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Review of DC Series Arc Fault Testing Methods and Capability Assessment of Test Platforms for More-Electric Aircraft

Vasileios Psaras, *Member, IEEE,* Yljon Seferi, *Student Member, IEEE,* Mazheruddin H. Syed, *Member, IEEE,* Richard Munro, Patrick Norman, *Member, IEEE,* Graeme Burt, *Member, IEEE,* Russell Compton, Kevin Grover, and John Collins

***Abstract*—In the new era of increasingly electric aircraft, the need for reliable and safe electrical systems is more important than ever. In addition, the wide scale adoption of DC distribution is considered a key enabling technology for more efficient aircraft operation. In this context, arc fault detection devices have become a topic of interest for the aviation industry with ongoing research to characterize the impact and adequately protect against severe DC series arc faults. Although DC arc faults have been widely investigated for utility applications (such as solar photo-voltaic systems), direct adoption of current practices for validating arc detection devices is not straightforward due to the distinct aircraft operating environment. This paper provides a first of its kind, landscaping exercise of published series arc fault testing based on factors associated with aircraft applications which have the potential to influence the arc characteristics. In addition, an appraisal and associated gap analysis of published arc test platforms is undertaken in order to assess their suitability to support in-depth testing of the impact and mitigation of series arcs within future aircraft DC electrical systems and identify future testing needs in particular to better facilitate a comprehensive performance validation of new arc fault detection devices.**

***Index Terms*—Arc fault detection, arc generators, arc test platforms, DC series arc fault, more-electric aircraft**

I. Introduction

THE electrification of propulsion and secondary systems has been identified as a key enabling technology towards increased energy efficiency, lower aircraft costs and weight, and better impact of air transportation on the environment (cleaner environmental footprint) [1], [2]. In this context, the aeronautical industry has been moving towards more-electric aircraft (MEA) and all electric aircraft (AEA) by increasingly electrifying subsystems that were traditionally using mechanical, pneumatic, and hydraulic power [3]. This transition to electric aircraft has led to the consideration of DC power distribution as a favorable solution to accommodate the increase of on-board energy generation at higher efficiency while yielding a reduction in wiring weight [4]. Current commercial aircraft such as the Airbus 380 and Boeing 787 utilize ±135 VDC and ±270 VDC electrical systems, respectively, while further increase in bus DC voltages is being investigated. Nevertheless, to support these trends, it is crucial to ensure a high level of reliability and safety for the DC power distribution systems at least equal to current aircraft technologies [5].

One of the risks arising from the increase in system voltage is the growing likelihood of DC series arc faults [6]. Electric arcs are formed when ionization occurs in air gaps between conductors, and is a common phenomenon in both AC and DC systems. Series arc faults may occur due to vibration of loose or degraded terminal connections, ruptures of electrical circuits, aging cables, abrasion of the conductive parts, poor maintenance, contamination by aircraft fluids, and chemicals [7]–[9]. In contrast to AC systems where the arc may extinguish when the current naturally passes through zero during the sinusoidal cycle, the absence of zero-crossing in DC systems can lead to long-lasting arcs that can inflict damage to the aircraft if not dealt with appropriately. The arc fault current is typically lower than the normal operating current due to the introduction of a series impedance due to the formation of the arc itself. This presents a challenge as conventional over-current protection techniques are unable to detect and isolate a DC series arc fault [10]. This has led to a growing interest in the development of arc fault detection devices (AFDDs), which has been an area of active research with novel arc fault detection approaches relying on time-domain techniques [11], [12], frequency-domain techniques [13], [14], or a combination of the two [15]–[17]. More recently, the application of data-driven approaches (or artificial intelligence) for identification of such faults has been explored [18], [19].

With this stream of research advancing well, it is also equally important to rigorously validate the proposed series arc detection approaches to ensure their robustness and applicability in real systems. Towards this aim, representative arc fault data records that sufficiently capture the arc dynamics are required, which can be obtained either numerically or experimentally. Efforts towards accurate representation of arcs through numerical and modelling approaches have been reported in literature [20]–[26]. Although such techniques have been utilized for system level analysis in simulations, they are still considered to be inadequate for realistic arc

V. Psaras is with WSP UK, Glasgow G1 3BX, United Kingdom. e-mail: vasileios.psaras@wsp.com (corresponding author)

Y. Seferi, M. H. Syed, R. Munro, P. Norman and G. M. Burt are with the Institute for Energy and Environment, University of Strathclyde, Glasgow G1 1XQ, United Kingdom. (e-mail: yljon.seferi@strath.ac.uk; mazheruddin.syed@strath.ac.uk; richard.munro@strath.ac.uk; patrick.norman @strath.ac.uk; graeme.burt@strath.ac.uk)

R. Compton, K. Grover and J. Collins are with GE Aviation Systems Ltd, Gloucestershire GL52 8SF, United Kingdom. (e-mail: russell-mark.compton@ge.com; kevin.grover@ge.com; john.o.collins@ge.com)

representation. This is because the arc is a complex and chaotic physical phenomenon, the behavior of which depends on a plethora of factors such as the material of the conductor, the electrical system characteristics, and its operating state and environmental conditions [27]. The understanding of the impact of influencing factors on the arc fault characteristics has been progressed through realization of experimental test platforms capable of generation of sustained, repeatable and representative electric arcs. For EA applications, the test platforms to date have been adopted from utility applications such as PV systems. Nevertheless, such approaches do not necessarily take into account the variability of the influencing factors, and the complexities introduced in aircraft, where the wiring is often exposed to a dynamic environment with simultaneous variations in altitude, vibration, and temperature [13], [28], [29]. Therefore, arc test setups need to be further developed in order to address the emerging needs of series arc fault testing within an aircraft operational environment and enable validation of AFDDs.

This paper provides a first of its kind review of the current state-of-the-art of DC series arc fault testing in DC systems with special emphasis on the factors that have been found to influence arc faults, and the current testing practices that have been used to date for analyzing such events. In detail, this review works towards identifying all relevant influencing factors and revealing those which have received limited attention but are particularly important for EA applications. In addition, an assessment of the capabilities of existing arc fault test beds for the generation of representative DC series arc faults that would typically occur in an aircraft is performed. The above collectively will contribute towards identifying new requirements for supporting the development of validation and testing procedures for AFDDs by highlighting the existing practices that can be readily adapted and those that need to be modified.

The rest of the paper is organized as follows: the characteristics of DC series arc faults are discussed in Section II, followed by Section III, which reviews the identified factors influencing arc faults and presents the reported findings with respect to their impact. The existing test platforms for characterizing arc faults and validating AFDDs are presented in Section IV. Finally, Section V concludes the paper.

II. Series DC Arc Fault Characteristics

Despite the complex, chaotic and stochastic nature of arc faults, their general electrical behavior can be conceptualized by means of an equivalent circuit [30]–[32]. Such a circuit is shown in Fig. 1, where a gap is formed in the conduction path that is in series with a line inductance L, and a load supplied by DC voltage source V. The gap separation x is formed between one electrode assumed stationary and the other electrode that moves away with velocity u, which is a function of time. An arc is assumed to be formed at the gap upon initial separation, with an arc voltage v_{arc} and an arc current i_{arc}. The arc voltage, current and resistance are the main characteristics used to represent the electrical behavior of an arc, and to characterize their impact on the power system in which they may appear.

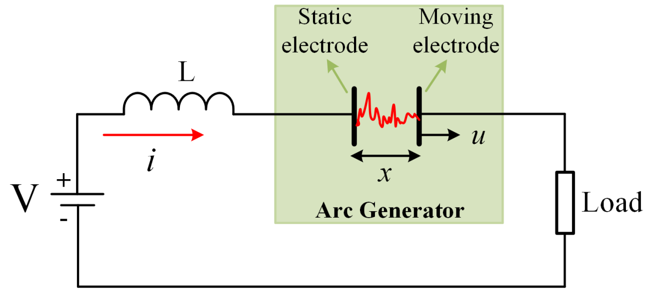

Fig. 1. Equivalent circuit of DC series arc fault.

The behavioral trends in each of these characteristics are the following:

- **Arc voltage:** This is the voltage that appears between the edges of the gap. A minimum arc voltage is required to initiate the arc, and this voltage increases until the arc is extinguished. Depending on the gap length the voltage could remain stable leading to a sustained arc, otherwise if the gap is too long the arc will self extinguish.
- **Arc current:** This is the current that flows through the gap. Arc current has the opposite behavior to arc voltage; it suddenly decreases when the arc is initiated and keeps decreasing as the arc voltage rises until the arc is sustained, or it will go to zero if the arc is extinguished.
- **Arc resistance:** A series arc demonstrates resistive behavior with a highly nonlinear arc resistance owing to the volatile nature of the arc phenomenon. By measuring the arc voltage and current, the arc resistance can be calculated at each time instant and is often averaged throughout the stable burning period.

Fig. 2 presents typical traces of arc voltage and current (see Fig. 2(a)), and arc resistance (see Fig. 2(b)). The traces have been obtained using a DC experimental setup based on the UL1699B drawn arc generator. The setup comprises a DC programmable power supply in series with an arc generator and a 4.8Ω load resistor. The arc is generated by pulling two round tip copper electrodes horizontally apart using a remotely controlled motorized actuator. The copper electrodes are 6 mm in diameter, pulled apart at a constant speed of 2 mm/s under loading conditions of 48 V and 10 A. The distance between the electrodes (or gap separation) is also indicated in Fig. 2(a)). The experiment was conducted in a closed room with an environmental temperature of 22.5 ^{o}C. Under these conditions, voltage and current measurements were captured, based on which the arc resistance was calculated.

As can be observed in Fig. 2, five distinct regions can be identified [33]. In region (I), the moving electrode and the static electrode are completely closed. At this time, the current flowing through the electrodes is equal to the load current and the voltage between them is zero (as is the arc resistance). In region (II), the electrodes start to separate and the arc voltage and resistance rise sharply to an initial value, while the arc current drops sharply from the load current. This sharp increase in the arc voltage indicates the initiation of the arc. In region (III), the arc voltage increases and the arc current decreases linearly with increase of the arc length. The arc current, voltage, and resistance exhibit linear characteristics up to the critical length which is dependent on the system characteristics. In region (IV), the arc current decreases abruptly towards zero and the arc voltage rises towards the source voltage value indicating the process of arc extinguishing. In this region, the arc resistance also presents an abrupt increase. The duration of the arc event spanning regions (II)-(IV) is defined as the arc extinction time. In region (V), the arc is completely extinguished, the arc voltage is equal to the source voltage, the current flowing through the electrodes is zero, and the arc resistance reaches theoretically a value close to infinity.

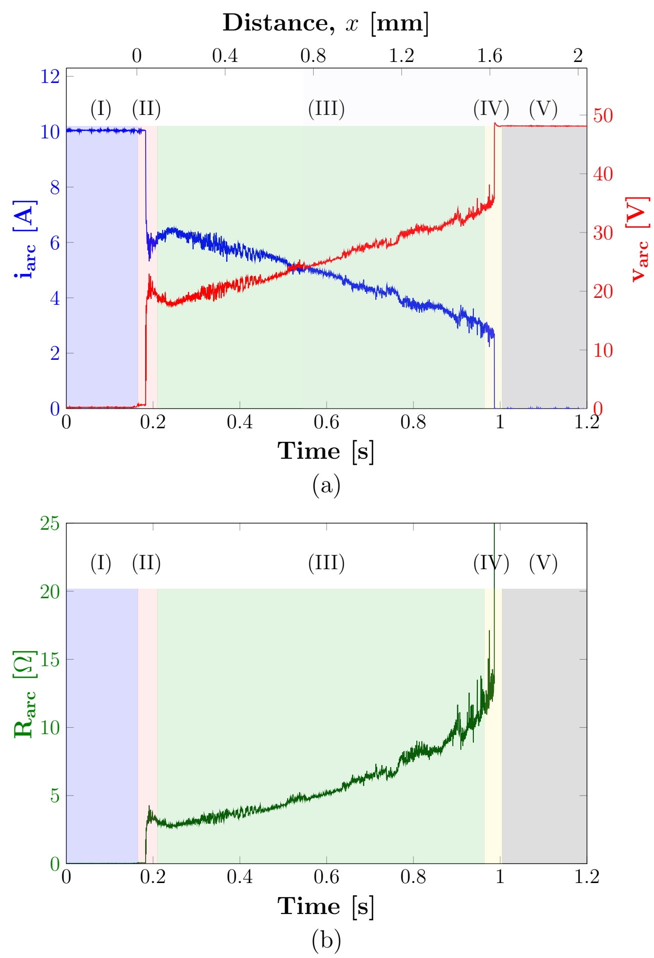

Fig. 2. Typical waveforms: (a) arc voltage and current, and (b) arc resistance.

III. Factors Influencing Arc Fault Characteristics

Arc fault characteristics are recognized to be highly stochastic [34]; however, there are various factors that can support the development of repeatable experimental series arc faults in DC systems. The main factors influencing series arc fault characteristics can be broadly classified into three categories: 1) mechanical, 2) electrical, and 3) environmental. This section summarizes the outcomes of existing research on the impact of each factor on arc fault characteristics and on arc fault recreation for investigative purposes. Special emphasis is paid on characteristics such as the arc voltage, current, extinction time, and sustainability (capability to sustain a series arc). The section further analyzes the role of each factor in allowing repeatable and consistent arc fault generation.

A. Mechanical Factors

Most series arcs are produced by a loose cable or a broken wire that introduces a small gap in the conductive circuit. This effect is emulated experimentally by separating two electrodes that are initially in contact. It has been reported that the shape, material, and mounting of the electrode, in addition to the opening speed of the gap are mechanical factors that influence the arc characteristics.

1) Electrode motion: The gap between two electrodes is a result of the motion of electrodes, i.e., separation of the electrodes. The behavior of the arc current and voltage with respect to the variation in gap length is analyzed below.

Gap opening at constant speed: The opening of a gap at constant speed represents the longitudinal tearing of conductors (connector malfunction or internal mechanical damage), which are well-supported mechanically [34]. In [30], an analysis of voltage and current waveforms for dynamically varying gap lengths was undertaken. The results shown were obtained for a fixed DC source voltage of 680 V, and 175 A load current for a gap opening at a constant speed of 2.54 mm/s. The arc voltage and current exhibited a linear trend with the arc extinguishing after 8 seconds. More extensive analysis in [35], [36] demonstrated that the arc duration is inversely proportional to the gap opening speed. In terms of arc testing procedures, the speed at which the gap opens affects the arc extinction time, which in turn affects the degradation of the electrode and the repeatability of the experiments especially if the opening speed is not accurately controlled.

Constant gap length: A constant gap may be achieved by opening the electrodes at constant speed until the desired distance is established or by maintaining the electrodes at a fixed distance while using an igniter to cause an electric arc. The selection of the gap length aims to emulate the size of a loose connection or the distance between the two parts of a broken conductor. Greater gap lengths can be anticipated on aircraft due to vibrations over time [11]. A study on the impact of gap length on arc voltage in [11], concluded that there exists an overall trend of the arc voltage increasing for larger gap lengths under all load current levels when a range of [75-300] V and [3-25] A is considered for supply voltages and load currents, respectively. In [30], it was argued that there is a gap length (or a range of gap lengths) that can sustain stable arcs for an extensive period of time. This was demonstrated experimentally through an arc test with the electrodes held at a fixed gap distance of 6.35 mm. After arc ignition, voltage and current settled at new relatively constant values and the gap was manually forced open after tens of seconds to stop the series arc fault. It was further concluded that there is a maximum gap length that can support an arc as well as a minimum current such that the arc is not self-extinguishing.

Gap opening at constant acceleration: Electrodes opening at an accelerated rate may be used to reflect the case of an energized cable that breaks and falls [37]. Similar to the gap opening at constant speed, an experiment with constant acceleration (9800 mm/s^2) was performed in [30]. The relationship between the arc voltage and current was found to be exponential with a much faster arc extinction time (approximately 22 times smaller than the constant speed test). From the experiments performed in [30], it was shown that the extinction gap is dependent on the dynamics of gap opening with the arc extinguishing at a length of 18 mm for the constant speed test and at 700 mm for the constant acceleration test.

2) Direction of electrode motion: The direction (or type) of electrode movement creating the arc fault can also affect the arc characteristics. Horizontal, vertical and vibrating movements for the reproduction of series arc faults have been identified in the literature.

- **Horizontal (linear) movement:** The process of separation of electrodes horizontally away from each other, also referred to as "pull-apart" method, is the most widely used technique for performing series arc experiments. This is due to its definition within the Standard UL1699B for testing arc fault detectors in PV systems [38]. The horizontal movement can be achieved manually or through stepper motors, with the latter preferred for its accurate control and increased safety.
- **Vertical (linear) movement:** There is no reported practical experience of vertical separation of electrodes for testing series arc faults. However, there are several references to the impact that electrode orientation has on arc flash [32], [39], [40]. A summary of the tests performed for updating the standard on arc flash testing are summarized in [39] while further assessment can be found in [40].
- **Vibratory (nonlinear) movement:** A vibration mechanism is typically used for emulating the series arc caused by loose contacts under vibratory operating conditions, which often represents realistic conditions for transport applications such as aircraft, ships or land vehicles. Vibration tests have been typically performed with a shaker table with loose terminals. Using this configuration in [41], it was observed that the arc is more easily initiated at lower vibration frequencies (under 20 Hz), while it tends to sustain for longer time under higher vibration frequencies. In addition, it was noted that a higher amplitude of vibration displacement (the distance the vibration plate moves during the two peaks of one cycle of the vibration) helps to generate and maintain DC arc faults.

Linear movement mechanisms have been widely adopted in literature and practice due to their capability to reproduce arc faults in a consistent manner. Conversely, a vibratory movement for the reproduction of series arc tests may lead to inadequate repeatability in arc testing.

3) Electrode shape and diameter: The choice of shape and diameter of the electrode for performing series arc fault experiments needs to be thoroughly considered as they have been identified in the literature to strongly affect the arc characteristics. The diameter of the electrode is selected to represent the cross-sectional area of an actual conductor or a loose contact which may result in the formation of an arc. In [31], it has been highlighted that as the diameter of the conductor increases, the contact resistance reduces, while for arcs generated using electrodes of smaller diameters, the rate of change of the arc current increases for increasing load currents.

In [42], the fast degradation of the anode when using a point shape electrode led to an uncontrolled increase in the gap and therefore inconsistent results. A flat anode was found to perform much better during the experiments as the degradation was highly reduced. In [43], rounded electrode tips were found to be superior for sustaining the arc in comparison to flat-surface electrodes. It was recommended to flush the electrodes using abrasive paper on a regular basis to facilitate the initiation and sustenance of the arc. It was reported that the rounded electrodes tend to produce less arc-fault noise because the arc fault is consistently and 'cleanly' established at the radial center of the electrodes. Similarly, smaller electrodes produce higher noise signatures due to increased off-gassing rates and oxygen depletion due to a lower plasma cavity volume, which increases arc-power instabilities. Choice of electrode shape is therefore a trade-off between ensuring repeatability of the experiments and realism. In practical applications, it is highly unlikely that the two electrodes would have either a perfectly flat surface or a rounded shape.

4) Electrode material: Copper is the main material used for electrodes in most of the reported work, while other considered materials include aluminium, silver, stainless steel, nickel, tungsten, brass, gold and platinum [36], [44]–[48]. At the arc initiation, the arc voltage will increase to a minimal arc voltage V_m, which is the minimal voltage to sustain the electric arc for the specific contact material. V_m is determined by the contact material and the surrounding atmosphere and is independent of the supply voltage [49]. In [44], according to the author's tests, V_m is slightly affected by supply voltage but the average minimal arc voltage for each contact material was found to be very similar to [49]. In [50], it was demonstrated that the electrode material hardly influences the arc duration and the gap length at extinction.

Each material also leads to different requirements with regards to electrode polishing or replacement practices. For instance in [45], silver and copper electrodes were utilized and subjected to 30 successive arc faults without replacement. Silver electrodes led to more consistent results with similar extinction times, while the arc duration times tended to be longer for the copper electrodes as the experiments progressed.

B. Electrical Factors

The characteristics of the arc are influenced by the electrical system in which an arc fault occurs. Factors such as the loading in the system where the arc appears or the system voltage can influence the initiation and extinction of the arc. Similarly, the type of loads connected and the exact location at which the arc appears can modify the characteristics. Accordingly, in this section a review of the reported impact that these electrical system factors can have on the arc is presented.

1) System voltage and load current: In an effort to characterize the arcs for different loading conditions, several studies have conducted a sensitivity analysis of system voltage and current. The analysis in [11] considered a current range of [3-25] A and a voltage range of [75-300] V. First, an assessment of the variation of the arc resistance with respect to the current and voltage of the system was performed, concluding that the former impacts the arc resistance more than the system voltage. It was further noticed that the impact of system voltage on arc resistance is more prominent for lower load currents. The impact of system voltage on arc voltage was also assessed and it was found that the arc voltage was typically higher for decreasing system voltages. As the system voltage increased, the arc voltage decreased until it saturated for system voltages higher than 180 VDC. On the other hand, the arc voltage varies significantly with load current, exhibiting larger magnitudes at lower currents. In [35], it was observed that the arc extinction time is hardly affected by the supply voltage when it is higher than 150 V. Nevertheless for lower voltages, both studies in [35] and [36] concluded that the arc extinction time is proportional to the supply voltage. In both cases, constant opening speeds (between 5 to 80 mm/s), and load currents equal or less than 10 A were considered.

2) Load and grid components: The size of inductance, resistance and capacitance can influence voltages and currents when a series arc appears, both in terms of amplitude and rise times, as highlighted in [51]. Moreover, the voltage and current waveforms produced by a DC arc are dependent on the load with which the arc interacts [8]. The work presented so far in this paper has assumed only resistive components in the circuit in which the arc is generated. In this subsection, the impact of different grid and load components is presented.
Inductive components: The presence of inductance in the system forces the current to resist to changes and hence, higher inductance results in slower current variations [47]. This gives the electrode more time to evaporate the metal in the material for an arc to be created, as was observed in [52]. It was also concluded that the introduction of inductive components can help the generation of series arc faults [52], and extend the duration of the arc [53]. In [54], the arc extinction time and gap were measured for both a resistive and an inductive load under the same loading conditions (42 V, 30 A). For the inductive case, both the extinction times and gaps were greater than the ones in the resistive load case across a range of opening speeds [10-700] mm/s.
Capacitive components: Capacitors have the characteristic of limiting the rate of change of voltage, thereby preventing fast changes in the gap voltage. As a result, the current density on the electrode is weaker and less likely to melt the metal to form plasma channel bridging the gap [52]. Therefore, the addition of capacitance will reduce the probability of generating an arc. In [55], the impact of load capacitance on the arc severity (classified as 'open circuit', 'failed to sustain arc', and 'sustained arc') was discussed. A comparison was made by fixing the load current at 25 A and observing the differences in severity between 350 V and 540 V source voltages across all capacitances. For load capacitance of 213 μF and lower, more than 80% of the tests undertaken led to a sustained arc. With the increase in load capacitance over 213 μF (and up to 1385 μF), a higher ratio of open circuits was exhibited, while the percentage of sustained arcs fell dramatically.
Constant power loads: In modern systems, constant power loads (CPLs) connected via power electronic converters are becoming more prevalent. Such converters typically operate in current control mode and modulate the current depending upon the voltage at the point of common coupling, ensuring a constant power throughput [56]. The behavior of series arc fault current in a DC microgrid in the presence of CPLs was analyzed in [56]. An increase of the current was observed for an arc fault at the CPL which can pose a challenge to typical fault detection methods that expect a fall in both load current and voltage. This further points towards the need for load-specific detection techniques that can identify faults for different loads including CPLs. Similar to the capacitive loads, the input capacitance of a CPL decreases the chances for the development of sustained arcs [57].

3) Arc location: An analysis of DC arc faults in aircraft distribution networks showed that voltage and current characteristics during arc faults depend on the location of the fault [8]. This also indicates that different voltage and current profiles would be observed depending on the location of the AFDD (and hence, the point of measurement). It was further discussed that an AFDD should be designed to operate at a specific network location and that if the same device was used at a different point, it might fail to operate as intended.

Investigation of the arc location has also been performed in DC microgrid applications [51], [58], [59]. In [58], an analysis of arc fault currents was undertaken for arc faults occurring at different locations within a DC network integrating a PV unit, two battery energy storage units, and three loads, all interfaced via individual respective DC/DC converters. The cases considered included arc faults on either side of each DC/DC converter of the units. Significant differences in arc fault currents were noticed in each case, which introduced significant challenges in arc fault detection.

C. Environmental Factors

Along with mechanical and electrical factors, the environment in which the arc fault appears can also have an impact on the characteristics of the arc. Temperature, air flow, pressure, and humidity are the main identified environmental factors. Controllability of these factors for arc testing may be achieved with the use of environmental chambers which can maintain specific and consistent test conditions (e.g., adjustable temperature and pressure) [41].

1) Temperature: The impact of temperature on arc fault characteristics has briefly been touched upon in [60] for PV systems. The temperature was varied in equal steps in a range from $-20\,^{o}$C to $60\,^{o}$C, and it was noticed that the arc fault current increases with temperature. Nevertheless, the temperature has a major influence on the string current and voltage and hence on the operation point of a photovoltaic system. An increasing temperature heightens the short circuit current of a solar cell and thus the current of a mono-string photovoltaic plant. Therefore, the impact of temperature on the arc fault current is difficult to quantify, and can be dependent upon the electrical characteristics of the system itself.

2) Air flow: The air flow across the gap formed during arcing has been found to be an environmental factor that affects the arc characteristics. In experiments conducted to characterize arc extinction times, variable results were obtained until the electrode gap was shielded [61]. In the UL1699B standard, a polymer cover around the arc gap is included to emulate the typical DC cable connectors. In [43], it was found that including a hole in the polymer allows oxygen to enter the plasma stream and provides a more sustainable plasma arc discharge. The above studies demonstrate the need for the air flow across the gap to be considered as one of the factors towards achieving consistent results.

3) Pressure: In contrast to other DC applications, the pressure can vary significantly in the aircraft environment depending on flight altitude. For this reason, the impact of pressure on arc fault characteristics has recently received significant attention [9], [13], [28], [31], [62]. This was first reported in [62], where the pressures of 97.7, 37.7 and 18.8 kPa were considered to simulate the flight altitudes of 1000, 25000 and 40000 ft, respectively. The data was collected by measuring voltage and current while the gap was driven open at a constant speed of 0.19 mm/s after arc initiation. It was reported that the arcs have significantly different physical appearance at different pressures, however the arc power did not vary. With decreasing pressure values, the gap length at which the arc tended to extinguish was shorter. This was associated to the presence of significantly lower number of gas molecules, leading to rapid diffusion of the localized, high temperature ionized gases needed to sustain the arc. It was therefore concluded that at higher altitudes or lower pressures, it was more difficult to sustain the series arc.

In [28], an assessment of electric arcs at different pressure values (10 and 100 kPa) has been performed. An initial assessment of arcs that were generated by separating copper electrodes at a constant speed until the electric arcs naturally extinguished showed that the arc extinction time varied and consequently, extinction occured at different electrode gaps when the pressure was varied. At 10 kPa, the maximum electrode gap was about two times greater than that at 100 kPa, suggesting a larger arc duration with a larger arc gap at flying altitude (10 kPa). This finding is in direct contradiction to the results presented in [62]. This difference can be attributed to the magnitude of load current in consideration, the load current was limited to 3.3 A in [62], while a load current of ~350 A was considered in [28]. The analysis of the impact of current intensity on the arc voltage and gap length under varied pressure conditions was further undertaken, and it was observed that the arc voltage is significantly influenced by the pressure, presenting lower magnitudes for smaller pressures values and increasing as pressure rises. The arc exhibited a larger gap length with a decrease in pressure and an increase in current.

The analysis presented so far was limited to voltages in the range of 30-60 V. In [9], a similar analysis at a representative voltage of 540 V was undertaken and results were presented for various current values (10, 25, 50, 100 A), pressure values (10, 20, 40, 60 , 80 and 100 kPa), and separation velocities of the electrodes (50 mm/s and 600 mm/s). In each case the electrode gaps at which the arc extinction occurred were measured. It was underlined that for 50 mm/s separation velocity and for current values up to 50 A, the extinction electrode gap is independent of pressure. The dependency on pressure was evident only for the highest current value considered, i.e., at 100 A, and for pressures lower than 40 kPa. It was highlighted that for current values under 50 A, the relation between extinction electrode gap and the current is linear, for every pressure value considered. Contrarily, when considering current intensity values higher than 50 A, two behaviors are observed: a linear relation for low pressure and a saturation for pressure from 60 kPa to atmospheric pressure. The increase of separation speed promotes the saturation phenomenon, even at high currents. When the electrode separation velocity was set to 600 mm/s, it was observed that the extinction electrode gap is independent of the pressure for every current value. It is worth noting that the same saturation phenomenon occurred and the extinction gap remained about constant for currents higher than 50 A regardless of the pressure conditions.

4) Humidity: Humidity is often mentioned as one potential factor that can change the air characteristics and hence affect the formation of the arc [27], [63], [64]. Nevertheless, there has not been any study that provides insight on the impact of humidity on series arc fault characteristics. As discussed in [28], the humidity conditions encountered in different parts of the aircraft may vary considerably indicating that its impact should be assessed in future research.

D. Discussion

Through a thorough analysis of the literature and the documented practical experience from arc test beds for PV, microgrid and aircraft applications, several factors have been identified that influence and impact the arc characteristics, and these have been categorized in this paper into mechanical, electrical and environmental factors. In the reviewed work, a variety of parameters and conditions have been considered, and a summary of the range or list of parameters examined for each influencing factor is provided in Table I. It can be seen that representative values or parameters that may be met in MEA have been considered for most arc influencing factors. Nevertheless, very few findings have been identified in the literature for applications employing voltages greater than 600 VDC, indicating that DC series arc fault testing has not been well addressed to the same extent for higher voltage levels. Although consideration of voltages less than 600V is considered adequate for current MEA applications, it is recognized that future MEA/AEA will incorporate DC power distribution systems with higher voltage levels to support the trend of electrification.

In addition, it has been found that not all influencing factors have been assessed to the same extent. This is shown in Table II, which summarizes the outcomes of the reported work, by indicating whether the influence of each identified factor on the DC series arc fault characteristics (i.e. arc voltage, current, extinction time, and sustainability) has been examined or not.

TABLE I. Range or list of parameters considered for each arc influencing factor.

Category	Factor	Range/list
Mechanical	Electrode motion	constant speed, constant gap, constant acceleration
	Electrode opening speed	[0.1-700] mm/s
	Direction of motion	horizontal, vertical, vibratory
	Electrode shape	rounded, conical, flat
	Electrode material	Cu, Al, Ag, Pt, Ni, Au, Brass
	Electrode diameter	[3-19] mm
Electrical	System voltage	[30-680] V
	Current	[3-350] A
	Load/grid components	resistive, inductive, capacitive, CPL
Environmental	Temperature	-20^{o}C to 60^{o}C
	Pressure	[10-100] kPa
	Humidity	N/A

In detail, Table II summarizes the pairs of factor-characteristics that have been analyzed and reported (with a green tick) and the factor-characteristic pairs that have yet to be analyzed (with a red cross). It is evident that although a significant effort has been made to characterize DC series arc faults, the exact impact of several factors on the arc characteristics has not been quantified or recognized yet. Mechanical factors have received the most attention, with the exemption of the direction of motion which has not been sufficiently considered, but is of particular importance in aircraft (as in most transport applications) due to the vibratory operating conditions. The least attention has been paid to the environmental factors, and the impact of humidity, air flow, and temperature on arc behavior has not been adequately discussed. Considering the special characteristics of aircraft with respect to PV systems, microgrids or other residential systems, it becomes understood that it is imperative to consider arc generation under the specific environmental conditions expected to be met on aircraft.

TABLE II. Synopsis of influencing factors and reported work.

Factor	Arc Voltage	Arc Current	Extinction Time	Arc Sustainability
Electrode motion	✓	✓	✓	✓
Direction of motion	×	×	×	✓
Electrode shape	×	✓	×	✓
Electrode material	✓	×	✓	×
Loading conditions	✓	×	✓	×
Load/grid components	×	×	✓	✓
Arc location	×	✓	×	×
Temperature	×	×	×	×
Air flow	×	×	×	✓
Pressure	✓	×	✓	✓
Humidity	×	×	×	×

The analysis has revealed that on a number of occasions, the findings of the studies contradict those documented in others, when only one factor is considered in isolation, due to the different assumptions made for the remaining factors. This indicates that there are inter-dependencies between the factors, which further complicate the investigation of arc faults and the validation process of AFDDs. For instance, it has been noticed that the exact impact of certain factors (e.g., pressure) on the arc varies depending on system voltage and current. Consequently, observations made in arc test rigs for PV or other similar applications with lower voltages may not hold true for aircraft applications where the DC voltage can be 270/540 VDC or higher. This reported inconsistency and the lack of generalization highlights the need for further research to establish the impact of the influencing factors such as the pressure and voltage, and the necessity for a more focused investigation using experimental testbeds specifically designed for aircraft applications.

To enable the validation of AFDDs for aircraft applications, arc test setups for the generation of sustained, repeatable and representative electric arcs are required. As a minimum requirement to achieve this, the setup shall have electrode separation mechanisms with controllable separation speed and distance, as well as vibration mechanisms. In addition, the capability for replaceable electrodes and electrodes material shall be ensured. These measures will enable the incorporation of mechanical factors in an attempt to capture the realistic behaviour of the arc fault itself. Furthermore, methods that can simulate location, loading conditions and different loads are desirable in an effort to incorporate the electrical factors, and represent the electrical characteristics and particularities of power distribution systems in aircraft. Finally, the use of an environmental chamber is considered necessary for arc testing in aircraft applications to ensure controllability in emulating different pressure, temperature and humidity conditions, which are anticipated during flight.

IV. Analysis of Existing Test Platforms

Experimental test platforms typically comprise an electrical system (PV System, microgrid, land or aero) with an arc generator incorporated to generate the desired arcs as shown in Fig. 1. This section aims to review the existing test platforms accounting both for the arc generation units and the surrounding electrical systems, and assess their suitability for adoption in aircraft applications. Although data acquisition, metrology, protection and other equipment would be required as part of any test platform, such auxiliary equipment is out of the scope of this analysis. Therefore, only the essential equipment for generating representative series arc faults is considered as this is the key area of development towards addressing the needs and uncertainties of arc testing within an aircraft operational environment.

A. Arc Generating Units

The most important and integral element of arc test platforms is the unit which is responsible for the generation of the arc itself. A number of generators that artificially produce series arc fault conditions have been designed in an effort to understand and study the features of such faults.

1) UL1699B arc generator: UL1699B arc generator, also referred to as the drawn arc generator, is the most common series arc generator discussed in literature and utilized in practice. A typical UL1699B arc generator is shown in Fig. 3, comprising of a stationary electrode and a moving electrode housed on a fixed base. The moving electrode is mounted on a sliding block that allows for lateral separation of the electrodes for generation of the arc. The arc can be ignited either through

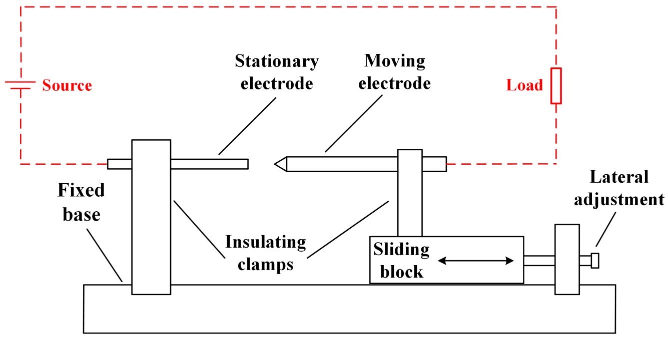

Fig. 3. Arc generator as defined by UL1699B Standard.

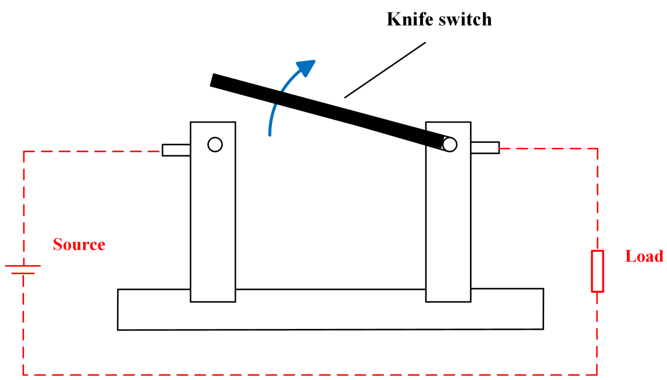

Fig. 4. Knife Switch based Arc Generator [67].

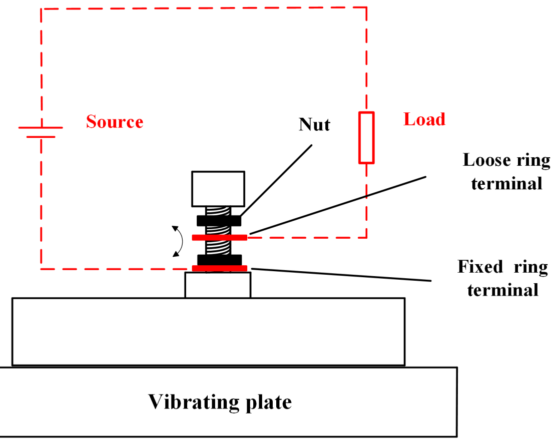

Fig. 5. Shaking table based arc generator [41].

the fuse-ignition or the pull-apart method [65]. In the former, a steel wool or tuft is utilized as an igniter for the arc fault and is placed between the two electrodes, which are held at a fixed distance (constant gap) inside a polycarbonate (PC) tube. In the pull-apart method, the two electrodes are initially in contact maintaining continuity between the power source and the load, and are then driven apart to produce contact separation and initiate a DC series arc fault. This is typically implemented via a motorized setup, in which the actuator is driven by a stepper motor (controlled based on a micro-controller) in order to offer precise control of the separation distance between the electrodes as well as the opening speed of the moving electrode. Such setups have been widely used in the literature with a varying range of opening velocities with maximum observed speeds of 600 mm/s [9] and 700 mm/s [54]. An arc generator enclosure is very often used to provide a safe environment for initiating the arcs [66], [67].

2) Knife switch based arc generator: This arc generator makes use of a knife switch to initiate arc faults more flexibly, and it has been introduced in [67]. The switch is initially closed to set up a current and then, an arc can be generated by opening the switch as shown in Fig. 4. The knife switch can be maintained at fixed position thus establishing a constant gap between the electrodes, which if correctly adjusted will lead to a sustained DC arc. Nevertheless, the design explained in [67] lacks the ability to control the motion of the electrodes and the electrode material and shape.

3) Shaking Table based Arc Generator: An arc generator based on shaking table has been presented in [41] in an effort to emulate the vibration effects present in aircraft, ships and other vehicles. The setup includes a shaking table that is driven by an amplifier and is located within an environmental chamber, which in turn aims to control environment conditions. The arc generating unit is installed on the sample holder of the shaker head as shown in Fig. 5. This unit comprises of one loose ring terminal and a loose connection with the unthreaded part of a bolt. The movement of the latter is limited by two nuts which are firmly fitted on the bolt. Prior to initiation of the arc, the shaker head is at fixed position, and a physical contact is established between the bolt and the ring terminal, thus allowing the steady state current to flow freely. Under vibration conditions, a DC series arc is generated between the loose ring terminal and the unthreaded part of the bolt. Using the amplifier and a graphic user interface controller, it is possible to control the velocity, acceleration, displacement, and vibration frequency.

4) Replay Arc Emulator: Although drawn arc generators are widely utilized for testing of AFDDs, they do suffer from the drawback of lack of consistent repeatability. To remedy this, the replay arc emulator has been proposed [68]–[71]. A replay arc emulator introduces a pre-recorded real arc as an emulated arc within the electrical system test bench. Recording of arc signals (voltage and current) with sufficient sampling rate is typically required for the reproduction of the arcs. Two different approaches have been discussed in the literature as below. In [68], the classical DC source is substituted with a digital-to-analog converter (DAC), which reproduces recorded arc signals. The output of the DAC is amplified by a power amplifier that is interfaced with the AFDD as shown in Fig. 6.

Although the proposed approach is simple and cost-effective, it does present limitations in terms of the flexibility in application of faults at desired locations within the electrical system. In [69], a waveform generator is used to reproduce the recording of a real arc signal within the system under test, effectively emulating the arc behavior as can be seen from Fig. 7. In this case, accurate location of the arc and a more accurate representation of the arc compared with [68] is possible.

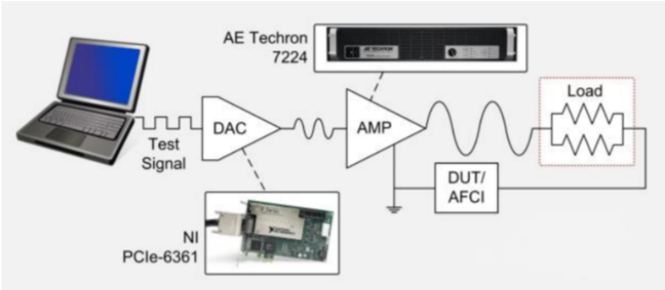

Fig. 6. Replay arc test bed [68].

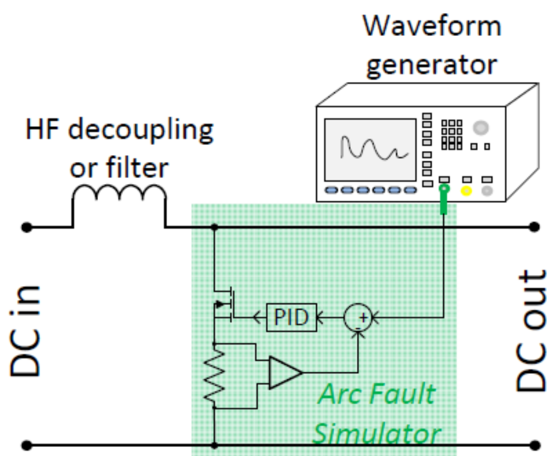

Fig. 7. Replay arc generator configuration (Fraunhofer ISE) [69].

B. Electrical Systems

It has been identified in section III-B that the specific arc location and the characteristics of the electrical equipment surrounding the arc fault will have an influence on the arc, as well as the system characteristics. Therefore, an important aspect of DC arc fault testing is the overall test bed which includes the electrical system in which the arc generating unit is integrated. In this section, the main options that have been reported in the literature for representing the electrical system are presented, while their limitations and capabilities are analyzed. The findings are mainly drawn by practical experience obtained through PV applications rather than the aerospace sector. Nevertheless, based on these findings, an attempt is made to draw analogies between the two applications.

1) Simplified Electrical Circuit: The most common and straightforward approach to represent the electrical system in which the arc fault appears is by using a voltage source and a DC load as shown in Fig. 1. In detail, the drawn arc generator is supplied by an infinite voltage source that is used to simulate the grid to which the equipment is connected. These platforms provide controllability of the pre-arc voltage and current, where the former is regulated by the DC supply, and the latter is adjusted by connecting appropriate DC loads. The DC load is typically a resistor while in a few cases a buck or boost converter has been used to form a constant power load [19], [73]. The advantages of this testbed include the low cost of the required equipment and the increased safety. Due to its simplicity, this setup is equally applicable for PV and aircraft applications. However, this approach fails to take into account the effects that the arc location, the network characteristics or the interaction with other system components might introduce.

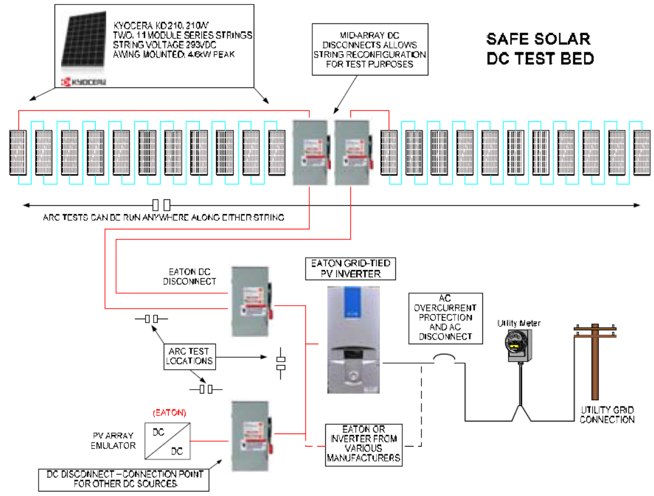

Fig. 8. Test bed with hardware PV installation [72].

2) Real System: In direct contrast to the previous approach where a simplified circuit is used, there is the option to apply and study DC arc faults in a real system using actual hardware equipment. This approach has been performed in existing PV systems as reported in [60], [63], [72], [74]. An example testbed is shown in Fig. 8, which constitutes a residential type system with two strings of 11 PV modules where DC arc faults can be applied anywhere along either string. A similar scaled-down approach has been reported in [46], [48] where a limited number of PV modules is considered. These platforms allow the application of arc faults and the validation of AFDDs in real systems under normal operating and environmental conditions. In addition, the influence of the arc location can also be taken into account. Nevertheless, performing an adequate number of tests can be challenging when large systems are involved or when downtime of the associated assets presents a constraint. Furthermore, the repeatability of the tests performed under varying and potentially uncontrolled system parameters and environmental conditions needs to be considered.

Acquiring series arc fault data from real systems simply for the purpose of testing arc fault detection devices can be challenging and costly. Considering the critical nature of power distribution in MEA/AEA, ‘intentional’ arc faults cannot be initiated under flight conditions, as they might lead to power interruptions, system damage or even onboard fires and other catastrophic fires if not dealt with properly. Furthermore, relying on natural occurrences of such events can result in long lead and developmental times. At the same time, the same arc fault phenomena cannot be repeated when the aircraft is back on ground due to changes in the operating and environmental conditions [75]. Consequently, alternative methods incorporating mechanisms that can emulate realistic conditions met in actual systems would be more beneficial for testing AFDDs for aircraft applications.

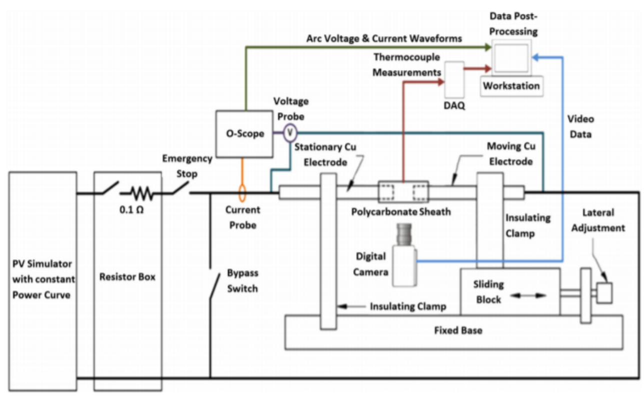

Fig. 9. Test bed with PV simulator [79].

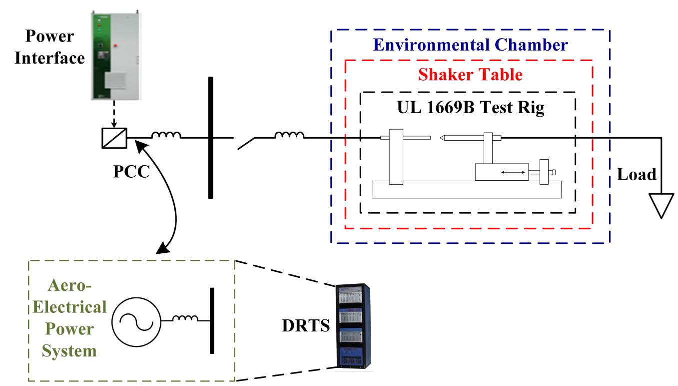

Fig. 10. Conceptual schematic of a potential experimental platform for DC series arc testing in MEA applications.

The need for extensive testing of aircraft equipment including protection devices has led to the creation of the 'iron bird' [76], [77] and 'copper bird' [78] test environments, where the entire aircraft electrical system is mocked up (with the equipment installed according to their actual location in the aircraft) for extensive testing ahead of aircraft construction. Although currently no examples can be found in the literature, such test beds can potentially be utilized for late-stage testing of AFDDs.

3) Emulated Electrical System: As a middle ground between a simplified circuit and an actual real electrical system, the solution of an emulated system has been put forward. This can be in the form of a hardware emulator, such as the PV emulators used in [15], [79] (concept shown in Fig. 9), which are currently available as off the shelf equipment.

For EA applications, a similar solution could be achieved through hardware in the loop (HIL) techniques in which the voltage source, rather than being ideal, can be represented by a detailed electrical system simulated through a digital real time simulator (DRTS) [80]. Based on this arrangement, the response of the actual hardware can be fed back to the DRTS by forming a closed loop and thus allowing continuous and realistic interaction between the hardware components (arc generator, AFDD under test) and the simulated system [81], [82]. One such approach has been presented in [83], where a virtual electrical test bench is designed for performing verification activities over different aircraft electrical architectures and validating energy management strategies. Although theoretically capable of emulating the entire aircraft electrical system, this test bench is recommended to run along a full electrical testbed (a 'copper bird') for conducting HIL studies in order to overcome limitations around sensitivity issues with regards to the exact specifications of the equipment supplied by aircraft manufacturers.

C. Discussion

By analyzing the presented arc generating units individually, it becomes evident that most existing setups fail to consider all the arc influencing factors that were recognized in Section III. The drawn arc generator is used in the vast majority of the reported work due to the capability it offers to incorporate and flexibly adjust almost all mechanical factors, which are more important for ground applications such as PV installations. Nevertheless, using the existing configurations it is possible to form an experimental setup for MEA/AEA applications that considers all mechanical and environmental factors. This can be achieved by combining the UL1699B drawn arc generator with a shaker plate (for introducing vibratory movements) and an environmental chamber for permitting controllability of environmental conditions. However, the capability of such a setup in incorporating the impact of electrical factors is limited by the characteristics of the utilized electrical system.

Real systems or full electrical test beds can be used for equipment validation with high fidelity, but these approaches suffer from high capital costs, and the lack of flexibility and controllability of electrical system parameters. Further future developments in virtual electrical test benches may offer the potential to consider different electrical architectures and provide greater controllability and flexibility of the electrical factors, while also lowering the cost of testing. By combining the merits of a virtual electrical test bench with those of the drawn arc generator using an environmental chamber and shaker plate, and forming an experimental setup that incorporates all potential influencing factors, it is possible to complete the knowledge in terms of their impact on the arc characteristics (see Table II) and to perform a comprehensive assessment of the inter-dependencies between them. Fig. 10 presents a conceptual schematic of such an experimental platform. Besides the drawn arc generator and the environmental chamber for the consideration of mechanical and environmental factors, the utilization of HIL technique could also allow incorporation of all electrical factors that have been identified to impact the arc characteristics. With the help of HIL setup (using a DRTS), the actual electrical characteristics and conditions of any location within the electrical power system of the aircraft can be replicated. The load end (or moving electrode end) will need to be connected to a representative load, which can potentially be emulated by means of power converters.

The learnings and practical experience that can be obtained through such an experimental arrangement can support the development of testing procedures specifically tailored for aircraft applications for the validation of AFDDs, based on which representative DC series arc fault records can be collected for realistic scenarios that may be encountered under in-flight conditions. The determination of appropriate testing procedures is another important aspect of the validation process of AFDDs, which should take into account the exact conditions under which these devices are expected to operate. For instance, if location-specific AFDDs are employed, the tests that incorporate variations in pressure can be omitted for devices to be installed within pressure-controlled regions of the aircraft. As more data on DC series arc fault testing in an aircraft environment becomes available, this will enable identification of the desired operating space of the AFDDs in which they should function correctly and reliably. To further facilitate and bring a level of automation in AFDD testing, replay arc emulators introducing recorded arc measurements can be developed for reducing complexity and overall costs, and enhancing the repeatability, ease, and speed of testing.

V. Conclusions

In this paper, the current state-of-the-art of DC series arc fault testing has been reviewed with emphasis on the arc influencing factors and the common test platforms that have been utilized in practice regardless of the DC application. The review has allowed the classification of the factors into three main categories, namely: mechanical, electrical, and environmental factors, all of which are equally important to be considered in aircraft operational environment. It was shown that the exact impact of several factors on the arc dynamics has not been quantified or recognized yet. Mechanical factors have received the most attention, while the least attention has been paid to the environmental factors. Moreover, it has been revealed that there are interdependencies between these factors and that the arc dynamics can vary unpredictably from application to application. This has further stressed the necessity for developing experimental test beds, which are specifically designed for aircraft applications.

Having identified the factors, the paper then summarizes the test platforms that have been reported in the literature for analyzing DC series arc faults. In particular, the common electrical systems and the arc generating units used in arc test beds as well as the strengths and limitations of each option are discussed in detail. It has been shown that existing platforms, with some adaptation, have the capability to properly explore all the under-considered aspects of series arc fault behaviour. The next step towards reaching an enhanced level of automation in the development and validation of AFDDs is to set up a suitable framework to coordinate testing, manage the new knowledge captured from test platforms for MEA and determine appropriate testing scenarios and the desired operating space for AFDDs. Such a framework shall also determine an efficient mix of in-field testing and offline testing through arc replay emulators using pre-recorded arc fault events.

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