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Characterization, Multiphysics Modeling and Mitigation of Insulation Material Degradation and Breakdown

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14. ABSTRACT
Wide bandgap (WBG) devices made from materials such as SiC, GaN, Ga2O3, and diamond can tolerate high voltages and currents and are the most promising approach for reducing the size and weight of power management and conversion systems. These systems are envisaged to be widely used in next-generation aircraft, which are expected to be more electric or, possibly, all-electric. However, accelerated aging of solid dielectrics used in various apparatuses for electrification of aircraft under fast (slew rates (dv?dt) ranging from tens to hundreds of kV/?s) and repetitive voltage pulses (frequencies ranging from hundreds of kHz to MHz) originating from WBG-based systems can offset or even be an obstacle to using WBG-based systems. To date, the combination of (1) fast, repetitive voltage pulses with the specifications above, (2) low-pressure environments, and (3) harsh conditions, which are expected to lead to the worst accelerated insulation aging, has not been experimentally or theoretically researched. This lack of experimental and theoretical information prevents us from having a clear understanding of the phenomena behind insulation degradation, which eventually leads to the breakdown of solid dielectrics. Without a clear understanding of these pre-breakdown mechanisms, developing effective methods to mitigate accelerated aging is impossible. The discovery of new dielectrics is one solution to the problem of accelerated aging under the combined conditions described above. However, we believe there is another solution, which we call “critical frequency,” that is in accord with the trend toward increasing the switching frequency of WBG-based systems. Although the lifetime of solid dielectrics and breakdown voltages in air decrease with frequency, they reach a saturation limit at the critical frequency; thus, working above this frequency might resolve the accelerated aging issue. The critical frequency may decrease by a few tens of kHz with decreasing air pressure, making this solution feasible for aeronautical applications. The specific objectives of this project include: (1) Developing “theoretical”-based Multiphysics models to understand phenomena behind i) internal partial discharges (PD) in solid dielectrics, and ii) electrical breakdown in air, under fast, repetitive voltage pulses in low pressure and harsh environments (-60°C - +250°C, and 0-100% humidity; Note: the harsh condition part will be optional research if the resources are available); (2) Carrying out experimental investigations to characterize the influence of the factors in i) and ii) above and validate the models and theories developed in (1); (3) Conducting experimental investigations to identify the critical frequency for (a) various solid dielectrics with gas-filled cavities and (b) various electrode geometries in air; and (4) Developing a Multiphysics theory capable of quantitatively modeling PDs and air breakdown over a wideband frequency to theoretically determine the critical frequency for insulating materials and compare to the experimental data provided in 3). The merit of this proposal lies in its unique blend of experimental investigations and “theoretical”-based Multiphysics modeling of PDs, aging mechanisms, and electrical breakdown.

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1. Accomplishments

1.1 Research Objectives

Wide bandgap (WBG) devices made from materials such as SiC, GaN, Ga_2O_3, and diamond can tolerate high voltages and currents and are the most promising approach for reducing the size and weight of power management and conversion systems. These systems are envisaged to be widely used in next-generation aircraft, which are expected to be more electric or, possibly, all-electric. However, accelerated aging of solid dielectrics used in various apparatuses for electrification of aircraft under fast (slew rates (dv/dt) ranging from tens to hundreds of kV/µs) and repetitive voltage pulses (frequencies ranging from hundreds of kHz to MHz) originating from WBG-based systems can offset or even be an obstacle to using WBG-based systems. To date, the combination of (1) fast, repetitive voltage pulses with the specifications above, (2) low-pressure environments, and (3) harsh conditions, which are expected to lead to the worst accelerated insulation aging, has not been experimentally or theoretically researched. This lack of experimental and theoretical information prevents us from having a clear understanding of the phenomena behind insulation degradation, which eventually leads to the breakdown of solid dielectrics. Without a clear understanding of these pre-breakdown mechanisms, developing effective methods to mitigate accelerated aging is impossible.

The discovery of new dielectrics is one solution to the problem of accelerated aging under the combined conditions described above. However, we believe there is another solution, which we call "critical frequency," that is in accord with the trend toward increasing the switching frequency of WBG-based systems. Although the lifetime of solid dielectrics and breakdown voltages in air decrease with frequency, they reach a saturation limit at the critical frequency; thus, working above this frequency might resolve the accelerated aging issue. The critical frequency may decrease by a few tens of kHz with decreasing air pressure, making this solution feasible for aeronautical applications.

The specific objectives of this project include:

(1) Developing "theoretical"-based Multiphysics models to understand phenomena behind i) internal partial discharges (PD) in solid dielectrics, and ii) electrical breakdown in air, under fast, repetitive voltage pulses in low pressure and harsh environments (-60°C - +250°C, and 0-100% humidity; <u>Note:</u> the harsh condition part will be optional

research if the resources are available);

(2) Carrying out experimental investigations to characterize the influence of the factors in i) and ii) above and validate the models and theories developed in (1);

(3) Conducting experimental investigations to identify the critical frequency for (a) various solid dielectrics with gas-filled cavities and (b) various electrode geometries in air; and

(4) Developing a Multiphysics theory capable of quantitatively modeling PDs and air breakdown over a wideband frequency to theoretically determine the critical frequency for insulating materials and compare to the experimental data provided in 3).

The merit of this proposal lies in its unique blend of experimental investigations and "theoretical"-based Multiphysics modeling of PDs, aging mechanisms, and electrical breakdown.

1.2 Details of Accomplishments

Even though achieving carbon-free and reduced NO_x emission transportation is a prevailing goal, the aviation industry is in its infancy to arrive at passenger-class all-electric aircraft (AEA) properly operating over commercial missions. Challenges are mainly associated with the components of the aircraft electric power system (EPS). Considering today's technologies, power electronics components are not capable of sustaining tens of megawatts of required power during takeoff and meet aviation limits in terms of size, weight, and cost at the same time. The state-of-the-art electrochemical energy units (EEUs), including battery, fuel cell, and supercapacitor, cannot provide the 25–30-MW thrust power needed for the takeoff, and electrical circuit breakers (CBs) are not able to clear a fault in a large AEA propulsion system, and multimegawatt electric drives/motors can barely be found being able to provide 2–3-MW thrust power so that they can be employed in a distributed propulsion architecture. Taking the mentioned challenges into account, we prepared two articles published in the IEEE Transactions on Transportation Electrification [1] and IEEE Access [2] to tackle challenges associated with protection devices, EEUs, electric machines, and other powertrain components in passenger class more electric aircraft (MEA) and AEA and presented promising solutions using an envisioned medium voltage direct current ±5-kV EPS for an AEA, all-electric NASA N3-X aircraft. Based on findings and discussions made through these articles, we concluded that although technology advancements are essential in all research areas, high-voltage wide bandgap electrical CBs, Li-air and Li-S batteries with >1000-kW/kg specific power, and multimegawatt superconducting electric machines will turn a commercialized passenger class AEA into reality within the next 20–30 years.

While current commercial aircraft operate at voltages below 1 kV, it is widely accepted that higher operating voltages are 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 in 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. As one of the major activities in this project, challenges associated with the electrical insulation design of future aircraft were critically 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, was 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 were investigated. Findings from this critical and comprehensive review identifying technical gaps and future research needs were published in the IEEE Transactions on Transportation Electrification [3].

Toward developing “theoretical”-based Multiphysics models for air discharge, the influence of needle electrode geometry on the behavior of gas discharge plasmas was investigated. The findings of this study highlight the significance of considering not only the radius of curvature but also the overall geometry and the location of open artificial boundaries in simulation of needle-plane electrode systems. The simulations demonstrated that elliptic needles can generate denser plasmas with increased magnitude and frequency of Trichel pulses compared to hyperbolic needles. Additionally, circle-with-tangents geometries exhibited diverse discharge characteristics with the tangent angle playing a crucial role. These studies were presented in [4, 5]. In [4, 5], numerical simulations were utilized to conduct a thorough examination of how different needle electrodes, characterized by conic cross-sections, influence negative corona discharge. By focusing on Trichel current pulses, we aimed to gain valuable insights into the behavior of gas discharge plasma under varying geometric conditions. The needle cathodes introduced and examined in this research encompass hyperboloid, paraboloid, and ellipsoid shapes, with differing eccentricities but a consistent radius of curvature. Emerging from the intensified electric field concentration near the tip of narrower needle electrodes (i.e., lower degree of electrostatic field uniformity η) associated with lower eccentricities, significant unprecedented trends became apparent. Below, we outline significant conclusions derived from our analysis:

- The dominant factor influencing Trichel pulse characteristics is the eccentricity of the conic cross-sectional needle cathodes, with the transition in cathode geometric shape showing no abrupt changes.
- An inverse relationship exists between the eccentricity of the conic cross-sectional needle cathodes and the magnitude of the resulting Trichel current pulse. In other words, narrower needles produce higher Trichel pulse magnitudes. This trend demonstrates an almost linear behavior across a wide range of eccentricity values.
- A direct relationship exists between the eccentricity of the conic cross-sectional needle cathodes and the timing of Trichel pulse occurrence. This implies that needles with lower eccentricities, representing narrower bodies, lead to a higher frequency of pulsating discharge current. This behavior exhibits a non-linear pattern, where increased needle width leads to more significant delays in pulse occurrence.
- While transitions in cathode geometric shape do not yield deviations from expected trends, a consistent sequence in Trichel current pulse characteristics is evident among conic cross-sectional needles. This sequence is established based on the inherent order of eccentricity values for different conic section types, with elliptic needles demonstrating the highest Trichel pulses magnitude and frequency values, followed by parabolic, and finally hyperbolic needles.
- Despite a declining trend in Trichel pulse train frequency as eccentricities increase, the pulse rise and decay times, as well as pulse width, exhibit nuanced variations in response to changing eccentricities. Specifically, the pulse rise time demonstrates a gradual ascending

pattern, while the pulse's decay and total time follow a distinctive U-shaped trend concerning eccentricity variations.

- The findings of [4, 5] underscore the paramount significance of needle geometries in influencing gas discharge plasma behavior. This study emphasizes the limitations of defining a needle electrode with a conic section profile solely based on its geometric shape type and curvature. Instead, this research delves into a more comprehensive understanding by considering both eccentricity and radius of curvature as defining factors for conic sections. Such precise definitions emerge as essential elements in unraveling the complexities of discharge behavior, pulse dynamics, and the optimization of plasma-based applications.

We also presented a tutorial exploring the intricate realm of gas discharge plasma simulations, offering a profound understanding of its theoretical framework and providing a detailed description of the finite-element simulation process in COMSOL Multiphysics [5]. Firstly, a solid mathematical foundation essential for modeling gas discharge plasmas is established. Subsequently, the key aspects of finite-element simulation for these phenomena are detailed. This includes defining the computational domain, setting appropriate initial and boundary conditions, configuring adaptive meshing, addressing computational challenges, and fine-tuning solver settings. In addition to explaining the theoretical basis of each simulation component, this tutorial provides practical guidance on their implementation within the software. Building upon these foundations, a comprehensive case study, focusing on negative corona discharges as a representative of low-temperature plasmas is discussed. We scrutinize the influence of various needle electrode geometries and applied voltages on the dynamics of negative corona discharges. Utilizing finite element simulations, we analyze the magnitude and temporal characteristics of the Trichel pulses to assess the impact of these parameters. Additionally, the effects of different adaptive meshing strategies, stabilization techniques, time integration methods, and linear system solvers on the convergence, accuracy, and efficiency of the simulations are examined. Indeed, this tutorial explains in detail all the simulation processes and provides a range of comparative and parametric/sensitivity analyses to comprehensively investigate the influence of various parameters, conditions, and settings on the efficiency and outputs of the simulations. This tutorial can serve as a valuable resource for students, researchers, engineers, and practitioners engaged in the dynamic field of gas discharge plasma simulations.

We also studied the intricate relationship between altitude-adjusted atmospheric pressure, gap distance, and partial discharge inception voltage (PDIV) in the sphere-sphere electrode system under applied negative DC voltage [6]. PD behavior was studied under a negative DC voltage for flight-level air pressure and a peculiar pattern in PDIV was observed for different pressures and interelectrode distances. The findings reported in [6] advance our understanding of the underlying mechanisms governing PDs in such configurations, paving the way for more informed design and operation of high-voltage systems, particularly in the context of electric aviation.

The reliability of electrical equipment is closely tied to the health of their insulation system. A well-known symptom of the aging phenomenon in dielectrics is partial discharge (PD) which can occur in all media. Internal PDs in solid dielectrics occur in air-filled voids which are difficult to eliminate thoroughly and may appear simply during the manufacturing process. Although much research on PD measurement for solid dielectrics has been conducted, this is not the case for PD modeling. Besides, the simulation of a case study and its comparison with experimental results can provide further insights into the possibility of other PD sources.

As another major activity in this project, a finite element analysis (FEA) model for internal PD in an air-filled cylindrical void inside a solid dielectric under 60 Hz sinusoidal voltage was developed and its results were published in the IEEE Transactions on Power Delivery [7]. For the estimation of the parameters of the model, experimental data was needed. In [7], we validated our FEA model with the experimental results in the literature. In the continuation of this activity, we did experimental investigations ourselves. To this end, a cylindrical void was artificially made within a 3D-printed polylactic acid (PLA) block. Then, phase-resolved partial discharge (PRPD) patterns were measured for the mentioned samples. Using deterministic PD measurement data, our FEA model was improved. This model can help us understand and explain internal PD behavior in the case of a cylindrical void and study the influence of void size on PD behavior. The results from this work were presented at the 2021 IEEE Electrical Insulation Conference [8].

Then, we used our FEA model to study the behavior of internal PDs in low pressures where lower air pressure accelerates the aging of insulating materials due to PDs. We in [9-12] did put forth an approach to model the PD behavior in an IGBT module under two conditions: (1) Sea level (atmospheric pressure) and (2) Altitude of 18,000 ft. (half atmospheric pressure). Our FEA model is developed in three dimensions to detect the discharges in the silicone gel encapsulant of a WBG-based IGBT module according to the standard IEC 61287-1. In one of the case studies [9, 10], the existence of a single void close to the triple joint of the HV electrode causes PD occurrence in both pressure levels. However, at the lower pressure level, the rate of PD occurrence doubles, and although the intensity of individual PDs decreases, the total amount of produced charge per cycle increases by more than 40%. In the double-void case [9], coupling two voids could be devastating at the cruising altitude and increase the PD intensity by more than 100% compared to the sea-level pressure. The studies presented in [9] can be a foundation for building an online condition monitoring system to determine the extent and severity of internal defects in insulation systems. By measuring PRPD patterns and using our PD model, we may predict the voids' dimension, number, and location.

With the growing concern about the global warming crisis, the electrification of commercial aircraft is targeted to reduce greenhouse gas emissions from the aviation industry. However, the environment that an aircraft operates in provides significant design challenges. Moreover, the technologies that enhance the power density of the powertrain (such as higher voltage levels and wide bandgap devices) lead to severe tension in the insulation systems. The combination of harsh environmental conditions and insulation-threatening technologies raises concern about the reliability of electrical equipment such as power generators, motors, and cables. Since the failure of the insulation system translates into the failure of the entire equipment, it is crucial to investigate the behavior of discharge sources under low-pressure conditions. As another major activity in this project, we developed a dense convolutional neural network (DenseNet) model based on experimental data to separate and classify various sources of corona discharge under low-pressure conditions. The results show that DenseNet models can achieve high accuracy within a reasonable training time. The accurate detection and classification of discharge sources provide the backbone of a dielectric online condition monitoring system (DOCMS) that can actively monitor the health of electrical equipment in an electric aircraft. Results from this work were presented at the *American Institute of Aeronautics and Astronautics (AIAA)/IEEE Electric*

Aircraft Technologies Symposium (EATS) [13] and a recent paper in IEEE Transaction on Dielectrics and Electrical Insulation [14], where we developed a test setup based on standard IEC 60270 and tested different cases of corona discharge (needle-needle, needle-plane, sphere-plane, and sphere-sphere). After preprocessing, the data were converted into PRPD images and fed to three DenseNet models (DenseNet-121, 169, and 201). The results demonstrated the promising performance of all three models (average accuracy >83%).

1.3 How were the results disseminated to communities of interest?

In total, 14 papers, including nine journal papers and five peer-reviewed conference papers, see section Publications, were the results of our activities in this project disseminated to communities of interest.

2. Impacts

2.1 Development of the Principal Discipline(s) of the Project

Electric aircraft have been considered a sustainable replacement for conventional aircraft to address the demand for emission reduction, lower fuel consumption, and lower noise levels. 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 subject to accelerated aging and reduced lifetime at high altitudes and must deal with various challenges, including PDs, arc tracking, and thermal degradation. We believe the achievements explained in Section 1 have a significant impact on the envisioned wide-body all-electric aircraft.

Publications:

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

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[4] M. Hamidieh and M. Ghassemi, “Impact of cathode geometry on negative corona discharge and Trichel pulse characteristics: A comparative analysis of hyperbolic, elliptic, and tangent-circular needle shapes,” *IEEE Transactions on Plasma Science*, To be published.

[5] M. Hamidieh and M. Ghassemi, “Theory and finite-element simulation methodology of gas discharge plasmas: A tutorial,” *IEEE Access*, under review.

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IEEE Trans. Power Delivery, vol. 36, no. 4, pp. 2570-2581, Aug. 2021.

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[11] M. Borghei and M. Ghassemi, "Investigation of low-pressure condition impact on partial discharge in micro-voids using finite-element analysis," *IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 3293-329.

[12] M. Borghei and M. Ghassemi, "Partial discharge investigation in an air-filled cavity inside silicone gel under low-pressure conditions using finite-element analysis," *American Institute of Aeronautics and Astronautics (AIAA)/IEEE Electric Aircraft Technologies Symposium (EATS),* Virtual*, Aug. 11-13, 2021.*

[13] M. Borghei and M. Ghassemi, "Classification of partial discharge in electric aircraft based on short-term behavior of insulation systems," *American Institute of Aeronautics and Astronautics (AIAA)/IEEE Electric Aircraft Technologies Symposium (EATS),* Virtual*, Aug. 11-13, 2021.*

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