Detection of DC series arc in more electric aircraft power system based on optical spectrometry

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Abstract: Series arcing faults have been recognised as a hazardous phenomenon in the power system of more electric aircraft (MEA), especially with the increasing voltage level and power supply. Instead of the electrical method, the optical method can be used as an approach to detect arc fault with the advantages of fast response and immunity to electromagnetic interference. It is the basis of optical arc detection to determine the distribution spectrum range of direct current (DC) arc fault. Aiming at series arc optical detection in the MEA DC system, a DC series arc test platform was established to measure the series arc spectrum. The spectrum was disassembled though empirical mode decomposition to extract characteristic wavelengths of arc light and denoised by means of wavelet decomposition and reconstruction (wavelet transformation) to reduce equipment noise. To resolve the baseline drift, the baseline of the arc spectrum measured was calculated and corrected based on Savitzky–Golay. The experimental results indicate that there are several series arc characteristic spectra of the MEA DC system, including 309.3 and 324.5 nm in the ultraviolet range. Moreover, the arc spectrum with different metals, copper and aluminium, were contrasted, indicating the arc spectral behaviour is related to the melting/boiling point and chemical properties of the anode material. The measurement of the series arc spectrum makes it more effective to apply optical detection in the MEA discharging faults diagnosis.

1 Introduction

To reduce the size and weight of the aircraft, the secondary power system of the more electric aircraft (MEA) is increasingly distributed and replaced by the form of electricity [1]. With great advantages of large capacity, few distribution cables and high reliability, a MEA high voltage direct current (HVDC) system is recognised as the ideal power supply system of MEA [2, 3]. However, the higher voltage level (+270 V) [4] increases the risk of arc faults, easily leading to overheating accidents, even as high as thousands of Celsius [5, 6], and the high temperature can damage the structure of the aircraft within a short period of time. Different from the well-known parallel arc fault, the series arc phenomenon occurs on the conditions of crushed cables, poor connections or pin–socket connections, making the arcing current less than the load current and it is difficult to be detected [7]. Therefore, it is of great importance to carry out the series arc detection in the MEA HVDC power system.

Since increasing similar DC power systems, especially photovoltaic systems, have been utilised and the demand to detect DC arc accidents effectively has attracted much attention [8]. The majority detection techniques are based on electrical parameters, such as the arc current, voltage drop, electromagnetic radiation [9, 10], and so on. Various algorithms are applied and explored to obtain time- and frequency-domain signatures to distinguish the arc phenomena [11, 12]. However, it is difficult to get a universal algorithm to detect the arc due to its randomness and instability. Non-electrical techniques provide another approach to detect arc effectively, and ultraviolet (UV) light is introduced due to its immunity to electromagnetic interference [13]. Therefore, optics-based techniques are given high priority to detect a discharging phenomenon [14]. For instance, the partial discharge spectrum in a gas-insulated switchgear or high-voltage power transformer can be analysed by light radiation [15–17], and optical image arc welding also has been investigated [18]. With regard to arc light, it has been recognised as a useful tool to judge the occurrence of arcing events or temperature distribution [19]. However, the decomposition products and discharge mechanism are mainly focused and discussed but not intended for arc fault detection. Since both the power capacity and the series arc current of the MEA power system is still very limited, in contrast to the current of circuit breakers in the power grid, the excitation sources and phenomena are quite different. Except for the light scale, there are still several challenges, which remain unsolved and need further exploration for the special application in the MEA power system including the applied materials and specific structures. As for the series arc light detection, it is fundamental to obtain the characteristic spectrum of the arcing activities in which, the optical sensor with a detection range containing the visible (VIS) width is interfered by sunlight and malfunction. Therefore, the detection range of the optical arc detection module in the MEA should be focused on the UV region.

In this study, an experimental study of the DC arc features in the MEA power system is conducted and factors such as the supplied source voltage, electrode materials, and their combinations are studied. With the experimental results, the arc spectral signals excited by different material electrodes were analysed and arc light characteristic wavelength was extracted through the proposed algorithms. The DC arc behaviour under the specific MEA condition is examined to provide a solid foundation for arc detection. This study aims at providing an experimental and comprehensive understanding and the detection of arcing behaviours that might occur in the MEA DC power system.

2 Experimental set-up

In an air-insulated DC power supply system of MEA, the series arcing events are occurred directly in the electrical wiring interconnection system, especially in wires and cables, which rapidly melts or vaporises most aircraft materials in the atmosphere. The wires and cables in the MEA are mainly made up of copper and aluminium [20], such as the typical cable models as shown in Table 1. Thus, four
Table 1: Electrodes combinations and corresponding cable model cases

| Group | Electrode combinations | Cable model cases |
|-------|------------------------|-------------------|
| 1     | copper (anode) and copper (cathode) | MIL-C-5554-3 |
| 2     | aluminium (anode) and aluminium (cathode) | F2793-33 |
| 3     | copper (anode) and aluminium (cathode) | AD series |
| 4     | aluminium (anode) and copper (cathode) | KL-F 4704-13 |

3 Measurement results and preliminary analysis

To describe the arc spectrum, the broadband spectral centre \( \lambda \) and the spectral width \( \Delta \lambda \) are considered. The spectrum reaches the maximum light intensity \( I_0 \) with the central broadband spectrum located at \( \lambda \), and the light intensity exceeds \( I_0 / 2 \) in the spectral width [21]. It should be noted that the air dielectric in the DC system of MEA is also excited by the electric arc to generate specific spectral lines, which are considered as part of the arc spectrum. The measured spectral results of the copper arc containing the integration effect of the air and the electrodes in the dark are shown in Fig. 2.

According to the original copper arc spectrum, the copper spectrum was distributed in the UV and near infrared (NIR) regions and the VIS range. However, there existed a baseline drift phenomenon in the spectral line of the copper arc, whose value was equal to the line averaged and the approximated background noise reached 2535 counts.

To capture the random arc with varieties of positions and durations, the direct reading spectrometer compromises measurement accuracy. Background noise signals of the arc spectrum include spectrum rotation, limit drift, waveform distortion, spectral peak superposition etc. It means that the effective information of the spectrum is evenly immersed in the background noises.

To extract the characteristic wavelength of the arc light, the arc spectrum results were handled by fundamental wave decomposition [empirical mode decomposition (EMD)], noise filtering (wavelet threshold de-noising) and baseline correction [Savitzky–Golay (S–G) convolution derivative calculation]. The characteristic wavelength of the arc spectrum was obtained using the feature extraction process, as shown in Fig. 3.

The EMD can represent the spectral signal as the sum of signals with zero average amplitude adaptively [22]. The signals called the intrinsic mode functions (IMFs) with multiple frequencies from the hight to the bottom represent the local characteristics of the original function [23]. The extremum of each IMF decomposed from the spectral curve corresponds to the characteristic wavelength of the spectrum. To obtain the IMFs of the arc spectrum, the local extremum was calculated. \( S \) in Fig. 3 is an expected standard deviation with a type value between 0.2 and 0.3. Besides the upper envelope \( r_j(\lambda) \) and lower envelope \( r_j(\lambda) \) of the original signal, the process residual function played an important role in the IMF signals. \( m_j(\lambda) \) is the mean of the two envelope lines, which is related to IMFs with a low frequency of the arc spectrum, while \( h_j(\lambda) \) is related to the IMFs with high frequency. If the standard deviation \( \text{SD}_j \) of \( h_j(\lambda) \) is less than the expected standard deviation \( S \), \( h_j(\lambda) \) was exactly the IMF \( j \), which can be explained by

\[
h_j(\lambda) = x_j(\lambda) - m_j(\lambda)
\]

\[
= x_j(\lambda) - (r_j(\lambda) + r_j(\lambda))/2
\]

As long as \( S \) is greater than \( \text{SD}_j \), then

\[
\text{IMF}_j(\lambda) = h_j(\lambda)
\]

For further extraction of spectral information, equipment noise reduction was carried out by means of wavelet decomposition and reconstruction. Equipment noise was always composed of white noise. Wavelet coefficients with localised arc spectrum features can separate the overlapping signals in the time domain and the frequency domain [24]. In wavelet transform, signals can be represented in space \( V_j = V_{j-1} + W_{j-1} \). IMF \( j \) in space \( V_j \) can be represented by the basic functions of space \( V_{j-1} \) and space \( W_{j-1} \), as
and signal features separation of $-1$, which are obtained after decomposing the coefficient of equipment noise and spectral information [25]. A reconstructed to data by means of local polynomial least-square calculation in the global threshold calculated from the original signal screening was be weakened. The low-frequency part coefficient, while the wavelet coefficient of equipment noise, which was supposed to decomposition caused a large value gap between the wavelet describing the coefficient, $\lambda_1$ is the low-frequency part of the wavelet $\phi_j$, while $\lambda_0$ is the high-frequency part. $\lambda_j$ is the scaling function and $\lambda_{j-1}$ is the scaling function of $\lambda$. The copper wavelength can be obtained in Fig. 4 and wavelengths of 793.0 and 809.0 nm. In the NIR region, the copper arc has two central atomic lines and copper ion lines. The copper atomic lines come plasma emission spectrum contains a large number of copper monatomic gas or metal vapour. Band spectra consist of many bands that are irradiated by molecules. To avoid interference from other light sources, the distribution of arc light in the UV region was extracted. The UV region can be more finely divided into three regions: UVA within the range of 320–420 nm, UVB within the range of 275–320 nm and UVC within the range of 200 nm–270 nm.

The spectral characteristic wavelength of the copper arc can be obtained by the extraction algorithm, copper arc spectral signal-changing process during de-noising is shown in Fig. 4. EMD transformed arc spectrum from an envelope to a pulse cluster. Wavelet transformation (WT) reduced the noise of the arc spectrum. S–G fitting makes the intensity distribution concentration at the characteristic wavelength of the arc spectrum stronger and the feature extraction more obvious. It is advised to change the value of the original spectral signal after the de-noise processing. Instead, the light intensity of the de-noise spectral signal was expressed by relative intensity to show the spectral detection clearly.

In the final denoised signal of Fig. 4, the copper arc has a central wavelength of 324.5 nm in the UV region (10–400 nm). In the VIS region (400–760 nm), the central wavelength is located at 521.0 nm. In the NIR region, the copper arc has two central wavelengths of 793.0 and 809.0 nm.

For the same element, different spectral lines can be radiated due to the corresponding levels of electron transition. A copper arc plasma emission spectrum contains a large number of copper atomic lines and copper ion lines. The copper atomic lines come from the evaporation of copper, while copper ions due to electron removal. The copper wavelength can be obtained in Fig. 4 and Table 2.

### Table 2. Wavelength distribution of copper electrodes

| Parameters | UV   | VIS  | NIR  |
|------------|------|------|------|
| $\lambda$, nm | 324.5 | 521.0 | 793.0 | 809.0 |

Spectral data $x(\lambda)$ were weighted and averaged during the convolution calculation. The baseline drift phenomenon of spectral signal was suppressed [27, 28], so an effective baseline correction $p(\lambda)$ of $x(\lambda)$ was achieved. Characteristic wavelength of arc can be obtained according to the maximum point of $p(\lambda)$.

### 4 Arc spectrum characteristics analysis

#### 4.1 Copper arc optical and electrical analysis

Spectra can be divided into a linear spectrum and band spectrum. Linear spectrum is composed of narrow spectral lines, emitted by monatomic gas or metal vapour. Band spectra consist of many bands that are irradiated by molecules. To avoid interference from other light sources, the distribution of arc light in the UV region was extracted. The UV region can be more finely divided into three regions: UVA within the range of 320–420 nm, UVB within the range of 275–320 nm and UVC within the range of 200 nm–270 nm.

The principle of S–G convolution derivation is fitting spectral data by means of local polynomial least-square calculation in the time domain. Spectral data $x(\lambda)$ can be arranged as $2M+1$ data centred at $t=0$. After $N$-dimensional polynomial $p(\lambda)$ fitting, a residual error between $p(\lambda)$ and $x(\lambda)$ can be expressed. In accordance with a minimising residual error, the derivative of the residual error of the fitting coefficient is supposed to be zero [26], and the multinomial coefficient $a_0$ was further determined. Then, $p(\lambda)$ can be expressed as

$$p(\lambda) = \sum_{k=0}^{T} a_k \lambda^k \tag{5}$$

Wavelet decomposition and reconstruction are suitable for describing the arc spectrum transient signals. Wavelet decomposition caused a large value gap between the wavelet coefficient of equipment noise and spectral information [25]. A global threshold calculated from the original signal screening was the effective spectral information, so more precise local description and signal features separation of $x(\lambda)$ can be performed.

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4.2 Aluminium arc optical and electrical analysis

Aluminium arc spectral signal-changing process during denoise is shown in Fig. 5.

Series arc released a large amount of heat energy, accelerating aluminium electrode oxidised into a molecule when the arc occurs, so aluminium arc presents a wideband spectrum in the range of 500–1000 nm in the original signal of Fig. 5. Consisting of the processing method of the copper arc spectral data, the band spectrum of aluminium spectral data in higher-order intervals can be detected by a UV photosensitive tube. In this study, the 180° spectroscopy, the DC series arc excited by copper and aluminium excited the photons excited by the arcing heat in the case of the copper anode and the aluminium cathode. At a fixed electrode gap, the spectral intensity of the copper line increased with time. During this process, more and more copper vapour and cupric ion were produced in the air. Aluminium copper arc spectrum measured was also dynamically changed. Aluminium anode–copper cathode DC series arc spectrum from 0 to 8 s is shown in Fig. 6.

When the anode electrode material was aluminium, cathode material was copper and the spectrum data of the DC series arc detection is shown in Fig. 7. The light intensity of the aluminium–copper arc spectrum gradually decreased as the time increased. When 0 ≤ t < 4 s, the arc spectrum was consistent with the spectral wavelength of the copper line increased with time. During this process, more and more copper vapour and cupric ion were produced in the air.

To explain why the wavelength distribution changed at different time intervals, the study deduced the arc behaviour based on the physical and chemical properties of the two metals. The physical properties of copper and aluminium are shown in Table 5.

4.3 Copper aluminium arc behaviours at different time intervals

Copper aluminium arc spectrum measured was dynamically changed. To study the arc spectra of different electrodes at different time intervals, the distance between electrodes was 20 mm at t = 0 s, and the spectra were recorded every 2 s. The copper anode–aluminium cathode DC series arc spectrum from 0 to 8 s is shown in Fig. 6.

Actually, the atoms of the metal electrode are excited by arcing heat to release photons. The intensity of the copper–aluminium DC series arc spectrum gradually increased with time. However, spectral wavelength distribution and the ratio of light intensity at each wavelength remained the same. At each moment, the arc spectrum in Fig. 6 is mainly composed of a linear spectrum, and the characteristic spectral wavelength λ is shown in Table 2. It indicated that the copper electrode would emit the photons excited by the arcing heat in the case of the copper anode and the aluminium cathode. At a fixed electrode gap, the spectral intensity of the copper line increased with time. During this process, more and more copper vapour and cupric ion were produced in the air.

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When 0 ≤ t < 4 s, the melting and boiling points and work function of aluminium are lower than those of copper; besides, the anode electrode is more capable of absorbing energy, so the number of aluminium atoms and ions between the discharge gaps were much higher than the copper atoms at the beginning of the arc fault. Whereas, prolonged exposure to air, aluminium with strong arcing activity easily leads to oxidation. Moreover, the extra energy released by the arc-like UV light and heat accelerates the oxidation process, leading to the decreasing of aluminium atoms.

When t ≥ 6 s, the number of aluminium atoms in the discharge gap was much lesser than copper atoms, the remaining copper atoms and ions absorb energy, turning to higher energy but unstable copper particles. The unstable copper particle radiates corresponding to characteristic lines.
A wide-angle fibre optical sensor in Fig. 1 was used as a detector to test the copper/aluminium-excited DC series arc. The optical sensor has a wavelength-detected range of 250–420 nm containing the characteristic wavelengths of copper arc and aluminium. The response of the optical sensor with the copper arc burning is obtained as shown in Fig. 9.

The occurrence of the arc was detected by the arc current signal, while the optical sensors responded as a signal shockwave. From 0 to 1 ms, the circuit was working normally without the arc. The average current signal \( I_{\text{mean}} \) was 2.10 A, the average voltage signal \( V_{\text{mean}} \) was 63.73 V and the average optical signal \( U_{\text{mean}} \) was close to 0 V. Prior to the series arc, the ripple peak value of the current signal reached 1.43 A, and the ripple peak value of the voltage signal reached 219.07 V, when the optical signal was \(-7.34\) V. Corresponding to the response of the respective sensors, the threshold value was set as 10 times the difference between the ripple peak value and the average value without the arc, then the average value was also considered, as shown in (6)

\[
\text{Thr} = \frac{R_{\text{max}} - R_{\text{mean}}}{20} + R_{\text{mean}}
\]

As a result, the threshold of the current signal was 2.06 A, the threshold of voltage signal was 79.26 V and that of the optical signal was 1.12 V. The arc fault was detected by the optical signal at \( t = 0.938 \) ms prior to the current and voltage signal at \( t = 0.976 \) ms.

The measurements in this study indicate that the spectrum of the copper arc and copper–aluminium arc is consistent, with a central wavelength of 324.5 nm in the UV region, 521.0 nm in the VIS region and 793.0 and 809.0 nm in the NIR region. The spectral wavelength of the aluminium arc is 307.8 nm in the UVB region and 396.2 nm in the UVA region. Aluminium arc optical can focus on 307.8, 396.2 nm or both. Aluminium copper arc wavelength distribution changes with time, whose character wavelength was regarded as 307.8 and 324.5 nm. Considering that the optical sensor containing the intersection of the spectral line width is interfered by sunlight and malfunction, the detection range of the optical arc detection module in the MEA should be specific in the UV region. A range of 300–330 nm in the UVA, covering copper and aluminium spectral wavelengths, is suitable and effective. In the case, when the arc is excited by the aluminium anode–copper cathode, as long as the optical sensor detects the DC series arc before 4 s, the series arc protection reliability can be ensured.

### Table 4

| Time, s | UV     | VIS    | VIS   |
|---------|--------|--------|-------|
| 0       | 309.3  | 396.2  | —     |
| 2       | 309.3  | 396.2  | —     |
| 4       | 309.3  | 396.2  | —     |
| 6       | —      | —      | 521.0 | 809.0 |
| 8       | —      | —      | 521.0 | 809.0 |

### Table 5

| Material | Melting point, °C | Boiling point, °C | Electron work function, eV |
|----------|-------------------|-------------------|--------------------------|
| aluminium| 660               | 2500              | 4.28                     |
| copper   | 1083              | 2580              | 4.65                     |

### 5 Conclusion

The purpose of this study is to obtain the characteristics of arc light and provide a basis for the optical sensor selection of the arc light detection platform. The main conclusions are listed below:

1. An efficient algorithm comprising the EMD, WT, and S–G convolution derivative calculation is proposed for the extraction of spectral characteristic wavelengths.
2. The characteristic spectrum of the series arc in the UV band is related to the materials and the polarity of electrodes: copper (anode)–copper (cathode) and copper (anode)–aluminium (anode)–aluminium cathode.
(cathode), 324.5 nm; aluminium (anode)–aluminium (cathode), 307.8 nm; aluminium (anode)–copper (cathode), 307.8, 324.5 nm.

(3) An available wavelength range of 300–330 nm is recommended for the practical series arc detection in the DC power system of MEA. This conclusion can also be applied and expanded in other power systems with similar voltage levels, such as power distribution networks and DC microgrids.

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