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REVIEW

A review on insulation challenges towards electrification of aircraft

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Abstract

Compared to the traditional aircraft, electrification of power system in aircraft has potential to revolutionise the aviation industry. Typically, more-electric aircraft (MEA), even all-electric aircraft has been developed and delivered to decrease the greenhouse gas emission and increase the energy efficiency. The next generation of MEA will operate at high voltage to facilitate the transfer of significant levels of electrical power in an electrified aircraft. However, the higher voltage inevitably leads to an increased risk to the insulation of the electrical components and power system. This study aims to provide a critical overview of the insulation challenges from the perspective of electrified aircraft, typically MEA application. The development of MEA and the special working conditions are explained at the beginning. Then the insulation challenges of power modules, electric machines, aeronautical cables etc. are discussed in detail. Finally, the existing technical barriers and future prospects of insulation for electrified aircraft are summarised. It provides a reference for the future design and test in power system of next generation MEA and related electrified air transportations.

1 | INTRODUCTION

World population is still growing, and is about to reach 10 billion by 2100 [1]. To have a viable aviation transport system for such large population, commercial aeroplanes would double in the next 2 decades [2], causing increased carbon emissions across the globe leading to long-term climate change and a backward push to Net Zero efforts. The carbon emission of the aviation industry exceeds 900 million tons, accounting for 2%–2.5% of the global carbon emission [3]. The greenhouse gas emission of the US aviation industry even accounts for 11% of the national transportation industry [4]. A large amount of carbon emissions exacerbated the rate of global warming. However, the air traffic industry in 2040 is forecasted to be 2.1 times larger than that in 2019, including demand for air passengers, air cargo, aircraft (passenger jets, passenger turboprops, and cargo jets), and aircraft engines [5, 6], according to Worldwide Market Forecast 2020–2040 by Japan Aircraft Development Corporation. In China, aerospace constitutes a strategic industry with major investments [7]. The Commercial

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Aircraft Corporation of China Ltd. has been funded in 2008 to support an expanding air market (with a growth rate reaching 30%) [8]. With the aggravation of the international energy crisis and the enhancement of environmental protection awareness, it has become an international consensus to reduce energy consumption and carbon emissions, and the electrification of aircraft has arisen at the historic moment. A carbon neutral environment is aimed to achieve by 2060 in China as an example [9, 10].

Driven by ambitious goals for the future of aviation, electrified aircraft has emerged as a key enabling technology for concepts ranging from more-electric aircraft (MEA), hybrid-electric propulsion aircraft to all-electric aircraft (AEA) [10, 11]. Even some small-scale electric air transport systems are proposed and demonstrated, such as electric vertical take-off and landing, Urban Air Mobility vehicles [12, 13]. The electrified air transport systems provide an inspiring revolution for the conventional approach.

The aeronautics industry is challenged on many fronts to decrease the dependency on carbon-based fuels, reduce the emissions, and increase the energy efficiency [14]. In fact, electrification of aeroplanes is not only beneficial from the fuel/energy savings, but also good to establish performance metrics like noise reduction, favourable operation cost [15]. Beyond the purview of commercial investment, a suit of investments to meet long-term demands has been carried out by The NASA Aeronautics Research Mission Directorate [16, 17]. Typically, MEA technique aims to increase the use of electrical power to reduce the use of non-propulsive power source, for example, pneumatic, mechanical, and hydraulic [18]. This would bring in significant changes in the electric power system (EPS) in terms of power generation, transmission, and distribution. As an example, Boeing 787 uses electricity to power the equipment such as air conditioning systems and wing ice protection instead of pneumatic systems used in conventional aircraft [19].

MEAs and AEAs use more electrical power than their predecessors. The aircraft electrical system used in MEA/AEA will need to manage a significant power requirement. The voltage increase and frequency variation will help to deliver the increased power ratings efficiently but will also increase the risk of electrical insulation failure. These modifications lead to new types of failure modes, including a higher risk of partial discharge (PD), electric arc and breakdown appearance, which can be potentially harmful. Increasing insulation thickness can decrease the risk, but it will increase the weight of aircraft and decrease the energy efficiency. In addition, the defects are not only affected by electrical stress, but also closely related to environmental and mechanical stresses. Different from the operating environment of power equipment on the ground, air pressure, temperature and humidity vary widely during the course of flight [20]. And during the flight of the MEA, strong vibration, narrow internal space of the fuselage and compact arrangement may lead to insufficient heat dissipation of the equipment, cable wearing and other problems [21]. These further aggravates the risk of insulation failure of electrical equipment of MEA.

In MEA, some electrical components such as electric machines, power module, printed circuit boards (PCBs), aeronautical cables and busbars are responsible for the main power transmission and application functions. The electrical and environmental stresses to which each component is subjected are quite different. The aeronautical cables are distributed throughout the fuselage, so they work within a wide range of temperature, pressure, and humidity. The insulation of electric machine is often subjected to large thermal stress concentration. The insulation of power module is often subjected to high frequency voltage shock. Therefore, the complex stresses bring great challenges to insulation design for different components. If the insulation state of electrical components cannot be timely and effectively detected, it can bring the risk of failure for MEA. Therefore, insulation in electrification of aircraft needs to be evaluated for increased risk of failure.

This paper will provide an overview of the insulation challenge from the perspective of electrified aircraft, typically MEA application. The rest of the review paper is organised as follows. Section 2 is devoted to present the evolutionary process and future trends of MEA, and its insulation risks. Section 3 focuses on the insulation challenges for MEA, categorised as power modules, electric machines, and aeronautical cables. Section 4 lists the identified research needs in regard to the studied field, aiming to serve as future research guidelines that will meet the challenges disclosed throughout this review article. Finally, Section 5 summarises the main ideas and concludes the paper.

2 | MORE ELECTRIC AIRCRAFT AND ITS INSULATION RISKS

2.1 | The more electric aircraft and beyond

A number of emissions and effects from aviation have been considered [22]. Not only those from NO_x, CO_2, but also the emission of particles and the effects of contrails and other aviation-induced cloudiness are paid close attention to. The emissions from aviation industry are not large, but these are at a height of 8–12 km, which have increased effectiveness to cause chemical and aerosol effects relevant to climate change (e.g. cloud formation). These emissions and cloud effects modify the chemical and particle microphysical properties of the upper atmosphere, resulting in changes in radiative forcing of the Earth's climate system, which can potentially lead to climate change impacts and ultimately result in damage and welfare/ecosystem loss as illustrated in Figure 1 [23]. Radiative forcing is the change, radiative flux at the tropopause or top of atmosphere due to a change in an external driver of climate change.

The emergence of MEA can be a good solution to this problem, because using electricity as secondary energy source can significantly reduce emissions. In early aircraft, the proportion of electrical system was small, which was only used for lighting and other basic functions. Over time, the main power in the Boeing family and Airbus family continued to rise, which has reached 250 kW in Boeing 787 and will continue to rise in the future [24].

More-electric aircraft is characterised by the adoption of large-capacity power supply system and electric power actuation technology. The application of speed regulating motors, servo motors and high-speed motors continues to expand in MEA [25]. In order to meet the high-power demand of the electrical system of MEA and further improve the electrification degree and energy density, the power supply voltage of aircraft still needs to be continuously improved. The development trend of power supply voltage and power energy density of MEA in the future is shown in Figure 2. Boeing B787 as the representative of the first generation MEA has achieved 230 V_{AC}, 540 V_{DC} voltage under 1 MW power supply, and the second generation MEA will achieve 1–3 kV power supply voltage, power supply up to 5 MW [26]. According to the estimation of American Astronics Advanced Electronic Systems Company, MEA with voltage rating of 1.5–3 kV and frequency level in kHz range will be developed in 2023–2030 [27]. Around 2050, the power supply voltage of the MEA power supply system is expected to reach 5 kV, and the power supply is more than 10 MW. This development trend presents a whole new challenge for insulation systems in MEA. Once the voltage level reaches the kV level, the insulation system design of MEA will need to be completely reconsidered.

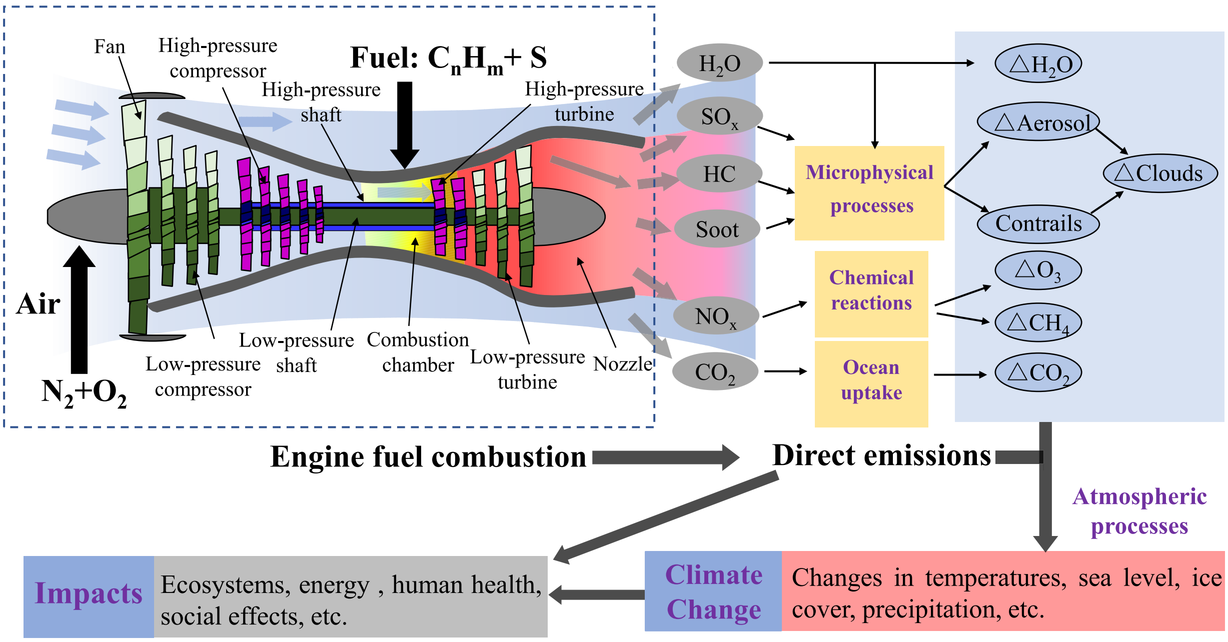

FIGURE 1 Environmental and social impacts of aircraft carbon emissions.

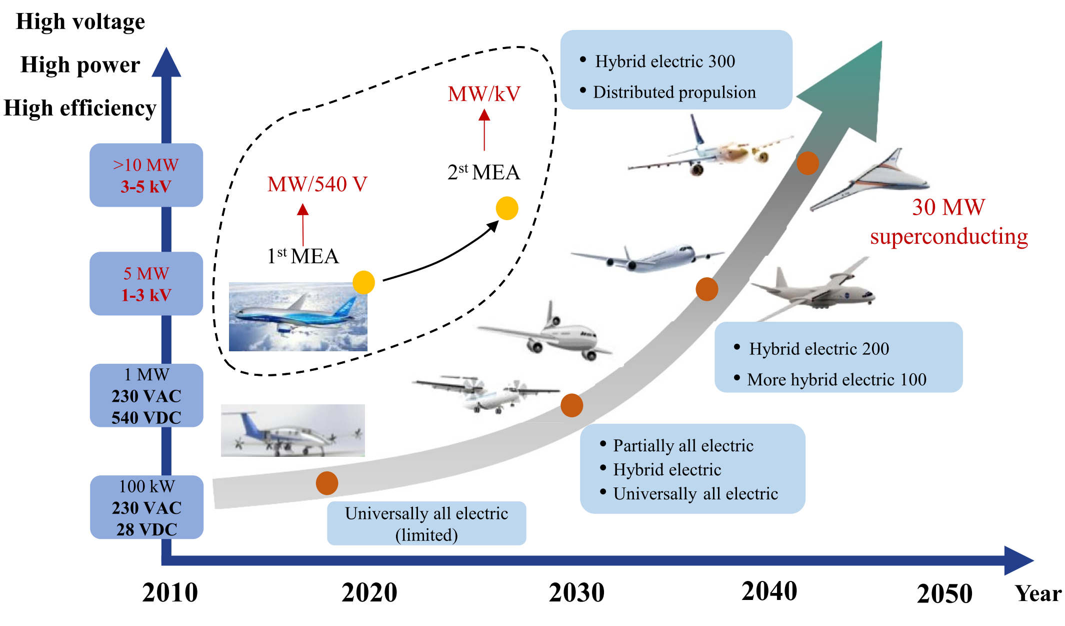

FIGURE 2 The development trend of voltage level and power supply in more-electric aircraft (MEA).

2.2 | Power system in more-electric aircraft

Nowadays, the most common EPS is showed in Figure 3. The DC EPS produces 230 V_{AC} from the generator and auxiliary power unit, 270 V_{DC} from the rectifier, and 28 V_{DC} or 230 V_{AC} from the converter or inverter respectively. The voltage is 230 V_{AC} on the primary alternating current (AC) bus, 115 V_{AC} on the secondary AC bus, 270 V_{DC} on the High Voltage Direct Current (HVDC) bus, and 28 V_{DC} for avionics. In general, DC voltage is generated by hybrid AC electrical power distribution system and rectifiers.

The 270 HVDC EPS concept is now considered as optimal option for future aircraft due to its relative simplicity, flexibility, and unique ability of DC systems to supply an uninterrupted power to electrical loads [28]. Because the control and design of variable frequency AC distribution and power electronics interface remain challenges, this EPS is complex and heavy. In addition to, energy storage component must be added to the power supply in the future, so the EPS should be improved. The selection between a constant system voltage (CSV) and a variable system voltage (VSV) architecture is presented and compared for a battery powered 6 MW electrical drive system in [29]. The optimum voltage level in VSV system was found to be the motor operating voltage whereas for the CSV system it was found to be between the range of 3–4 kV. To increase the voltage, the weight of the system should be taken into account. A preliminary power system sizing study conducted on Single-aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion, for 2.6 MW power application, it shows a potential for cable weight reduction of 1400 kg when increased the voltage level from 540 to 4800 V [30]. However, the impact from insulation material mass increase was not accounted in the study. NASA's N3-X design study suggested adoption of a minimum voltage level of 6 kV in order to capture the system entire weight reduction benefits [31]. Furthermore, for a cryogenically cooled DC system, the busbar voltage of 4.5 kV is recommended when optimised for the system mass accounting for detailed components [32]. The design of EPS not only need to improve voltage level, but also need to add battery system. After the design is completed, the weight, modelling, management, stability, and control should be considered.

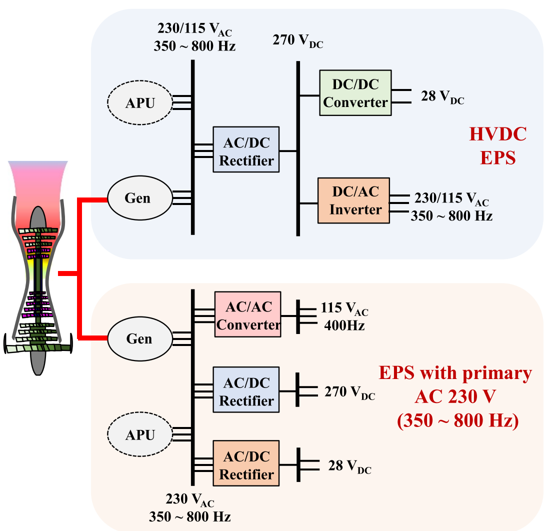

FIGURE 3 A DC High Voltage Direct Current electric power system (EPS) and an alternating current (AC) EPS.

2.3 | Insulation risks

Insulation system is facing many risks during the operation of MEA, among which the breakdown and arc of insulation system are the direct causes of electrical failure of MEA. When a breakdown or arc occurs, it indicates that a serious insulation failure has occurred. Partial discharge belongs to the deterioration phenomenon of insulation system under normal working state. Long-term PD may lead to breakdown or arc of insulation system. The breakdown, arc and PD respectively belong to the insulation system failure and degradation in two levels of the insulating risks. Therefore, this Section reviews the insulation risks and research status of aeronautical cables/busbars, electric machines and power modules/PCBs three electrical components, from the insulation failure (breakdown and arc) and PD two aspects in different work condition.

2.3.1 | Breakdown

It is well known that air pressure tends to decrease as the altitude increases. The aircraft goes from being stationary on the ground to cruising at high altitude over a wide range of air pressure and temperature. Based on data analysis of In-Service Aircraft for a Global Observing System (IAGOS), the combined pressure and temperature density of 324 flights in the last 3 years is analysed, as shown in Figure 4 [33]. The minimum air pressure of the navigation is below 20 kPa and the temperature is between −70 and 40°C. The counts of flights flying at 20 kPa and −50°C is the most. The military aircraft can fly above 50,000 feet (15,200 m), which approximately

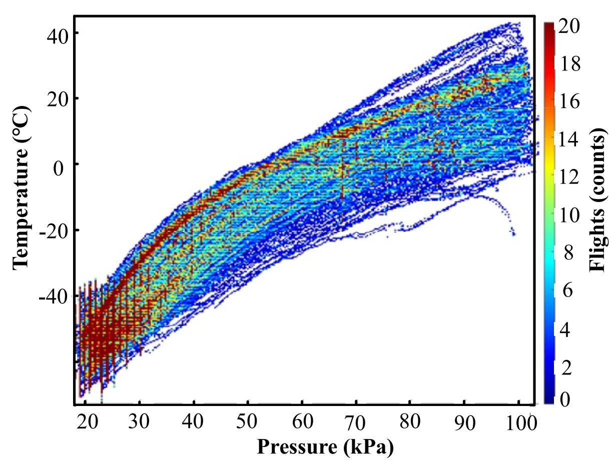

FIGURE 4 The number of flights at different temperatures and pressures.

corresponds to 10 kPa. Therefore, the electric and electronic systems placed in unpressurised areas of aircraft have to withstand a wide pressure range (10–101 kPa). Changes in air pressure and temperature can deeply cause differences in the characteristic of breakdown.

As the principal law to analyse breakdown voltage at low gas pressure, Paschen's Law states that the breakdown voltage (V_b) between two electrodes under a uniform electric field is a function of the product of gas pressure (P) and gap length (d), that is, $V_b = f(P \cdot d)$. According to Paschen's curve as shown in Figure 5, when d is fixed at 2.5 mm, the breakdown voltage reaches a minimum value of V_{bmin} at a specific $P \cdot d$. For air, V_{bmin} = 320–352 V_{pk} (226 V_{rms} ~ 249 V_{rms}) [34, 35]. V_{pk} stands for peak value. V_{rms} stands for average value. The Paschen's Law curves for different gases can also be seen in the figure [36–38]. The breakdown voltage shows a trend of first decreasing and then increasing with the increase of the product of gap distance and air pressure. Townsend theory proposed electron collapse process and secondary electron emission process to explain the Paschen's law at the micro level. The collision ionisation of electrons and space photoionisation are proposed to be the interpretation for self-sustaining discharge under high pressure and long gap by streamer theory.

Electrical systems in the generation of conventional aircraft tend to use a mix of AC and DC systems. DC systems are typically operated at 28 V while the AC system operates at 115 V_{rms} (equivalent to 163 V peak). In such a system there is no possibility of electrical discharge across an air gap during normal operating conditions. However, the supply voltage in the new generation of aircraft, like Boeing B787, is increased to 230 V_{rms} and 540 V_{DC} (±270V), which has exceeded the minimum value of breakdown voltage, which greatly increases the risk of breakdown in MEA.

Raising the operating voltage of future aircraft introduces the prospect of breakdown taking place across air gaps in the electrical system especially once the threshold of 327 V is passed. The air gaps exit between connector pins, between uninsulated busbars and ground planes or within air gaps between insulated cables. In addition, the widely used application of Pulse Width Modulation (PWM) technique on modern aircraft allows the typical pulse voltage change rate in aircraft

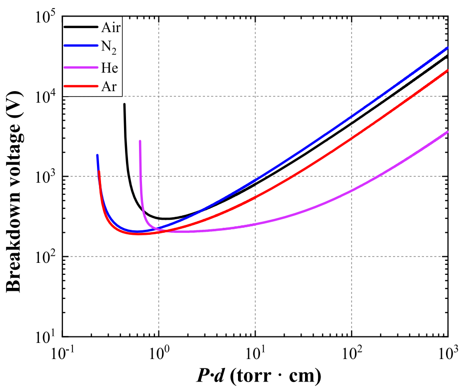

FIGURE 5 Paschen's Law for different gases

power supplies to reach about 1 kV/μs, which may even be doubled or more at the connection between the aircraft cable and the motor. Due to the mismatch between inverter, cable and motor impedance, multiple reflections of the PWM voltage pulses can occur on the windings, resulting in severe overvoltage [39]. Under high frequency pulse voltage, the breakdown voltage of the dielectric decreases with the increase of frequency. It is experimentally confirmed that the breakdown voltage decreases as the applied voltage frequency is increased for point-point electrode geometry in nitrogen [40].

2.3.2 | Partial discharge

Different from breakdown, PD is a kind of abnormal discharge caused by the local electric field concentration. Since PD usually occurs in the gaseous medium adjacent to solid insulation prior to solid insulation failure, it is called 'silent killer' [41]. Partial discharge is an early defect of insulation failure. Long-term PD causes the insulation material to gradually age, thereby reducing the insulation performance, even breakdown and arc fault, and eventually leads to insulation failure, causing huge damage to electrical equipment and even the entire operating system. Therefore, PD detection is also of great significance to ensure the operating reliability of power equipment in a MEA.

Partial discharge is affected by several electrical parameters, such as voltage amplitude, waveform, frequency, and rise time due to the practice of PWM in power system of electrified aircraft [42]. It shows that short rise time square wave voltages are expected to cause more intense discharges with longer durations, and the low-pressure conditions make these harmful changes even worse [43]. In addition, factors such as harsh environment (air pressure, temperature, humidity etc.), electrode shape, and insulating medium properties have an impact on field strength enhancement and PD characteristics [44]. Among them, the low-pressure environment is the most unique operating condition in the aircraft compared with ground equipment, and it is also a very critical factor affecting PD. At the same temperature, the length of the air gap under the pressure of 20 kPa (about 12 km high) must be increased to more than 5 times that under the atmospheric pressure to ensure the same $P \cdot d$ value as that under the atmospheric pressure. Short duration exposure to low temperatures (down to −60°C) has a small effect on partial discharge inception voltage (PDIV) and PD charge. On the other hand, sample exposed for hours to low temperatures (−20 to −60°C) shows a large decrease of PDIV, correlated to a large increase of PD charge [45]. With regard to humidity, when 100% relative humidity condensation occurs, it may impact the PDIV significantly [46]. Therefore, it is challengeable to design the insulation system for the aircraft.

Generally, the minimal onset voltage for PD is around 300 V, but the chance of PD increases significantly at low air pressure. Higher voltage (2–4.5 kV) will definitely introduce great PD risks for the insulation system. Moreover, PD pattern and mechanism at high dv/dt and PWM is far more complex, which has not been adequately studied for MEA application.

Partial discharges usually generate sound, light (mainly ultraviolet, UV), electromagnetic signal, heat, and chemical reactions. Sound propagates with difficulty under low pressure environments, so electromagnetic and UV-visible radiation can be used to detect the weak discharge phenomenon [15, 47].

2.3.3 | Arc tracking

Electrical tracking is one of the failure mechanisms that can cause the electrical systems to fail. In the MEA electrical power systems, a large number of exposed electrodes can be found on insulated gate bipolar translators (IGBTs) [48], PCBs [49], connectors, and terminal blockers [50]. The electrical tracking can be determined as a combination of electric stress and conductive solution applied to the solid organic insulation material, the surface of the insulation material could be carbonised and a permanent conductive path could form on the surface or within the polymeric insulating material [47]. Early symptoms of arc tracking include PDs and corona. Usually, an arc initiates between 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 carbonised conducting paths [47]. The increasing voltage levels of the future MEA/AEA increase the risks of tracking failure. In the aerospace high voltage (HV) system, a typical process of tracking failure (shown in Figure 6) can be divided into four steps, including sediment of contamination, evaporation, dry band arcing, and carbonisation [51]. In this phenomenon, large leakage currents on a wet insulation surface can vaporise 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 localised temperatures in the order of 1000°C. High-temperature causes thermal degradation of the insulation material used and, in the case of polyimide (PI), forms a conductive carbon path [52].

Compared with the ground environment, the dynamic environment of the flight cycles, especially during the descent phase, could deposit much condensation products on the insulation material surfaces. The higher voltage level provides more Joule heating that could accelerate the evaporation [53].

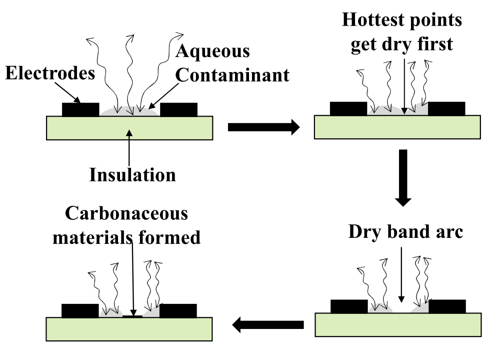

FIGURE 6 A typical process of electrical tracking under wet conditions.

Besides, the higher voltage level intensifies the dry band arcing. As a result, the risks of tracking failure are likely to increase in MEA/AEA. It is necessary to design new creepage distances for preventing tracking failure in future aerospace HV systems.

The process of tracking failure is non-linear and highly depends on contaminations. It is difficult to estimate suitable theoretical creepage distances. Existing design criteria [54, 55] are based on experimental data. International Electrotechnical Commission standards give guidelines for creepage distance selection under different conditions. However, none of these guidelines are suitable for aerospace applications. Besides, the test methods [56, 57] of tracking failure in the standards do not consider the low pressure and dynamic aerospace environment. Li et al. provided a design of a testbed for testing creepage distances in a dynamic aerospace environment [58]. For future investigations, the impacts of the combinations of dynamic aerospace environment parameters could be a challenge for design creepage distance in an aerospace environment.

It has been found that the major effect of pressure on electric arcs was to extend them and to increase the energy dissipated in them respectively by a factor of 2 and by a factor of 1.7 in the worst case, that is to say when the pressure decreases from sea level to the altitude of flight (10 kPa) [59].

The average anti-arcing time under low pressure is longer than that under atmospheric pressure. The arc characteristics are also affected by the insulating material, PI insulation is more easily damaged. The arcing behaviour of Ethylene Tetra Fluoro Ethylene (ETFE) is similar to that of PI. Poly Tetra Fluoro Ethylene (PTFE) insulated arcs are affected by the environment, Self-Extinguishing (SE) mode occurs at atmospheric pressure, while current interruption arc mode occurs only at low pressure [60]. Regarding to gap length, experimental results show that longer gaps exhibit a lower arc voltage with lower arc current, which is different to the arc behaviour observed in shorter electrode gaps [61].

Nowadays, arc fault circuit breakers (AFCBs) are deployed to protect against arcing and tracking in aircraft, which is based on electronic components. According to the AS 6019 standard [62], the AFCB must identify the arc fault and disconnect the circuit affected by the fault within 100 ms once the fault arc occurs. With regard to the next generation of MEAs, more electrical and electronic systems are applied, the use of current AFCBs is questionable [63], so it is required to develop new approaches for an early detection.

3 | INSULATION CHALLENGES FOR MORE-ELECTRIC AIRCRAFT

3.1 | Aeronautical cable and busbar insulation challenges

Aeronautical cable is the fundamental electric element in the power system of aircraft, which is widely distributed on both sides of the cabin and cockpit inside the fuselage, and near the wings and landing gear outside the fuselage. It is used to connect the electric equipment in the power system for power flow, signal control and delivering low-frequency analog/digital signal [21]. With the development of electrification in aircraft, it will be subjected to higher electrical stress with high frequency in the near future. Thicker insulation helps decrease the failure risk as far as possible, but it leads to an increase in weight [21]. Therefore, research on insulation characteristics and optimisation of insulation performance not only ensure the reliable power/signal flow between devices in aircraft, but also improve the economical operation. The insulation of aeronautical cable consists of rubber, Polyvinyl Chloride, Polyamide (PA), silica gel, and PI. With the rapid development and application of fluoropolymers, PTFE, Polyfluorinated Ethylene (FEP) and ETFE have gradually become the mainstream insulating materials owing to the excellent heat resistance and mechanical properties.

Several failures and disasters caused by insulation fault of aeronautical cable occurred in the past. For examples, the Trans World Airlines jet broke apart because of electrical arcing caused by cable insulation failure around fuel tank [64]. Two years later, electrical arc ignited insulation in Swiss Air Flight 111, eventually caused the crash [65]. In 2018, a Sichuan Airlines flight was forced to an emergency landing due to a continuous arc caused by damp conditions in the lower left part of the windshield, which damaged the cable insulation performance. There is one crack in every 1 km cable on average according to a mass of aircraft that have been operating for more than 20 years. Therefore, it will bring the security risk into the whole aircraft, if the cable insulation status is not timely and effectively detected.

3.1.1 | Discharge evaluation

In the early 2000s, numerous researches have been done on the effects and rules of gas type, air pressure, and voltage frequency on PD characteristics of aeronautical cables. Partial discharge tests were performed on cables in low pressure [66]. The results show that the PDIV is greatly affected by air pressure, and the maximum difference reaches up to about 4 kV. The influence of air pressure on PD is not only reflected in the change of PDIV, but also the waveform of PD. With the increase of air pressure, the rise time of PD decreases obviously, and the average amplitude of PD increases with the increase of air pressure [67]. The average discharge amplitude, discharge repetition rate, maximum discharge amplitude, cumulative discharge amplitude and other PD statistical characteristics are also affected by air pressure [68]. When PD occurs in helium, its waveform can only be detected/collected when it is greater than 10 Torr. In addition, only positive pulses can be detected in helium at 20 Torr, which is different from PD in atmosphere [69]. Some researchers detected PD of the typical insulating material ETFE at high temperature. The experimental results showed that the PD amplitude increases linearly with the increase of temperature, and the high electrical DC conductivity and its gradient are two main factors in facilitating the PD occurrence [70].

In the frequency range of 50–2000 Hz, corona discharge, gap discharge, surface discharge, and cable to metal plate discharge models are tested and analysed [71]. The test models are shown in Figure 7. The results of cable to metal plate are shown in Figure 8, which show that PDIV/Partial Discharge Extinction Voltage decreases slightly with the increase of frequency, and subsequently leasing to obvious increase in the damage level.

In order to improve the persuasiveness of experimental results, some models have been set up closer to aircraft operating conditions subsequently. According to the British Standard European Norm 3475-307, 4 models are suggested respectively: cable-to-plate, cable-to-rod, cable-to-bare wire and cable-to-braid. Partial discharge becomes more intense as the air pressure increases for cable to rod model, contrary to the cable to plate model. Regarding PDIV, the cable-to-rod model and cable-to-plate model is also inconsistent [72]. In short, PD behaviours vary in different configurations, leading to different results.

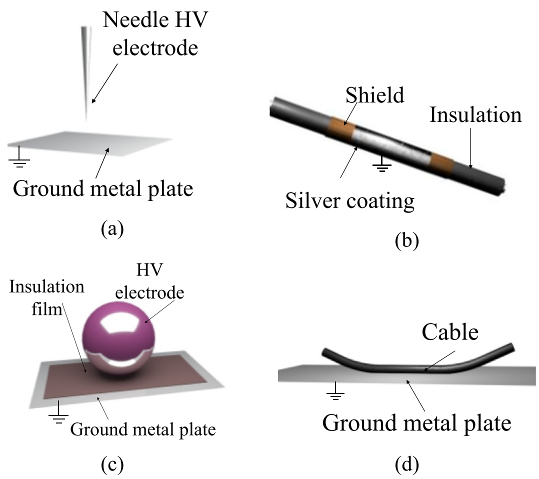

FIGURE 7 Four typical structure of cable discharge models: (a) Corona discharge; (b) Gap discharge; (c) Surface discharge; (d) Cable to metal plate discharge.

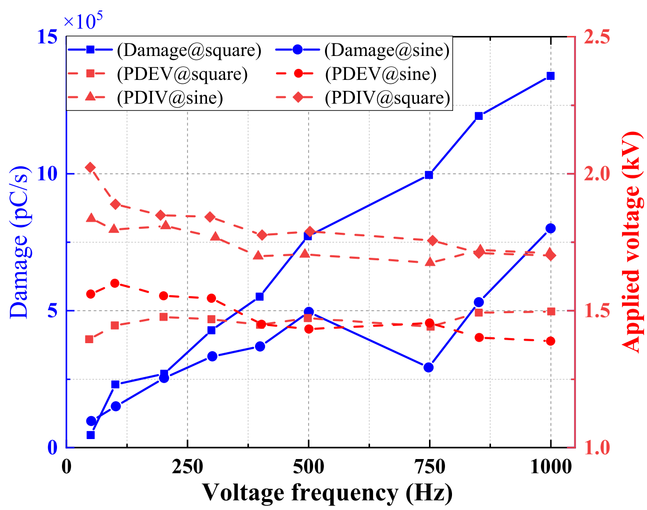

FIGURE 8 Partial Discharge Inception Voltage/Partial Discharge Extinction Voltage and accumulative damage degree with waveform frequency for wire to plane partial discharge (PD) model.

The prediction of PDIV is explored according to Paschen's law, so as to avoid the damage of PD to aeronautical cable [73]. The gap between the calculated and the measured value can be optimised by calculating the correction factor to predict the PDIV value. The calculation formula of the correction factor is shown in Equation (1).

$$\alpha = \frac{\sqrt{2}}{V_{\text{void}}} V_{\text{b}} \tag{1}$$

Wherein, V_{void} is the voltage between shield and insulation; V_{b} is the breakdown voltage, which is taken from Paschen's curves of references [74, 75]. Once the cable geometry is determined, the minimum PDIV can be estimated by using Paschen's curve after using correction factors.

3.1.2 | Insulation ageing and deterioration

In view of the ageing characteristics of the aeronautical cable's insulation, a variety of detection techniques for PTFE and PI have been carried out. In the early 20th century, Shull et al. proposed to use impedance spectroscopy to study the ageing characteristics of insulation materials, and quantified the insulation ageing process of PI film through characteristic parameters, such as dielectric constant and conductivity [76]. Ultrasonic technique can also be used to detect the ageing features of insulation, since the propagation velocity of the insulation layer varies with the ageing degree of ultrasonic wave [77]. The axisymmetric wave velocity of different cables after heating treatment is higher than the base value. By evaluating the mechanical properties of the cable, such as elongation at break, the insulation ageing degree of the cable can also be effectively measured [78]. The elongation at break of aeronautical cable is affected by thermal ageing treatment. The higher the temperature, the faster the rate of mechanical failure of the insulation. At 220°C, the elongation rate at break kept above 450% with the ageing time. At 250°C, when the ageing time is approximately 40 h, its mechanical properties were close to failure state. At 280°C, the insulation layer quickly failed. The above-mentioned ageing characteristics provide a certain reference for the ageing life assessment of aeronautical cables [79].

Measuring insulation breakdown voltage helps to judge the life of the insulation layer. Three voltage types of DC, power frequency AC and pulse voltage are applied to PI film after thermal ageing to explore the law of its breakdown strength [80]. The results showed that the breakdown resistance of PI film decreased with the increase in thermal ageing time. The breakdown voltage at high-frequency unipolar pulse is significantly lower than the breakdown voltage at DC or AC power frequency. Thermogravimetry (TG) is also used to evaluate the influence of thermal ageing on the insulation of PI within the range of 250–400°C [81]. The test results show that when the weight of the insulation was reduced by more than 25%, the film cannot maintain the standard mechanical properties. Through the life prediction models at 12 and 14.7 kV, the fitting curve of breakdown voltage indicated that the weight of insulation reduced in the process of thermal ageing had a certain relationship with breakdown voltage, which could be utilised for remaining useful life prediction.

The detection of breakdown voltage mainly stays on the performance of insulating film, without combining with actual working conditions [82]. The consideration of PD with ageing treatment can closely fill the gap to actual working conditions. Taking the cable-to-pipe model as an example, the detection of relationship between ageing time, air pressure and PDIV has been evaluated, the PDIV decreased with thermal ageing at different air pressures, except that at 100 mbar. The longer the thermal ageing time, the more decrement in PDIV was observed. The PDIV of 9072 h aged in the range of 300–1000 mbar was 30% lower than that of untreated.

3.1.3 | Detection of insulation defects

Insulation defects in power system of aircraft should be avoided since severe consequences may occur, leading to the loss of the functionality, even an in-flight fire hazard. Especially, the astronautical cables last hundreds of kilometers, the insulation defects could spread through the wires, thus there is a pressing need to detect and assess the occurrence and severity of possible insulation defects in the aircraft wiring systems. The aviation industry is continually developing and improving condition monitoring systems, although, even today, wiring issues frequently remain hidden. In particular, discharge activities are concerned to ensure stable, reliable and safe power system operation. For this purpose, the different measurable effects, including radio waves, sound, visible and ultraviolet light, heat or chemicals such as ozone etc. [83–85], need to be fully utilised.

As to arc tracking, it is very difficult to be detected in the very early stage, well before the development of major faults. The solar-blind sensors within the 185–260 nm ultraviolet spectral range have been verified the feasibility and accuracy of detecting electrical discharges at the very incipient stage in low-pressure environments for aircraft applications [86].

Owing to the immunity to electromagnetic interference, optical module has been applied in series arc detection [87]. The produced fault current is low, below the sensitivity of current circuit breakers, so it is difficult to be tripped when the problem is in an incipient stage. Then a spectrum platform of DC series arc for more-electric-aircraft power system was established to measure arc spectrum generated by different electrode combinations. With the experimental results, the arc spectral signals excited by different material electrodes were analysed and arc light characteristic wavelength was extracted through the proposed algorithms. The DC arc behaviour under the specific MEA condition is examined to provide a solid foundation for arc detection. This study aims at providing an experimental and comprehensive understanding and the detection of arcing behaviours that might occur in the MEA DC power system. The copper arc spectral characteristic wavelengths are 324.5 and 327.7 nm, as shown in Figure 9 [87].

Since sunlight also contains visible and UV wavelengths, it is necessary to exclude the interfering with the measurements of visible and UV sensors. In addition, the weak discharge typically can be detected by means of conventional devices, including Ultra High Frequency (UHF) sensors [88], radio interference voltage and PD detectors [89], noise metres [90], spectrophotometers [91] or some others, just like the application in power apparatus in high voltage power grid. The use of these sensors facilitates the application of predictive maintenance while offering the possibility to be combined with existing electrical protections to expand their capabilities, thus allowing timely fault identification and a fast response. Since insulation defects can lead to inflammation and intoxication to electrical devices and system in aircraft, it is crucial to consider the safety and reliability issues in the aircraft design associated with wiring [92].

3.1.4 | Optimisation of insulation design

In order to enhance the performance of cable insulation in high temperature resistance, anti-corona and high-voltage resistance, material selection and structure design should be concerned. Take ceramic materials (such as Al_2O_3, AlN) as an example, their thermal conductivity, heat dissipation capacity are high, so the kind of materials has been widely used in IGBT [93]. Compared with traditional polymer insulation materials, the dielectric constant of ceramic materials is higher, and the application is limited. 15% ceramic suspension is suggested to be the best choice for dip coating, and the dielectric strength of the film ranges from 24.2 to 43.6 kV/mm. When the insulation thickness is 40.3 μm, its breakdown voltage is 798 V, indicating that ceramic materials exhibit excellent performance of high-temperature and high-voltage resistance in the aviation field.

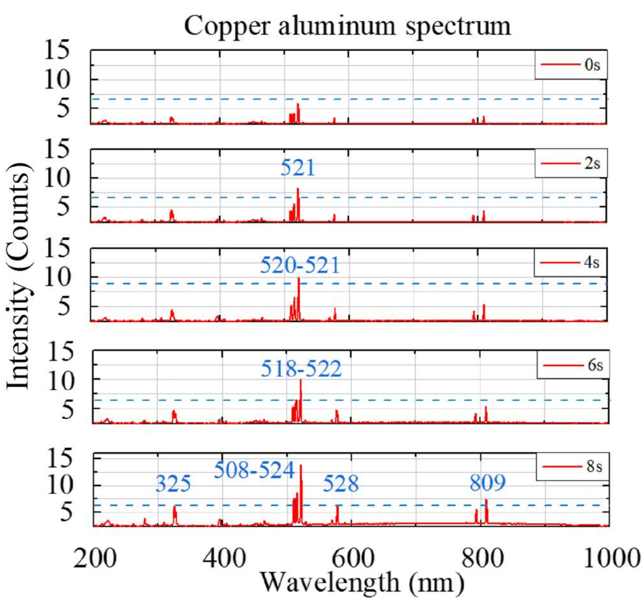

FIGURE 9 Copper aluminium arc spectrum at different time instants.

The optimisation and improvement of insulation structure can bring new breakthrough to insulation system in airspace system design. Micro-multilayer-Multifunctional-Electrical-Insulation (MMEI) is shown in Figure 10 [94]. Its multi-layer design can realise multiple functions, such as corona prevention, moisture resistance, heat dissipation, mechanical durability etc. It is verified that the MMEI structure with better insulation is $[1 \times \mathrm{HN}/1 \times \mathrm{PFA}]_{10}/1 \times \mathrm{HN}$. HN is a type of Kapton. PFA is Perfluoroalkoxy. Compared with single PI, the breakdown voltage increases by about 91% while the insulation thickness decreases by 98%. In addition, $0.3 \times \mathrm{HN}/[1 \times \mathrm{PFA}/1 \times \mathrm{HN}]_{10}/[1 \times \mathrm{PFA}/1 \times \mathrm{CR}]_2/2 \times \mathrm{PEEK}/0.3 \times \mathrm{HN}$ structure combination is expected to be a typical candidate structure for MMEI due to its excellent dielectric properties and some other outstanding functions. CR is a type of Kapton.

Regarding the selection of cable, one needs to consider the operating voltage, current density and voltage drop of the conductor. In addition, the thickness and weight of the insulation are also important factors for aeronautical cables. The power capacity of traditional aircraft is much lower than that of current aircraft systems, sometimes the possibility of PD is naturally ignored as well [95]. The HV group at The University of Manchester calculated the maximum Safe Operating Voltage (SOV) for defects in cable-to-metal model and cable-to-cable model. The calculation process is shown in Equations (2) and (3).

$$V_{\mathrm{d}} = \frac{d \cdot \varepsilon_{\mathrm{r}}}{d \cdot \varepsilon_{\mathrm{r}} + i} \tag{2}$$

$$V_{\mathrm{d}} \cdot V_{\mathrm{SOV}} = V_{\mathrm{b}} \tag{3}$$

Wherein, V_{d} represents the voltage distribution ratio between the insulation and the gap; d represents the gap width; i is the thickness of the insulation; ε_{r} represents dielectric constant of insulating material; V_{SOV} stands for SOV; V_{b} represents the breakdown voltage in air. Figure 11 shows the curve between the power to weight ratio and working voltage at four working conditions, where A, B, C, and D respectively represent three-phase four-wire system, three-phase three-wire system, DC grounded system and DC ungrounded system.

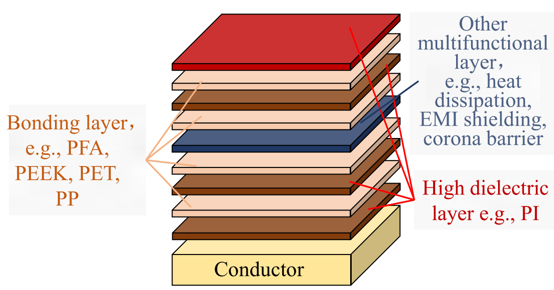

FIGURE 10 Typical design concept of Micro-Multilayer-Multifunctional-Electrical-Insulation structures.

The determination of SOV for aircraft electrical system needs to balance the constraints between weight of the wire and the power delivery. As well, DC system has the potential to provide higher power transmission than 400 Hz AC system when it comes to power to weight ratio [96].

In the design of MEA, finite element analysis (FEA) simulation is also used to calculate the electric field distribution, which can effectively indicate the probability of PD. Aiming at the simple model where the cable is located at a fixed distance from the ground (infinite plane, as shown in Figure 12), the optimal withstand voltage with regard to the cable with different sizes and insulation materials can be obtained by theoretical calculation [97]. In which, D represents the distance between the conductor centre and the ground; e is the distance between the outer insulation layer of the cable and the ground. c stands for conductor diameter. At the same operating voltage, the minimum insulation thickness that can be used for cables of different sizes and the maximum power weight ratio that can be further analysed. Safe Operating Voltage can also be calculated at fixed geometric constraints. In the structural design of bus, the stray inductance should be kept as small as possible while avoiding PD [98]. Existing simulation and calculation demonstrate that thicker insulation can reduce the peak electric field amplitude, but increase the total stray inductance. In the design, the insulation layer was double-layered, and the thickness of each layer was 250 μm. The stray inductance was calculated to be 11.2 nH, and PDIV was 1.8 kV at 0.2 atm, DC voltage.

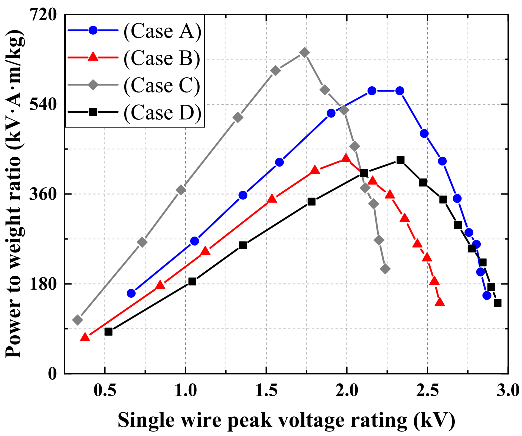

FIGURE 11 The relation curves between power weight ratio and voltage at different working conditions.

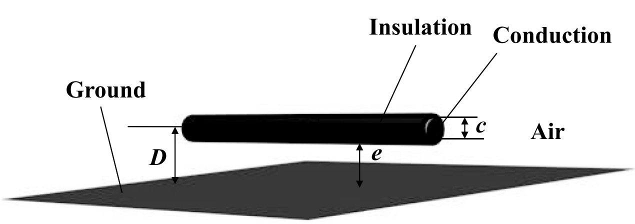

FIGURE 12 Simplified simulation model of aeronautical cable.

3.2 | Power module insulation

3.2.1 | Power device packaging

Power electronics are designed to improve power density which has been widely applied in electrified aerospace industry [99]. Power module is an indispensable component for aircraft electrification, and it is developing towards small size, high voltage, large power and high-power density. Especially with the development of wide-band gap (WBG) semiconductor materials, such as gallium nitride (GaN) and silicon carbide (SiC), it can withstand higher voltage stress with faster switching speed, lower switching loss and higher tolerant operating temperature. However, the high frequency surges and high temperatures generated by these wideband devices threaten the reliable operation of the electrical devices. Power module-based packaging structures and 'triple point' insulation structures are shown in Figure 13. Typical packaging structures mainly include power chip, substrate, solder, baseplate and encapsulant. Triple point intersection is the combination of ceramic, metallisation and encapsulant, where electric field distributes. The non-uniform electric field is the key concern of insulation design. In the power module, the main insulation structure is divided into two parts: (1) The ceramic provides insulation dielectric and mechanical support for the power module, and separate the metallisation with different potentials [100]. (2) The encapsulant wraps the substrate, providing insulation between them and protecting the chip and intersection from severe conditions such as moisture, chemical corrosion, high temperature etc. The main properties of typical material for encapsulant and substrate are respectively listed in Table 1 and Table 2 [101]. In the process of operation, the 'triple point' is easier to be deteriorated by ageing, PD and breakdown. At the same time, due to the difference of coefficients of thermal expansion (CTE) between the substrate and solder, cracking phenomenon between solder, metallisation and ceramic may occur [102]. Thus, subsequent studies regarding several insulation materials have been carried out from this perspective for PD detection or optimisation design.

3.2.2 | printed circuit board units

Printed circuit board is the mechanical and electrical base for electronic components, coated with insulating polymer to improve dielectric properties. Direct bonding copper (DBC)

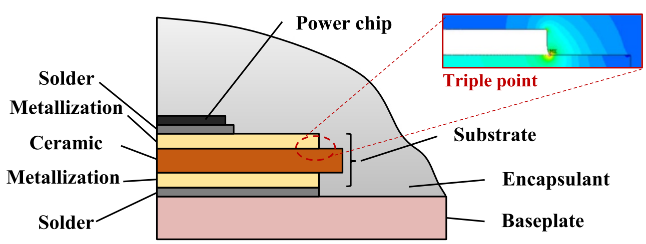

FIGURE 13 Power electronic module packaging structure

TABLE 1 Main properties of several typical encapsulant

Material	Dielectric constant	Dielectric strength (kV/mm)	Maximum tolerant temperature (°C)
Silicon gel	2.79 (100 kHz)	16–20	200
PI	4.2 (1 MHz)	100–280	280
Parylene	2.65 (1 MHz)	275	260
Epoxy resin	3.3–4.0 (1 MHz)	35–40	125

TABLE 2 Main properties of substrate

Material	Thermal conductivity (W/m°C)	Electrical resistivity (Ω·cm)	Dielectric strength (kV/mm)
Al_2O_3	24	$>10^{14}$	12
AlN	150–180	$>10^{14}$	15
BeO	270	$>10^{14}$	12
Si_3N_4	70	$>10^{10}$	10
SiC	250	0.02	300 [103]

also can etch a variety of line graphics like PCB [104]. In order to improve the performance of power electronics, PCB and DBC are often combined. Figure 14 illustrates a SiC-based, half-bridge (HB) module with a hybrid packaging method. Such a module can effectively suppress parasitic inductance and improve heat dissipation, which is based on PCB plus DBC structure. To pursue miniaturisation and high density is an important goal in the aerospace applications, the increasingly compact PCB layout leads to the continuous narrowing of the insulation distance between conductors. Coupled with higher voltage systems, there is bound to increase the possibility of electrical failure. The harsh environmental conditions experienced by power electronics in aircraft also reduce PCB life, such as PD, low atmospheric pressure, condensation, contaminants, extreme temperatures, and rapid temperature cycles. Once the electric field reaches the breakdown strength, surface discharge occurs between the PCB conductors. With the large amount of heat generated by these discharges, polymer insulation suffers from tracking failure due to electron bombardment and chemical degradation [105]. When the discharge intensity is large and lasts for a long time, the carbonised products gradually and rapidly form on the polymer surface. Once the electrodes are bridged, the insulation resistance suddenly drops [106], and insulation failure occurs.

3.2.3 | Power electronics transformer

Both high-power density and large power rating are necessary to meet the demands of power conversion in MEA. And high-power converters with significant weight and volume reduction are convenient for onboard power distribution. In this regard, isolated DC/DC converter based on medium or high

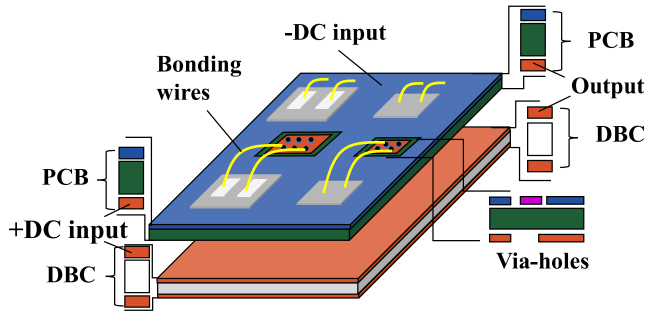

FIGURE 14 Illustration of electrical connection in a typical printed circuit board (PCB) and Direct bonding copper (DBC).

frequency transformers attracts the attention. The increased frequency is quite beneficial to reduction of volume. In general, it is critical to guarantee not only the high-power density and conversion efficiency, but also the excellent voltage insulation and outstanding heat dissipation. For example, a matrix core transformer (MCT) architecture and prototype (100 kW, 50 kHz) is proposed with improved electromagnetic and thermal performance [107]. As a result, the power density and efficiency of the MCT reach to 17.7 kW/L and 99.63% respectively. It is no doubt that high-power density and high-power operation capability advance the equipment and power system for aerospace applications [108–110].

As well, several high-power solid-state transformers (SSTs) designs and prototypes have been reported with variable parameters in the existing literature [111, 112]. Wherein, dual active bridge converter is the most commonly used building block, and bidirectional power delivery can be achieved and controlled by adjusting the phase shift between the two H-bridges. High frequency transformer is also the main component of SSTs to achieve electric isolation and voltage conversion. As SSTs tend to miniaturisation, high frequency, and high voltage; the insulation problem in High frequency transformer becomes increasingly rigorous. Therefore, it is crucial to perform insulation evaluation on SSTs and understand the discharge features in different frequency range [113], thus to provide practical support for the development of reliable SSTs in the application for MEA power system.

3.2.4 | Insulation evaluation of its factors

Based on the different PD phenomena under different voltage waveforms, space charge measurement and modelling have been utilised. The results show that the PDIV under PWM is smaller than that under DC [114]. This is mainly because charge is more likely to accumulate in silicone gel under DC and decreases the electric distribution. However, the field remains stable under square pulses since no obvious space charges are accumulated. According to the simulation results, the maximum electric field at the triple points under DC is ~90% of that under square pulses. Switching frequency has a dominant influence on PDIV and discharge amplitude of PCB, with the lowest PDIV of rapidly rising square wave and the highest PDIV under sinusoidal voltage [44]. As shown in Figure 15, the PD under square wave is more intense than that under sinusoidal wave, and the square wave with different polarity also has a certain impact on the discharge amplitude. The rapidly rising negative SWV has the largest PD amplitude and the smallest PDIV [115]. In addition, fast pulse rise time can increase the occurrence probability of electric branches of epoxy resin and promote its growth [116]. The damage and degradation degree of PD on the silicone gel coating was quantified and evaluated. The results show that PD imposes the strongest degradation effect when the coating thickness is 70 μm or less at atmospheric pressure, and the degradation effect decreases with the increase of the coating thickness, and it has the best protection when the coating thickness reaches 180 μm. Partial discharge extinguishes when the voltage is lower than 4.25 kV, and breakdown is easy to occur when the voltage is higher than 4.5 kV [117]. As well, PD occurred in the gap between the ceramic layer and the metallic layer leads to degradation of the silicone gel, and reduced the dielectric insulation performance [118].

In the early stage, the influence of corona discharge on PCB under low pressure was explored. It showed that corona discharge would degrade the surface of PCB device and produces white dust under low pressure. As an instance, 60 Hz AC voltage was applied for 200 h, an irreversible dark brown colour appeared on the PCB surface, and the deterioration became worse with the increase of voltage withstanding duration time [119]. The rise in air pressure may cause the stream to dissipate as it propagates, or even terminate, preventing it from crossing the PCB groove and reducing the chance of surface damage [115]. Under low pressure, PD activities under high frequency square wave with variable air pressure were observed by FEA. The results showed that with the decrease of air pressure, the duration of discharge increased, almost twice that of atmospheric pressure, and the apparent charge of PD also increased by about 20% [120]. However, the accumulated charge of the tracking failure of glass-cloth epoxy-resin laminate under low pressure was thought to be more under low pressure, but the failure time was longer than that under atmospheric pressure [121]. Overall, the low pressure improves the tracking resistance and breakdown resistance for the PCB.

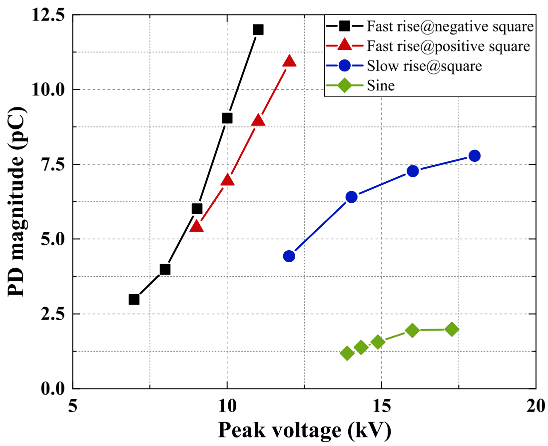

FIGURE 15 Partial discharge (PD) for different voltage sources.

The relationship between insulation distance and tracking failure is also explored. The results show that fewer electrons pass through the gap and less energy is generated by collisions at low pressure [121]. With the decrease of insulation distance between conductors, the accumulated charge quantity can be decreased, and the tracking failure time can be increased. Therefore, a narrower insulation distance can improve the insulation reliability of PCB under low voltage. Tracking failure is a non-linear and random process, and the test results may be dispersive. To explore the dispersive phenomena and mechanism of tracking failure under low pressure, two approaches were proposed by the fractal dimension of tracking pattern and recurrence plots of discharge current. The test results show that the fractal dimension of the trajectory decreased under low pressure, and the tracking process was more regular. The decrease in pressure delayed the tracking failure time [122].

It is reported that thermal-mechanical stress could accelerate the formation of cracks for silicone gel at −60°C [45]. Influenced by the cracks, PDIV decreased, and the discharge intensity increased, which considerably damaged the reliability of the module. Therefore, the influence of these environmental parameters should be taken into full consideration for power module which works in harsh environment for long time, especially in aircraft. Similarly, in the case of PCB at high temperature, the energy of carriers and particles is higher, and destructive threshold of the insulation material is reduced, which is more conducive to the growth of electrical branches and causes the cracking or stratification of the coating [116]. The results show that the thermal cycle failure mechanism of PCB in aerospace environment requires close attention [123].

In addition, the pollution layer on the coating surface can also affect the discharge intensity or breakdown position in the PCB. A model is proposed to highlight an alternative breakdown mechanism and pathway, whereby discharge between tracks occurs via the conductive pollution layer, rather than through the bulk polymer. Results showed that breakdown occurs preferentially through the contamination, and the thickness of the coating and the ratio of orbital separation determine the possibility of such a discharge mechanism. When the contamination layer is large and the conductivity is 2500 $\mu S \cdot cm^{-1}$ and greater, the discharge phenomenon would not occur [124, 125].

Various methods have been tried to control the electric field at the "triple point" by improving structural design, such as increasing substrate thickness, removing metal substrate, stacking ceramic substrate, and modifying edge shape. Thick substrate helps to weaken the electric field concentration to a certain extent, but doubling the thickness can only reduce the electric field intensity by 30% [126], but reduce the heat dissipation efficiency. The results show that the PDIV can be improved 94% by stacking two 0.32 mm Al_2O_3 stacks compared with a single 0.63 mm substrate. However, increasing the number of substrates has no significant effect on PD suppression. In the case of three-layer stacks, compared with two-layer stacks, PDIV increased by only 15% [127]. The FEA results show that the offset metal substrate and the use of appropriate dielectric coating can effectively relieve the high electrical stress at the 'triple point' [128].

Adjusting the electrical parameters of insulating medium to reduce the concentration of electric field can achieve better discharge suppression effect. Silicone gels filled with 15% barium titanite by volume have been tested using 50 Hz voltages to measure the permittivity over a range of electric fields. The results show that the dielectric can significantly reduce the electric field level near the edge of the substrate and increase the PDIV and breakdown voltage level [129]. In the FEA simulation, mixing zinc oxide into PI can reduce the field intensity of the 'triple point', thus adding a non-linear resistance layer at the edge is also beneficial to reduce defects [130]. Some composites show higher thermal conductivity, better stability and lower CTE, such as silicone elastomers with micro and nano-sized boron nitride and SiC particles. The PDIV of the composite is higher than that of the original silicone elastomer, and it increases with the doping level. This behaviour may be for the charge diffusion and transport weaken the local electric field near the high voltage side [131]. Metal solders can reach 300°C if weak metal compounds can be prevented from forming on the substrate and bottom plate. Metal materials with low CTE and ceramic materials with high fracture resistance are feasible. The melting temperature of paste nano-silver or transient liquid form of nano-silver can exceed 400°C, which can meet the needs of high temperature scenarios inside power equipment in MEA applications [132].

3.3 | Electric machine insulation

3.3.1 | Classification and typical structure

Electric machine is one of the key components in MEA with specific stringent requirements, and the applications vary in different sections or parts. According to the functions, it can be divided into actuation, taxiing, propulsion, starting and generation, and engine fuel pump etc. Electric actuation of MEA can be categorised into electromechanical actuator, electrohydraulic actuator, and electro-hydrostatic actuator [133]. If the existing hydraulic system is replaced by an electric one, it can reduce the response time and improve system reliability [134]. Recently, the high bypass ratio turbofans are used in MEA, but it is more feasible to replace the gas turbine with an electric motor [135]. In MEA, gearboxes tend to be replaced by electric motors combined with AC/DC and DC/AC back-to-back power converters or AC/AC matrix converters, and electrical wiring. The integrated drive generator is, therefore, substituted with a bidirectional variable speed constant-frequency system [136]. This system works as an engine starter in the motoring mode and guarantees constant-frequency electrical power in the generating mode. In addition, electrifying the high-pressure pumps can boost the system efficiency and reliability, and reduce weight and size. In addition, the electrochemical batteries can be replaced by flywheel energy storage systems for aerospace applications [137].

On the premise of reliability, there is an urgent technical need to develop the machine with high power density, high torque density and low temperature rise. NASA plans to develop machines with power densities of 13 kW/kg and 16 kW/kg, respectively in 10-year goal and 15-year goal. The United States Air Force anticipates 5 kW/kg in its 20-year goal [15]. Airbus anticipates 10–15 kW/kg in its 15-year goal. However, to enhance the power density may cause large temperature rise in a small volume, resulting in thermal overload and sacrificing the reliability of the machine to a certain extent. It is pointed out that temperature affects winding insulation system, and the insulation life can be reduced by half with an increase of 8–10°C [138]. Insulation must withstand high temperature under continuous operation and restrain significant thermal ageing [139, 140]. Therefore, for the reliable operation of machine, an effective cooling solution is also essential to keep the working temperature of different components within feasible range. High temperature put the most serious impact on permanent magnet synchronous motor (PMSM). Because permanent magnet is operated at a limited temperature, beyond which the magnetic force is affected, the performance may decrease if there is not enough cooling capacity. In addition, most motors are powered by voltage source inverter and PWM strategies. HVDC combined with fast power switching devices produces a fast rise rate [141], which may lead to PD in the insulation system. Therefore, the thermal stability, mechanical rigidity, and insulation performance should be considered while improving power density and efficiency during the design and application of electric machines [25].

According to the structure of the electrical motors, they can be mainly divided into wound-field synchronous motors (WFSMs), PMSMs, switched reluctance motors (SRMs), and induction motors (IMs). Induction motor do not need active excitation, whereas the excitation is controllable in WFSMs. Because of the advantages of controllability, simple operation and high flexibility of structure, wound magnetic field synchronous generators (WFSGs) are widely used in airliners. After studying the fault tolerance, power density, efficiency, vibration noise and other comprehensive factors of IMS, SRMs, and PMSMs, it is indicated that PMSMs are more suitable for MEA acting as the drive motor [142]. The schematic diagram of the three-stage WFSM and the three types of discharge forms in the stator are shown in Figure 16 [143]. Most insulation faults are caused by stator or rotor windings. Usually, there are inter-turn insulation (Location A) deteriorations occur first, and followed by phase to phase insulation defects (Location B) [144]. Because insulation failure is a slowly developing process and difficult to be detected. Therefore, high-quality winding structure and insulation design play a crucial role in the reliability of aviation motors. In addition, due to the pervasive use of high frequency switching motor drives, the problem for shaft currents to cause bearing failures has been studied [145]. There are several damage mechanisms for bearing by shaft currents. When the voltage across the bearing exceeds the dielectric strength of the grease, electric discharge machining (EDM) occurs which is the most destructive damage mechanism. And the raceways and rolling elements are etched by EDM which can cause failure. Removing all unsymmetrised of electric and magnetic circuit or ensuring bearing insulation can decrease the probability of failure at the time of machine design.

3.3.2 | Influence of voltage parameters

The PD difference of typical voltage waveforms (sinusoidal, square, triangular like PWM, square like PWM, and PWM with peaks) are compared, and the influence of PWM with peaks is the largest [146]. It turns out that the waveform of the applied voltage cannot be neglected when designing the test program of twisted-pair sample especially for motor insulation defects, because the waveshape greatly affects the degradation process. The average amplitude and number of PD increase with fast rising time for both bipolar and unipolar SWV. As shown in Figure 17, the average lifetime under sinusoidal voltage at 1 kHz is about three times that of SWV with a rise time of 50 ns [147]. Some evidences suggest that new power modules based on SiC or GaN, with high commutation frequencies, could indeed become an issue for electrical insulation of low voltage actuators [148]. The PD amplitude decreases with increasing frequency. A conservative estimate of the RPDIV could be achieved by increasing the supply frequency well above the operation frequency. RPDIV is defined as the minimum voltage which has a 50% probability of producing a partial discharge pulse. In addition, the simplified motor model was tested, features could be concluded as: a higher repetition pulse rate made the PDIV more stable and PD is easier to be incepted with larger duty cycles for a given frequency and pulse voltage.

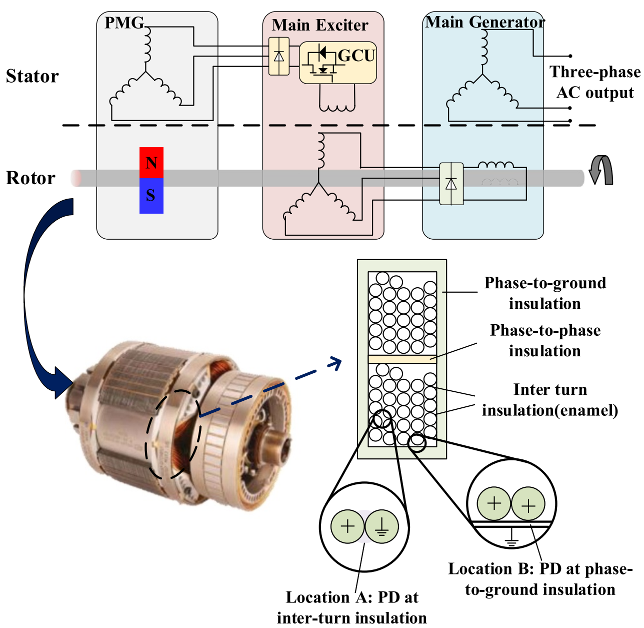

FIGURE 16 Schematic diagram of three-stage wound magnetic field synchronous generator (WFSG) and the typical discharge locations.

3.3.3 | Influence of pressure and temperature

Typical magnet wire used electric motors may not withstand an increase of voltage in the worst case scenario at low pressure, and the PD amplitude at low pressure is higher than that at atmospheric pressure [149]. With the decrease of air pressure, PD amplitude and number increase. This indicates that insulation systems are more threatened under low pressure conditions. For aeroplanes with atmospheric pressures as low as 100 mbar, PD activity could incept at lower voltage amplitude, resulting in equipment damage to insulation dielectric [150]. For PI film, both the electric amplitude and the degradation rate increased under high temperature [151]. When humidity varied from 90% to 25%, the lifetime of PI reduced by about 70%, and there is a factor leading to greater endurance under humid conditions. Partial discharge detection for typical defects (twisted pair wire) has been conducted in motor windings under different air pressures and voltage frequencies, and the test results are shown in Figure 18. The variation trend shows that the cumulative amplitude of PD is the highest at the combination of 30 kPa and 1 kHz, indicating that low pressure and high frequency have more serious damage to the insulation of MEA motor [152]. A non-electrical technique based on the use of optical fibres was proposed and verified [18]. As a new tool, the feasibility of detecting PD ultrasonic signal by means of Sagnac interference structure was demonstrated and developed according to analysis of electro-force-acoustic analogy theory and optical sensing based on Sagnac effect. Partial discharge characteristics at different frequencies in low and medium frequency bands from 50 to 1000 Hz were measured and analysed.

According to NASA, a stator winding design method without PD was proposed in the process of 1 MW high frequency PMSM (PMSM) [153]. The determination of PDIV at

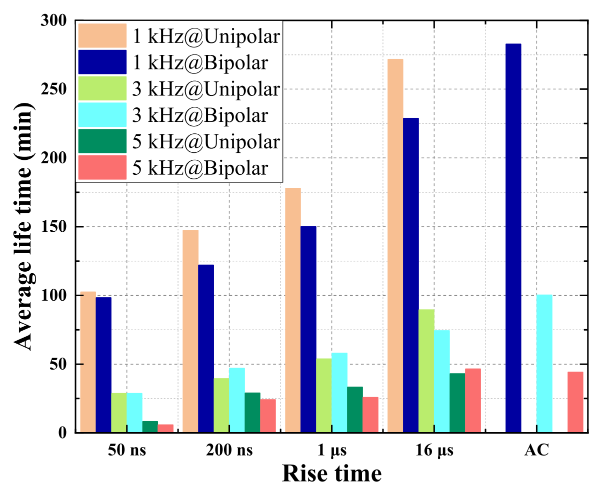

FIGURE 17 Average life time versus rising time under different frequencies.

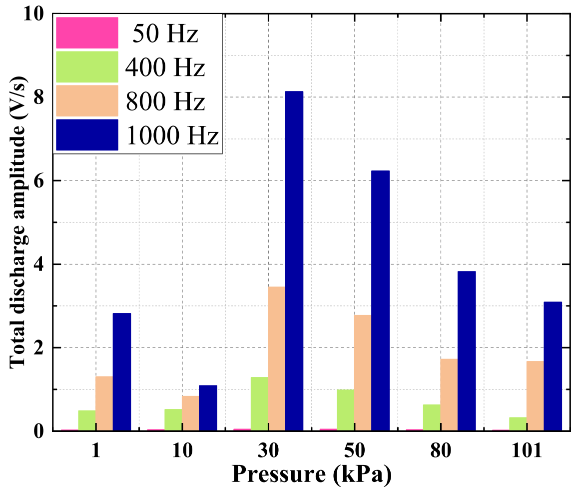

FIGURE 18 Relationship between accumulated discharge amplitude and air pressure at different frequencies.

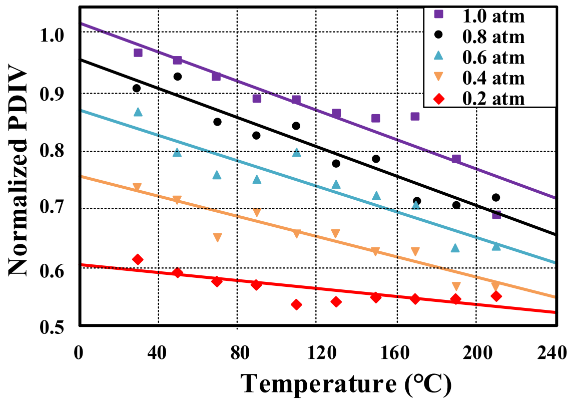

FIGURE 19 Partial Discharge Inception Voltage on pressure and temperature (10 measurements for each condition).

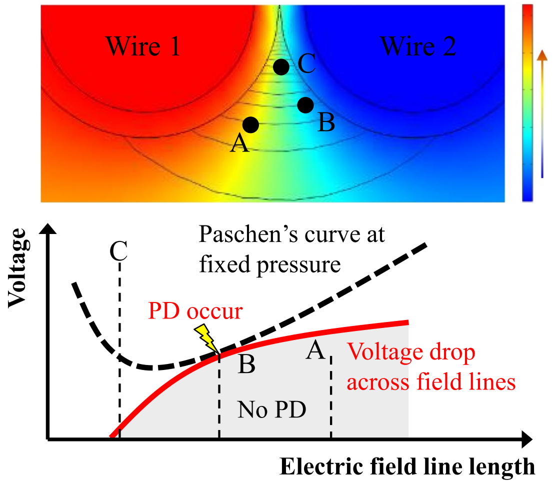

FIGURE 20 The Partial Discharge Inception Voltage criterion with the consideration of electric field distribution.

air pressure and temperature is performed experimentally, and the criterion of PD free was confirmed. Then the electric field and temperature distribution were simulated by finite element model to verify the effectiveness of design. The experimental results on PDIV can be seen in Figure 19. It is obvious that PDIV decreases with the drop of air pressure and the increase of temperature. Based on Paschen's curve with the consideration of temperature effect, PDIV can be predicted [154]. Although the prediction result consists of some error, it basically locates within acceptable range. The error mainly comes from the correction factor, which is influenced by wire and humidity. As shown in Figure 20, when the solid line intersects or tangles the dashed line (Paschen's curve), the voltage between the windings reaches the air breakdown voltage and PD can be generated. When the line does not intersect, it indicates that it is in the safe zone.

4 | PROBLEMS AND PROSPECTS

The MEA, as demonstrated, has been envisioned as a long-term development effort to mature technologies and close gaps in key performance parameters and reliability. The related research is partitioned between power electronics, electric machines, aeronautical cables, and aircraft configuration system. The current problems of each component and the directions of future research are discussed and analysed in this section. Regarding to the specific power, the parametric sensitivity can be evaluated as the relationship with weight for the voltage of electric machines, power electronics, and aeronautical cables in electrified aircraft [30]. The operating voltage of cables is the most influential element for the weight in entire aircraft with respect to specific power, and the converters show the least impact on the whole weight, as shown in Figure 21.

As abovementioned researches, high voltage system benefits a lot, and is a necessity for the large power system in electrified aircraft. However, the insulation poses the challenges for the high voltage applications, including power modules, electric machines, and cables, as illustrated in Figure 22. Although most of the failures that have occurred so far have been caused by thermal failures. As the voltage level increases in MEA, the risk of failure caused by overvoltage significantly.

(1) The possible insulation phenomena arisen in the aeronautical cable/busbar include PD, ageing, and tracking. Currently, PD on aeronautical cables is mainly focussed on the influence of atmospheric pressure, but the factors of temperature and humidity are ignored. In fact, the damage due to multiple-stresses ageing like thermal, mechanical, and electrical, affect the insulation system of aeronautical cable. On the other hand, it is necessary to put forward and develop new PD detection devices and standards which are more suitable for the special ambient conditions viz. low air pressure and high frequency in MEA. With the development of HVDC system, it is necessary to pay close attention to the PD detection and defect identification of aeronautical cables under DC steady state and during

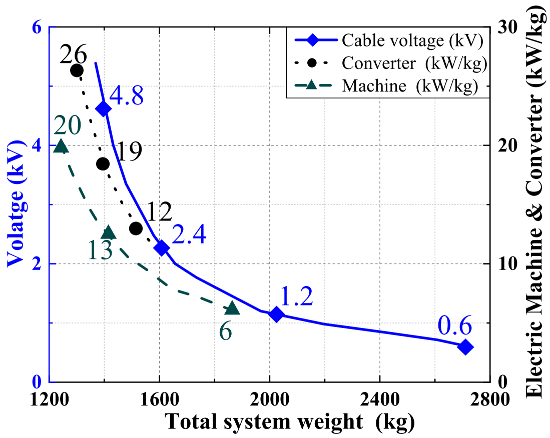

FIGURE 21 Power system weight sensitivity versus voltage level of cable, electric machine and converter.

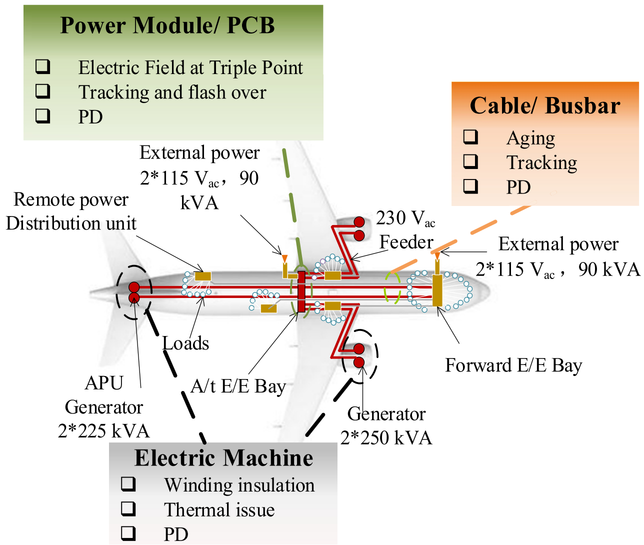

FIGURE 22 Insulation challenges for power module, and aeronautical cable and electric machine.

voltage (and load) transients [155]. Especially, aeronautical cable is always working in a narrow space, which is not conducive to observe PD, insulation state or arc tracking in time. Therefore, one need to develop fast and simple inspection procedures to evaluate health status of wiring system. It might be helpful to improve PD measurement and/or corona activity before arc tracking occurrence to avoid or minimise the damage in insulation wiring systems, as well as the development of suitable signal processing techniques to interpret the data of such sensors. For this purpose, it is suggested to develop fast response, small-size and cost-effective sensors, as well as specific signal processing techniques specially conceived to operate under aeronautic environmental conditions.

Additionally, an active PD control method for the power module or components is also possible, which targets regulation of electrical stress of insulation through managing the voltage frequency, amplitude and power (temperature). Active control the working parameters of the power equipment with some viable feedback information of PD amplitude, and repetition rate can suppress and even extinguish PD while maintaining similar expected operating conditions. Then it helps to extend the insulation life of the power modules.

There have been many accidents caused for aeronautical cables by arc tracking. It is a difficult task to recreate the arc tracking phenomenon in laboratory conditions, since it requires gathering residues and dust in the locations and amounts needed to recreate natural arc tracking conditions, which can be an arduous and non-repeatable task. Therefore, it is required to develop realistic and standardised arc tracking tests based on extensive test plans to take into account all the above-mentioned factors influencing arc tracking occurrence and the effects accounting for aeronautic conditions, to explore the mechanism on arc tracking occurrence and the related insulation faults.

(2) Most MEA electric machines are fed by voltage source inverters. With the deployment of PWM technique, the electric machines are applied the square-wave voltage in electrified aircraft, which is of high frequency, fast rising time and high amplitude [141]. To cope with the damage of overvoltage, thickening the insulation is the direct and easy way. However, the insulation system has a significant impact on the heat dissipation capability and temperature distribution within the electric machine. The insulating performance can be influenced obviously by concentration of temperature for continuous operation [156]. But thickening insulation might decrease the power to weight ratio and the efficiency. Hopefully, the application of new material can solve the problem. In recent efforts, ceramic materials depicted a promising outlook due to their high thermal conductivity and high dielectric strength [157]. Polymer matrix composites have also been proposed as a potential material due to the lightweight, moldability, and high strength [139]. Or applying a thin layer of slightly conductive coating on the traditional materials can release the charges accumulation and restore the dielectric strength. This approach can make traditional materials widely used in a wider range of fields [158].

Furthermore, to decrease the power losses of generator, low loss materials, such as high silicon content steels, are potential candidates for high power density and cost-effective WFSGs in high-speed applications. The distribution of electric field in long-time operation, there may be some air gaps or defects in the insulation of the stator such as slot opening and inter insulation [159]. Partial discharge may occur in these locations, because of the local distortion of electric field distribution. Especially, PD can be triggered easily at low pressure for aircraft. Although PD detection in electric machines have been verified, the test objects are mostly twisted-pair models, instead of the entire electric machines. The obtained test results and conclusions are not convincing enough to guide the actual operation. Furthermore, the detection of PD cannot analyse the insulating status and predict remaining useful lifetime. Currently, related work on the electrical-insulation system of power plant generators have been carried out with the combined stress of thermal, electrical, mechanical, and chemical stress to a establish a mature degradation model [160]. In this regard, the electric machines can refer to the degradation model to avoid possible failure in MEA.

(3) Wide-bandgap (WBG)-based semiconductors (SiC, GaN) are emerged as the shimmering components of next-generation power device due to its inherent characteristics with higher current density, junction temperature, and switching speed. Due to the distorted electric field at the triple point, PD issues is still challenging the reliability and stability of the power modules and converters in the future electrified aircraft scenarios. The special point is to detect PD and evaluate the insulation damage under high dv/dt, high frequency, and heat concentration. Generally, PD collection is difficult to be distinguished with the pulse-like waveforms since they are too similar. Even with the state-of-the-art PD systems, it is extremely difficult to detect PD for impulse voltage waveforms with good signal-to-noise ratio (SNR) at high frequencies while simultaneously obtaining stable repetitive PDIV under the influence of noise generated by the switching power electronics devices [161]. Moreover, high-frequency electromagnetic wave and displacement current produced by high frequency pulse voltage, the conventional PD measurement cannot be used directly. Optical methods and ultraviolet imaging techniques can be regarded as potential alternatives. Or combining traditional detection methods with other methods to improve SNR can also achieve good results such as suppression of the energy below 400 MHz captured by the UHF sensor [162]. The influence of voltage parameters and installation environment should be fully considered when detecting PD of power modules to avoid weak even wrong data reference. In order to take the advantages of SiC- and GaN-based devices, it is necessary to improve the power module from two aspects: (1) improve the structure of the high electrical stress at the intersection; (2) select appropriate high temperature materials or add appropriate elements to the original materials to improve the high temperature performance.

In addition, the quality of PCB also needs special consideration, which might be critical to reduce the distorted electric field at the triple point. And the thermal and electrical stresses in the PCB play important role in the ageing and damage process of the whole module, which is influential on the reliability of power system in aircraft.

(4) With the development of aircraft electrification technology, the EPS is becoming more and more complex [163]. HVDC topology is considered a very promising architecture for future MEA. As the demand of electric power onboard modern aircraft rises dramatically, the low maintenance and high EPS reliability are essential for the design of future MEA. Developments of insulation material with high voltage withstanding capacity, advanced circuit breaker technologies- solid state circuit breakers (SSCBs), hybrid CBs, fault current limiter with large capacity are crucial. Better performing high temperature tolerant MW-class, and kV class compact power electronics switch developments, innovative topology/modular design are further needs to achieve the scalability in the power converter component. Moreover, energy storage is a critical component for fully/hybrid electric aircraft application due to its dominance in determining the aircraft's range [164]. It means the insulation in future energy storage also needs special attention. Besides, a special attention is needed to make the electrical components fault-tolerant, immune to the electromagnetic interference and surge phenomenon.

(5) The high voltage problems can be revolutionised by possible efficient and enhanced superconducting technique. For example, the conventional rotating machines composed of copper windings and iron cores are excessively heavier than the maximum permitted weight limit of the aircraft. High-Temperature Superconducting (HTS) can generate a high magnetic field larger than the saturation magnetic flux density of the iron cores, so it can eliminate the iron cores [165]. The superconducting rotating machine can be designed to be light in weight. And the current density and output power density of superconducting synchronous rotating machine are better than conventional motor. A recent technology survey concluded that superconducting machines can achieve an efficiency above 99% and a specific power above 50 kW/kg [166]. In order to achieve high specific power and eliminate excessive hysteresis loss in saturated yoke, the HTS rotor needs to be supplemented by an air-core, high dB/dT armature winding. Compared with the traditional machines, the electrical stress of Superconducting machines windings can be 3–4 times or more. To ensure the safety requirements at high voltage, excellent-performance "form-wound" coils would be desirable. However, the insulation and heat dissipation problems are still worth paying attention to [167]. Insulation system in cryogenic environments should withstand the cooling/heating cycles without substantial compromise and the cooling mechanism ought to work consistently under all operational conditions and be reduced the cost. Moreover, it would require additional developments for an efficient and higher power to weight to ratio associated cryocooler system. Finally, there has not much work on the long-term reliability of the superconducting machine and its expected lifetime thus far. This should be addressed in future studies. Lower thermal interaction, lower emissions and higher power density can be achieved by HTS cables [168]. However, one problem with HTS is that the behaviour of dielectrics might change under cryogenic systems. Therefore, finding insulating materials that can properly work in cryogenic environments is a challenge towards the development of HTS technology.

Furthermore, robustness and safety are other major bottleneck that has to be surmounted to make a superconducting system useable in aircraft service.

(6) Structural optimisation and material innovation are crucial to improve the components and the power system for electrified aircraft. As an example, aeronautical cable material, structure, size and other parameters are tightly related. At present, the research only stays in the aspect of simulation and calculation, neglecting the design scheme which is closer to real application. Two aspects can be considered for improvement: on the one hand, the performance of the traditional material can be improved and promoted; on the other hand, advanced insulation materials/structures in other fields can be applied to aviation. In addition, the improvement of the material should also pay attention to the surface characteristics of the material to avoid the occurrence of creepage and arc tracking. Insulation material with higher thermal capacity and voltage withstanding capacity in the electrical machine component is paramount for developing a high specific power and high efficiency product. Whether the new insulating material can be widely manufactured and applied also need to consider the difficulty and cost of its preparation. The safe and stable development of electrification cannot be separated from the breakthrough and innovation in the field of materials.

5 | CONCLUSIONS

The next generation of MEAs is being developed with the final goal of evolving towards AEAs, since they are environmentally friendly with high energy efficiency. With the extensive application and development of more-electric techniques in the aviation field, the voltage level and power supply capacity of aircraft power system definitely increase, and the electrical stress has changed significantly within electric machines, power modules, and aeronautical cables. Not only the insulating material, structure and details of each electric component are highlighted, but also future technical research needs are discussed.

Electric machines are developing towards high power density, high torque. Switched reluctance and Permanent magnet show some potentials; however, due to windings insulation problems and high temperature ageing problems, the machines currently developed need more actions to satisfy long-term reliability. The development of WBG semiconductor has broken through the traditional limits of power modules, but the short rise time also puts forward higher requirements on the insulation. Stress concentration at the junction of triple point and heat dissipation of some materials need to be further solved. Aeronautical cables will be subjected to higher voltage levels in the future, so it is necessary to balance insulation weight and insulation reliability.

The PD waveform under low pressure is quite different from that under atmospheric pressure, definite characteristics need to be confirmed with more experimental data. The current commercial testing system and standards are more suitable to atmospheric pressure, thus detailed standards should be regulated for PD detection under low pressure in the future MEA application. The accurate measurement should be developed to detect PD in a more standardised manner, so as to put forward more reasonable suggestions for insulation system design in MEA.

Due to the complex operating conditions of MEA, the combined effects of environmental, electrical, and mechanical stress continuously degrade the insulation system. The safety and stability of MEA are critical, so the superimposed damage of various deterioration conditions should be considered during the design. In the future, it is necessary to conduct in-depth research on the influence of multiple stresses, comprehensively judge the risk of insulation failure of aviation electrical equipment. Partial discharge, arc tracking, high temperature concentration, and ageing failure are not allowed, so as to support the safe and stable operation under the wide application of more electric techniques.

We anticipate that this review will inspire improvements in insulation on electrified aircraft, especially for reliable insulation design, materials, evaluation, and diagnosis approaches.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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