

A Survey on Arc Fault Detection and Wire Fault Location for Aircraft Wiring Systems

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ABSTRACT

This paper provides an overview of recent developments in the area of arc fault detection (AFD) and wire fault location for aircraft wiring systems. Arc faults have been identified as one of the greatest threats to human lives and properties, and the likely cause of several aircraft disasters. With the introduction of high voltage transmission in aircraft to reduce the wiring weight and to meet the increasing power demands, the probability of initiating and sustaining continuous arcs in modern aircraft have been increased. However, arc faults are hard to detect and wiring problems are difficult to locate in aircraft, due to their complex profiles, high impedance property, and pressure sensitive characteristic, etc. The difficulty in resolving this problem is also due to the fact that false alarms cannot be tolerated but missing alarms can be fatal, and arc faults are normally intermittent as a result of the in-flight vibration.

For arc fault detection, a great number of methods have been proposed, which can be categorized into mechanical and electrical methods; in general, features can be extracted from time domain, frequency domain, or time-frequency domain; and algorithms have been developed based on adaptive techniques, Kalman filter, fractal theory, neural networks, fuzzy logic reasoning, and expert systems to enhance arc fault detection. Regarding wire fault location, numerous techniques have been developed and practiced, including visual inspection, impedance measurement, pulse arrested spark discharge diagnostics, high voltage test, inert gas method, and various kinds of reflectometry. Each of these techniques is effective to a certain extent, but all of them come with drawbacks as well.

This paper is intended to provide a constructive summary of the present arc fault detection and wire fault location techniques, together with discussions on the current and future research and development opportunities and challenges in this field.

INTRODUCTION

Detection and location of arc faults in power distribution systems have attracted attention from numerous researchers in the past decade. Arc faults, if not dealt with properly, may interrupt power supply, damage electrical devices, pose fire hazards, and even threaten human lives [1]. Arc faults can occur in any electrical system such as in residences [2], factories, coal mines [3], nuclear power plants [4], telecommunication installations [5], automobiles [6], ships [7], submarines [8], and spacecraft [9].

In recent years, numerous arc faults have been observed on aging aircraft, and aircraft wiring problems have been identified as the likely cause of several tragic mishaps and hundreds of thousands of lost mission hours [10]. Modern and future public transport aircraft rely more on electrical power for flight control, environment control, engine management, computers and communication, passenger services and entertainment. The increased reliance on electrical power makes such aircraft more vulnerable to wiring problems and arc faults. Therefore, there is an urgency to develop efficient and reliable online arc fault detection and location algorithms for aircraft power distribution systems.

By definition, an arc fault is an unintended, self-sustaining discharge of electricity in a highly conductive ionized gas, which allows current flow between the conductors, limited only by circuit parameters that are predominantly resistive. Arcing is a special form of high impedance fault, which is difficult to detect by traditional protection devices (e.g., fuses, relays, and circuit breakers, etc.) since there is sufficiently high impedance in the circuit to limit current below their trip thresholds [11]. Arc faults can arise as a consequence of loose connections, inadvertent damage (when a wire is cut, pinched, cracked or broken), or insulation aging [12].

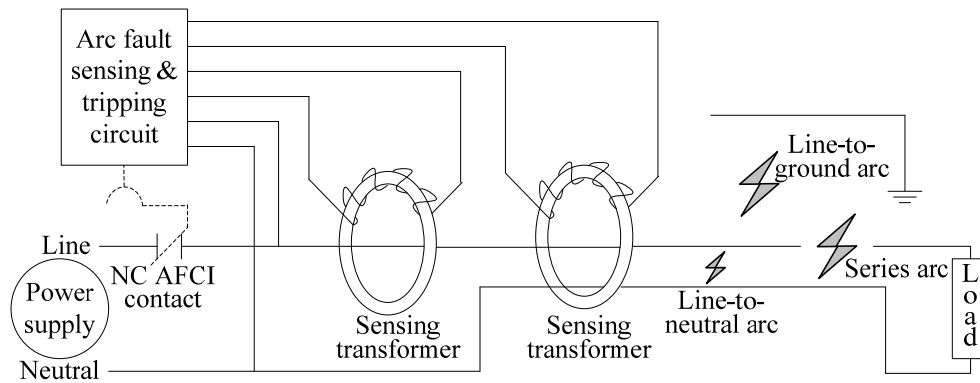


Figure 1. Typical AFDI sensing arrangement [19]

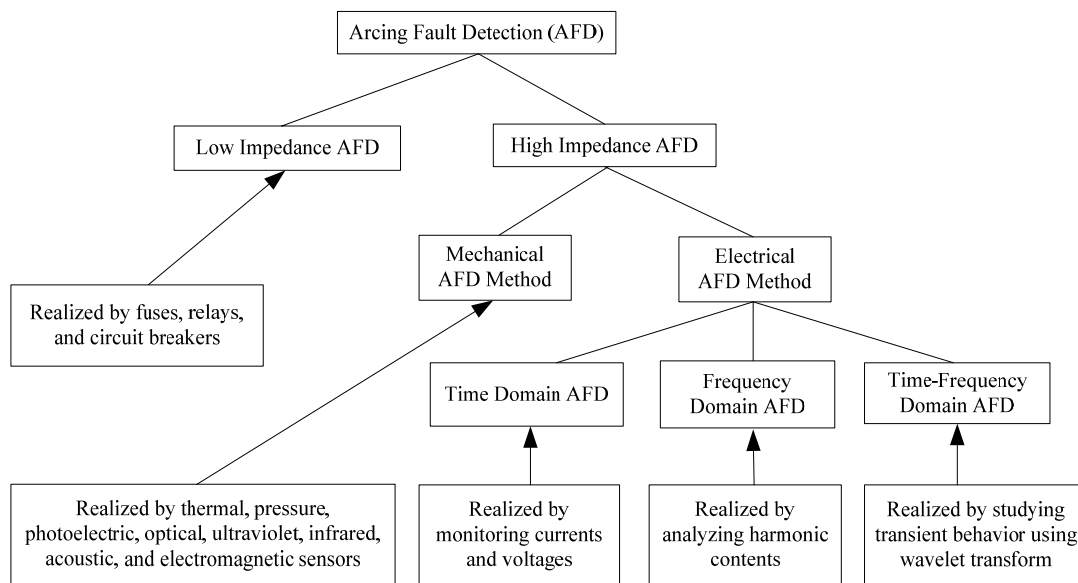


Figure 2. Classification of arc fault detection methods

Arc faults can be broadly classified into two categories, namely series faults and parallel faults. A series arc fault can occur when the conductor in series with the load breaks. It can also occur when two lines are loosely connected as well as when plugging and unplugging connectors under load. On the other hand, a parallel arc fault occurs when two distinct conductors, at different potentials, are brought into close proximity. The current flow through the resulting fault is limited by the system impedance and the impedance of the arc itself. Arc fault models can take the form of series arcing, line-to-ground arcing, line-to-line (neutral) arcing, or arcing between phases, as shown in Figure 1.

The charge transport properties (conductivity) of a DC arc are affected by the gas density surrounding the arc, which could cause a perfectly functioning AFD algorithm on the ground to fail when the aircraft fly to a higher altitude [11]. Moreover some aircraft loads may produce transients or even arcs during their normal operations, which are difficult to distinguish from arc faults. Furthermore, the high reliability requirements driven by critical aircraft loads have put more constraints on the accuracy and sensitivity of the AFD algorithms, as false

alarms are usually not well tolerated on the aircraft. In addition, intermittent faults are common in aircraft due to the in-flight vibration that causes wires with breached insulation to touch each other, or the airframe, pins, splices, and corroded connections to pull loose, or water to drip on wires with breached insulation. Intermittent faults are difficult to diagnose because they occur only under a particular condition or strain and are difficult or even impossible to be reproduced on the ground [13]. As a result, even if an arc fault can be effectively detected and cleared during flight, its root cause may not be easily identified when the aircraft is back on the ground. All of the above mentioned characteristics have made arc fault detection and location extremely challenging.

The rest of this paper is organized as follows: the present arc fault detection techniques are summarized in the next section; reviews on arc fault and wiring failure location methods are presented in Section 3; the challenges and opportunities for future research are discussed in Section 4; Some concluding remarks are given in the final section.

HIGH IMPEDANCE ARC FAULT DETECTION

In the past two decades many techniques have been proposed for high impedance arc fault detection in power distribution systems. Generally, arc fault detection techniques are divided into mechanical and electrical detection methods. In mechanical methods, pressure, thermal, optical (or ultraviolet), infrared, ultrasonic, acoustic, photoelectric, or radio frequency sensors have been widely adopted to detect arc faults [8,14-21]. According to the signature extracting techniques exploited, electrical detection methods can be categorized into time domain, frequency domain, and time-frequency domain methods, as shown in Figure 2.

MECHANICAL ARC FAULT DETECTION METHODS

As for mechanical detection methods, thermal and pressure rises are always taken as indications for arc faults [14]. Optical or ultraviolet sensors are reliable instruments for arc fault detection. An arc has a unique acoustic signature, the detection of which is possible, particularly in high power arcs. The arc also emits a wide bandwidth electromagnetic interference that can be detected by a simple "pick-up" coil, or AM radio.

In related research, an arc fault detection instrument was designed conceptually for electrical apparatus [15], in which acoustic, infra-red, and electromagnetic radiation produced by electric arcs were detected by a pressure zone microphone, photo-transistor, and loop antenna, as shown in Figure 3. This instrument has been improved and implemented to detect and locate low-level arc faults in dry-type transformers [16] and metal-clad motor control center switchgear panels [17].

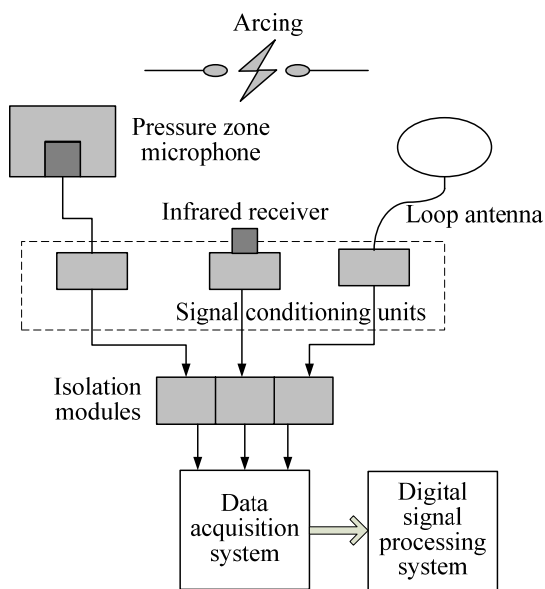


Figure 3. A microprocessor based arc fault detection instrument [15]

A system was developed to locate parallel arc faults by sensing leading edges of electromagnetic waveforms

and ultrasonic emissions, as reported in [18]. An arc-fault circuit interrupter (AFCI) has been developed as a product intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc fault is detected [19,20]. Hitherto, the AFCI is primarily applied in residences, the typical arrangements of which were as shown in Figure 1. It is reported that more than 10, 000 photo-sensors, 4, 000 pressure sensors, and 175 control units have been built and deployed on all classes of US Navy submarines [8]. Recently, the optical fiber technique was introduced into the field of arc fault detection in [21].

Apart from the high installation and maintenance costs, the main flaw of mechanical arc fault detection methods is that the sensors must be set near the arc location to have reliable detection, which is not practical in general. Furthermore, electromagnetic detection also suffers the added disadvantage in that it can be prone to false trips. With respect to acoustic sensors, it is rather difficult to discern arcing noise in a continuous series arc from the noise generated by contactors, switched-mode power supplies or other emitters onboard an aircraft [11].

ELECTRICAL ARC FAULT DETECTION METHODS

Electrical arc fault detection methods normally detect arc faults according to the abnormality of current, voltage, and the corresponding derivatives of these electrical signatures. At the early stage of research on time-domain methods, the average or RMS current magnitudes are monitored for overload protection and the peak current magnitudes are examined for over-current alarm [22,23]. Some recent research trends in time domain involve the analysis of characteristics such as the ratio of current and voltage measurement values [24], the imbalance of three-phase currents [25], [26], the voltage unbalance along a feeder [27], the differential voltage [28], the differential current [29], the arc fault energy [30], and the chaotic property of arcing current and voltage [31].

Fourier transforms have been widely accepted as a way to map the time domain signals into frequency domain, and discrete Fourier transform (DFT) has the ability to decompose the signals into a series of spectral components. Fast Fourier transform (FFT) has provided a computationally efficient solution to DFT and has boosted the rapid development of signal processing. For the frequency domain methods, the harmonic content of phase and neutral currents during arc faults are compared with that of normal conditions; in addition, some coefficients measuring waveform distortion are generally monitored, as shown in Equation (1), [32-34].

$$k_{dis} = \left\{ \sqrt{h_0^2 + \sum_{i=2}^n h_i^2} \right\} / h_1 \quad (1)$$

where k_{dis} is the distortion coefficient; h_i denotes the i_{th} harmonics; i and n represent the harmonic number and the total number of discrete signal data, respectively.

Furthermore, recursive algorithms may be developed on the basis of moving window DFT, as shown in Equation (2), which is suitable for transforming non-stationary input signals continuously [35].

$$h_n(k) = [h_{n-1}(k) + x(n) - x(n-N)] \cdot \exp\left(\frac{j2\pi k}{N}\right) \quad (2)$$

where $h_n(k)$ and $h_{n-1}(k)$ denote the k_{th} harmonics at the instant $n \cdot \Delta t$ and $(n-1) \cdot \Delta t$, respectively; N is the size of the window, i.e., the window is composed of N values $x(n-N+1), x(n-N+2), \dots, x(n)$.

The time–frequency domain methods determine how the frequency behavior of a signal changes over time and the transient behavior of arc faults in both time and frequency domain can be analyzed. Unlike the Fourier analysis, wavelet transforms possess time and frequency information, which makes it ideally suitable for dealing with non-stationary signals such as those encountered under high impedance arc faults. Though more complex, wavelet transforms have proved to be superior to the other signal processing techniques in arc fault detection, especially in terms of increased reliability and dependability [36–39]. By definition, wavelet transform is a convolution of the continuous signal $x(t)$ and the mother wavelet function $g(t)$, as shown in Equation (3). Analogous to the relationship between continuous Fourier transform (CFT) and DFT, the continuous wavelet transform (CWT) has a digital counterpart known as discrete wavelet transform (DWT), as given by Equation (4).

$$CWT(a, b) = \frac{1}{\sqrt{a}} \cdot \int_{-\infty}^{\infty} x(t) g\left(\frac{t-b}{a}\right) dt \quad (3)$$

where a and b are the coefficients of scale and translation; $x(t)$ is the signal function; and $g(t)$ is the mother wavelet function.

$$DWT(k, a, b) = \frac{1}{\sqrt{a}} \cdot \sum_{n=0}^{N-1} x(k-n) g\left(\frac{n-b}{a}\right) \quad (4)$$

In related research and development on time-domain electrical arc fault detection, many patents can be found. Numerous arc fault detection methods have been proposed, and corresponding apparatus have been developed. A numerical algorithm was presented for arc fault detection and fault distance estimation of overhead lines by processing the line terminal currents and voltages [22]. An apparatus was devised to determine arc fault location, energy and type in a real time manner, the block diagram of which is as shown in Figure 4, [30]; the circuit is tripped whenever a determined value of arc fault energy exceeds a predetermined threshold value; series and parallel arc faults can be identified according

to the ratio of source current and nominal load current; and the parallel arc location can be determined by a microprocessor from the source voltage, the current, the load voltage, and a wire resistance and conductance per unit length of the circuit. On the basis of solid state power controller (SSPC), an arc fault detection method and associated apparatus were developed for vehicle electrical power distribution systems by comparing the measured load current with a reference stored in memory, as shown in Figure 5, [40]. An arc fault detector was developed for an aircraft 400 Hz AC electrical system by monitoring a cumulative sum of amounts by which the AC current, in each most recent cyclic interval, exceeds the current in the immediately preceding half cycle in absolute magnitude [23]. A non-contact series arc fault diagnosis device was developed for aircraft wiring systems, which comprises a capacitive probe for clamping to the outer insulation layer of the wire to sense a first voltage at a first node, and a floating high-impedance meter having a ground reference at a second node; the latter was adapted to measure a voltage difference between the two nodes and was further adapted to indicate the presence of series arc fault when the measured voltage exceeds a predetermined level [41]. An arc fault detection method was proposed for relatively constant power consumption by calculating the ratio of measured current values and voltage values, which are detected in parallel [24]. An invention was presented by incorporating current imbalance detection and circuit interrupter into the existing aircraft power control relay package [25]. Apparatus and methods for detecting high level arc faults in three-phase aircraft power systems were disclosed, which with reduced susceptibility to nuisance trips includes three low pass filters, each having an output connected to a threshold detector, as shown in Figure 6, [26]; an embodiment of the invented arc fault detection method involves detecting at least one of the three phases having a current exceeding a predetermined threshold, detecting differences between the three phases and generating a signal indicative of difference being detected between the three phases for a time period exceeding a predetermined duration. Parallel DC arc events are identified when a difference between the maximum and minimum DC current signal value exceeds a threshold [42]. An AC arc fault detection device was developed by acquiring AC current signals and monitoring the occurrence of the acquired signal moving into the over-current regions [43]. By monitoring the voltage unbalance along a feeder, high impedance faults caused by broken conductors can be detected and located easily and reliably by the algorithm proposed in [27]. By sensing the differential current (di/dt) characteristics and the absolute current ($|i|$) waveform and correlating them, electrical arc faults can be distinguished from nuisance loads, and then a reliable arc fault detection method can be derived with reduced nuisance tripping [29].