New Markers Based on HF Signals For Series DC Arc Detection

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***Abstract*—The current approach towards the More-Electrical and All-Electrical Aircraft (MEA and AEA, respectively) is pulling the new designs of electric power systems to higher rated voltages. This is giving new concerns related to ionization phenomena, and, among then, the DC series arc has revealed hazards in the short-term operation in aircraft. This ionization phenomenon is difficult to detect and there are no commercial devices are still available for this purpose. In addition to the appropriate sensor, conditioning and processing techniques, it is needed to extract from the system, accurate information to detect the arc. This paper point to new markers from HF signals measured by inductive devices.**

Keywords—Electric arcs, DC series arcs, ionization, aircraft safety, aircraft electrification, more electric aircraft, all electric aircraft.

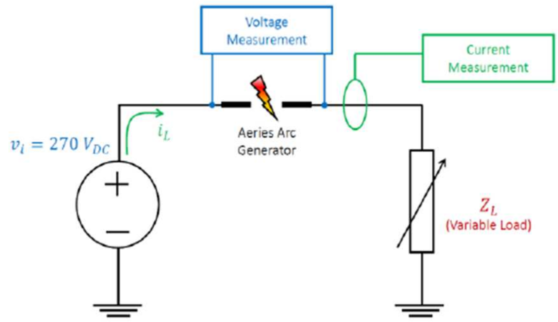

Fig. 1 Complete experimental setup

I. INTRODUCTION

There is a clear trend in aviation towards an important increase of electrification and use of electric loads. Firstly, electrical actuators are being used in applications which have traditionally been powered by hydraulic, mechanical or pneumatic power sources [1]. In addition, at the end of the 20th century, environmental requirements for civil aviation became the 2nd most important topic after flight safety [2], what is pushing the development of electric and hybrid propulsion.

This evolution entails a drastic increment of electrical power demand onboard, leading to the incorporation of High Voltage (HV) architectures [3]. The HV networks provide several benefits, allowing weight reduction and increased performances, and enabling electric or hybrid propulsion, but they also represent a technological challenge [4], since these voltage levels will have a significant impact on physical phenomena such as insulation ionisation that were, until now, almost absent in the conventional architectures. One of the most significant effects to be addressed is the electric arc fault.

An electric arc is a particular kind of discharge which occurs between two conductive materials, that is formed when the voltage difference between them breakdowns the dielectric insulation of the gas. The resulting ionization of this gas creates a high temperature plasma that may trigger an electrical fire [5], posing an important hazard for the aircraft integrity.

Electric arcs may occur equally in AC or DC circuits and are classified in two types: series arcs, produced due to a current discontinuity within one only conductor or parallel arcs, due to an accidental contact between two conductors at different potential [6].

Compared with ordinary power cables, aviation wiring is characterized by thinner insulation layers and longer service periods in humid environments with intense vibration, friction, and radiation, so they are highly susceptible to premature degradation [7], thus inducing arc faults [8].

The arc fault is well known for typical architectures of 115 VAC and 28 VDC and is properly prevented by the use of commercial Arc Fault Circuit Breakers (AFCB) [9]. Nevertheless, the particular characteristics of series arc, where the current does not show a remarkable rise (as for parallel arcs), makes it difficult to be detected with conventional protection devices. As a consequence, a series arc fault can be very destructive because it can lead to long-duration overheating in a wire bundle, resulting in pyrolysis to the surrounding materials [9]. This circumstance is aggravated in DC, where no zero crossing in the current/voltage signal takes place, avoiding the self-extinction.

At present, different DC series arc fault detection methods are being developed to face this problematic. These methods can be grouped according the feature employed for the detection of the arc. Therefore, some techniques are focused on the capturing physical phenomena like the arc lighting (optical methods) [10] or the arc sound emission (acoustical methods) [11]. Although the detection methods based on the characteristic changes of voltage and current (electrical methods) are the most promising for practical applications [12]-[16], the vast majority of works are focused in the detection of transient currents in frequency ranges below 1 MHz, and discuss deeply the signal processing techniques needed for the detection [13]-[16]. It should be mentioned that these sensors sometimes are too heavy [16] or show relatively low sensitivity and/or require an external power supply to work, rendering them inconvenient for aircraft applications [15].

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Recently, the detection with inductive sensors in a higher frequency range (up to 10 MHz) has been revealed as a good candidate to be implemented in real applications [17], [18]. This frequency range is in agreement with the accumulated experience and knowledge from partial discharge measurements [19]. The reasons are that HF pulses propagated through a power cable are a reliable indicator of the presence of an arc in the circuit. Besides, these signals can be monitored by inductive sensors, that can be designed light, small, non-invasive to the circuit and without the need of an additional power supply, accomplishing the aerospace needs [17]. Another advantage of these sensors is the possibility of rejection of the maximum levels of conducted RF interference which, following the standard DO-160G, are below 2 MHz [20]. However, signal processing techniques applied to these types of pulses are needed for the accurate detection of the arc, and for this purpose the most meaningful output variables from these signals which shall be used as a marker for DC arc detection method must be identified, so this is the scope of this research.

II. Experimental Setup

Arcs are created interrupting a DC current flowing from a source to a load by controlling the opening of a switch. This switch is built with two electrodes where one remains still and the other is shifted with a stepper motor. The opening speed is controlled via WiFi and a specific cell phone application in Android. The voltage of the DC source is set to 270 V, which a standard level for high-voltage aircraft systems. The voltage is applied to a 6 kW variable resistor which acts as a load; the load is fixed to draw 5 A, which is nominal value for many loads in this industrial application. The experimental setup is the same as the one shown in [17].

Measurements are done using a high frequency current transformer with gain of 6 V/A and lower cut-off frequency of 100 kHz which measures the HF conducted signals through the power circuit. The signals are acquired with an oscilloscope with resolution of 14 bits a sampling frequency of 25 MS/s and a bandwidth of 200 MHz. Fig. 1 shows a sketch of the complete experimental setup.

Finally, the electrode materials will be changed to analyse whether this has any influence in the created HF signals from the arcs. Steel-steel and copper-steel combinations will be used. This comparison is relevant since a previous study revealed changes of the RF currents from arcs when the electrode material changed from copper to graphite [18].

III. Experimental Results

A. Characterisation of arcs and commutation.

Opening the switch slowly leads to visible and audible arcs. In addition to this, the arc can also be detected in the time domain measuring the conducted current pulses through feeding cable. A sample of these signals is shown in Fig 2. where it can be clearly seen a rise in the magnitude of the conducted pulses due to the inception of the arc after 20 ms, so two different regions are observed in the sample: before and after transient.

The average spectral power density has been calculated along 20 ms before and after the arc inception to characterize these two regions (or time intervals) in the frequency domain, The results are shown in figures 3 and 4. Upper plots show the signals in the time domain during 20 ms and the middle plot is the spectral power of the highlighted interval shown in the lower plot. The time axis is in milliseconds up to 200 and the frequency axis is in MHz up to 12.5. The vertical axis for the time signal is in volts and for the power spectral density is in dB.

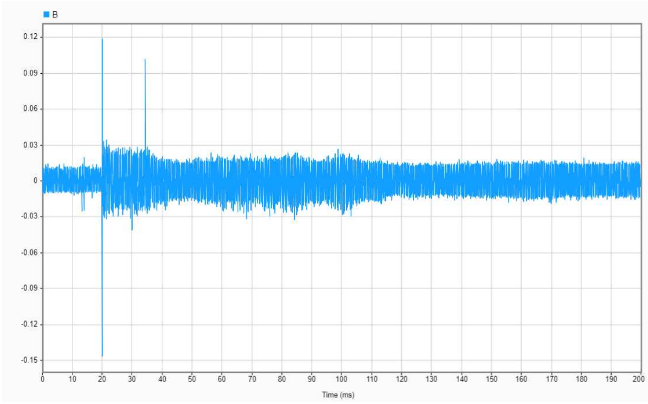

Fig. 2 Typical arc phenomenon registered by the HF sensor in the time domain. Signal amplitude (V) versus time (ms). Steel-copper electrodes.

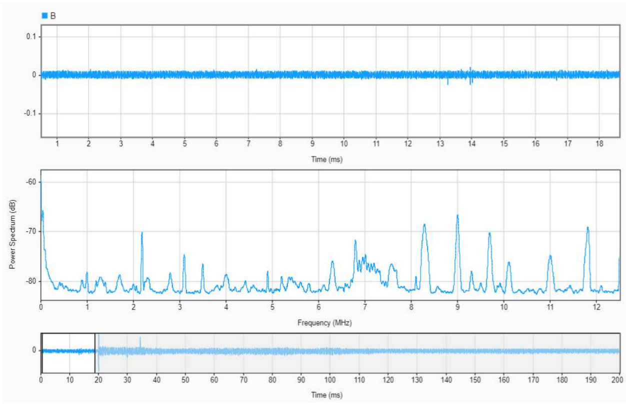

Fig. 3 Typical arc phenomenon registered by the HF sensor in the time domain. Steel-copper electrodes. Time interval before the transient.

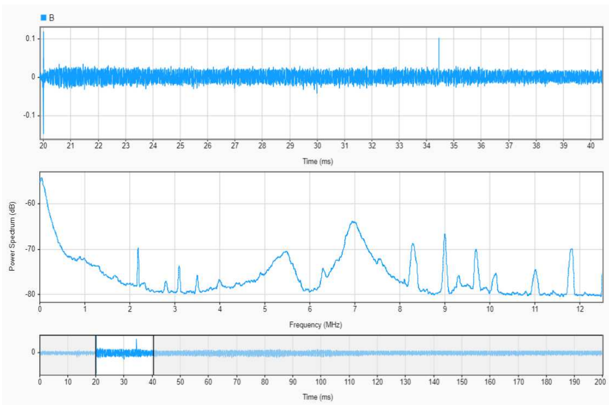

Fig. 4 Typical arc phenomenon registered by the HF sensor in the time domain. Steel-copper electrodes. Time interval after the transient.

The comparison of the figures reveals great differences in the spectral behaviour of the signals before and after the transient, with an increase of magnitudes in the bandwidth of interest that spans from a few kHz to 12 MHz. These frequencies are in the same range as those presented in [17], where it was shown how the specific frequencies where the spectral magnitudes are larger depend on the power circuit length, type of load and, specially, on the joints location. In any case, the rise in spectral power unveils the existence of arcing and hence justifies the use of the selected sensor.

In addition to arcs, the authors have registered another set of signals with conventional commutations which do not show arcs. This is simply achieved just putting the electrodes back together to let the current flow. Fig. 5 show a time-domain acquisition for the closing event, selecting a range in millivolts similar to the one in Fig. 2 for the sake of comparison. It is important to also analyse and characterise these events to discard any false-positive detection of an arc. As seen in Fig. 5, the detected signal after the transient does not give a rise in HF pulses as large as the ones detected in Fig. 2, despite showing an initial fast transient with large magnitude which is detected for both phenomena, arc and switching. It is clear that this fast transient cannot be used to distinguish between arcs and commutations. In the following section, these experiments were repeated up to 5 times for each case and the increase of spectral power pre-transient and post-transient for some milliseconds, will be quantified.

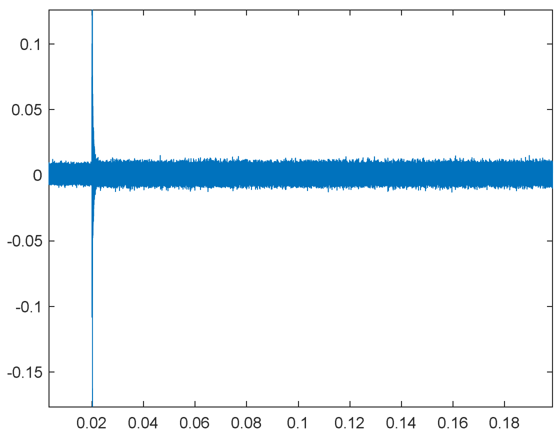

Fig. 5 Typical conventional commutation registered by the HF sensor in the time domain. Signal amplitude (V) versus time (s). Steel-copper electrodes

B. *Cuantification for arc detection*

The following table reviews the results for calculated root mean square (RMS) values of the conducted signals measured in the HF range along 20 ms and squared to calculate the power before and after the transient phenonmenon. The RMS value is obtained from the well-known equation:

$$V_{RMS} = \sqrt{\frac{1}{T} \cdot \int_0^T v(t)^2 \cdot dt} \qquad (1)$$

where *v(t)* is the acquired signal, and T=20ms.

In table I, every data (V_{RMS}^2) is the average for 5 phenomena. The SNR column is the ratio of both quantities, which serves as a quantification for the appropriate detection of the arc phenomenon. The "commutation" action refers to the electrode closing which does not create a visible or audible arc, whereas the "arc" is created during the electrode opening. A quantification approach to compare both phenomena is needed for the appropriate detection of the arc trying to avoid trips due to false positive events.

TABLE I. QUANTIFICATION FOR ARC DETECION

	Average power in V^2 (dB)			
		Before transient	***After transient***	***SNR***
Steel-steel	Arc (opening)	6.65E-6 (-51.7dB)	3.5E-5 (-44.6dB)	5.4 (7.34dB)
	Commutation (closing)	3.9E-6 (-54.1dB)	5.9E-6 (-52.3dB)	1.51 (1.2dB)
Steel-cooper	Arc (opening)	7.73E-6 (-51.1dB)	4.43E-5 (-43.5dB)	5.74 (7.6dB)
	Commutation (closing)	7.3E-6 (-51.4dB)	9.3E-6 (-50.3dB)	1.3 (2.1dB)

It is clear from the results that the spectral power shows a higher sustained growth for arcs than for conventional commutation (SNR column). There is a small rise in the spectral power also for commutation due to the HF spectral components of the conducted current due to noise introduced by the DC voltage source. However, in any case this interference is smaller than the increase of power due to arcs. In fact, the initial part from the signal of Fig. 2 is similar to the final part of Fig. 5 which corresponds to a steady state current circulating through the switch.

There are no differences in terms of discrimination between arcs and commutations when the material of the electrodes is different. To compare the HF response of the conducted pulses for both types of electrodes, the spectrograms of two examples of arcs are shown in Fig. 6 and Fig. 7. This graphical representation gives information about the evolution of the spectra during the time the arc is active. It is clear from both figures that both combinations of electrodes give similar response after the arc occurrence with a small rise of spectral power for all frequencies and a remarkable rise for 5.5 MHz and 7 MHz, being this consistent with the spectra shown in Figs 2 and 3.

IV. Conclusion

Inductive sensors measuring in the high-frequency range give good results to detect series DC arcs. From the observation of time-domain waveforms and the change in the power spectral density of the signals, the authors propose the sustained increase of the RMS value as a successful marker for the appropriate detection of the arc phenomenon. This figure of merit also permits to avoid false positive detections of short transients events such as switching. The marker is also robust in case there is a change in the electrode materials from steel-steel to steel-cooper. It can be interesting to test other combinations of materials in the future to confirm this. There are no changes in the spectral response in HF from the arc for a change in one electrode from steel to copper. More future work will be done on the arc detection capability when real conducted electrical noise is superimposed to the ionization phenomenon.

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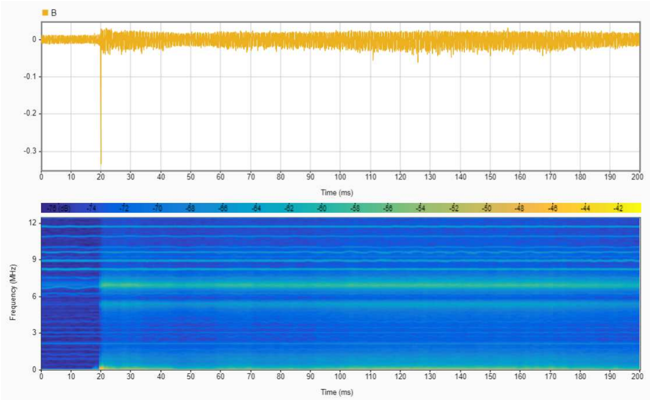

Fig. 6 Arc phenomenon event. Upper plot: time-domain pulse detected. Lower plot: spectrogram. Steel-copper electrodes.

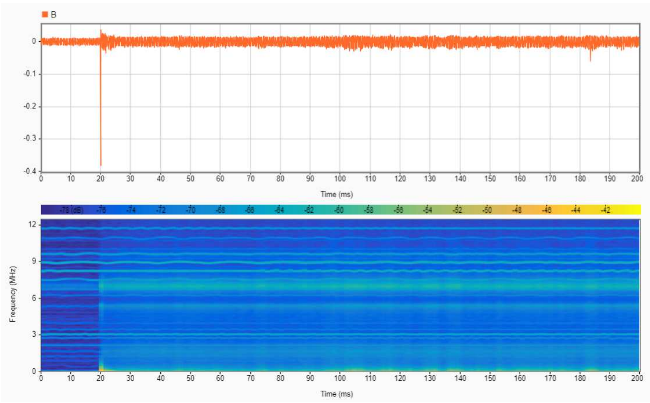

Fig. 7 Arc phenomenon event. Upper plot: time-domain pulse detected. Lower plot: spectrogram. Steel-steel electrodes.

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