# Arc Fault Protections for Aeronautic Applications: A Review Identifying the Effects, Detection Methods, Current Progress, Limitations, Future Challenges, and Research Needs

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***Abstract*—** Arc faults are serious discharges, damaging insulation systems and triggering electrical fires. This is a transversal topic, affecting from residential to aeronautic applications. Current commercial aircrafts are being progressively equipped with arc fault protections. With the development of more electric aircrafts (MEA), future airliners will require more electrical power to enhance fuel economy, save weight and reduce emissions. The ultimate goal of MEAs is electrical propulsion, where fault management devices will have a leading role, because aircraft safety is of utmost importance. Therefore, current fault management devices must evolve to fulfill the safety requirements of electrical propelled aircrafts. To deal with the increased electrical power generation, the distribution voltage must be raised, thus leading to new electrical fault types, in particular arc tracking and series arcing, which are further promoted by the harsh environments typical of aircraft systems, i.e., low pressure, extreme humidity and a wide range of temperatures. Therefore, the development of specific electrical protections which are able to protect against these fault types is a must. This paper reviews the state-of-the-art of electrical protections for aeronautic applications, identifying the current status and progress, their drawbacks and limitations, the future challenges and research needs to fulfill the future requirements of MEAs, with a special emphasis on series arc faults due to arc tracking, because of difficulty in detecting such low-energy faults in the early stage and the importance and harmful effects of tracking activity in cabling insulation systems. This technological and scientific review is based on a deep analysis of research and conference papers, official reports, white papers and international regulations.

***Index Terms*—Electrical protections, series arcs, arc tracking, partial discharges, corona effect, wiring systems, wiring insulations.**

## I. Introduction

The European aviation industry jointly with the European Union are developing the next generation of more electric aircrafts, which are more environmentally friendlier than their predecessors. Due to the increased levels of electrical power, the tendency in next generations of more electric aircrafts (MEA) is to raise the voltage level above 1 kV [1], [2], which in future designs can be as high as 6 kV, with variable frequency in the 400 Hz - 4000 Hz range, being a serious challenge for insulation systems [3] due to an increased risk of degradation because of partial discharge occurrence [4]. These changes will increase the d*v*/d*t* and the power density, while reducing distances among wires, thus leading to new failure modes, such as an increased risk of electric arc formation [5]. The increase of the voltage level is required to limit the current requirements, and thus the weight of the involved electrical components, while boosting fuel economy and the overall efficiency. Although the transition to electrical systems is beneficial, it presents some drawbacks due to the increased number of connection points and a potential growth of electrical faults, including arcing events [6].

Such increased voltage levels lead to challenging difficulties, since insulation materials are exposed to an increased level of electrical stress, which is amplified by the harsh environments typical of aircraft systems, especially the low pressure conditions. Therefore, arcing events due to damage in the insulation are more likely to occur. For example, the dielectric strength of air greatly reduces at low pressure, which favors ionization activity, including partial discharges (PD), arcing, and eventually arc tracking, thus producing premature ageing and degradation of insulation systems, especially in non-pressurized aircraft circuits [7], which are more prone to arcing activity. In particular, severe weather and moisture prone (SWAMP) areas, which are also subjected to vibration and a wide temperature range, require special consideration. SWAMP areas include wheel wells, leading and trailing edge flaps, and unpressurized compartments. Other areas requiring high maintenance are of special interest, including passenger cabins, avionics bays or environmentally controlled areas [8]. The ultimate goal of MEA aircrafts is electrical propulsion, where fault management devices will play a key role, because aircraft safety is of paramount importance [9]. Therefore, existing fault management technologies must adapt and evolve for use in future electrical propelled aircrafts [10].

In the aeronautical field, arcing occurrence can have catastrophic consequences, since it can generate important local damage, the effects of which tend to spread along the wires. As a consequence, affected systems can be shut down, losing various functionalities, and a fire can even start [11], [12]. The risks associated to arcing faults and electrical hazards increase with the voltage level, so it is critical for MEAs to have the capability to detect and isolate electrical faults. Fault detection and identification methods must consider the voltage, i.e., HVDC (High Voltage Direct Current) or HVAC (High Voltage Alternating Current) under constant and variable frequency. It is noted that HVDC distribution in MEA aircrafts is acquiring more importance, because DC does not require synchronization when parallelizing non-synchronous generators while allowing to reduce cable size and weight, among other advantages [13].

Electrical systems for MEA aircrafts offer increased power density, although they must comply with the safety and reliability requirements. In this context, arcing and arc tracking are among the major issues to be solved [14]. However, the impact of arc tracking on future MEAs is still not well understood [15], so it deserves exhaustive research plans.

Current wide body aircrafts incorporate hundreds of kilometers of wires and cables. Only in the US Navy, electrical wiring faults have causes around two in-flight fires per month, over one-thousand mission aborts and more than 100 000 lost mission hours per year, so that the Navy requires over one million man hours to find and fix wiring related problems [16], [17]. The aerospace industry is very active in developing health monitoring systems, but problems in wiring systems often persist hidden. Due to its low level, the fault current generated by tracking activity usually remains undetected by existing protections, although their continuous effect damages insulation systems until complete failure. Some of these incidents have led to the grounding of the aircraft, aborted takeoffs or emergency landing operations [18]. Table 1 summarizes the reported electrical wiring interconnection system (EWIS) failures among five major airlines in 2016 [18].

Table 1. Reported EWIS failures among five major Airlines in 2016 [18]

| | Number of EWIS failures |
|---|---|
| Airline #1 | 233 |
| Airline #2 | 286 |
| Airline #3 | 98 |
| Airline #4 | 78 |
| Airline #5 | 55 |

Table 2 describes the main types of faults in wiring systems.

Table 2. Fault types in wiring systems

| Fault type | Consequences |
|---|---|
| Insulation damage | Arc tracking, arcing and heating, ultimately leading to short circuit |
| Arcing | Insulation degradation, heating, ultimately leading to short circuit |
| Overload | Reversible heating |
| Short circuit | High-current circulation, fast heating and fire risk |
| Open circuit | Circuit disconnection |
| Wire breakage | Circuit disconnections, risk of electrical shock, short circuit, , or even fire |
| Stray currents and ground faults | Cause current to flow through paths not intended to carry current |
| Poor connections | Localized heating, more oxidation and creep, until high temperatures are attained |

Operators currently consider cabling as a system, deserving special consideration during maintenance operations. According to the Federal Aviation Administration (FAA) [19], there is a direct relationship between insulation problems severity and aircraft age. Insulation faults in cabling systems are often not directly evaluated, instead some measurable physical effects can be analyzed [20], such as acoustic noise, electromagnetic radiation, radio interference voltage, ultraviolet or visible emissions, generation of chemical components such as ozone or others, or temperature changes. There is an imperious need to evaluate the severity of insulation faults in existing installations, since it is vital for ensuring a safe, reliable and stable operation of power systems.

According to the IEEE Std1584-2018 [21], an electrical arc is defined as a cloud of plasma produced in the gap between two electrical electrodes when applying a sufficient potential difference. When the arc occurs, an arcing fault current flows through the electrical arc plasma. Arcs are often classified as parallel or series, as shown in Fig. 1. Parallel arcing occurs between opposite polarity conductors which are connected in parallel with the load. The current associated to this fault can be limited by a high fault impedance, hence preventing tripping. Parallel arcing faults to ground are due to a live conductor contacting a grounded conductor or a grounded metal enclosure [22]. Series arcs typically occur when a conductor connected in series with the load is broken, or due to a loose connection or a defect in the insulation of a wire. Series arc currents are often discontinuous and they are below the trip currents magnitude of conventional thermal/magnetic circuit breakers, so they often produce long-duration overheating of wiring systems, often leading to electric shock hazards [23]. As a result, they pyrolyze the surrounding insulation materials, generating char, a solid carbon-rich compound. This sort of arcing could ultimately lead to parallel faults to adjacent wires [22]. Arcing activity due to arc tracking can be considered as a series arc fault, since it severs partially or completely the series path with the load. Unlike shunt arcing faults, series arcing faults usually have very low energy, thus being unable to trigger an event unless the threshold of this event is very low [24]. This makes it challenging to detect series arcing activity, since the average value of the arc current is low, usually well below the rated current [24]. Because of the above mentioned issues, conventional protections based on the analysis of the current and voltage waveforms fail in detecting series arcing faults [25].

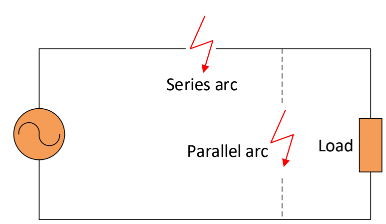


Figure 1. Series versus parallel arc faults.

Arc tracking is a particular discharge type occurring in organic insulating materials such as polymers or plastics type that reduces the insulation strength. The IEC 60050-212 standard [26] defines the tracking phenomenon as a "*progressive degradation of the surface of a solid insulating material by local discharges to form conducting or partially conducting paths*". Thus, the tracking activity produces tracks on the surface of insulating materials, i.e., carbonization paths which are partially conductive. If the insulation path between two wires or a wire and a ground surface is breached by a conductive fluid coming from a leaking pipe or condensation, or simply the insulation makes contact with a conductive surface, leakage currents are generated, which ultimately lead to arcing phenomena and could produce irreversible insulation damage.

Although the insulation used in wiring systems is often not subject to sufficient levels of electrical stress to produce tracking, thermal stress, chemical degradation and mechanical damage can breach the insulation, giving rise to tracking activity or scintillation. Scintillation is perceived as the existence of a small arc of yellow, white and even blue color that tends to burn away the surface of the insulation, ultimately leading to tracking failure [27]. The magnitude of the current associated with the tracking phenomenon is limited by the electric arc that forms between the two wires, the magnitude of the arc voltage being similar to the system voltage. Therefore, higher voltage levels expected in future MEAs will aggravate the problems related to arc tracking activity. Due to the small levels of current involved, such arcing events are difficult to detect, although they can significantly damage insulation systems [28].

A study performed on damaged aeronautic insulated wires exposed to AC short circuits [29] proved that 50-65% of the input electrical power is transferred to the wires, damaging the insulation and the metallic core. The remaining energy is transferred to the arc column, being either conducted, convected or radiated.

To fulfill the safety requirements, one possibility is to use arc fault detection and protection (AFDP) solutions. To this end, arcs can be detected with specific sensors by applying suitable computer-based algorithms based on pattern recognition techniques, including support vector machine [30], singular value decomposition [31], Fourier transform [32] and neural network approaches [33], [34], among others, to detect and identify arc fault patterns according to their specific characteristics.

Current commercial aircrafts use electronic arc fault circuit breakers (AFCBs) to protect electrical cables against the effects of arcing produced due to insulation faults. Similar devices, known as arc fault circuit interrupter (AFCI), are also used in industrial and household installations, to protect against electric arcs and to reduce fires occurrence. However, different factors such as inverter and switching harmonics noise, antenna effect, crosstalk or system topology among others, have an important impact on the arc signal, thus producing false trips on AFCIs [35].

AFCBs usually identify the fault condition by analyzing the waveform of the electric current, which is affected by arcing activity, and according to the AS6019 standard [36], they must trip faster than 100 ms. However, commercially available AFCBs react after arcing occurrence, that is, when cable insulation has suffered some level of damage, so they are unable to anticipate the fault condition and to identify the precise location of the fault. In addition, commercial industrial protections currently applied for detecting and protecting against arcing activity do not totally remove the associated transients [37]. Therefore, there is still much room to improve current AFCBs in order to anticipate arcing activity and thus minimize the associated degradation effects in insulation systems, the related risks and aircraft downtime. Since next generations of MEA aircrafts are expected to make a more intense use of electronic and electrical systems, AFCBs use is problematic [38], thus requiring new developments to ensure an early detection and location of very incipient faults as well as to predict the remaining useful life of the insulation (RUL).

There is a lack of technical literature focused on the analysis of arc tracking effects in wiring systems for aeronautic applications. This shortage of data is due to the difficulty for arc characterization because its behavior is very unpredictable [29], as well as the difficulty of reproducing the electromagnetic, and aeronautic environmental conditions.

It is worth noting that aircraft safety and maintenance are directly related, electrical protections having a key role in both aspects. Scheduled aircraft maintenance activities allow minimizing lost flights due to failures, maintaining aircraft systems under good performance, ensuring passenger safety, and extending aircraft lifetime.

This work reviews and analyzes the state of the art of arc fault protections intended for aeronautic applications to safeguard wiring systems from the harmful effect of arcs, with a special emphasis on the protections against tracking effects, focusing on the developments required to fulfill MEA requirements. This review also focuses on describing the current progress and detecting the challenges and research needs in this field, with a special emphasis on the need to locate the discharge points in the very early stage, before irreversible damage is produced in the insulation. The information found in this work has been gathered mainly from international standards, latest technical and scientific publications such as thesis, conference papers, journals, technical reports and white papers.

Finally, it should be noted that arcing is a transversal topic, since arcing-related failures have negative impacts in different areas such as residential, industrial, automotive or aeronautics, among others. However, in aeronautics it is even more vital to develop specific fault detection tools and protections due to the critical safety consequences of such faults. Therefore, the information found in this document is of interest to many other areas.

## II. Wire related accidents and incidents in aircrafts

In the last decades, damage to aircraft wiring and electrical arcing have been identified as potential sources of numerous aircraft accidents and incidents. Despite more awareness of the issues related to aircraft wiring systems, maintenance and ageing wiring related incidents still occur [39]. Whereas accidents are unexpected events causing damage, harm or injury, incidents are unexpected events that do not result in serious injury or losses.

Table 3 summarizes some of the accidents and serious incidents attributed to electrical and insulation related issues.

Table 3. Aircraft accidents and serious incidents attributed to electrical and insulation related issues.

| Year | Aircraft type | Location |
|---|---|---|
| 1983 | DC93 | Cincinnati, USA[1] |
| 1999 | AS55 | Fairview, Alberta, Canada[1] |
| 2005 | A319 | London, UK[2] |
| 2006 | AT43 | Geneva, Switzerland[1] |
| 2007 | B777 | London Heathrow, UK[2] |
| 2008 | B762 | San Francisco, USA[1] |
| 2009 | A319 | London Heathrow, UK[1] |
| 2011 | B772 | Cairo, Egypt[1] |

Data collected from: [1] [40], [2][41]

Table 4 includes some of the incidents attributed to electrical and insulation related issues.

Table 4. Aircraft incidents attributed to electrical and insulation related issues.

| Year | Aircraft type | Location |
|---|---|---|
| 1996 | B741 | East Moriches, USA[3] |
| 1998 | B767 | London Heathrow, UK[2,3] |
| 1998 | MD11 | Nova Scotia, Canada[3] |
| 1998 | B763 | France[1] |
| 1998 | B763 | Manchester, UK[1] |
| 2002 | B737 | London Heathrow, UK[3] |
| 2003 | B737 | Lyon, France[3] |
| 2007 | B763 | Frankfurt, Germany[1] |
| 2011 | A388 | Singapore [1] |
| 2013 | E170 | Nuremberg, Germany[1] |
| 2015 | DH8B | Windsor Locks, USA[1] |
| 2019 | A332 | North Atlantic[1] |

Data collected from: [1] [40] , [2][41], [3][39]

## III. The origin of arc tracking leading to series arcing faults

### A. Degradation of wiring systems

Electrical systems in aircraft environments are exposed to dust, moisture [42], a broad range of temperatures, low pressure, and mechanical stresses [43], agents that promote the creation of a conductive path between conducting elements of the electrical system. Current aircrafts mainly use three types of insulation systems, PI (polyimide insulation), XL-ETFE (cross-linked ethylene tetrafluoroethylene), and composite PTFE/PI insulation. Although PVC is already used, its use is discouraged due to ageing issues. PI insulation is less resistant to arc tracking, thus its use must be avoided when arc tracking is an issue [44]. Arc tracking activity depends on electrode nature, insulation composition and state, type of voltage (voltage level, DC, AC, frequency range) or environmental conditions [11], including the presence of dirt, debris or contaminants [3]. The frequency content of the induced current pulses covers a wide band, so that the electromagnetic coupling with other wires may interfere with control and communication systems [45]. Early investigations made between 1978 and 1982 by the US navy, documented hundreds of wiring incidents, some of which caused aircraft in-flight fires. They were attributed to insulation breakdown due to pyrolysis (aggravated by moisture, temperature and mechanical stresses), wet arc tracking (due to moisture and aircraft fluids) and dry arc tracking (occurs in dry condition) [22].

Table 5 shows the most widely wires used in aircrafts.

Table 5. Wires used in aircrafts

| Designation | Insulation Material |
|---|---|
| M5086/1,2 | PVC/Nylon (it use is discouraged) |
| M81381 | Kapton® -Aromatic polyimide (its use is discouraged) |
| M22759/34 | Cross-linked ETFE |
| M22759/80-92 | TKT composite (PTFE/Polyimide/PTFE) |
| M22759/11 | Teflon®-PTFE |
| M22759/18 | Tezfel®-ETFE |

### B. Partial discharges and arc tracking

Electric systems designed for ground operations can generate partial discharges in the electrical insulation at flight altitude, due to the low pressure operation. PD activity is deepened because of moisture condensation due to the sudden pressure changes produced during rapid ascent and descent operations [7]. Therefore, electrical insulations for aeronautics are more prone to PDs, particularly when working at higher voltages [46], [47], because of the low pressure environment [48], thus presenting lower inception voltages than at sea level [49]. PDs are a type of low intensity discharges that partly bridge the insulation of electric systems exposed to intense electric field stress [50], [51]. Surface PDs, often in the form of corona discharges, are generated in the air medium surrounding the insulation [52]. Corona/surface discharges often occur in MEA insulation systems [53], thus being the sources of early insulation systems failure [54]. They occur earlier at low pressure conditions [54], [55], because the development of electrical discharges is directly related to the pressure reduction [56]. The activity associated with electrical discharges weakens the insulation material due to the induced chemical reactions [57] that erode the insulation [42], thus ultimately producing arc tracking and even complete breakdown [58]. Tracking weakens the physical and chemical properties of the insulation due to the overheating produced by impact of the discharge produced electrons, which are accelerated by the local electric field [54], thus growing partially conductive carbon tracks along the insulation surface. Consequently, small-size electric arcs can form, sustain and spread, producing further damage to the insulation material [45]. Despite the continuous damage they produce until complete failure, PDs often induce very low fault currents, which makes it difficult to detect these low-energy discharges by standard electrical protections [53]. Such discharges generate chemical reactions, heat, UV and visible light, sound, light (mainly UV but also visible) and broad frequency radio interference voltage. Arcing produced in small air gaps is often preceded by corona activity generated in the most stressed region [51], [59], [60]. Corona activity on wire insulation materials usually produces discoloration and leaves a white dust [55], [61] because of the chemical reactions associated with the breakdown of the material. As the effect worsens, carbon tracks develop, and finally, wire insulation could be severely damaged.

Arc tracking is an electrical discharge induced by an electric field of sufficient strength on the surface of an insulation material due to the presence of conductive contaminants. It locally produces low magnitude electrical currents and short circuits on this surface, occasionally leading to sparks and small arcs, which damage the insulation, producing conductive surface tracks [62], and under certain circumstances can cause serious damage [63], resulting in fire hazard [22]. Low arcing currents occurring due to insulation breakdown produce conducting carbon micro-spots, which eventually can join up to complete an electrical path, resulting in an arc with further carbonizing effect. Arcing is recognized by aircraft organizations as a damaging fault mode, although test standardization is still unsatisfactory. Finite element method simulations have shown that when increasing the applied voltage, both the electric field strength and the maximum current density increase, which in turn favors dry-band formation [64]. The carbon tracks do not necessarily provide a continuous conductive path, since gaps may exist in the track. Depending on the applied voltage, such gaps may prevent current flow, but when the applied voltage increases or the pressure reduces and the electric field strength exceeds the dielectric strength of the track-gap, arcing can reappear [65]. These small discharges are often too weak to activate standard circuit breakers. The magnitude of such currents and the energy involved in the arcs between wires or electrodes grows as the insulation gets more damaged [66], finally leading to sustained and stabilized arcs due to the formation of conductive tracks randomly positioned. Such arcs can be extinguished due to a self-extinguishing process or when the protection de-energizes the circuit. Once the system is re-energized, this arcing activity can reappear, depending on cable design, nature of the insulation material, or degree of damage previously produced [62]. The arc is sustained as the Joule heat generated by the current flow is high enough to continue pyrolizing the insulation, otherwise the arcing event extinguishes [65]. It is known that the arc length at the pressure corresponding to flight altitude is almost twice that corresponding at sea level, whereas the mean electric field in the arc column reduces with pressure. As a consequence, the energy dissipated by arcing events is amplified by a factor of 1.7 under pressure conditions corresponding to flight altitude [11].

Fig. 2 shows the UV light emitted at the early stage of the phenomenon, well before arcing occurrence.

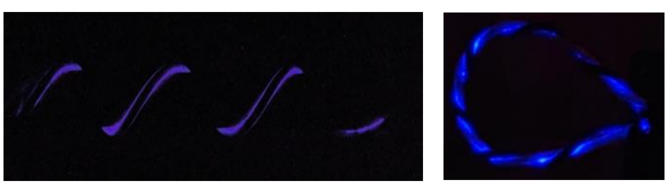
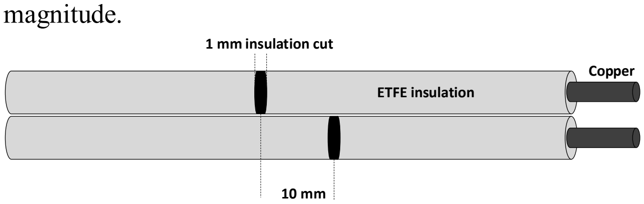



Figure 2. Visible/UV light emitted by stressed wires. Photographs taken at the AMBER laboratory of the Universitat Politècnica de Catalunya. a) UV emission from an insulated wire twisted around a grounded conducting rod. b) UV emission from a twisted pair

Fig. 3 shows the evolution of the surface PDs until arc formation between two parallel and adjacent 24 AWG ETFE insulated wires at 20 kPa when applying voltages of increasing magnitude.




a)

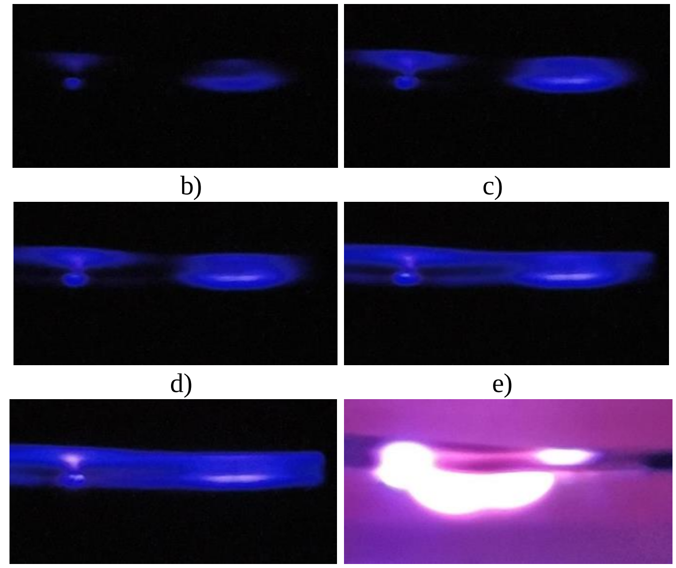



Figure 3. Arc formation process as seen by the visible/UV light between two 24 AWG ETFE insulated wires at 20 kPa. Photographs taken at the AMBER laboratory of the Universitat Politècnica de Catalunya. a) Wires layout. b) 636 V. c) 684 V. d) 714 V. e) 773 V. f) 899 V. g) Arc formation at 987 V.

### *C. Tests to recreate premature ageing in insulation materials*

Arcing can occur due to dry or wet arc tracking. Wet arc tracking is triggered by aircraft liquids or/and moisture, which can favor the formation of a short circuit between nearby wires or between the aircraft structure and an exposed wire at different electric potentials. Dry arc tracking often occurs under dry conditions due to insulation damage, abrasion or because of poor installation practices, thus inducing a short circuit between two nearby wires [58].

The ASTM D-495 [67] and the UL 746A [68] standards allow evaluating the resistance to arc tracking of different materials under the action of a low-current, high-voltage arc produced on the insulation surface of insulation under dry conditions. The usual test setup is simplified in Fig. 4.

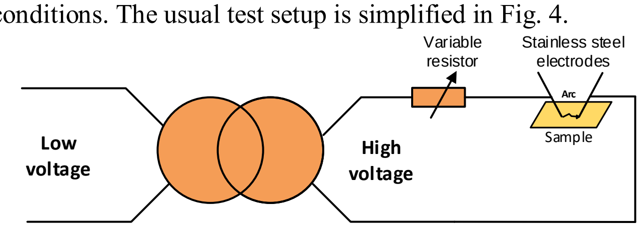



Figure 4. Dry arc tracking test setup adapted from [67].

The IEC 60587 standard [27] describes the test methods to evaluate the resistance to wet arc tracking of electrical insulating materials using inclined plane specimens and a liquid contaminant. Fig. 5 shows the test setup of the inclined plane test.

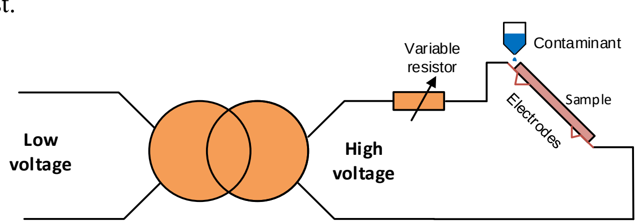



Figure 5. Wet arc tracking test setup adapted from [27].

### D. *Arcing current faults*

Arcing current faults (ACFs) usually exhibit a random, transient and burst nature behavior. The arc generates high frequency components in the current [69]. ACFs are classified as high impedance faults, since the fault path is often air or a non-conducting medium. Therefore, electrical currents generated by such faults are usually of low magnitude, although the arcing itself releases a considerable amount of energy during a short time [37]. Because of the low magnitude of the associated arcing currents, high impedance faults are difficult to detect, so they can remain undetected by standard overcurrent protection, since the relays require high short-circuit currents to trip [69], thus resulting in poor sensitivity to detect such faults. This produces a risk for persons and assets, because the current magnitudes during fault operation can be comparable to those under normal operation [69]. Arcing events are also possible in low voltage circuits operating below 240 V generated from wiring breakage over a short air gap [70], [71]. Such arcing phenomenon may pose a fire hazard, especially in the presence of flammable materials.

Arc behavior under AC and DC supply differs. In AC systems, the arc tends to extinguish at each current zero crossing. At lower pressures, AC arc duration is even shorter, tending to stop quickly after the first zero-current crossing. Under DC supply, when the applied current is low, the arc tends to self-extinguish after a short period, thus a minimum current is required to sustain the arc. Under the minimum current, the arc is sustained as long as the protections do not act.

## IV. Methods for arcing fault detection

Electric faults in aircrafts are among the main failure causes, so it is required to apply effective protection devices for fast fault detection and isolation. Overload and overcurrent protection is ensured by using conventional magnetic and thermal circuit breakers. However, a comparable reliability level is not guaranteed in the case of arcing faults [72]. Low-energy, intermittent arcs are difficult to be detected by such conventional thermal circuit breakers, because they require a sufficient current to heat up a thermally sensitive element incorporated in the protection [17].

### A. *Effects of arcing faults*

As already explained, the partially conductive arc track or carbon path exhibits a high enough electrical resistance, so that it limits the arc current, thus being difficult to detect when using conventional circuit protections. The current flow along the conductive cracks creates intermittent arcs, which have too low energy to trip standard circuit breakers. The low-level activity associated with these arc discharges is often unable to interfere with the signal transfer along the wire [12], thus making it difficult to apply standard detection methods. Therefore, conventional methods based on analyzing the current and voltage waveforms have low sensitivity to sense small arc discharges, leading to the failure of arc fault circuit interrupters [25].

Arcing activity generates broadband noise (tens of kHz to 1 GHz) as long as the arc current is sustained. The energy involved in the broadband noise spectrum depends on the branch circuit and the arc current. Arcs are commonly detected and isolated by analyzing the line current waveform and its broadband RF content [73]. The shape of the current waveform and its harmonic content during arc fault occurrence are unique and complex, thus requiring specific techniques for its detection [74].

### B. *State of the art methods to detect arcing faults*

Algorithms for arc fault detection usually include three stages, i.e., measurement and feature or signature extraction, classification between normal and fault conditions, and decision [22]. The technical literature describes different approaches to detect arc faults, although most of them are based on identifying specific patterns or signatures categorizing the arcs [37], [75], [76], so it is required to apply suitable signal processing algorithms [72]. The simplest indicator or signature to detect high energy arcing currents is the magnitude of the current, a time-domain feature, which has shown good performance to detect high energy arcing currents [37]. In [77] a step-change detector is proposed to detect arcing occurrence, since load voltage and current undergo a step change during arc occurrence. Other time-domain signatures have been applied to detect arc faults, such as the rate of change of the current or geometric features of the current waveform [78]. However, protections based on time-domain signatures require acquiring data, training the protection and defining threshold values, thus limiting their widespread use [70], [75]. Mathematical methods such as artificial neural networks [74], [79], [80], Kalman filters [81] or fuzzy logic [72], [82] have been applied to identify the specific patterns of the arcs. Another possibility is to apply frequency-domain signatures, such as the harmonic content of the fault current [83], but fault current harmonic frequencies can be masked by those triggered by other faults [84]. Harmonic-based protections often compare the extracted harmonics by means of the fast Fourier transform (FFT) [85] using pre-established threshold values, thus limiting once again its applicability. In [74] the fast Fourier transform (FFT) was combined with an artificial neural network (ANN) to detect series arc faults. Harmonic extraction based on the fast Fourier transform can be improved by applying wavelet decomposition [12] to enhance identification accuracy [86]. Wavelets (WTs) have been applied to analyze high impedance faults [87], which can be based on decomposing voltage or current signals, or by combining WT decomposition with other mathematical techniques [88], such as the Kernel density estimation [89]. Time-frequency signatures have been also applied to detect series arcing faults, even under DC supply [24].

It is also possible to analyze the negative-sequence components of the current in microprocessor-based protections [90], due to the high sensitivity of this technique towards unbalanced faults [91]. Attempts to detect such faults currents have been carried out by measuring their zero-sequence components using several types of sensing devices [37]. In [92], it was proposed to analyze the zero-sequence value of the current flowing in a distribution feeder, whereas in [93] a method combining the analysis of the negative-sequence current and the residual voltage components was applied. However, each method has some drawbacks and limitations [88], some of them being developed for particular types of high impedance faults. One of the issues of the methods found in the technical literature is the definition of threshold values for fault detection, which is a critical point to avoid false detections of the fault condition [88]. Fig. 6 summarizes different methods for arcing faults detection.

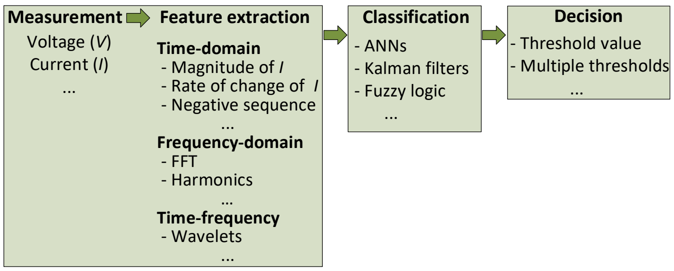


Figure 6. Arcing faults detection methods.

Arc discharges can also be sensed from the physical effects they produce. Therefore, non-conventional methods, including acoustic emission, ultraviolet (UV), and transient earth voltage sensors can be used for this purpose [25]. It is known that arcing generates ultraviolet (UV) radiation, so the analysis of UV pulses has been used to detect arcing events. The number of UV pulses allows determining the condition of the equipment generating such pulses [94], [95]. By analyzing the current and voltage waveforms it is very difficult to distinguish arcing from other transient non-arcing events presenting features similar to those of the arcs [12].

### C. *State-of –the-art methods to locate arcing faults*

Finally, conventional circuit breakers are unable to locate the position of the fault on the wire they are protecting. Reflectometry has been widely applied to detect, identify and locate faults in cabling systems [96], [97]. Reflectometry approaches are found in early studies during the eighties to locate faults in underground transmission cables [98]. It is based on the radar theory of electromagnetic waves, allowing it to detect impedance discontinuities in cables and being possible to localize the fault. The fault distance is computed from the time delay between the incident and reflected signals due to the impedance discontinuity. Reflectometry is classified into TDR (time-domain reflectometry, the most widely applied method for wire fault identification and location [88]), FDR (frequency-domain reflectometry), and TFDR (time-frequency domain reflectometry) [99], [100]. Time domain reflectometry (TDR) can potentially detect very small impedance changes, although this method needs a very precise baseline to compare with the faulty wires [88], this method being difficult to calibrate and apply in commercial or military fleets. However, wire vibrations, which are unavoidable in aircrafts, can produce impedance changes, which can be even larger than the impedance change due to the arc activity [17]. Another possibility is to apply spread spectrum reflectometry (SSR) because it can locate low-energy, intermittent faults on energized aircraft wiring systems. SSR applies a pseudo-noise test signal on the wire, i.e., a very low-voltage code. By correlating the reflected and incident signals, it is potentially possible to identify and locate the fault [17].

Methods based on visible-UV imaging allowing to locate the discharge point [7], [101] being very immune to electromagnetic noise produced by nearby electrical or electronic devices.

## V. Arcing Protections For Aircraft Applications

Nowadays, military and civilian aircrafts are typically protected against overheating by using magnetic and thermal circuit breakers, arc fault circuit breakers (AFCBs) or solid state circuit breakers (SSCBs). The function of AFCBs and SSCBs is to quickly disconnect the circuit once an arc fault is detected [87]. To minimize unwanted or nuisance trips, these protections must discern between a potentially dangerous arcing event and a usual operating condition in which a particular arc can be expected in the circuit under a usual load [87]. As explained, conventional protection cannot detect and protect against arcing faults produced between a wire and ground, between parallel wires, or in series due to a loose connection, a defect in the insulation of a wire, or a broken wire. Protections must minimize the possibility of arcing occurrence due to different causes, such as insulation ageing, chemical contamination, wire breakage or chafing [22]. Fig. 7 describes the main characteristics of the existing arc protection devices.

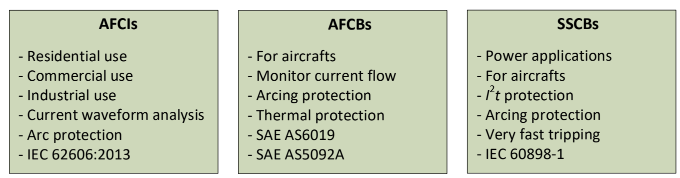


Figure 7. Existing arc protection devices.

Fig. 8 describes the main blocks of the existing arc protection devices.

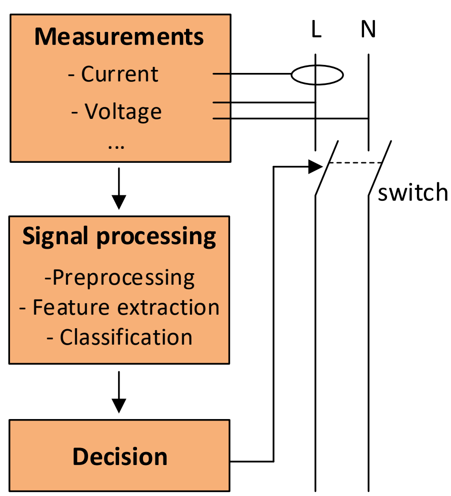


Figure 8. General diagram of existing arc fault protection devices.

### A. *Arc Fault Circuit Breakers (AFCBs)*

Conventional thermal circuit breakers do not react to intermittent arcing events until they develop into a severe fault.

Arc fault circuit interrupters (AFCIs) were commercially introduced in 1998 for residential use, but today are being increasingly applied in industrial and commercial offices and workrooms [46]. The IEC 60364-4-42:2014 international standard [103] recommends the use of AFCIs for high risk situations. Since 2013, arc fault detection devices are regulated by the IEC 62606:2013 standard [104], which does not impose any current requirement for a minimal arcing persistence under the occurrence of a series arc [105]. Fig. 9 shows the diagram of an AFCI.

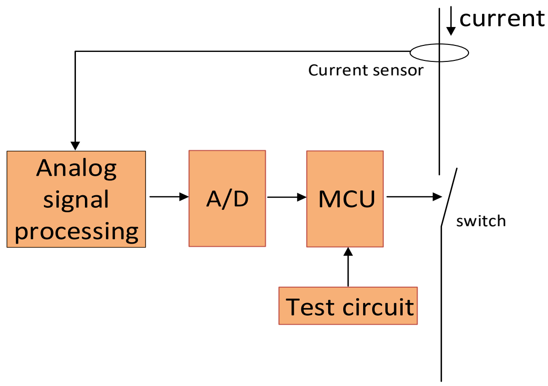



Figure 9. Typical diagram of an AFCI.

AFCIs use current and voltage sensors, and discriminate the detected waveforms, tripping the circuit when detecting arc-related patterns. By analyzing the current waveform, AFCIs can discriminate between an abnormal and a normal event, so they trip the contacts when detecting an arcing event, de-energizing the circuit [22]. According to its pattern or signature, AFCIs distinguish an arc due to the ordinary operation of plugs, switches, or brushed machines from a dangerous arc, in this last case breaking the circuit. However, commercially available AFCIs have a reliability around 50%. Under low-energy series faults, arc features are often masked because conventional current and voltage methods present low sensitivity [25].

AFCBs are now incorporated in modern aircrafts to break the circuit in case they detect an arcing event. AFCBs are similar to AFCIs and protect the network and the load disconnecting the circuit when arcing occurs [6]. AFCBs were developed at the beginning of this century to prevent aircraft from fires originated by glowing contacts and low-current series arcs [8]. The objective was to incorporate arc-fault protection to existing thermal protection [22], while trying to maintain the standard size of the protection package. AFCBs are based on electronics and they continuously monitor the current flow [22]. They incorporate algorithms that must be sensitive enough for a fast identification of an arc condition, without tripping under other transient events, to minimize unintended or nuisance trips. Different challenges must be met, such as the development of suitable arc-fault detection algorithms and to pack the arc-fault and the thermal overcurrent protection components into a standard aircraft circuit breaker package. They also require to operate under aircraft environments (-20ºC-70ºC, 0-13700 m, electromagnetic interference, vibration, electrical transients) [8]. The next challenge is to develop lower cost, more reliable [6], and compact size AFCBs [72].

Fig. 10 shows the diagram of an AFCB.

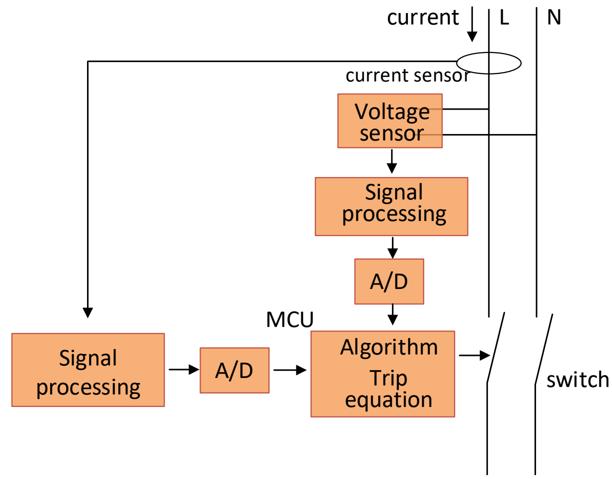



Figure 10. Typical diagram of an AFCB.

AFCB attributes include fast reaction to arcing events, good arc sensitivity under the presence of masking loads, good discrimination between normal and transient load patterns and arcing events and immunity to electromagnetic noise. While the arc energy detection threshold of typical bimetal circuit breakers in an arcing event falls in the 80-500 J range, the sensitivity of the initial AFCBs was set in the 5-30 J interval [22]. Today there exist 28 V-DC AFCBs standardized under SAE AS6019 [36], and 115 V-AC single- and three-phase AFCB for 400 Hz (constant frequency) standardized under SAE AS5692A [106].

AFCBs mitigate arcing effects before a severe fault develops, preventing catastrophic effects on electrical wires by limiting the arc fault energy, thus reducing the risk to burn nearby materials, such as wire insulation. The tripped AFCB identifies the circuit or wire on which the fault has occurred. Arc detection and location are still subjects of research. Since distribution networks vary in different aircrafts, the most suitable position of the AFCB can be defined. AFCBs usually break the circuit at the point in which the current is measured. Since most detection algorithms rely on line current time or frequency analyses, then, the operation of the AFCB could not be accurate and reliable [6]. AFCBs offer active monitoring to system faults, whereas conventional thermal circuit breakers provide passive electro-thermal reaction, because they are set to trip at pre-established current levels over a specific period of time. However, in some circumstances active monitoring introduces nuisance tripping, so the Society of Automotive Engineers (SAE) has defined a set of demanding qualification tests [8].

### *B. Solid State Circuit Breakers (SSCBs)*

The research tendency on protection from series arc faults produced in aircraft wiring systems focus on the use of SSCBs [22]. SSCBs are based on fast switching semiconductor switches that control the power supplied to a load, usually MOSFETs. Turned-off MOSFETS present a small leakage current, which needs to be controlled [8]. Fig. 11 shows the diagram of a SSCB.

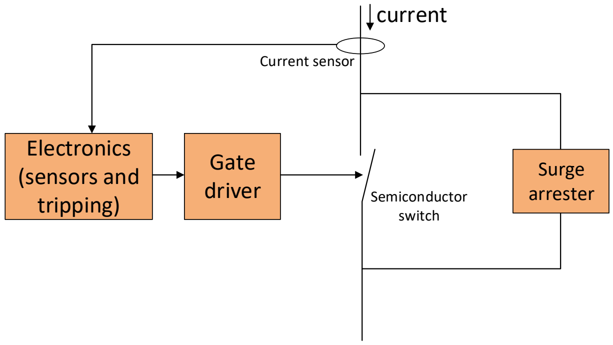



Figure 11. Typical diagram of an SSCB adapted from [107].

SSCBs emulate the time-current circuit breaker curve, perform diagnostic and supervisory functions, being now introduced in different military and civilian aircrafts for protection against overheating [22]. Unlike circuit breakers, SSBCs disconnect the circuit when there is too much energy transfer because they provide true $I^2t$ protection. An SSCB, whereas a standard overload circuit breaker will trip only when the current reaches the trip point. SSCBs are very fast, since they can switch in 0.05 ms, thus reducing the energy of the arc and the potential damage, allow remote switching control, have trip indication and the status of the breaker is known. SSCBs are mostly limited to new designs, because their packaging differs from that of existing applications. SSCBs exhibit faster response time and lower weight compared to AFCBs and standard thermal circuit breakers [108]. It is believed that solid-state technology can remove electromechanical relays and thermal breakers in most aircraft applications. SSCBs can offer thermal and arc-fault protection for both loads and wiring, whereas thermal breakers only offer wire protection [109].

### C. Other protection strategies

To protect against arcing faults it is possible to lower the trip level of circuit breakers, at the expense of increasing nuisance tripping occurrence [22]. Different protections based on both time and frequency domain signatures are being developed. They use supplementary sensors such as temperature and pressure sensors jointly with voltage and current measurements to detect and clear the faults in the early formation stage. Others employ fiber optic sensors jointly with current and voltage measurements to increase the accuracy and speed of clearing ACFs. Despite some improvements, the new protections still present some practical concerns, which must be solved previous to their wide use [37].

## VI. Next Steps in the Development of the Future Arc Fault Protections

There are three major issues in state of the art arc protections. The first one is related to the low level current leakage in the early stage of insulation degradation, which can remain undetected until it increases during a long period of time, during which insulation becomes degraded. The second one is related to the misdiagnosis leading to nuisance tripping. Finally, the third issue is related to the location of the fault, since current state of the art protections are unable to determine the exact point where the fault is produced. Fig. 12 summarizes the three major aspects and their related benefits to improve in current state of the art arc fault protections.

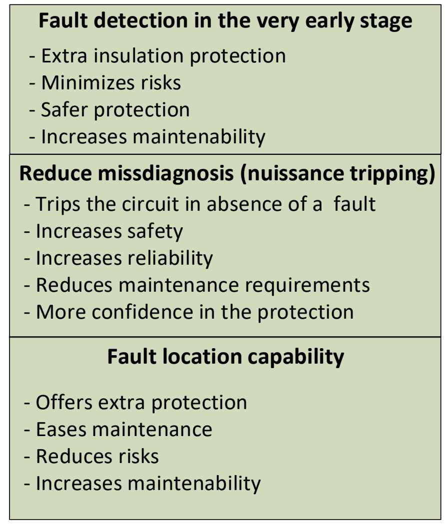



Figure 12. Three major aspects and their related benefits to improve in current state of the art arc fault protections

### A. Limitations of Existing Arcing Protections for Aircraft Applications

This section summarizes the identified limitations related to existing arc fault protections for aeronautic applications, which are listed below.

1) Due the low magnitude of series arcing events, especially in the early stage, they are difficult to be detected by existing phase overcurrent protection [37].
2) Conventional methods based on analyzing the current and voltage waveforms have low sensitivity to sense small arc discharges, leading to the failure of existing AFCBs [25]. Current AFCBs can detect false positives, i.e., they can recognize normal circuit behaviors as arcing faults, leading to nuisance tripping, thus reducing AFCBs overall effectiveness [37][110].
3) Conventional circuit breakers are unable to locate the exact position of the fault on the wire they are protecting.
4) Despite the diversity of techniques found in the literature for detecting and identifying arcing currents, which allow different possibilities for designing accurate protections, all of them have a common point, i.e., the fact that they trip once the fault is in an advanced stage. Existing arc fault protections act under fault occurrence, when the arc is well developed and with a sufficient level of energy, so they are unable to anticipate nor to locate the exact position of the fault. Therefore, there is a lack of preventive protections that act before the fault evolves, in the very early stage before irreversible damage in the insulation is produced [111].

### B. Identified Research Needs

This section summarizes the research needs detected from the systematic scientific and technical literature review done in this paper, related to arc fault protections for aeronautic applications.

1) More research is required on tracking resistance, erosion and long-term behavior of insulation materials under

aeronautic environmental conditions [58], since they have a great impact on arc fault development and evolution.

2) Lightning activity and some electrical machines generate current and voltage patterns that resemble arc faults. Nuisance tripping reduces overall performance of arc fault protections, having a negative impact on aircraft performance and requiring significant efforts to resolve and diagnose. More research in this area is required [9].
3) It is necessary to develop robust nondestructive technologies which allow to determine the location at which the arc fault occurred, even during in-flight conditions.
4) There is an imperious need to develop arc fault protections capable of detecting the arc tracking phenomenon at the very early stage, before major and irreversible wire insulation damage is produced. To this end, PD/corona detection methods could complement current protections since they are able to detect arc tracking activity well before arcing effects are fully developed. Cost-effective, small-size and fast response sensors designed for operation under stringent aeronautic environments must be developed, jointly with suitable instrumentation and signal processing methods.
5) Characteristics of the voltage waveform of the distribution bus (AC, constant frequency, wild frequency, AC, positive DC, negative DC, impulsive, pulsed, etc.) impacts the signatures of the discharges and their long-time effects on insulation systems [58]. This area requires further research, especially under aeronautic environments.
6) There is a lack of studies focusing on arc-fault protections for low pressure conditions, such as those typical of aircraft systems. Therefore, more research is needed in this area, accounting for the specificities of these harsh environments.

### *C. Challenges of Arcing Protections for Aircraft Applications*

There are different challenges to be faced in order to improve current protections, which are described in the following lines.

1) Constructive aspects
   - It is required to pack the arc-fault and the thermal overcurrent protection components into a standard aircraft circuit breaker package. They also require to operate under aircraft environments (-20ºC-70ºC, 0-13700 m, electromagnetic interference, vibration, electrical transients) [8].
   - Miniaturization of AFCBS in order to not exceed the size of standard circuit breakers packages is another challenge that protection manufacturers are facing [8], so more compact AFCBs are required [72].
2) Performance improvement
   - Future developments in arc fault protections should emphasize aspects such as reduce the cost, and increase their reliability AFCBs [6].
   - Future protections should record electrical waveforms for maintenance, operation, or accident investigations. They also need to include built in diagnostics such as self-test and self-monitoring can be of great help, to clearly indicate that the protection is fully functional. Protection coordination must be contemplated, as already incorporated in existing circuit breakers, although coordination of arc fault detection is a challenge [8]. Thus, different performance improvements are required [112].
   - The development of performance specifications and requirements for arc fault protections has been proven to be problematic. For example, tests to assess undesired effects such as crosstalk, feedback susceptibility, nuisance tripping, and others need further work [8].
   - Solid state fault interrupters enable establishing more sensitive trip thresholds, thus offering the possibility to reduce nuisance tripping [110].
   - There is a need to develop specific electrical protections to detect partial discharge and/or corona activity well before arc tracking occurrence, since partial discharge is an early symptom of insulation failure, thus safeguarding electrical wiring systems and aircraft integrity.
3) Development of more effective detection and location approaches
   - It is required to develop suitable arc-fault detection algorithms [8].
   - The development of arc fault protections that can determine the exact position of the arc fault to facilitate maintenance operations [58]. The use of UV photo sensors can be beneficial for this purpose [113].
   - AFCBs act once the arcing occurs but not before, so they can be improved to reduce the damage level and shorten the reaction time. With next generations of MEA aircrafts, which depend more and more on electrical and electronic systems, the use of current AFCBs is questionable [38], so it is required to develop new approaches for an early detection [58].

## VII. Conclusion

With the growing demand of MEA aircrafts which require more electrical power, fault management devices have a key role, due to the extreme importance of aircraft safety. The increased levels of electrical power generation impose to rise the values of the distribution voltage, thus appearing new fault modes, such as arc tracking and series arcing. However, commercially available protections do not offer a total protection against these fault modes.

This review paper has performed a systematic and exhaustive literature analysis of the knowledge about arc fault protections for aeronautic applications, identifying the current progress, aspects to improve, limitations, future challenges, and research needs. The paper has identified different aspects that arc fault protections need to face, including among others,

- Packaging miniaturization.
- Nuisance tripping issues.
- Compatibility with the harsh aircraft environments.
- The need to reduce the cost and increase the reliability of the protections.
- Inclusion of self-diagnostics and self-monitoring capabilities.
- The problematics related to the development of performance specifications and requirements for arc fault protections.

- Incorporation of fault location and detection at the very early stage, well before arcing occurrence.
- High immunity to electromagnetic noise.

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## ACRONYMS

| | |
|---|---|
| AC | Alternating current |
| ACF | Arcing current fault |
| AEA | All electric aircraft |
| AFCB | Arc fault circuit breakers |
| AFCI | Arc fault circuit interrupter |
| AFDP | Arc fault detection and protection |
| ANN | Artificial neural network |
| DC | Direct current |
| ETFE | Ethylene tetrafluoroethylene |
| EWIS | Electrical wiring interconnection system |
| FAA | Federal Aviation Administration |
| FDR | Frequency-domain reflectometry |
| FFT | Fast Fourier transform |
| HVAC | High-voltage alternating current |
| HVDC | High-voltage direct current |
| IEC | International Electrotechnical Commission |
| MCU | Microcontroller unit |
| MEA | More electric aircraft |
| MOSFET | Metal oxide semiconductor field effect transistor |
| PD | Partial discharge |
| PI | Polyimide insulation |
| PTFE | Polytetrafluoroethylene or Teflon® |
| PVC | Polyvinyl chloride |
| RUL | Remaining useful life |
| SAE | Society of Automotive Engineers |
| SSCB | Solid state circuit breakers |
| SSR | Spread spectrum reflectometry |
| SWAMP | Severe weather and moisture prone |
| TDR | Time-domain reflectometry |
| TFDR | Time-frequency domain reflectometry |
| UV | Ultraviolet |
| XL-ETFE | Cross-linked ethylene tetrafluoroethylene |
| WT | Wavelets |

## REFERENCES

[1] A. C. Mermigkas, D. Clark, and A. Manu Haddad, "Investigation of High Altitude/Tropospheric Correction Factors for Electric Aircraft Applications," in *Lecture Notes in Electrical Engineering*, 2020, vol. 598 LNEE, pp. 308–315, doi: 10.1007/978-3-030-31676-1_30.

[2] H. El Bayda *et al.*, "Energy losses from an arc tracking in aeronautic cables in DC circuits," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 1, pp. 19–27, Feb. 2013, doi: 10.1109/TDEI.2013.6451337.

[3] M. Borghei and M. Ghassemi, "Insulation Materials and Systems for More and All-Electric Aircraft: A Review Identifying Challenges and Future Research Needs," *IEEE Trans. Transp. Electrif.*, 2021, doi: 10.1109/TTE.2021.3050269.

[4] T. Shahsavarian, C. Li, M. A. Baferani, and Y. Cao, "Surface discharge studies of insulation materials in aviation power system under DC voltage," in *2020 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Oct. 2020, pp. 271–274, doi: 10.1109/CEIDP49254.2020.9437456.

[5] G. Belijar, G. Chanaud, L. Hermette, and A. Risacher, "Study of electric arc ignition, behavior and extinction in aeronautical environment, in presence of FOD." Saint-Exupéry, pp. 1–8, 2017.

[6] J. Andrea, M. Buffo, E. Guillard, R. Landfried, R. Boukadoum, and P. Teste, "Arcing fault in aircraft distribution network," in *Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts*, Oct. 2017, pp. 317–324, doi: 10.1109/HOLM.2017.8088106.

[7] J.-R. J.-R. Riba, Á. Gómez-Pau, and M. Moreno-Eguilaz, "Experimental Study of Visual Corona under Aeronautic Pressure Conditions Using Low-Cost Imaging Sensors," *Sensors*, vol. 20, no. 2, p. 411, Jan. 2020, doi: 10.3390/s20020411.

[8] R. Pappas, "Arc Fault Circuit Breaker Development and Implementation." NASA, Washington, D.C., USA, p. 9, 2002, Accessed: Jul. 02, 2021. [Online]. Available: https://www.fire.tc.faa.gov/2001Conference/files/FireProtection/RPappasPAPER.PDF.

[9] M. C. Flynn *et al.*, "Protection and Fault Management Strategy Maps for Future Electrical Propulsion Aircraft," *IEEE Trans. Transp. Electrif.*, vol. 5, no. 4, pp. 1458–1469, Dec. 2019, doi: 10.1109/TTE.2019.2940882.

[10] M. C. Flynn, C. E. Jones, P. J. Norman, and G. M. Burt, "A fault management-oriented early-design framework for electrical propulsion aircraft," *IEEE Trans. Transp. Electrif.*, vol. 5, no. 2, pp. 465–478, Jun. 2019, doi: 10.1109/TTE.2019.2913274.

[11] R. Landfried, L. Savi, T. Leblanc, and P. Teste, "Parametric study of electric arcs in aeronautical condition of pressure," *EPJ Appl. Phys.*, vol. 67, no. 2, p. 20802, Aug. 2014, doi: 10.1051/epjap/2014140065.

[12] Z. Hongkun, C. Tao, and L. Wenjun, "Arc fault signatures detection on aircraft wiring system," in *Proceedings of the World Congress on Intelligent Control and Automation (WCICA)*, 2006, vol. 2, pp. 5548–5552, doi: 10.1109/WCICA.2006.1714135.

[13] T. Kostakis, P. J. Norman, S. J. Galloway, and G. M. Burt, "Demonstration of fast-acting protection as a key enabler for more-electric aircraft interconnected architectures," *IET Electr. Syst. Transp.*, vol. 7, no. 2, pp. 170–178, Jun. 2017, doi: 10.1049/iet-est.2016.0065.

[14] Clean Sky, "Annex: 11 th Call for Proposals (CFP11)-List and Full Description of Topics Call Text," 2019. Accessed: Nov. 12, 2020. [Online]. Available: https://ec.europa.eu/info/funding-tenders/opportunities/docs/cap/h2020/jti-cs2-2020-cfp11-tht-12/1875197-cfp11_call_text_-_list_and_full_description_of_topics_r1_en.pdf.

[15] CleanSky, Clean Sky, and CleanSky, "9th Call for Proposals (CFP09) - List and Full Description of Topics." Clean Sky, pp. 1–354, 2018, Accessed: Nov. 12, 2020. [Online]. Available: https://ec.europa.eu/research/participants/portal/doc/call/h2020/jti-cs2-2018-cfp09-air-01-40/1837622-cfp09_call_text_-_list_and_full_description_of_topics_r1_en.pdf.

[16] M. A. Dornheim, "New rules and hardware for wiring soon to emerge," *Aviat. Week Sp. Technol.*, vol. 154, no. 13, pp. 1–5, 2001.

[17] C. Furse, M. Safavi, P. Smith, and C. Lo, "Feasibility of spread spectrum sensors for location of arcs on live wires," *IEEE Sens. J.*, vol. 5, no. 6, pp. 1445–1449, Dec. 2005, doi: 10.1109/JSEN.2005.858900.

[18] Lectromec, "2016 Statistical Analysis of EWIS Failures of the US Commercial Aircraft Fleet and How to Improve," Chantilly, VA, VA, 2017. [Online]. Available: https://d2wwvh76f5odon.cloudfront.net/lectromec-wp/wp-content/uploads/2017/07/11154506/Lectromec-Commercial-Airline-White-Paper-20172.pdf.

[19] FAA, "Aircraft EWIS Practices Job Aid 2.0 Federal Aviation Administration Aircraft Electrical Wiring Interconnect System (EWIS) Best Practices Job Aid," 2021.

[20] Z. Yuan, Q. Ye, Y. Wang, and Z. Guo, "State Recognition of Surface Discharges by Visible Images and Machine Learning," *IEEE Trans. Instrum. Meas.*, pp. 1–1, Oct. 2020, doi: 10.1109/tim.2020.3031543.

[21] IEEE, "1584-2018 - IEEE Guide for Performing Arc-Flash Hazard Calculations | IEEE Standard | IEEE Xplore," New York, USA, 2018. Accessed: Jun. 25, 2021. [Online]. Available: https://ieeexplore-ieee-

org/document/8563139.
[22] B. C. Brusso, "History of Aircraft Wiring Arc-Fault Protection," *IEEE Ind. Appl. Mag.*, vol. 23, no. 3, pp. 6–11, May 2017, doi: 10.1109/MIAS.2017.2659022.
[23] M. Jalil, H. Samet, T. Ghanbari, and M. Tajdinian, "An Enhanced Cassie-Mayr Based Approach for DC Series Arc Modeling in PV Systems," *IEEE Trans. Instrum. Meas.*, pp. 1–1, 2021, doi: 10.1109/TIM.2021.3124832.
[24] A. Maqsood, D. Oslebo, K. Corzine, L. Parsa, and Y. Ma, "STFT Cluster Analysis for DC Pulsed Load Monitoring and Fault Detection on Naval Shipboard Power Systems," *IEEE Trans. Transp. Electrif.*, vol. 6, no. 2, pp. 821–831, Jun. 2020, doi: 10.1109/TTE.2020.2981880.
[25] G. Wang, W.-H. Kim, H.-K. Ji, and G.-S. Kil, "Detection and analysis of series arc using non-conventional methods in low-voltage switchboards," *J. Electr. Eng.*, vol. 69, no. 4, pp. 317–322, Aug. 2018, doi: 10.2478/jee-2018-0045.
[26] International Electrotechnical Commission, "IEC 60050-212:2010. International Electrotechnical Vocabulary (IEV) - Part 212: Electrical insulating solids, liquids and gases," Geneva, Switzerland, 2012. [Online]. Available: https://webstore.iec.ch/publication/187.
[27] IEC, "IEC 60587:2007 Electrical insulating materials used under severe ambient conditions - Test methods for evaluating resistance to tracking and erosion." Geneva, Switzerland, pp. 1–28, 2007.
[28] "EUROPA - Assessment of arc tracking hazards in high voltage aerospace systems | TRIMIS - European Commission." https://trimis.ec.europa.eu/project/assessment-arc-tracking-hazards-high-voltage-aerospace-systems#tab-outline (accessed Jun. 25, 2021).
[29] T. André, F. Valensi, P. Teulet, Y. Cressault, T. Zink, and R. Caussé, "Arc tracking energy balance for copper and aluminum aeronautic cables," in *Journal of Physics: Conference Series*, Apr. 2017, vol. 825, no. 1, p. 012001, doi: 10.1088/1742-6596/825/1/012001.
[30] C. Han, Z. Wang, A. Tang, H. Gao, and F. Guo, "Recognition Method of AC Series Arc Fault Characteristics under Complicated Harmonic Conditions," *IEEE Trans. Instrum. Meas.*, vol. 70, 2021, doi: 10.1109/TIM.2021.3051669.
[31] R. Jiang, G. Bao, Q. Hong, and C. D. Booth, "A Coupling Method for Identifying Arc Faults Based on Short-Observation-Window SVDR," *IEEE Trans. Instrum. Meas.*, vol. 70, 2021, doi: 10.1109/TIM.2021.3067660.
[32] Q. Xiong *et al.*, "Series arc fault detection and localization in DC distribution system," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 1, pp. 122–134, Jan. 2020, doi: 10.1109/TIM.2019.2890892.
[33] G. Zhou *et al.*, "Intever Public Database for Arcing Event Detection: Feature Analysis, Benchmark Test, and Multi-Scale CNN Application," *IEEE Trans. Instrum. Meas.*, vol. 70, 2021, doi: 10.1109/TIM.2021.3082998.
[34] Y. Wang, F. Zhang, and S. Zhang, "A New Methodology for Identifying Arc Fault by Sparse Representation and Neural Network," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 11, pp. 2526–2537, Nov. 2018, doi: 10.1109/TIM.2018.2826878.
[35] J. C. Gu, D. S. Lai, J. M. Wang, J. J. Huang, and M. T. Yang, "Design of a DC series arc fault detector for photovoltaic system protection," in *IEEE Transactions on Industry Applications*, May 2019, vol. 55, no. 3, pp. 2464–2471, doi: 10.1109/TIA.2019.2894992.
[36] SAE, "AS6019: ARC Fault Circuit Breaker (AFCB), Aircraft, Trip-Free 28 VDC - SAE International." SAE, Warrendale, Pennsylvania, United States, pp. 1–60, 2012.
[37] S. A. Saleh, M. E. Valdes, C. S. Mardegan, and B. Alsayid, "The State-of-the-Art Methods for Digital Detection and Identification of Arcing Current Faults," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 4536–4550, Sep. 2019, doi: 10.1109/TIA.2019.2923764.
[38] M. Lisnyak, "Theoretical, numerical and experimental study of DC and AC electric arcs," Apr. 2018.
[39] Air Accidents Investigation Branch, "Overview: Incidents resulting from damage to electrical wiring, 1 June 2004," 2014. https://www.gov.uk/aaib-reports/overview-incidents-resulting-from-damage-to-electrical-wiring-1-june-2004 (accessed Nov. 14, 2021).
[40] "Electrical Fires - SKYbrary Aviation Safety." https://www.skybrary.aero/index.php/Electrical_Fires (accessed Nov. 14, 2021).
[41] "Arcing Archives - Aviation Accident Database." https://www.aviation-accidents.net/tag/arcing/ (accessed Nov. 14, 2021).
[42] I. Cotton and A. Nelms, "Higher voltage aircraft power systems," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 23, no. 2, pp. 25–32, Feb. 2008, doi: 10.1109/MAES.2008.4460728.
[43] A. M. Bruning and W. G. Linzey, "High voltage gradients in aircraft low voltage systems," in *Conference Record of the International Power Modulator Symposium and High Voltage Workshop*, 2004, pp. 15–16, doi: 10.1109/modsym.2004.1433495.
[44] D. H. Berkebile and B. G. Pike, "Aircraft Wire and Cable Requirements for Fire Performance." Elm City, NC, USA, p. 6, 1998, [Online]. Available: Aircraft Wire and Cable%0ARequirements for Fire Performance.
[45] V. Degardin, L. Kone, P. Laly, M. Lienard, P. Degauque, and F. Valensi, "Measurement and analysis of arc tracking characteristics in the high frequency band," in *AUTOTESTCON (Proceedings)*, Oct. 2016, doi: 10.1109/AUTEST.2016.7589591.
[46] CleanSky, "9th Call for Proposals (CFP09) - List and Full Description of Topics." Clean Sky, pp. 1–354, 2018, [Online]. Available: https://ec.europa.eu/research/participants/portal/doc/call/h2020/jti-cs2-2018-cfp09-air-01-40/1837622-cfp09_call_text_-_list_and_full_description_of_topics_r1_en.pdf.
[47] A. N. Esfahani, S. Shahabi, G. Stone, and B. Kordi, "Investigation of Corona Partial Discharge Characteristics Under Variable Frequency and Air Pressure," in *2018 IEEE Electrical Insulation Conference (EIC)*, Jun. 2018, pp. 31–34, doi: 10.1109/EIC.2018.8481047.
[48] L. Capineri, G. Dainelli, M. Materassi, and B. D. Dunn, "Partial discharge testing of solder fillets on PCBs in a partial vacuum: new experimental results," *IEEE Trans. Electron. Packag. Manuf.*, vol. 26, no. 4, pp. 294–304, Oct. 2003, doi: 10.1109/TEPM.2003.820822.
[49] R. Rui and I. Cotton, "Impact of low pressure aerospace environment on machine winding insulation," in *2010 IEEE International Symposium on Electrical Insulation*, Jun. 2010, pp. 1–5, doi: 10.1109/ELINSL.2010.5549718.
[50] O. El Mountassir, B. G. Stewart, A. J. Reid, and S. G. McMeekin, "Quantification of the performance of iterative and non-iterative computational methods of locating partial discharges using RF measurement techniques," *Electr. Power Syst. Res.*, vol. 143, pp. 110–120, Feb. 2017, doi: 10.1016/j.epsr.2016.10.036.
[51] IEEE, "IEEE Std 100-2000 The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition," *IEEE Std 100-2000*. pp. 1–1362, 2000, doi: 10.1109/IEEESTD.2000.322230.
[52] M. Tabrizchi and F. Rouholahnejad, "Corona discharge ion mobility spectrometry at reduced pressures," *Rev. Sci. Instrum.*, vol. 75, no. 11, pp. 4656–4661, Nov. 2004, doi: 10.1063/1.1809301.
[53] L. Zhang, "Electrical tracking over solid insulating materials for aerospace applications," University of Manchester, 2011.
[54] B. X. Du, Y. Liu, and H. J. Liu, "Effects of low pressure on tracking failure of printed circuit boards," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 5, pp. 1379–1384, Oct. 2008, doi: 10.1109/TDEI.2008.4656247.
[55] G. G. Karady, M. D. Sirkis, and J. R. Oliva, "Degrading effect of high-altitude corona on electronic circuit boards," *IEEE Trans. Electr. Insul.*, vol. 26, no. 6, pp. 1216–1219, 1991, doi: 10.1109/14.108161.
[56] A. Robledo-Martinez, H. Sobral, and A. Ruiz-Meza, "Effect of pressure in fast-front lightning discharges in air," *IEEE Trans. Plasma Sci.*, vol. 36, no. 4 PART 1, pp. 948–949, Aug. 2008, doi: 10.1109/TPS.2008.924536.
[57] M. A. M. Piah, A. Darus, and A. Hassan, "Leakage current and surface discharge phenomena: Effect on tracking and morphological properties of LLDPE-natural rubber compounds," in *Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials*, 2003, vol. 1, pp. 347–350, doi: 10.1109/icpadm.2003.1218423.
[58] J.-R. Riba, Á. Gómez-Pau, M. Moreno-Eguilaz, and S. Bogarra, "Arc Tracking Control in Insulation Systems for Aeronautic Applications: Challenges, Opportunities, and Research Needs," *Sensors*, vol. 20, no. 6, p. 1654, Mar. 2020, doi: 10.3390/s20061654.
[59] J.-R. Riba, A. Morosini, F. Capelli, J.-R. Riba, A. Morosini, and F. Capelli, "Comparative Study of AC and Positive and Negative DC Visual Corona for Sphere-Plane Gaps in Atmospheric Air," *Energies*, vol. 11, no. 10, p. 2671, Oct. 2018, doi: 10.3390/en11102671.
[60] C. Abomailek, J.-R. Riba, and P. Casals-Torrens, "Feasibility analysis of reduced-scale visual corona tests in high-voltage laboratories," *IET Gener. Transm. Distrib.*, vol. 13, no. 12, 2019, doi: 10.1049/iet-gtd.2018.5756.
[61] D. Kouadria and G. Watt, "Partial discharge patterns and the identification of defects in high voltage stator windings insulation," in *IEE Conference Publication*, 2000, no. 473, pp. 236–240, doi: 10.1049/cp:20000511.

[62] F. Dricot and H. J. Reher, "Survey of Arc Tracking on Aerospace Cables and Wires," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 1, no. 5, pp. 896–903, 1994, doi: 10.1109/94.326657.

[63] R. R. Stephenson, "Physics of DC carbon tracking of plastic materials." pp. 1–12, 2005, Accessed: Jun. 27, 2021. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.554.7589.

[64] F. L. Muhamedin, M. A. M. Piah, and N. A. Othman, "Modelling on Tracking Test Condition of Polymer Nanocomposite using Finite Element Simulation," *TELKOMNIKA*, vol. 13, no. 4, pp. 1194–1203, Dec. 2105, doi: 10.12928/TELKOMNIKA.v13i4.2362.

[65] T. J. Stueber, A. Hammoud, M. W. Stavnes, and K. Hrovat, "Evaluation of pyrolysis and arc tracking on candidate wire insulation designs for space applications," in *Conference Record of IEEE International Symposium on Electrical Insulation*, 1994, pp. 473–476, doi: 10.1109/elinsl.1994.401416.

[66] J. C. Kim, D. O. Neacsu, R. Ball, and B. Lehman, "Clearing Series AC Arc Faults and Avoiding False Alarms Using only Voltage Waveforms," *IEEE Trans. Power Deliv.*, vol. 35, no. 2, pp. 946–956, Apr. 2020, doi: 10.1109/TPWRD.2019.2931276.

[67] ASTM, "ASTM D495 - 14 Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation." ASTM International, West Conshohocken, PA, USA, pp. 1–10, 2014, Accessed: Nov. 15, 2021. [Online]. Available: https://www.astm.org/Standards/D495.htm.

[68] UL, "UL 746A. Polymeric Materials - Short Term Property Evaluations." Underwriters Laboratories Inc. (UL), Northbrook, IL, USA, pp. 1–48, 2012, Accessed: Nov. 15, 2021. [Online]. Available: https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL746A .

[69] G. de Alvarenga Ferreira and T. Mariano Lessa Assis, "A Novel High Impedance Arcing Fault Detection Based on the Discrete Wavelet Transform for Smart Distribution Grids," in *2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, Sep. 2019, pp. 1–6, doi: 10.1109/ISGT-LA.2019.8895264.

[70] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, S. Nuccio, and G. Tine, "Arc Fault Detection Method Based on CZT Low-Frequency Harmonic Current Analysis," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 5, pp. 888–896, May 2017, doi: 10.1109/TIM.2016.2627248.

[71] D. Mohla, C. M. Wellman, and K. J. Lippert, "Prevention through design: Reducing risks near service and main disconnects," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 45–50, Jan. 2015, doi: 10.1109/TIA.2014.2330252.

[72] R. Grassetti, R. Ottoboni, M. Rossi, and S. Toscani, "A low-cost arc fault detector for aerospace applications," in *AUTOTESTCON (Proceedings)*, 2012, pp. 239–243, doi: 10.1109/AUTEST.2012.6334544.

[73] C. E. Restrepo, "Arc Fault Detection and Discrimination Methods," in *Electrical Contacts - 2007 Proceedings of the 53rd IEEE Holm Conference on Electrical Contacts*, Sep. 2007, pp. 115–122, doi: 10.1109/HOLM.2007.4318203.

[74] M. A. Abdulrachman, E. Prasetyono, D. O. Anggriawan, and A. Tjahjono, "Smart Detection Of AC Series Arc Fault On Home Voltage Line Based On Fast Fourier Transform And Artificial Neural Network," in *2019 International Electronics Symposium (IES)*, Sep. 2019, pp. 439–445, doi: 10.1109/ELECSYM.2019.8901671.

[75] S. A. Saleh, M. E. Valdes, C. Mardegan, and B. Alsayid, "State-of-the-art methods for detecting and identifying arcing current faults," in *Conference Record - Industrial and Commercial Power Systems Technical Conference*, May 2019, vol. 2019-May, doi: 10.1109/ICPS.2019.8733359.

[76] J. R. Dunki-Jacobs, "The escalating arcing ground fault phenomenon," *IEEE Trans. Ind. Appl.*, vol. IA-22, no. 6, pp. 1156–1161, 1986, doi: 10.1109/TIA.1986.4504848.

[77] S. N. Ananthan *et al.*, "Signatures of series arc faults to aid arc detection in low-voltage DC systems," *IEEE Power Energy Soc. Gen. Meet.*, vol. 2020-August, Aug. 2020, doi: 10.1109/PESGM41954.2020.9281618.

[78] Y. Wu, Z. Song, and J. Wang, "A Method for Parallel Arc Fault Detection and Identification," Mar. 2013, pp. 66–69, doi: 10.2991/iccsee.2013.17.

[79] X. Han *et al.*, "Series arc fault detection method based on category recognition and artificial neural network," *Electron.*, vol. 9, no. 9, pp. 1–21, Sep. 2020, doi: 10.3390/electronics9091367.

[80] Y. Wang, L. Hou, K. C. Paul, Y. Ban, C. Chen, and T. Zhao, "ArcNet: Series AC Arc Fault Detection Based on Raw Current and Convolutional Neural Network," *IEEE Trans. Ind. Informatics*, 2021, doi: 10.1109/TII.2021.3069849.

[81] E. Calderon-Mendoza, P. Schweitzer, and S. Weber, "Kalman filter and a fuzzy logic processor for series arcing fault detection in a home electrical network," *Int. J. Electr. Power Energy Syst.*, vol. 107, pp. 251–263, May 2019, doi: 10.1016/j.ijepes.2018.11.002.

[82] H. D. Vu, E. Calderon, P. Schweitzer, S. Weber, and N. Britsch, "Multi criteria series arc fault detection based on supervised feature selection," *Int. J. Electr. Power Energy Syst.*, vol. 113, pp. 23–34, Dec. 2019, doi: 10.1016/J.IJEPES.2019.05.012.

[83] S. A. Saleh, A. S. Aljankawey, R. Errouissi, and E. Castillo-Guerra, "Extracting the phase of fault currents: A new approach for identifying arc flash faults," *IEEE Trans. Ind. Appl.*, vol. 2015, pp. 1226–1240, 2015, doi: 10.1109/TIA.2015.2483698.

[84] Y. H. Lin, C. W. Liu, and C. S. Chen, "A new PMU-based fault detection/location technique for transmission lines with consideration of arcing fault discrimination - Part II: Performance evaluation," *IEEE Trans. Power Deliv.*, vol. 19, no. 4, pp. 1594–1601, Oct. 2004, doi: 10.1109/TPWRD.2004.835276.

[85] É. M. Lima, C. M. dos S. Junqueira, N. S. D. Brito, B. A. de Souza, R. de A. Coelho, and H. G. M. S. de Medeiros, "High impedance fault detection method based on the short-time Fourier transform," *IET Gener. Transm. Distrib.*, vol. 12, no. 11, pp. 2577–2584, Jun. 2018, doi: 10.1049/iet-gtd.2018.0093.

[86] Z. Wang, S. McConnell, R. S. Balog, and J. Johnson, "Arc fault signal detection - Fourier transformation vs. wavelet decomposition techniques using synthesized data," in *2014 IEEE 40th Photovoltaic Specialist Conference, PVSC 2014*, Oct. 2014, pp. 3239–3244, doi: 10.1109/PVSC.2014.6925625.

[87] G. Ala *et al.*, "A Smart Sensing Method for Real- Time Monitoring of Low Voltage Series-Arc-Fault," *20th IEEE Mediterr. Electrotech. Conf. MELECON 2020 - Proc.*, pp. 512–516, Jun. 2020, doi: 10.1109/MELECON48756.2020.9140599.

[88] A. Laib, M. Melit, B. Nekhoul, K. El Khamlichi Drissi, and K. Kerroum, "Soft Fault Identification in Electrical Network Using Time Domain Reflectometry and Neural Network," in *Lecture Notes in Electrical Engineering*, vol. 522, Springer Verlag, 2019, pp. 365–376.

[89] N. Bahador, F. Namdari, and H. R. Matinfar, "Modelling and detection of live tree-related high impedance fault in distribution systems," *IET Gener. Transm. Distrib.*, vol. 12, no. 3, pp. 756–766, Feb. 2018, doi: 10.1049/iet-gtd.2017.0211.

[90] L. M. R. Oliveira and A. J. M. Cardoso, "Comparing Power Transformer Turn-to-Turn Faults Protection Methods: Negative Sequence Component Versus Space-Vector Algorithms," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2817–2825, May 2017, doi: 10.1109/TIA.2016.2613506.

[91] S. K. Al-Sachit, M. J. Sanjari, and N. K. C. Nair, "Negative sequence-based schemes for power system protection-review and challenges," in *Australasian Universities Power Engineering Conference, AUPEC 2018*, Nov. 2018, doi: 10.1109/AUPEC.2018.8758012.

[92] J. T. A. Vianna, L. R. Araujo, and D. R. R. Penido, "High Impedance Fault Area Location in Distribution Systems Based on Current Zero Sequence Component," *IEEE Lat. Am. Trans.*, vol. 14, no. 2, pp. 759–766, Feb. 2016, doi: 10.1109/TLA.2016.7437220.

[93] K. Sarwagya, S. De, and P. K. Nayak, "High-impedance fault detection in electrical power distribution systems using moving sum approach," *IET Sci. Meas. Technol.*, vol. 12, no. 1, pp. 1–8, Jan. 2018, doi: 10.1049/iet-smt.2017.0231.

[94] J. Wang, C. Xu, and J. Sun, "Experimental study of fault arc protection based on UV pulse method in high voltage switchgear," *Int. J. Emerg. Electr. Power Syst.*, vol. 15, no. 3, pp. 247–252, Jun. 2014, doi: 10.1515/ijeeps-2013-0151.

[95] C. Xu, J. X. Sun, J. G. Wang, and Y. Luo, "Study of fault Arc protection based on UV pulse method in high voltage switchgear," in *Advanced Materials Research*, 2014, vol. 853, pp. 641–645, doi: 10.4028/www.scientific.net/AMR.853.641.

[96] W. Ben Hassen, M. Kafal, E. Cabanillas, and J. Benoit, "Power Cable Network Topology Reconstruction Using Multi-carrier Reflectometry for Fault Detection and Location in Live Smart Grids," in *2018 Condition Monitoring and Diagnosis, CMD 2018 - Proceedings*, Nov. 2018, doi: 10.1109/CMD.2018.8535596.

[97] M. Kafal, F. Mustapha, W. Ben Hassen, and J. Benoit, "A Non Destructive Reflectometry Based Method for the Location and Characterization of Incipient Faults in Complex Unknown Wire Networks," in *AUTOTESTCON (Proceedings)*, Nov. 2018, vol. 2018-Septe, doi: 10.1109/AUTEST.2018.8532500.

[98] W. E. Anderson, J. D. Ramboz, and A. R. Ondrejka, "The detection of

incipient faults in transmission cables using time domain reflectometry techniques: Technical challenges," *IEEE Trans. Power Appar. Syst.*, vol. PAS-101, no. 7, pp. 1928–1934, 1982, doi: 10.1109/TPAS.1982.317481.
[99] S. J. Chang and J. B. Park, "Multiple Chirp Reflectometry for Determination of Fault Direction and Localization in Live Branched Network Cables," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 10, pp. 2606–2614, Oct. 2017, doi: 10.1109/TIM.2017.2700178.
[100] S. S. Bang and Y.-J. Shin, "Classification of Faults in Multi-Core Cable via Time-Frequency Domain Reflectometry," *IEEE Trans. Ind. Electron.*, pp. 1–1, Jun. 2019, doi: 10.1109/tie.2019.2920606.
[101] J.-R. Riba, A. Gomez-Pau, and M. Moreno-Eguilaz, "Sensor Comparison for Corona Discharge Detection Under Low Pressure Conditions," *IEEE Sens. J.*, pp. 1–1, Jun. 2020, doi: 10.1109/jsen.2020.2998827.
[102] G. D. Gregory, K. Wong, and R. Dvorak, "More about Arc-Fault Circuit Interrupters," in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)*, 2003, vol. 2, pp. 1306–1313, doi: 10.1109/ias.2003.1257720.
[103] IEC, "IEC 60364-4-42. Low-voltage electrical installations – Part 4-42: Protection for safety – Protection against thermal effects." IEC, Geneva, Switzerland, Switzerland, p. 64, 2014.
[104] IEC, "IEC 62606:2013. General requirements for arc fault detection devices." IEC, Geneva, Switzerland, p. 329, 2013, [Online]. Available: https://webstore.iec.ch/publication/7248.
[105] C. Vasile, V. D'Orchymont, J. Meunier-Carns, J. F. Rey, and H. Raisigel, "Arcing persistency measurement for IEC62606 arc-fault detection device certification," *2019 IEEE Symp. Prod. Compliance Eng. SPCE Austin 2019*, Nov. 2019, doi: 10.1109/SPCE47297.2019.8950836.
[106] SAE Standards, "SAE AS 5692. ARC Fault Circuit Breaker (AFCB), Aircraft, Trip-Free Single Phase and Three Phase 115 VAC, 400 Hz - Constant Frequency AS5692." Warrendale, Pennsylvania, USA, 2009, [Online]. Available: https://www.sae.org/standards/content/as5692a/?src=as5692.
[107] R. Rodrigues, Y. Du, A. Antoniazzi, and P. Cairoli, "A Review of Solid-State Circuit Breakers," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 364–377, Jan. 2021, doi: 10.1109/TPEL.2020.3003358.
[108] K. Ni *et al.*, "Electrical and Electronic Technologies in More-Electric Aircraft: A Review," *IEEE Access*, vol. 7, pp. 76145–76166, 2019, doi: 10.1109/ACCESS.2019.2921622.
[109] Federal Aviation Administration, "Solid-State Secondary Power Distribution," Atlantic City, NJ, USA, 2014. [Online]. Available: http://www.tc.faa.gov/its/worldpac/techrpt/tc13-19.pdf.
[110] D. Nemir, A. Martinez, and B. Diong, "Arc Fault Management Using Solid State Switching," *Trans. J. Aerosp.*, vol. 113, no. 1, pp. 1–10, Nov. 2004, doi: 10.4271/2004-01-3197.
[111] P. Meckler, K. F. Eichhorn, and W. Ho, "Detecting and Extinguishing of Arcs in Aircraft Electrical Systems," *SAE Tech. Pap.*, Sep. 2001, doi: 10.4271/2001-01-2657.
[112] S. Li, "Study of Low Cost Arc Fault Circuit Interrupter Based on MCU," *Int. J. Control Autom.*, vol. 8, no. 10, pp. 25–34, 2015, doi: 10.14257/ijca.2015.8.10.03.
[113] H. B. Land, C. Eddins, and J. M. Klimek, "Evolution of Arc Fault Protection Technology at APL," *Johns Hopkins Apl Tech. Dig.*, vol. 25, pp. 140–153, 2004.