency components generated by power electronics devices.

A PD event not only causes a transient current to flow but is also accompanied by vibration and ultrasonic signals. Therefore, one can use acoustic emission (AE) sensors to detect these signals [216]. However, in the case of electric aircraft where the power network energizes by a variable frequency generator, an optical method, such as the frequency-dependent Sagnac optical fiber sensor, is more beneficial [216].

In [217] and [218], a radio frequency (RF) ultrahigh-frequency (UHF) PD detection method was proposed for online detection of PD in an aerospace environment experiencing both standard and low-pressure conditions. In [219]–[222], a nonintrusive sensor associated with the high-frequency filtering method was introduced especially for PD detection under PWM-like voltages. In [102], [117], and [223], the feasibility of using a special commercial UHF sensor and PD detection system under both sinusoidal and square wave voltages with very short rise times under low-pressure conditions was assessed, and the influence of both frequency and pressure on the inception of PDs was experimentally investigated. Benefitting from the PD detection method developed in [219] and [220], it was found that pressure affects the PD spectrum [224], [225], where, with decreasing pressure, the amplitudes of low-frequency components increase and high-frequency components decrease. Thus, the bandwidth of the sensors and filters should be adapted for air pressure [224]. In contrast to the high-voltage equipment for testing at sea level, the high-voltage equipment for testing aerospace applications is not well-documented [33].

In [24], it was again shown that the PD signal frequency content at higher altitudes is different than that at sea level and is in a lower range. This observation was also confirmed in [81] in which the frequency content of low-pressure PDs was found to be much lower than sea-level PDs. In the comparison of negative and positive discharges, the former had even lower frequency content. In [71], the change in the magnitude and phase distribution with pressure reduction was reported, resulting in a different pattern of PD. All these show that specialized equipment is needed for PD testing under high-altitude conditions. Schweickart *et al.* [226] discussed the PD detection circuit for aeronautical applications and the impact of circuit parameters on the valid simulation of the PD phenomenon.

A typical detection method for an arc in electric aircraft can be an electrical method. On the other hand, an optical method based on characteristics of arc lights can be beneficial due to its faster response and immunity to electromagnetic interference (EMI) [227].

Despite the applicability of existing standards to some extent, the insufficiency of the existing standards to address insulation challenges at high altitudes is obvious. As a result, the standards designed for marine space have been proposed as a partial substitute/complement for the standards of dc power systems for aircraft with distributed propulsion [10].

Most standards addressing PD phenomena are designed based on sea-level conditions. Such standards are unlikely to suit high-altitude conditions. For instance, the PD measurement according to standard IEC 60270 cannot be used to measure the apparent PD charge at high-altitude flight conditions [228]. The slow rise time and long duration of discharge could exceed the analog integration form defined by IEC 60270 and falls out of the cutoff frequency of the instrument [81], [82]. While, in IEC 60270 [229], the measurements are done in a frequency range below 1 MHz, two nonconventional electrical PD detection methods are used in IEC 62478. In this standard, measurements are conducted in higher frequencies (up to 3 GHz). The larger frequency range and bandwidth help to have smaller noise interference in the measured signal [230].

To test random wound coils' insulation, IEC 60034-18-41 [231] is designed for Type I rotating machines working under 700 V_{rms} and does not allow repetitive PDs to happen during the service of the machine. However, it does not consider the impacts of pressure, humidity, and frequency [232], [233]. For the form-wound (Type II) machines that are the main choices for electrical aircraft and operate at voltages above 700 V_{rms}, IEC 60034-18-42 was developed [234]. The qualifications of Type II machines are quite different from the Type I machines. For the insulation system of a converter-fed type II machine, the stress factors considered are frequency, rise time, and peak-to-peak voltage, but the environmental conditions are still unaddressed.

In IEC 61378-1 [235], the standard does not require taking PD tests, and IEC 60317-0-1 [236], which enforces the minimum requirements for winding wires, does not address PD activity and only stands for breakdown endurance [232]. IEC 60270 addresses PD measurements under the dc voltage or the ac voltage limited to frequencies under 400 Hz, again without any focus on low-pressure conditions.

To evaluate the arc tracking properties, the comparative tracking index (CTI) is proposed. In IEC 60112 [237], CTI is described as a maximum voltage at which a material can withstand 50 drops of contaminated water without generating tracking and a persistent flame. The equivalent standard in ASTM international standard system is ASTM D368 [57], [238]. However, this standard is not designed for aeronautical applications. Despite the existence of some standards for aeronautic applications, not all the design criteria are addressed by these standards. For instance, IEC 60664 [239] is restricted to altitudes less than 2 km above sea level. Also, the guidelines provided to obtain creepage distances cannot be applied to low-pressure conditions.

There are some testing procedures proposed for HTS cables. For instance, CIGRE TB 538 was developed for type testing, factory testing, and after laying tests of HTS cables based on IEC 60840, IEC 60502, and IEC 62067 for ac voltages of up to 170 kV [240]–[243]. In these standards, the bending and *LC* measurement tests, the pressure test, the load cycle test, the ac voltage test, the lightning impulse test followed by the ac voltage test, and PD tests are performed on the assembly. However, the test is restricted to frequencies below 300 Hz. Considering the minimum frequency of 400 Hz projected by NASA [17], further development in the standardization of tests for HTS cables is required.

The electromagnetic disturbance standard, DO-160G [244], is not sufficient according to [108]. It is claimed that the cable and ground plane must have a minimum distance of 5 cm; however, in [108], it was shown that, even for distances higher than 5 cm, there is still a large variation in the impedance.

There are also several active standards for the electric propulsion system. The active standard ASTM F3239 [245] addresses the requirements of hybrid-electric propulsion systems in terms of the design and installation of power plants, energy distribution systems, control systems, and hazard mitigation. The active standard ASTM F3316/F3316M [246] targets the electrical systems for electrical propulsion in electric or hybrid-electric aircraft. The scope of this standard includes but is not limited to the power source capacity and distribution, cables, circuit protective devices, switches, and storage systems.

VIII. Conclusion and Discussion

Electric aircraft has been considered as a sustainable replacement for conventional aircraft to address the demand for emission reduction, lower fuel consumption, and lower noise levels. Besides critical reviews of insulation materials and systems used in different electrification components of MEA/AEA, technical gaps and future research needs for each electrification component or topic are identified and discussed, summarized in this section as well.

Electric machines play a significant role in power generation, motors, and actuators. The main challenge of electric machinery for MEA/AEA is the availability of a reliable, cost-efficient, and high power-density machine. The WFSGs that are the state-of-the-art power generator for aeronautic applications do not meet the power density requirements. On the other hand, the SR and, especially, PM machines are offering much higher power densities, but the long-term reliability of these machines is not fully addressed yet. Another challenging aspect of rotating machines is the insulation system of windings. The threat of PD in inverter-fed machines, especially at high-altitudes, imposes a serious reliability challenge that has urged researchers to work on new candidates, such as Litz wire.

Cables as the power transmission agents must resist tracking and discharges at higher altitudes in lower air pressures and higher humidity levels. Also, great potential resides in the weight reduction of cables. All these have led to the introduction of new cable designs, such as MMEI structure and cables insulated by self-healing Surlyn. These candidates can offer higher insulation strength; however, these technologies are at their early stage, and more research needs to be done on the standards that guarantee life-long reliability and improved performance compared to conventional cables.

The introduction of WBG semiconductors has led to much more efficient, high-frequency power converters with higher voltage and temperature tolerance capabilities. On the other hand, the fast-rise, high-repetitive surges generated by these converters can harm the insulation systems at an accelerated rate. Keeping in mind that, at higher altitudes, the dielectric strength of insulation systems is lower, serious challenges exist in this area. Moreover, the surface discharges (tracking) at the contaminated and wet surface of solid insulators have raised concerns on the leakage current that flow over the surfaces and the occurrence of arcs. Surface treatment for creating material with a hydrophobic surface is proposed to overcome this challenge. Further research in this area is needed as there are other (potentially) game-changing factors, such as microgravity, low-pressure conditions, and variable frequency voltages that need to be addressed. Finally, due to the mismatches between the coefficients of thermal expansion of different layers in a power module, some components, such as the semiconductive layer, may deform, or breakage of joints or chips occur. Cooling methods, using a thermal controller, and flux-less bonding layer have been proposed to solve this problem. The next step in this area is to find a reliable solution that suits the aircraft application.

Superconducting equipment has received attention for the MEA/AEA applications due to the potential for lower risk of PD, high power density, and efficiency. The superconducting machines can achieve the targeted power density only if a lightweight, cost-efficient cooling system is found. Besides, the research ought to be done on the superconducting wires that can make these machines viable against conventional ones in terms of cost. On the insulation side, the response of the potential dielectrics in a cryogenic environment should be fully understood.

To financially justify this transformation in the aviation industry, improvement in the power density of aircraft electrical power systems is predestined. A core technology in this path is insulation systems that must deal with various challenges, including PDs, arc tracking, and thermal degradation. This article reviewed the research that has been performed to address these challenges and provided insights to enlighten the following steps. The following are the gist of several vital issues.

1) Material improvement should not only be made in the bulk characteristics of the insulating materials but also in the surface conditions to prevent tracking and surface flashover voltages.
2) The HTS equipment can offer much higher power density, but significant improvements must be made in terms of efficient cryocooler systems. There are multiple variables in this problem to deal with: operating temperature range, safety, insulating properties, critical current magnitude, and so on. In a report by NASA, cryogenic systems are expected to dominate the electrical system of MEA/AEA. However, as discussed, we are a long way from designing an efficient, safe, and cost-effective cryogenic system.
3) The most significant challenge of the insulation system is the handling of superimposed detrimental impacts of various aging mechanisms and conditions. While the environmental conditions at high-altitude shrink the dielectric strength, the emergence of WBG semiconductors and their high switching frequency endangers the insulation even more. Medium type and environmental conditions have been shown to have a huge impact on aging mechanisms. If the system is operating under ambient conditions, the type of gas determines the critical electric field magnitude. Similarly, the cryogenic liquid has a profound impact on the dielectric breakdown and is a candidate for the insulation role as well.
4) It has been demonstrated in multiple studies that the frequency content of PDs at higher altitudes has lower inception voltage and is more intense. Also, the pattern of PD at low pressure is much different than at the sea level. Lower frequency content makes conventional testing equipment ineffective under aircraft testing conditions. To this end, the standards for comprehensive testing are not sufficiently progressed. Medium-voltage dc power systems are not mature enough and lack standards for the design of electrical system components. As a result, the long-term reliability of these systems is not ensured.

REFERENCES

[1] R. DeIasi and J. Russell, "Aqueous degradation of polyimides," *J. Appl. Polym. Sci.*, vol. 15, no. 12, pp. 2965–2974, Dec. 1971.

[2] F. J. Campbell, A. K. Brewer, R. J. Orr, T. A. Janicke, and A. M. Bruning, "Hydrolytic deterioration of polyimide insulation on naval aircraft wiring," in *Proc. Ann. Rep., Conf. Electr. Insul. Dielectr. Phenomena*, Ottawa, ON, Canada, 1988, pp. 180–188.

[3] B. Moffat, E. Abraham, M. Desmulliez, D. Koltsov, and A. Richardson, "Failure mechanisms of legacy aircraft wiring and interconnects," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 808–822, Jun. 2008.

[4] National Transportation Safety Board (NTSB), "In-flight breakup over the Atlantic ocean Trans world airlines flight 800 Boeing 747-131, N93119 Near East Moriches," Nat. Transp. Saf. Board, New York, NY, USA, Accident Rep. NTSB/AAR-00/03, Jul. 1996.

[5] *Fire in the Sky*, Syst. Failure Case Stud., Nat. Aeronaut. Space Admin. (NASA), Jan. 2011, vol. 5, no. 1.

[6] G. Tissandier, *Air Navigation, Aviation and Aerostats Management*. Paris, France: Hachette Livre BNF, (in French), 1886.

[7] B. Sarlioglu and C. T. Morris, "More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft," *IEEE Trans. Transport. Electrific.*, vol. 1, no. 1, pp. 54–64, Jun. 2015.

[8] D. K. Hall *et al.*, "Feasibility of electrified propulsion for ultra-efficient commercial aircraft, final report," Nat. Aeronaut. Space Admin. (NASA), Cleveland, OH, USA, Tech. Rep. NASA/CR-2019-220382, 2019.

[9] V. Madonna, P. Giangrande, and M. Galea, "Electrical power generation in aircraft: Review, challenges, and opportunities," *IEEE Trans. Transport. Electrific.*, vol. 4, no. 3, pp. 646–659, Sep. 2018.

[10] P. Gemin *et al.*, "Architecture, voltage and components for a turboelectric distributed propulsion electric grid (AVC-TeDP)," GE Aviation & GE Global Res., NASA, Tech. Rep. NNC10BA06B, Niskayuna, NY, USA, Jul. 2015.

[11] T. S. Williams, "Multifunctional polymers and composites for aerospace applications," in *Proc. ACS Polym. Compos. High Perform. Mat. Workshop*, Rohnert Park, CA, USA, Jul. 2019, pp. 1–16.

[12] P. W. Wheeler, J. C. Clare, A. Trentin, and S. Bozhko, "An overview of the more electrical aircraft," *Proc. Inst. Mech. Eng. G, J. Aerosp. Eng.*, vol. 227, no. 4, pp. 578–585, Dec. 2013.

[13] M.-C. Flynn *et al.*, "Protection and fault management strategy maps for future electrical propulsion aircraft," *IEEE Trans. Transport. Electrific.*, vol. 5, no. 4, pp. 1458–1469, Dec. 2019.

[14] D. Barater *et al.*, "Multistress characterization of fault mechanisms in aerospace electric actuators," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1106–1115, Mar. 2017.

[15] J. Kuseian, "Naval power systems technology development roadmap PMS 320," NAVSEA, Naval Sea Syst. Command, Washington, DC, USA, Annu. Rep., Apr. 2013.

[16] National Academies of Sciences and Medicine, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC, USA: The National Academies Press, 2016.

[17] M. Lizcano, "High voltage materials research overview and current high voltage test capabilities and build-up," SAE Aircraft High Voltage Workshop, Mukliteo, WA, USA, Mar. 2018.

[18] L. Niemeyer, "A generalized approach to partial discharge modeling," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 2, no. 4, pp. 510–528, Aug. 1995.

[19] X. Liu, D. Furrer, J. Kosters, and J. Holmes, "Vision 2040: A roadmap for integrated, multiscale modeling and simulation of materials and systems," Nat. Aeronaut. Space Admin. (NASA), Cleveland, OH, USA, Tech. Rep. NASA/CR-2018-219771, Mar. 2018.

[20] J. Felder, H. Kim, and G. Brown, "Turboelectric distributed propulsion engine cycle analysis for hybrid-wing-body aircraft," in *Proc. 47th AIAA Aerosp. Sci. Meeting including New Horizons Forum Aerosp. Expo.*, Jan. 2009.

[21] J. K. Noland, M. Leandro, J. A. Suul, and M. Molinas, "High-power machines and starter-generator topologies for more electric aircraft: A technology outlook," *IEEE Access*, vol. 8, pp. 130104–130123, Jul. 2020.

[22] A. Barzkar and M. Ghassemi, "Electric power systems in more and all electric aircraft: A review," *IEEE Access*, vol. 8, pp. 169314–169332, 2020.

[23] A. Barzkar, M. Borghei, and M. Ghassemi, "Challenges and future research needs for components of electric power systems in more and all electric aircraft," *IEEE Trans. Transport. Electrific.*, to be published.

[24] D. G. Kasten, X. Liu, S. A. Sebo, D. F. Grosjean, and D. L. Schweickart, "Partial discharge measurements in air and argon at low pressures with and without a dielectric barrier," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 12, no. 2, pp. 362–373, Apr. 2005.

[25] K. Koppisetty and H. Kirkici, "Breakdown characteristics of helium and nitrogen at kHz frequency range in partial vacuum for point-to-point electrode configuration," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 749–755, Jun. 2008.

[26] S. S. Kalsi, *Applications of High Temperature Superconductors to Electric Power Equipment*. Hoboken, NJ, USA: Wiley, 2011.

[27] B. Gholizad *et al.*, "Reliability considerations of electrical insulation systems in superconducting cables," in *Proc. 12th Int. Conf. Properties Appl. Dielectr. Mater. (ICPADM)*, Xi'an, China, May 2018, pp. 194–197.

[28] M. Hara, H. Koishihara, and K. Saita, "Breakdown behavior of cryogenic liquids in the presence of thermal bubbles under ramped voltage," *IEEE Trans. Electr. Insul.*, vol. 26, no. 4, pp. 685–691, Aug. 1991.

[29] M. J. Armstrong, C. A. H. Ross, M. J. Blackwelder, and K. Rajashekara, "Trade studies for NASA N3-X turboelectric distributed propulsion system electrical power system architecture," *SAE Int. J. Aerosp.*, vol. 5, no. 2, pp. 325–336, Oct. 2012.

[30] R. Jansen, C. Bowman, and A. Jankovsky, "Sizing power components of an electrically driven tail cone thruster and a range extender," in *Proc. AIAA Aviation Technol., Integr., Oper. Conf.*, 2016, p. 366.

[31] S. Sahoo, X. Zhao, and K. Kyprianidis, "A review of concepts, benefits, and challenges for future electrical propulsion-based aircraft," *Aerospace*, vol. 7, no. 4, p. 44, Apr. 2020.

[32] I. Cotton and A. Nelms, "Higher voltage aircraft power systems," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 23, no. 2, pp. 25–32, Feb. 2008.

[33] I. Christou, A. Nelms, M. Husband, and I. Cotton, "Choice of optimal voltage for more electric aircraft wiring systems," *IET Electr. Syst. Transp.*, vol. 1, no. 1, pp. 24–30, Mar. 2011.

[34] T. Billard, C. Abadie, and B. Taghia, "Non-intrusive partial discharges investigations on aeronautic motors," in *Proc. Aerosp. Technol. Conf.*, Hartford, CN, USA, 2016, pp. 1–18.

[35] M. Abdel-Salam, H. Anis, A. EI-Morshedy, and R. Radwan, *High Voltage Engineering: Theory and Practice*, 2nd ed. New York, NY, USA: Marcel Dekker, 2000.

[36] E. Kuffel, W. S. Zaengl, and J. Kuffel, *High Voltage Engineering, Fundamentals*, 2nd ed. Oxford, U.K.: Newnes, 2000.

[37] M. Borghei and M. Ghassemi, "Investigation of low-pressure condition impact on partial discharge in micro-voids using finite-element analysis," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Detroit, MI, USA, Oct. 2020, pp. 3293–3298.

[38] M. Lauriente and H. B. Garrett, "A space environment data resource," in *Proc. Spacecraft Charging Tech. Conf.*, 1989, p. 556.

[39] H. Okubo, S. Yuasa, K. Ota, N. Hayakawa, and M. Hikita, "Discharge characteristics under non-uniform electric field in he, ar and air at low pressures," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 4, no. 4, pp. 450–455, Aug. 1997.

[40] P. Seri *et al.*, "Partial discharge inception voltage in DC insulation systems: A comparison with AC voltage supply," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Calgary, AB, Canada, Jun. 2019, pp. 176–179.

[41] K. Koppisetty, H. Kirkici, and D. L. Schweickart, "Breakdown characteristics of nitrogen in partial vacuum under pulsed electric fields of kHz range," in *Proc. Electr. Insul. Conf. Electr. Manuf. Expo*, Nashville, TN, Oct. 2007, pp. 169–171.

[42] K. Koppisetty, H. Kirkici, and D. Schweickart, "Partial vacuum breakdown characteristics of helium at 20 kHz for inhomogeneous field gap," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 3, pp. 553–559, Jun. 2007.

[43] F. W. Peek, *Dielectric Phenomena in HV Engineering*. New York, NY, USA: McGraw-Hill, 1929, p. 228.

[44] M. Nagel and T. Leibfried, "Investigation on the high frequency, high voltage insulation properties of mineral transformer-oil," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Kansas City, MO, USA, Oct. 2006, pp. 226–228.

[45] J. H. Mason, "Effects of frequency on the electric strength of polymers," *IEEE Trans. Electr. Insul.*, vol. 27, no. 6, pp. 1213–1216, Dec. 1992.

[46] M. Ghassemi, "Accelerated insulation aging due to fast, repetitive voltages: A review identifying challenges and future research needs," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 5, pp. 1558–1568, Oct. 2019.

[47] B. Zhang, M. Ghassemi, and Y. Zhang, "Insulation materials and systems for power electronics modules: A review identifying challenges and future research needs," *IEEE Trans. Dielectr. Electr. Insul.*, to be published.

[48] M. Ghassemi, "PD measurements, failure analysis, and control in high-power IGBT modules," *High Voltage*, vol. 3, no. 3, pp. 170–178, Sep. 2018.

[49] M. Ghassemi, "Electrical insulation weaknesses in wide bandgap devices," in *Simulation and Modelling of Electrical Insulation Weaknesses in Electrical Equipment*, R. Albarracin, Ed., London, U.K.: IntechOpen, 2018, pp. 129–149.

[50] P. Wang, A. Cavallini, G. C. Montanari, and G. Wu, "Effect of rise time on PD pulse features under repetitive square wave voltages," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 1, pp. 245–254, Feb. 2013.

[51] P. Wang, A. Cavallini, and G. Montanari, "The influence of repetitive square wave voltage parameters on enameled wire endurance," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1276–1284, Jun. 2014.

[52] M. Borghei and M. Ghassemi, "Partial discharge finite element analysis under fast, repetitive voltage pulses," in *Proc. IEEE Electric Ship Technol. Symp. (ESTS)*, Arlington, VA, USA, Aug. 2019, pp. 324–328.

[53] M. Borghei and M. Ghassemi, "Finite element modeling of partial discharge activity within a spherical cavity in a solid dielectric material under fast, repetitive voltage pulses," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Calgary, AB, Canada, Jun. 2019, pp. 34–37.

[54] M. Borghei and M. Ghassemi, "Partial discharge analysis under high-frequency, fast-rise square wave voltages in silicone gel: A modeling approach," *Energies*, vol. 12, no. 23, p. 4543, Nov. 2019.

[55] M. Borghei, M. Ghassemi, J. M. Rodríguez-Serna, and R. Albarracín-Sánchez, "A finite-element-analysis and an improved induced charge concept for partial discharge modeling," *IEEE Trans. Power Del.*, to be published.

[56] K. Elanseralathan, M. J. Thomas, and G. R. Nagabhushana, "Breakdown of solid insulating materials under high frequency high voltage stress," in *Proc. Int. Conf. Prop. Appl. Dielect. Mater.*, vol. 2, Jun. 2000, pp. 999–1001.

[57] J.-R. Riba, Á. Gómez-Pau, M. Moreno-Eguilaz, and S. Bogarra, "Arc tracking control in insulation systems for aeronautic applications: Challenges, opportunities, and research needs," *Sensors*, vol. 20, no. 6, p. 1654, Mar. 2020.

[58] G. B. Hillard and H. Kirkici, "High voltage design guidelines: A timely update," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Oct. 2001, pp. 409–411.

[59] F. Dricot and H. J. Reher, "Survey of arc tracking on aerospace cables and wires," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 1, no. 5, pp. 896–903, Oct. 1994.

[60] P. L. Cahill and J. H. Dailey, "Wet-wire arc tracking of aircraft wire insulations," *Electr. Manufact.*, vol. 3, no. 3, pp. 39–43, 1989.

[61] M. D. Hathaway, R. Del Rosario, and N. Madavan, "NASA fixed wing project propulsion research and technology development activities to reduce specific energy consumption," in *Proc. 49th AIAA/ASME/SAE/ASEE Joint Propuls. Conf.*, Jul. 2013, p. 36.

[62] E. Balaban, P. Bansal, P. Stoelting, A. Saxena, K. F. Goebel, and S. Curran, "A diagnostic approach for electro-mechanical actuators in aerospace systems," in *Proc. IEEE Aerosp. Conf.*, Mar. 2009, pp. 1–13.

[63] V. Madonna, P. Giangrande, L. Lusuardi, A. Cavallini, and M. Galea, "Impact of thermal overload on the insulation aging in short duty cycle motors for aerospace," in *Proc. IEEE Int. Conf. Electr. Syst. Aircr., Railway, Ship Propuls. Road Vehicles Int. Transp. Electrific. Conf. (ESARS-ITEC)*, Nottingham, U.K., Nov. 2018, pp. 1–6.

[64] G. C. Montanari and L. Simoni, "Aging phenomenology and modeling," *IEEE Trans. Electr. Insul.*, vol. 28, no. 5, pp. 755–776, Oct. 1993.

[65] V. Madonna, P. Giangrande, L. Lusuardi, A. Cavallini, C. Gerada, and M. Galea, "Thermal overload and insulation aging of short duty cycle, aerospace motors," *IEEE Trans. Ind. Electron.*, vol. 67, no. 4, pp. 2618–2629, Apr. 2020.

[66] Y. Wang, S. Nuzzo, H. Zhang, W. Zhao, C. Gerada, and M. Galea, "Challenges and opportunities for wound field synchronous generators in future more electric aircraft," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 4, pp. 1466–1477, Dec. 2020.

[67] C. Anghel, "Modeling and simulation of a power generation system with a high-power generator," SAE, Tech. Paper 2013-01-2126, 2013.

[68] A. Woodworth, R. Jansen, K. P. Duffy, P. Naghipour, and E. E. Shin, "Creating a multifunctional composite stator slot material system to enable high power density electric machines for electrified aircraft applications," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp.*, Cincinnati, OH, USA, Jul. 2018, pp. 1–8.

[69] J. D. Lenz, N. J. Renner, X. Yi, and K. S. Haran, "Insulation considerations in form-wound armature windings for high-frequency electric machines," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Portland, OR, USA, Aug. 2018, pp. 1–5.

[70] A. Yoon, X. Yi, J. Martin, Y. Chen, and K. Haran, "A high-speed, high-frequency, air-core PM machine for aircraft application," in *Proc. IEEE Power Energy Conf. Illinois (PECI)*, Urbana, IL, USA, Feb. 2016, pp. 1–4.

[71] Y. Wang, T. Balachandran, Y. Hoole, Y. Yin, and K. S. Haran, "Partial discharge investigation of form-wound electric machine winding for electric aircraft propulsion," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 4, pp. 1638–1647, Dec. 2020.

[72] Y. Wang *et al.*, "Partial-discharge-free insulation design of air-core permanent magnet synchronous machine for aircraft propulsion," *IEEE Trans. Transport. Electrific.*, early access, May 2020, doi: 10.1109/TTE.2020.2992052.

[73] G. C. Stone, I. Culbert, E. A Boutler, and H. Dhirani, *Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing and Repair*, 2nd ed. Hoboken, NJ, USA: Wiley, 2014.

[74] I. Christou and I. Cotton, "Methods for partial discharge testing of aerospace cables," in *Proc. IEEE Int. Symp. Electr. Insul.*, San Diego, USA, Jun. 2010, pp. 1–5.

[75] T. Billard, C. Abadie, and T. Lebey, "Partial discharge testing in aeronautic environment on magnet wire and feeder cables," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Montreal, QC, Canada, Jun. 2016, pp. 101–104.

[76] L. Fang, I. Cotton, Z. J. Wang, and R. Freer, "Insulation performance evaluation of high temperature wire candidates for aerospace electrical machine winding application," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Ottawa, ON, Canada, Jun. 2013, pp. 253–256.

[77] R. Rui and I. Cotton, "Impact of low pressure aerospace environment on machine winding insulation," in *Proc. IEEE Int. Symp. Electr. Insul.*, San Diego, CA, USA, Jun. 2010, pp. 1–5.

[78] E. Sili, J. P. Cambronne, N. Naude, and R. Khazaka, "Polyimide lifetime under partial discharge aging: Effects of temperature, pressure, and humidity," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 2, pp. 435–442, Apr. 2013.

[79] X. Liu, "Low pressure partial discharge investigation with FEM modeling for a twisted pair of insulated conductors," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Kansas City, MO, USA, Oct. 2006, pp. 611–614.

[80] F. Koliatene, T. Lebey, J. P. Cambronne, and S. Dinculescu, "Impact of the aeronautic environment on the partial discharges ignition: A basic study," in *Proc. Conf. Rec. IEEE Int. Symp. Electr. Insul.*, Vancouver, BC, Canada, Jun. 2008, pp. 603–606.

[81] D. Grosjean, D. Schweickart, D. Kasten, S. Sebo, and X. Liu, "Development of procedures for partial discharge measurements at low pressures in air, argon and helium," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 6, pp. 1535–1543, Dec. 2008.

[82] D. L. Schweickart, D. F. Grosjean, D. G. Kasten, S. A. Sebo, and X. Liu, "Low-pressure partial-discharge measurements: Monitoring the insulation integrity of aircraft power wiring systems," in *Proc. IEEE Int. Power Modulators HV Conf.*, Las Vegas, NV, USA, May 2008, pp. 568–571.

[83] M. Fenger, G. C. Stone, and B. A. Lloyd, "The impact of humidity on PD inception voltage as a function of rise-time in random wound motors of different designs," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, Cancun, Mexico, 2002, pp. 501–505.

[84] V. Peesapati, L. Fang, R. Giussani, and I. Cotton, "Comparison of standards requirements for clearances in aerospace," in *Proc. IEEE Electr. Insul. Conf.*, Ottawa, ON, Canada, Jun. 2013, pp. 434–438.

[85] F. Alrumayan, I. Cotton, and A. Nelms, "Partial discharge testing of aerospace electrical systems," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 46, no. 2, pp. 848–863, Apr. 2010.

[86] R. Gardner, I. Cotton, and M. Kohler, "Comparison of power frequency and impulse based partial discharge measurements on a variety of aerospace components at 1000 and 116 mbar," in *Proc. IEEE Electr. Insul. Conf.*, Seattle, USA, Aug. 2015, pp. 430–433.

[87] R. Acheen, C. Abadie, T. Billard, T. Lebey, and S. Duchesne, "Study of partial discharge detection in motors fed by SiC MOSFET and Si IGBT inverters," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Calgary, AB, Canada, Jun. 2019, pp. 497–500.

[88] D. R. Meyer, A. Cavallini, L. Lusuardi, D. Barater, G. Pietrini, and A. Soldati, "Influence of impulse voltage repetition frequency on RPDIV in partial vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 3, pp. 873–882, Jun. 2018.

[89] L. Lusuardi, A. Cavallini, P. Mancinelli, G. De La C. Manuel, J. M. Martínez-Tarifa, and G. Robles, "Design criteria for inverter-fed type I motors," in *Proc. IEEE Int. Conf. Dielectr. (ICD)*, Montpellier, France, Jul. 2016, pp. 605–608.

[90] T. S. Williams, "Polymeric materials for aerospace power and propulsion," Mater. Chem. Phys. Branch, NASA Glenn Res. Center, Cleveland, OH, USA, Aug. 2018.

[91] C. Gerada, M. Galea, and A. Kladas, "Electrical machines for aerospace applications," in *Proc. IEEE Workshop Electr. Mach. Des., Control Diagnosis (WEMDCD)*, Turin, Italy, Mar. 2015, pp. 79–84.

[92] F. Miyashiro, N. Iwase, A. Tsuge, F. Ueno, M. Nakahashi, and T. Takahashi, "High thermal conductivity aluminum nitride ceramic substrates and packages," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 13, no. 2, pp. 313–319, Jun. 1990.

[93] M. Stark, "A decade of vacuum pressure impregnation," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Chicago, IL, USA, Oct. 1983, pp. 202–203.

[94] D. Evans, J. Knaster, and H. Rajainmaki, "Vacuum pressure impregnation process in superconducting coils: Best practice," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 4202805.

[95] N. E. Frost, D. Hughes, D. Laurenty, G. H. Miller, and V. R. Isola, "A review of vacuum pressure impregnation procedures for form wound stators," in *Proc. Electr. Insul. Conf. Electr. Manuf. Coil Winding Technol. Conf.*, Indianapolis, IN, USA, 2003, pp. 641–644.

[96] A. Gegenava, A. Khazanov, and B. Moore, "Evaluation of electrical insulation quality for high voltage stator windings machines through visual inspection of dissected coils," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Montreal, QC, USA, Jun. 2016, pp. 156–161.

[97] R. D. Middlebrook, "Input filter considerations in design and application of switching regulators," in *Proc. IEEE Ind. Appl. Soc. Conf.*, 1976, pp. 94–107.

[98] C. M. Wildrick, F. C. Lee, B. H. Cho, and B. Choi, "A method of defining the load impedance specification for a stable distributed power system," *IEEE Trans. Power Electron.*, vol. 10, no. 3, pp. 280–285, May 1995.

[99] S. D. Sudhoff, S. F. Glover, P. T. Lamm, D. H. Schmucker, D. E. Delisle, and S. P. Karatsinides, "Admittance space stability analysis of power electronic systems," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 36, no. 3, pp. 965–973, Jul. 2000.

[100] M. Armstrong, C. Ross, D. Phillips, and M. Blackwelder, "Stability, transient response, control, and safety of a high-power electric grid for turboelectric propulsion of aircraft," NASA, Washington, DC, USA, Tech. Rep., CR-2013-217865, Jun. 2013.

[101] L. Paulsson *et al.*, "High-frequency impacts in a converter-based back-to-back tie; the eagle pass installation," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1410–1415, Oct. 2003.

[102] G. Pietrini, D. Barater, G. Franceschini, P. Mancinelli, and A. Cavallini, "An open problem for more electrical aircraft (MEA): How insulation systems of actuators can be qualified?" in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Milwaukee, WI, USA, Sep. 2016, pp. 1–8.

[103] *Insulation Degradation under Fast, Repetitive Voltage Pluses*, document CIGRE WG D1.43: Sep. 2017.

[104] U. Patel, S. H. Jayaram, A. El-Hag, and R. Seetahpathy, "MV cable termination failure assessment in the context of increased use of power electronics," in *Proc. Electr. Insul. Conf. (EIC)*, Annapolis, MD, USA, Jun. 2011, pp. 418–422.

[105] Y. Ohki and E. Al, "Role of the voltage zero-crossing in the growth of water trees—Effect of superposition method of a high-frequency voltage and a low-frequency voltage," in *Proc. Int. Conf. Condition Monitor. Diagnosis*, Beijing, China, 2008, pp. 328–331.

[106] T. Maeda and E. Al, "Effect of the applied voltage frequency on the water tree shape in polyethylene," in *Proc. IEEE Int. Conf. Solid Dielectr. (ICSD)*, Toulouse, France, vol. 1, Jul. 2004, pp. 276–279.

[107] J. Kurek, "Aircraft wiring degradation study," U.S. Dept. Transp., Federal Aviation Admin., Washington, DC, USA, Tech. Rep. DOT/FAA/AR-08/2, 2008.

[108] I. T. Kiely, P. J. Norman, and B. G. Stewart, "Modelling the impact of ground planes on aircraft transmission cable impedance," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Richland, WA, USA, Oct. 2019, pp. 299–302.

[109] A. B. J. M. Driessen, J. van Duivenbode, and P. A. A. F. Wouters, "Partial discharge detection for characterizing cable insulation under low and medium vacuum conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 1, pp. 306–315, Feb. 2018.

[110] H. Schefer, L. Fauth, T. H. Kopp, R. Mallwitz, J. Friebe, and M. Kurrat, "Discussion on electric power supply systems for all electric aircraft," *IEEE Access*, vol. 8, pp. 84188–84216, 2020.

[111] T. S. Williams, "Nature-inspired motivation for developing self-healable electrical insulation," Mater. Struct. Division, NASA Glenn Res. Center, Cleveland, OH, USA, Tech. Rep. GRC-E-DAA-TN53154, Mar. 2018.

[112] E. E. Shin, "Development of high voltage micro-multilayer multi-functional electrical insulation (MMEI) system," in *Proc. AIAA/IEEE Electr. Aircr. Tech. Symp. (EATS)*, Indianapolis, IN, USA, Aug. 2019, pp. 1–14.

[113] A. Woodworth, E. E. Shin, and M. Lizcano, "High voltage insulation for electrified aircraft," in *Proc. EnergyTech, IX Center*, Cleveland, OH, USA, 2018, pp. 1–2.

[114] E. E. Shin, D. A. Scheiman, and M. Lizcano, "Lightweight, durable, and multifunctional electrical insulation material systems for high voltage applications," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp.*, Cincinnati, OH, USA, Jul. 2018, pp. 1–21.

[115] T. S. Williams, "Self-healable electrical insulation for high voltage applications," in *Proc. ACS Spring Nat. Conf.*, San Francisco, CA, USA, 2017, pp. 1–15.

[116] K. L. Gordon, R. K. Penner, P. B. Bogert, W. T. Yost, and E. J. Siochi, "Puncture self-healing polymers for aerospace applications," in *Proc. Amer. Chem. Soc. Nat. Meeting Expo.*, Denver, CO, USA, 2011, pp. 1–11.

[117] L. Lusaurdi, A. Cavallini, and M. Degano, "The impact of impulsive voltage waveforms on the electrical insulation of actuators for more electrical aircraft (MEA)," in *Proc. IECON 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Beijing, China, Oct. 2017, pp. 4414–4418.

[118] W. Pfeiffer, "High-frequency voltage stress of insulation: Methods of testing," *IEEE Trans. Electr. Insul.*, vol. 26, no. 2, pp. 239–246, Apr. 1991.

[119] M. Borghei and M. Ghassemi, "Characterization of partial discharge activities in WBG power modules under low-pressure condition," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, Rutherford, NJ, USA, 2020, pp. 297–300.

[120] M. Borghei and M. Ghassemi, "A finite element analysis model for partial discharges in silicone gel under a high slew rate, high-frequency square wave voltage in low-pressure conditions," *Energies*, vol. 13, no. 9, p. 2152, May 2020.

[121] M. Borghei and M. Ghassemi, "Effects of low-pressure condition on partial discharges in WBG power electronics modules," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Knoxville, TN, USA, Jun. 2020, pp. 199–202.

[122] M. Ghessemi, "Geometrical techniques for electric field control in (Ultra) wide bandgap power electronics modules," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Jun. 2018, pp. 589–592.

[123] M. M. Tousi and M. Ghassemi, "Combined geometrical techniques and applying nonlinear field dependent conductivity layers to address the high electric field stress issue in high voltage high-density wide bandgap power modules," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 1, pp. 305–313, Feb. 2020.

[124] M. M. Tousi and M. Ghassemi, "Characterization of nonlinear field dependent conductivity layer coupled with protruding substrate to address high electric field issue within high-voltage high-density wide bandgap power modules," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 1, pp. 343–350, Mar. 2020.

[125] N. Wang, I. Cotton, J. Robertson, S. Follmann, K. Evans, and D. Newcombe, "Partial discharge control in a power electronic module using high permittivity non-linear dielectrics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 4, pp. 1319–1326, Aug. 2010.

[126] T. A. T. Vu, J.-L. Auge, and O. Lesaint, "Low temperature partial discharge properties of silicone gels used to encapsulate power semiconductors," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Aug. 2009, pp. 421–424.

[127] H. Gui *et al.*, "Review of power electronics components at cryogenic temperatures," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 5144–5156, May 2020.

[128] R. Gardner, I. Cotton, C. Emersic, S. Rowland, and R. Freer, "Thermal stresses of conformal coating on printed circuit boards," in *Proc. IEEE Electr. Insul. Conf.*, Seattle, WA, USA, 2015, pp. 106–109.

[129] C. Emersic, R. Lowndes, I. Cotton, S. Rowland, and R. Freer, "Degradation of conformal coatings on printed circuit boards due to partial discharge," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 4, pp. 2232–2240, Aug. 2016.

[130] C. Emersic, R. Lowndes, I. Cotton, S. Rowland, and R. Freer, "Observations of breakdown through printed circuit board polymer coatings via a surface pollution layer," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2570–2578, Aug. 2017.

[131] C. Emersic, C. Zhang, I. Cotton, R. Lowndes, S. Rowland, and R. Freer, "Degradation of printed circuit board coatings due to partial discharge," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Seattle, WA, USA, Aug. 2015, pp. 420–423.

[132] C. Emersic, R. Lowndes, I. Cotton, S. Rowland, and R. Freer, "The effects of pressure and temperature on partial discharge degradation of silicone conformal coatings," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 2986–2994, Oct. 2017.

[133] I. Cotton, R. Gardner, D. Schweickart, D. Grosean, and C. Severns, "Design considerations for higher electrical power system voltages in aerospace vehicles," in *Proc. IEEE Int. Power Modulator High Voltage Conf.*, San Francisco, CA, USA, Jul. 2016, pp. 57–61.

[134] B. Du, L. Gu, and Y. Liu, "Application of nonlinear methods in tracking failure test of printed circuit boards under reduced pressure," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 548–554, Apr. 2010.

[135] W. Yongxing, D. Enyuan, C. Jiyuan, Z. Jiyan, and D. Koenig, "Arc tracking properties of the aging wires in aircraft," in *Proc. Int. Symp. Sys. Cont. Aerosp. Astron.*, Shenzhen, China, 2008, pp. 462–466.

[136] R. Arora and W. Mosch, *High Voltage and Electrical Insulation Engineering*. Hoboken, NJ, USA: Wiley, 2011.

[137] G.-J. Zhang, G.-Q. Su, B.-P. Song, and H.-B. Mu, "Pulsed flashover across a solid dielectric in vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 6, pp. 2321–2339, Dec. 2018.

[138] H. Kirkici, "Surface flashover and dielectric materials for space environment," in *Proc. Int. Electr. Electron. Eng.*, 1999, pp. 31–37.

[139] S. Raetzke and J. Kindersberger, "Role of interphase on the resistance to high-voltage arcing, on tracking and erosion of silicone/SiO2 nanocomposites," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 607–614, Apr. 2010.

[140] M. Suchitra, N. M. Renukappa, C. Ranganathaiah, and J. S. Rajan, "Correlation of free space length and surface energy of epoxy nanocomposites to surface tracking," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 6, pp. 2129–2138, Dec. 2018.

[141] B. Du, Y. Liu, and H. Liu, "Effects of low pressure on tracking failure of printed circuit boards," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 5, pp. 1379–1384, Oct. 2008.

[142] F. R. Frontzek, D. Konig, M. D. Judd, and H. J. Reher, "Fault arc propagation on cables for space applications in vacuum, oxygen-enriched air and air," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 2, no. 2, pp. 190–197, Apr. 1995.

[143] J. Hanson and D. Koenig, "Fault arcs effects in cable bundles for space applications in vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 4, no. 4, pp. 394–399, Aug. 1997.

[144] S. Kumagai and N. Yoshimura, "Tracking and erosion of HTV silicone rubber and suppression mechanism of ATH," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 8, no. 2, pp. 203–211, Apr. 2001.

[145] J. Hanson, D. Konig, M. Judd, and H. J. Reher, "Fault arc tests in cable bundles under microgravity conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 7, no. 6, pp. 804–811, Dec. 2000.

[146] R. Latham, "High voltage vacuum insulation: Basic concepts and technological practice," Lightning Source Inc, La Vergne, TN, USA, 1995.

[147] H. C. Miller, "Flashover of insulators in vacuum: Review of the phenomena and techniques to improved holdoff voltage," *IEEE Trans. Electr. Insul.*, vol. 28, no. 4, pp. 512–527, Aug. 1993.

[148] H. C. Miller, "Surface flashover of insulators," *IEEE Trans. Electr. Insul.*, vol. 24, no. 5, pp. 765–786, Oct. 1989.

[149] F. Hegeler, G. Masten, H. Krompholz, and L. Hatfield, "High speed and high resolution diagnostics for the early phase of dielectric surface flashover," in *Proc. Conf. Rec. IEEE Int. Symp. Electr. Insul.*, Baltimore, MD, USA, Jun. 1992, pp. 262–265.

[150] J. D. Smith and L. L. Hatfield, "Measurements of the effects of surface roughness on flashover," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, 1988, pp. 47–52.

[151] S. Li, "Improvement of surface flashover in vacuum," *High Voltage*, vol. 5, no. 2, pp. 122–133, Apr. 2020.

[152] A. Watson, "Pulsed flashover in vacuum," *J. Appl. Phys.*, vol. 38, no. 5, pp. 2019–2023, Apr. 1967.

[153] A. S. Pillai and R. Hackam, "Surface flashover of conical insulators in vacuum," *J. Appl. Phys.*, vol. 56, no. 5, pp. 1374–1381, Sep. 1984.

[154] H. Kirkici, M. Serkan, and K. Koppisetty, "Nano/micro dielectric surface flashover in partial vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 4, pp. 790–795, Aug. 2007.

[155] Y. Ohki and K. Yahagi, "Temperature dependence of surface flashover voltage of polyethylene in vacuum," *J. Appl. Phys.*, vol. 46, no. 8, pp. 3695–3696, Aug. 1975.

[156] Z.-J. Zhang, X.-Q. Zheng, W.-B. Wu, P. Yang, and P. Peng, "DC surface flashover characteristics on polyimide under different temperature in vacuum," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, Oct. 2013, pp. 468–471.

[157] A. Al-Taie *et al.*, "Understanding surface flashover strength in cryogenic helium gas for superconducting devices," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[158] Z. An *et al.*, "Improved flashover performance and tracking resistance of silicone rubber by direct fluorination," *J. Appl. Polym. Sci.*, vol. 137, no. 15, p. 48556, Apr. 2020.
[159] Q. Huang, S. Li, T. Zhang, F. Ni, and J. Li, "Improvement of surface flashover characteristics about 45° insulator configuration in vacuum by a new organic insulation structure," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 6, pp. 2115–2122, Dec. 2011.
[160] S. Li, Y. Nie, W. Wang, L. Yang, and D. Min, "Surface flashover performance of phenolphthalein modified LDPE in vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 3215–3223, Oct. 2016.
[161] G. D. Cooper and M. Prober, "The action of oxygen corona and of ozone on polyethylene," *J. Polym. Sci.*, vol. 44, no. 144, pp. 397–409, Jun. 1960.
[162] K. D. Wolter, M. T. Shaw, and J. F. Johnson, "Corona degradation of polyethylene under multiple stress conditions," in *Proc. IEEE Int. Conf. Electr. Insul.*, Jun. 1980, pp. 22–24.
[163] Y. Suzuoki, T. Mizutani, and M. Ieda, "Electron-beam induced conduction in some polymers," *Jpn. J. Appl. Phys.*, vol. 15, no. 9, pp. 1665–1668, Sep. 1976.
[164] L. M. Beckley, T. J. Lewis, and D. M. Taylor, "Electron-beam-induced conduction in polyethylene terephthalate films," *J. Phys. D, Appl. Phys.*, vol. 9, no. 9, pp. 1355–1365, Jun. 1976.
[165] G. G. Karady, M. D. Sirkis, and J. R. Oliva, "Degrading effect of high-altitude corona on electronic circuit boards," *IEEE Trans. Electr. Insul.*, vol. 26, no. 6, pp. 1216–1219, Dec. 1991.
[166] C. Qian *et al.*, "Thermal management on IGBT power electronic devices and modules," *IEEE Access*, vol. 6, pp. 12868–12884, 2018.
[167] J. Biela, M. Schweizer, S. Waffler, B. Wrzecionko, and J. W. Kolar, "SiC vs. Si-Evaluation of potentials for performance improvement of power electronics converter systems by SiC power semiconductors," *Mater. Sci. Forum*, vols. 645–648, pp. 1101–1106, Apr. 2010.
[168] P. J. Wang, J. S. Kim, and C. C. Lee, "A new bonding technology dealing with large CTE mismatch between large Si chips and cu substrates," in *Proc. 58th Electron. Compon. Technol. Conf.*, Lake Buena Vista, FL, USA, May 2008, pp. 1562–1568.
[169] M. H. M. Sathik, S. Prasanth, F. Sasongko, S. K. Padmanabhan, J. Pou, and R. Simanjorang, "A dynamic thermal controller for power semiconductor devices," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, San Antonio, TX, USA, Mar. 2018, pp. 2792–2797.
[170] J. Gerhold, "Potential of cryogenic liquids for future power equipment insulation in the medium high voltage range," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 878–890, Dec. 2002.
[171] M. Blaz and M. Kurrat, "Studies of breakdowns in liquid nitrogen at different pressures between rogowski electrodes," *Phys. Procedia*, vol. 36, pp. 1330–1336, 2012.
[172] J. Gerhold, "Cryogenic liquids—A prospective insulation basis for future power equipment," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 1, pp. 68–75, Feb. 2002.
[173] K. R. Davey, J. D. Herbst, J. Bravo, R. Ricket, and B. Gamble, "High speed generator trade study," in *Proc. ASNE Electr. Mach. Technol. Symp.*, Philadelphia, PA, USA, 2006, pp. 1–8.
[174] K. S. Haran *et al.*, "High power density superconducting rotating machines—Development status and technology roadmap," *Supercond. Sci. Technol.*, vol. 30, no. 12, 2017, Art. no. 123002.
[175] S. S. Kalsi, K. A. Hamilton, and R. A. Badcock, "Superconducting rotating machines for aerospace applications," in *Proc. Joint Propulsion Conf.*, 2018, p. 4796.
[176] C. A. Luongo *et al.*, "Next generation more-electric aircraft: A potential application for HTS superconductors," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1055–1068, Jun. 2009.
[177] D. Dezhin, I. Dezhina, and R. Ilyasov, "Superconducting propulsion system with LH2 cooling for all-electric aircraft," *J. Phys. Conf.*, vol. 1559, Jun. 2020, Art. no. 012143.
[178] S. Woo-Ju, H. Jae-Sang, S. Jae-Kyu, L. Jong-Geon, and L. Bang-Wook, "Breakdown characteristics of liquid nitrogen for transmission-class superconducting electric equipment," in *Proc. Condition Monitor. Diagnosis (CMD)*, 2012, pp. 766–769.
[179] I. Sauers and E. Tuncer, "Strategic dielectrics R&D for HTS and other OE applications," in *Proc. DOE Peer Rev.*, 2008, p. 32.
[180] D. Swaffield, P. Lewin, G. Chen, and S. Swingler, "Partial discharge characterization of streamers in liquid nitrogen under applied AC voltages," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 635–646, Jun. 2008.
[181] F. Krahenbuhl *et al.*, "Properties of electrical insulating materials at cryogenic temperatures: A literature review," *IEEE Elect. Insul. Mag.*, vol. 10, no. 4, pp. 10–22, Jul. 1994.
[182] P. Cheetham, C. Park, C. H. Kim, L. Graber, and S. V. Pamidi, "Dielectric properties of cryogenic gas mixtures for superconducting power applications," in *Proc. IOP Conf. Mater. Sci. Eng.*, vol. 278, p. 12040, Dec. 2017.
[183] C. Park, L. Graber, and S. Pamidi, "The dielectric properties of gaseous cryogen mixtures of He, H_2, Ne and N_2 in a temperature range of 50–80 K at pressures up to 2.0 MPa," *J. Appl. Phys.*, vol. 121, no. 8, p. 83304, Feb. 2017.
[184] W. G. Garlick, "Power system applications of high temperature superconductors," *Cryogenics*, vol. 37, no. 10, pp. 649–652, Jan. 1997.
[185] J. Rivenc *et al.*, "An evaluation of superconducting power cables for airborne application," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp.*, Cincinnati, OH, USA, Jul. 2018, pp. 1–21.
[186] S. Pamidi, C. H. Kim, and L. Graber, "High-temperature superconducting (HTS) power cables cooled by helium gas," in *Superconductors in the Power Grid: Materials and Applications*. Cambridge, U.K.: Woodhead Publishing, 2015, ch. 7, pp. 225–260.
[187] H. Suzuki, T. Takahashi, T. Okamoto, S. Akita, and Y. Ozawa, "Electrical insulation characteristics of cold dielectric high temperature superconducting cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 952–957, Dec. 2002.
[188] W. G. Dunbar and W. J. Seabrook, *High Voltage Design Guide for Airborne Equipment*. Seattle, WA, USA: Boeing Aerospace, 1976.
[189] H. G. Cheon, D. S. Kwag, J. H. Choi, H. J. Kim, J. W. Cho, and S. H. Kim, "A study on thickness effect of HTS cable for insulation design," *J. Phys. Conf.*, vol. 43, no. 1, pp. 889–892, 2006.
[190] P. Cheetham, W. Kim, C. H. Kim, S. V. Pamidi, L. Graber, and H. Rodrigo, "Use of partial discharge inception voltage measurements to design a gaseous helium cooled high temperature superconducting power cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 1, pp. 191–199, Feb. 2017.
[191] J. A. Demko *et al.*, "Cryostat vacuum thermal considerations for HTS power transmission cable systems," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1930–1933, Jun. 2003.
[192] Z.-Y. Li, W.-F. Sun, and H. Zhao, "Significantly improved electrical properties of photo-initiated auxiliary crosslinking EPDM used for cable termination," *Polymers*, vol. 11, no. 12, p. 2083, Dec. 2019.
[193] M. Hazeyama, T. Kobayashi, N. Hayakawa, S. Honjo, T. Masuda, and H. Okubo, "Partial discharge inception characteristics under butt gap condition in liquid nitrogen/PPLP composite insulation system for high temperature superconducting cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 939–944, Dec. 2002.
[194] H. Rodrigo, D. Kwag, L. Graber, B. Trociewitz, and S. Pamidi, "AC flashover voltages along epoxy surfaces in gaseous helium compared to liquid nitrogen and transformer oil," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–6, Jun. 2014.
[195] B. K. Fitzpatrick, J. T. Kephartl, and E. M. Golda, "Characterization of gaseous helium flow cryogen in a flexible cryostat for naval applications of high temperature superconductors," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1752–1755, Jun. 2007.
[196] P. Cheetham, W. Kim, C. H. Kim, L. Graber, H. Rodrigo, and S. Pamidi, "Enhancement of dielectric strength of cryogenic gaseous helium by addition of small mol% hydrogen," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017.
[197] P. Cheetham *et al.*, "Exploration of additive manufacturing for HTS cable components for electric aircrafts," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp.*, Cincinnati, OH, USA, Jul. 2018, pp. 1–13.
[198] O. Maruyama *et al.*, "Development of REBCO HTS power cables," *Phys. Procedia*, vol. 36, pp. 1153–1158, 2012.
[199] R. Bartnikas and K. D. Srivastava, *Power and Communication cables: Theory and Applications*. Hoboken, NJ, USA: Wiley, 2013.
[200] Y. P. Teng *et al.*, "Insulation of HTS power cables and properties of the insulation," *Insul. Mat.*, vol. 1, pp. 59–64, 2005.
[201] L. Jing *et al.*, "Experimental studies on the partial discharge of insulation for high TC superconducting cable," *J. Supercond. Novel Magnetism*, vol. 33, no. 9, pp. 2615–2620, Sep. 2020.
[202] M. Hara and H. Okubo, "Electrical insulation characteristics of superconducting power apparatus," *Cryogenics*, vol. 38, no. 11, pp. 1083–1093, Nov. 1998.

[203] M. Blaz and M. Kurrat, "Influence of bubbles in pressurized liquid nitrogen on the discharge behavior in a homogeneous electric field," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. no. 7700804.

[204] M. Kosaki, "Super electrical insulation of polymers in cryogenic region," in *Proc. Int. Conf. Properties Appl. Dielectr. Mater.*, Nagoya, Japan, 2003, pp. 9–14.

[205] M. Ieda, "Dielectric breakdown process of polymers," *IEEE Trans. Electr. Insul.*, vol. EI-15, no. 3, pp. 206–224, Jun. 1980.

[206] I. Sauers, D. R. James, A. R. Ellis, and M. O. Pace, "High voltage studies of dielectric materials for HTS power equipment," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 922–931, Dec. 2002.

[207] D. R. James, I. Sauers, M. O. Pace, and A. R. Ellis, "High voltage breakdown of solid epoxies at room temperature and in liquid nitrogen," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, Cancun, Mexico, 2002, pp. 542–545.

[208] E. Tuncer *et al.*, "Nanodielectrics for cryogenic applications," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 2354–2358, Jun. 2009.

[209] Y. J. Lee *et al.*, "High voltage dielectric characteristics of epoxy nano-composites in liquid nitrogen for superconducting equipment," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1426–1429, Jun. 2011.

[210] P. Cheetham, J. Viquez, L. Graber, C. Han Kim, H. Rodrigo, and S. Pamidi, "Novel design concept and demonstration of a superconducting gas-insulated transmission line," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017.

[211] P. Cheetham, C. H. Kim, L. Graber, and S. Pamidi, "Practical considerations for the design of a superconducting gas-insulated transmission line for shipboard applications," in *Proc. IEEE Electric Ship Technol. Symp.*, Arlington, VA, USA, Aug. 2017, pp. 292–298.

[212] H. Gui *et al.*, "Characterization of 1.2 kV SiC power MOSFETs at cryogenic temperatures," in *Proc. IEEE Energy Convers. Congr. Expo.*, Portland, OR, USA, Sep. 2018, pp. 7010–7015.

[213] Z. Zhang *et al.*, "Characterization of wide bandgap device for cryogenically-cooled power electronics in aircraft applications," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp.*, Jul. 2018, p. 5006.

[214] Z. Zhang *et al.*, "Characterization of high-voltage high-speed switching power semiconductors for high frequency cryogenically-cooled application," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2017, pp. 1964–1969.

[215] R. L. Patterson, A. Hammond, and S. S. Gerber, "Evaluation of capacitors at cryogenic temperatures for space applications," in *Proc. IEEE Int. Symp. Electr. Insul.*, Jun. 1998, pp. 468–471.

[216] J. Jiang *et al.*, "Optical sensing of partial discharge in more electric aircraft," *IEEE Sensors J.*, vol. 20, no. 21, pp. 12723–12731, Nov. 2020.

[217] R. Giussani, I. Cotton, and R. Sloan, "Comparison of IEC 60270 and RF partial discharge detection in an electromagnetic noise-free environment at differing pressures," in *Proc. IEEE Int. Symp. Electr. Insul.*, San Juan, PR, USA, Jun. 2012, pp. 127–131.

[218] R. Giussani, I. Cotton, and R. Sloan, "Detection of corona with RF methods and spectra analysis," in *Proc. IEEE Int. Symp. Electr. Insul.*, San Juan, PR, USA, Jun. 2012, pp. 132–136.

[219] T. Lebey, B. Cella, T. Billard, and C. Abadie, "Partial discharges in aeronautics: The last frontier?" in *Proc. IEEE 11th Int. Conf. Properties Appl. Dielectr. Mater.*, Sydney, NSW, Australia, Jul. 2015, pp. 268–271.

[220] B. Cella, T. Lebey, and C. Abadie, "Partial discharges measurements at the constituents' level of aerospace power electronics converters," in *Proc. IEEE Electr. Insul. Conf.*, Seattle, WA, USA, Aug. 2015, pp. 274–277.

[221] C. Abadie, T. Billard, S. Dinculescu, and T. Lebey, "On-line non-intrusive PDs' measurements on aeronautical systems," in *Proc. Int. Symp. Electr. Insul. Mater.*, Toyohashi, Japan, 2017, pp. 99–103.

[222] T. Billard, C. Abadie, and T. Lebey, "Recent advances in on-line PDs' detection in power conversion chains used in aeronautics," in *Proc. IEEE Workshop Electr. Mach. Design, Control Diagnosis*, Nottingham, U.K., Apr. 2017, pp. 281–289.

[223] A. Cavallini, L. Versari, and L. Fornasari, "Feasibility of partial discharge detection in inverter-fed actuators used in aircrafts," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena*, Shenzhen, China, Oct. 2013, pp. 1250–1253.

[224] C. Abadie, T. Billard, and T. Lebey, "Influence of pressure on partial discharge spectra," in *Proc. IEEE Electr. Insul. Conf.*, Montreal, QC, Canada, Jun. 2016, pp. 507–510.

[225] C. Abadie, T. Billard, and T. Lebey, "Numerical signal processing methods for partial discharge detection in more electrical aircraft," in *Proc. IEEE Int. Conf. Dielectr.*, Montpellier, France, Jul. 2016, pp. 540–543.

[226] D. L. Schweickart, D. F. Grosjean, X. Liu, D. G. Kasten, and S. A. Sebo, "Partial discharge detection for evaluation of insulation integrity in aerospace electric power system wiring and components," in *Proc. Conf. Rec. 27th Int. Power Modulator Symp.*, Arlington, VA, USA, May 2006, pp. 66–70.

[227] J. Jiang, M. Zhao, Z. Wen, C. Zhang, and R. Albarracín, "Detection of DC series arc in more electric aircraft power system based on optical spectrometry," *High Voltage*, vol. 5, no. 1, pp. 24–29, Feb. 2020.

[228] *High-Voltage Test Techniques—Partial Discharge Measurements*, document IEC 60270, 2000.

[229] *High-Voltage Test Techniques-Measurement of Partial Discharges by Electromagnetic and Acoustic Methods*, document IEC 62478, 2016.

[230] F. Álvarez Gómez, R. Albarracín-Sánchez, F. G. Vecino, and R. G. Arrabé, "Diagnosis of insulation condition of MV switchgears by application of different partial discharge measuring methods and sensors," *Sensors*, vol. 18, no. 3, p. 720, Feb. 2018.

[231] *Rotating Electrical Machines—Part 18-41: Partial Discharge Free Electrical Insulation Systems (Type I) Used in Rotating Electrical Machines Fed From Voltage Converters-Qualification and Quality Control Tests*, document IEC 60034, 2014.

[232] L. Lusuardi, A. Rumi, and A. Cavallini, "Assessment techniques to ensure reliable electrical insulation for more electric transportation," in *Proc. 45th Annu. Conf. IEEE Ind. Electron. Soc.*, Lisbon, Portugal, Oct. 2019, pp. 7083–7087.

[233] L. Lusuardi and A. Cavallini, "The problem of altitude when qualifying the insulating system of actuators for more electrical aircraft," in *Proc. IEEE Int. Conf. Electr. Syst. Aircr., Railway, Ship Propuls. Road Vehicles Int. Transp. Electrific. Conf.*, Nov. 2018, pp. 1–4.

[234] *Rotating Electrical Machines—Part 18-42: Partial Discharge Resistant Electrical Insulation Systems (Type II) Used in Rotating Electrical Machines Fed From Voltage Converters-Qualification Tests*, document IEC 60034, 2017.

[235] *Converter Transformers—Part 1: Transformers for Industrial Applications*, document IEC 61378, 2012.

[236] *Specifications for Particular Types of Winding Wires—Part 0-1: General Requirements—Enameled Round Copper Wire*, document IEC 60317, 2014.

[237] *CSV Method for the Determination of the Proof and the Comparative Tracking Indices of Solid Insulating Materials*, document IEC 60112:2003+AMD1:2009, Geneva, Switzerland, 2009, pp. 1–40.

[238] *Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials*, Standard ASTM D3638-12 ASTM; West Conshohocken, PA, USA, 2012, pp. 1–5.

[239] *Insulation Coordination for Equipment With in Low-Voltage Systems-All Parts*, document IEC 60664, 2020.

[240] *Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV (Um= 36 kV) up to 150 kV (Um = 170 kV)-Test Methods and Requirements*, document IEC 60840, 2020.

[241] *Power Cables With Extruded Insulation and Their Accessories for Rated Voltages From 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV)-All Parts*, document IEC 60502, 2020.

[242] *Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV)-Test Methods and Requirements*, document IEC 62067, 2011.

[243] *Recommendations for Testing of Superconducting Cables*, document Working Group B1.31, CIGRE Technical Brochure 538, 2013.

[244] *Environmental Conditions and Test Procedures for Airborne Equipment*, document DO-160G, RTCA Inc., Dec. 2010.

[245] *Standard Specification for Aircraft Electric Propulsion Systems*, Standard ASTM F3239-19, ASTM International, West Conshohocken, PA, USA, 2019.

[246] *Standard Specification for Electrical Systems for Aircraft With Electric or Hybrid-Electric Propulsion*, Standard ASTM F3316/F3316M-19, ASTM International, West Conshohocken, PA, USA, 2019.

Moein Borghei (Graduate Student Member, IEEE) received the B.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2018, and the M.Sc. degree in electrical engineering from Virginia Tech, Blacksburg, VA, USA, in 2020, where he is currently pursuing the Ph.D. degree with the Bradley Department of Electrical and Computer Engineering.

His research interests include high-voltage engineering, dielectrics, electrical insulation, multiphysics modeling, and transmission line designs.

Mona Ghassemi (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees (Hons.) in electrical engineering from the University of Tehran, Tehran, Iran, in 2007 and 2012, respectively.

She spent two years from 2013 to 2015 researching as a Post-Doctoral Fellow at the High Voltage Laboratory, University of Quebec, Quebec, QC, Canada. She was also a Post-Doctoral Fellow with the Electrical Insulation Research Center, Institute of Materials Science, University of Connecticut, Storrs, CT, USA, from 2015 to 2017. In 2017, she joined the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, USA, as an Assistant Professor. She has published more than 75 refereed technical articles and one book chapter. Her research interests include electrical insulation materials and systems, high-voltage/field technology, multiphysics modeling, electromagnetic transients in power systems, and power system analysis and modeling.

Dr. Ghassemi is an At-Large Member of the Administrative Committee of the IEEE Dielectrics and Electrical Insulation Society (DEIS) for the term 2020–2023, a Corresponding Member of the IEEE Conference Publication Committee of the IEEE Power & Energy Society (PES), an Active Member of several CIGRE working groups and IEEE Task Forces, and a member of the Education Committee of the IEEE DEIS and PES. She received two best paper awards from IEEE-sponsored conferences. She was a recipient of the 2020 National Science Foundation (NSF) CAREER Award and the 2020 Air Force Office of Scientific Research (AFOSR) Young Investigator Research Program (YIP) Award. She is a registered Professional Engineer in the Province of Ontario, Canada, and an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, the *High Voltage* (IET), and the *International Journal of Electrical Engineering Education*.