Feasibility of Spread Spectrum Sensors for Location of Arcs on Live Wires

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***Abstract*—Spread spectrum methods are an important emerging class of sensors that have the potential to locate small, intermittent faults on energized aircraft power circuit wires. Previous work has demonstrated the use of these methods for hard faults (open and short circuits). This paper extends that work to the location of typical intermittent faults that plague aircraft maintainers. Test results on 200-ft-long realistic aircraft wires demonstrate the feasibility of these techniques to locate both wet and dry arcs while the system is powered with 400-Hz 115-V ac power running a variety of aircraft lighting loads. The capability of the system to function with either the aircraft structure or a paired wire as the return path to ground is demonstrated. These results indicate that spread spectrum methods have significant promise for locating intermittent faults on wires as they occur in flight or other modes of operation, such as landing and takeoff, taxiing, and other critical times when possible vibration, etc., may cause intermittent faults.**

***Index Terms*—Reflectometry, spread spectrum, wire fault locations.**

I. Introduction

MAINTENANCE of aging wiring is a significant challenge for almost every major wiring system in the country including transportation vehicles and control systems, communication networks, power generation and distribution systems, consumer products, buildings and homes, etc. [1]–[3]. For aircraft, where both preventative and responsive maintenance are taken very seriously, aging wiring is a very expensive problem. Electrical wiring problems in the U.S. Navy cause an average of two in-flight fires every month, more than 1077 mission aborts, and over 100 000 lost mission hours each year [4]. Each year, the Navy spends from one to two million man hours finding and fixing wiring problems [5].

Among the most difficult to diagnose problems are those that are intermittent, that occur only during a particular condition or strain and are unable to be reproduced on the ground. The vast majority of car owners have had similar experiences when they take a malfunctioning car to the mechanic, only to have it work properly in the repair shop. Detection of intermittent arcs (short circuits) in aircraft is the focus of recent research [6]–[8]. Wet arcs are caused when moisture seeps into cracked insulation, creating a conducting path for current. Wet arcs are normally simulated in the lab by dripping saline onto wires with cracks in the insulation. Dry arcs are caused by a wire fraying against and eventually making contact with a metallic structure, by two wires rubbing together, or by bits of metal making contact between two wires. Dry arcs are simulated in the lab by using a guillotine to short a razor blade across two live wires.

Low-level, intermittent arcs are not normally detected by traditional thermal circuit breakers, which require enough current flow to heat up a thermally sensitive element in the breaker. Smart circuit breakers (SCBs) (also known as arc fault circuit breakers or interrupters) are being developed to identify the noise on the line associated with an arc and trip when an arc occurs [6]–[8]. SCBs are required on bedroom circuits in new home construction as of 2002, and are being considered for commercial products, specifically in-room air conditioners and heaters. Aircraft versions of SCBs as one-to-one replacement for the existing thermal breakers have been in development over the past four years. They are under consideration for targeted implementation on commercial and noncommercial planes in the near future. A significant challenge associated with the SCB is that it prevents or limits the extent of the arcing event, and, thus, the wire damage is so small that it may be extremely difficult to locate and repair. This is a critical issue that may slow the acceptance and widespread deployment of SCBs, as existing technologies have shortcomings in locating the fault.

There are several emerging sensor technologies that may help locate the small faults on the wire left behind when the SCB trips. Time domain reflectometry (TDR), long the traditional method of solving the industry's most puzzling wiring problems, has the potential to detect very small changes in impedance, perhaps as small as those created by a wet or dry arc. While promising, these methods require an extremely accurate baseline for comparison with the arced wires. Recording and maintaining baseline TDR data archives for even a limited number of circuits for an airline or military fleet may prove to be an enormous and costly task. In addition, moving the wire, which is inevitable in the high-vibration environment of the plane, can make impedance changes that are as large or larger than the fray, making these methods difficult to implement in practice [9]–[11]. Another variety of TDR that may be able to detect frays is the "excited dielectric test" [12]. Impedance spectroscopy [13] compares the reflections returned from a wide band of frequencies, seeking frequency-dependent impedance changes, and has been claimed to be able to find frays. The

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reflectometry techniques described above have shortcomings, however. After the arc occurs, the impedance change at the arc location is very small, commonly less than an ohm difference on a 50-Ω cable. The reflections are, therefore, necessarily minute. If the fault could be found while it is occurring, as will be described in this paper, its impedance change is significant over that very short period of time (often a few milliseconds), and the resultant reflection is much easier to detect and analyze.

High-potential testing (HiPot) or the dielectric withstand test (DWT) places a high-dc voltage across the wires, looking for leakage currents (arcs). Essentially, the arc condition is enhanced by increasing the voltage, which makes it easier to find the fault or wire damage/exposed conductor location, but existing electronics must be disconnected before testing, to prevent damage. Arcs may be located one of several ways, including audibly [14]. Another method of augmenting the arc is by surrounding the cable by an inert or ionized gas or a conductive fluid. [15] This enhancement effect has also been noted for TDR [9], [10] and impedance spectroscopy [13]. While highly effective, augmenting the fault with gas or water requires intimate contact with the wire, which is physically very difficult or impossible. If the wire is tested while the arc is present, as described in this paper, this augmentation occurs if moisture, a liquid or other contaminants are on the wire/s. However, high-voltage testing also opens up several issues. 1) The high-test voltage may jump from the wires under test to unintended wires or contacts and damage sensitive electronics. 2) The high-voltage sparking or arc may have sufficient energy to act as an ignition source in environments where flammable, ignitable, or explosion prone materials may be present. Therefore, the use of this test method is limited to de-fueled environments and where all the loads are disconnected.

Another emerging technique for fault location is spread spectrum reflectometry. [16]–[18] This method uses a very low-voltage pseudonoise (PN) code as the test signal on the wire. The correlation between the incident and reflected signals identifies the type of fault and its location. Because the signal can be extremely small and appears like noise, it can be imbedded within the noise margin of an existing signal. This is expected to enable real time monitoring of the wires in flight, without interfering with their function and without the existing signals interfering with the measurements. This gives the potential to detect and locate arcing conditions when they are nearly short circuits, rather than later when their impedance change is too small to easily detect. Thus, spread spectrum has a huge advantage over existing technologies, and the potential to resolve the fault location challenges associated with smart circuit breaker technology.

This paper demonstrates the feasibility of using spread spectrum methods for locating arcs on realistic aircraft cables, including noncontrolled impedance cable and the aircraft structure used as the ground return. Actual 400-Hz aircraft power systems and aircraft lighting systems were used, with prototype smart circuit breakers for in line protection. Both wet and dry arcs were simulated.

Section II describes the spread spectrum test method, and Section III describes the Boeing Wire Test Bench, where the tests were done. Section IV shows the results and analysis method, and Section V summarizes the results and describes the parameters needed for a real time, continuously monitored in-line test system.

II. Spread Spectrum Reflectometry

Spread spectrum methods have been used extensively in communication systems, where a PN code is used to code the data for wireless transmission. This basic concept can be applied with excellent precision to fault location on aging wiring [16]–[18].

Spectral reflectometry (STDR) is currently being used to qualify telephone lines for use with digital subscriber line (DSL) [17]. In this application, a maximum-length (ML) PN code is transmitted down an inactive twisted-pair telephone line, and the reflected signal is detected with an analog-to-digital converter (ADC). In software, the received signal which contains the original PN code plus the echo received when the code reflects from the end of the wire is correlated with the transmitted PN code to generate the equivalent of a TDR oscilloscope trace. Note that this correlation is performed in software rather than hardware, and that the method described in [17] does not enable use on live wires. When the PN code alone is used as the transmitted signal, this is called STDR. The accuracy of the distance to the fault (resolution) in the system described in this reference is about 10 ft, which is insufficient for aircraft applications.

Another application of spread spectrum reflectometry to test wiring is found in [18]. In this application, the PN code is modulated by a sinusoidal carrier and superimposed on 60-Hz power lines. As in [17], the response is sampled in time, and the correlation is done in software. When the PN code is modulated before transmission, this is called spread spectrum reflectometry (SSTDR). The resulting accuracy of the distance to the fault of the system in [18] is on the order of kilometers, which is also of course much too large for aircraft applications.

SSTDR has been shown to be an effective method for locating hard and soft faults on aircraft wiring with precisions on the order of a few inches [16]. In order to achieve this resolution, the correlation is done in hardware as described as follows.

The basic STDR/SSTDR system [16] is shown in Fig. 1. The 1023-bit ML PN code running 58 Mbits/s is generated using a series of tapped flip-flops. The 30-mV (RMS) PN code is added to the 115-V 400-Hz aircraft signal. Since this signal is zero mean and is well within the noise margin of the aircraft signal, there is minimal and controllable correlation and, therefore, interference between the PN code and the 400-Hz signal. The PN code is also highly immune to noise from the 400-Hz generator and the live loads on the line, so can provide accurate results in realistically noisy situations [16]. A multiply and integrate circuit is used to perform the correlation in hardware, and an analog phase shifter is used to shift the original PN code to find the correlation for every very small phase (time) delay and create the equivalent of a TDR trace. Fig. 2 shows the STDR response for an 80-ft wire (a pair of single 22 gauge wires bundled with other wires, as described in Section III) that is short or open circuited on the end. The magnitude of reflection is always relative to the incident signal. A reflection of $+1$ would be a pure

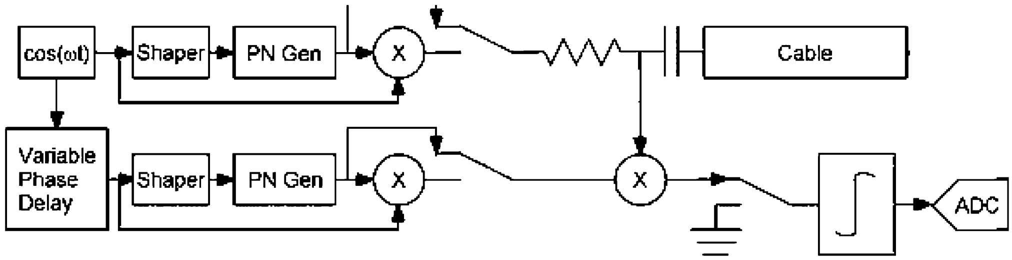

Fig. 1. Circuit diagram for STDR/SSTDR system.

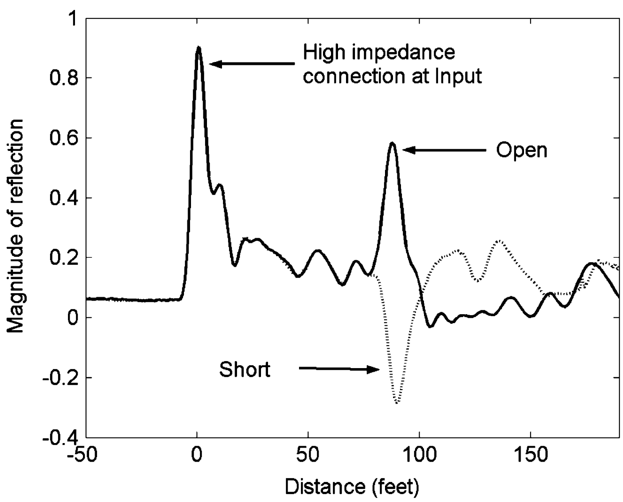

Fig. 2. STDR response for an 80-ft wire (paired single 22 gauge wires bundled with other wires) that is short or open circuited on the end.

open circuit, and a reflection of -1 would be a pure short circuit. Note the original positive peak that indicates the reflection that occurs where the high-impedance circuit is attached to the wire and the negative peak that indicates the short-circuited end of the wire. The height of the peaks indicates the magnitude of the fault, the polarity (positive/negative orientation) of the pulse indicates whether it is a high- or low-impedance fault, and the distance between them indicates the distance to the fault. Hard faults (open and short circuits) have been located to within 3–5 in on controlled impedance cables and 6–8 in on uncontrolled impedance cables [16]. Somewhat less accuracy is expected for intermittent or partial faults. The details of the STDR/SSTDR system can be found in [16] and are not repeated here for brevity. When the STDR/SSTDR system is used to locate the small, intermittent faults that can trip an SCB the system should show a low impedance (near short circuits), which is indeed the case, as will be shown in Section IV.

III. Boeing Wire Test Bench

The Boeing Wire Test Bench includes a 200-ft wire bundle with branches and splices mounted in a meander fashion about 1” above a metallic ground plane. Intentional fault or damage can be introduced in certain sections of the wire bundle for testing purposes. Most of the tests were performed on one of the branches of the wire bundle comprised of seven 20 AWG wires (four single and a twisted triple). A 400-Hz 115-V power source was used to power a variety of aircraft lights (one or two at a time) as loads. A thermal (7.5 A) breaker in series with a prototype SCB breaker was used to protect the circuit under test. The power supply was connected to one of the single wires (“hot”). For return, either a second single wire or the metallic backplane (“ground”) were used. Fig. 3 shows a typical single wire circuit from the subject wire bundle used in the tests. The single wires can be characterized as having uncontrolled impedance, as they can meander around within the bundle itself. The impedance of test circuits using the ground backplane as return is particularly uncontrolled because of the movement of the bundle relative to back plane. Also, the connection to the ground plane presented a somewhat chaotic impedance as long and/or short single lead wires were used between the test instrument measurement points and the wire bundle connection points.

During the tests, a wet arc was simulated by using an 8 inch long disposable wire bundle prepared for wet arc testing by circumferentially scoring the insulation on two of the adjacent wires, exposing the conductor. The wires were in contact, and the scores on each wire were about $1/4$” apart along their length. This was inserted at points C and D as shown in Fig. 3 and, subsequently, “dripped” upon with a 3% saline solution, approximately 8–10 drips/min.

The dry arc was simulated by connecting a 4’ long disposable wire bundle at points C and D as shown in Fig. 3 and, subsequently, guillotining it with a razor blade held by a nonconductive handle (somewhat similar to an office paper cutter).

Three different loads were used for both wet and dry arc tests:

- a bank of fluorescent lamps (this system is effectively a pulsed source, highly noisy);
- an anticollision strobe light (this system uses a capacitor bank that is charged/discharged during operation); the fluorescent and strobe lights were used either separately or in parallel;
- a retractable landing gear light and motor (separately or together); the motor extended or retracted the light, and was manually switched during the tests.

IV. Results

A. Dry Arcs

A dry arc test using a guillotine produces a short circuit that may last only a few milliseconds before the prototype SCB is designed to trip. An example of this is seen in Fig. 4, which shows the STDR trace at the exact time the short occurs, with the short clearly visible at 120 ft. The strobe light is the load. The system is not impacted by the noise from the strobe light,

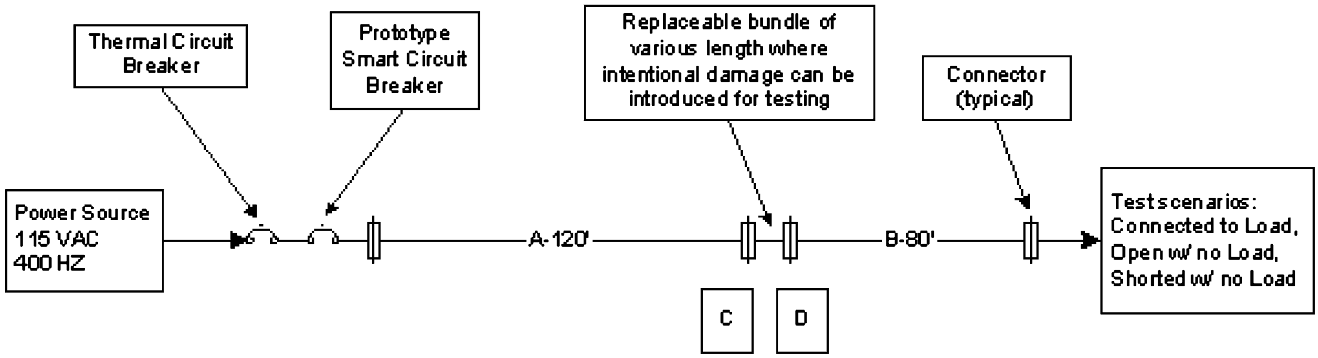

Fig. 3. Boeing wiring test bench.

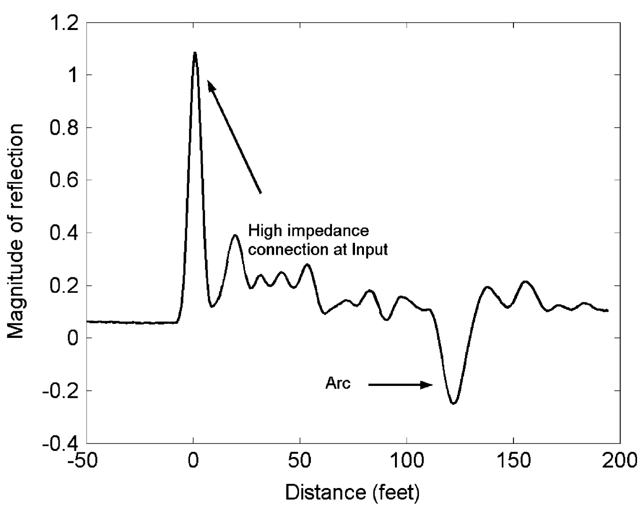

Fig. 4. STDR trace showing the instantaneous short circuit (at 120 ft) caused by the guillotine test before the SCB trips. The load is a strobe light. The time step shown is #172. The insert shows the RMS of the data as a function of time. The step in the RMS value shows the change that happens when the arc occurs and the SCB trips.

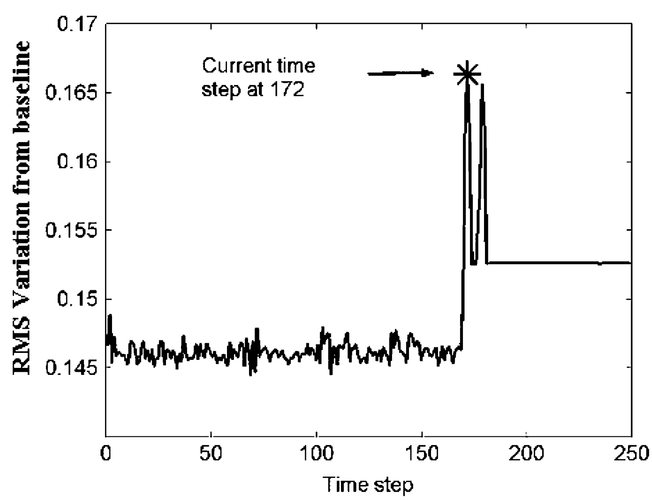

Fig. 5. STDR trace showing the instantaneous short circuit (at 120 ft) caused by the guillotine test before the SCB trips. The load is a landing gear light and associated retraction motor.

and no visible change in the circuit occurred because of running the STDR. Similar results are seen for fluorescent lights and the landing gear light and motor. The reflection is only about 30% of what would be expected for a complete short circuit, most likely because the guillotine (which does not cut all the way through the wires) does not create a complete short.

Fig. 5 shows the method that is used to identify the time that the fault occurs, so that all of the data does not need to be analyzed. The trace that is shown in Fig. 4 is a single time step of data. The RMS of this time step is taken and plotted as point 172 (this is the 172nd time step) along with the RMS of all of the other time steps. Each time step requires about 20 ms to store, due to the slow acquisition speed of the parallel port. When implemented on aircraft, this acquisition time could be shortened considerably. The system maintains a "rolling window" that is 200 time steps long. The first time step is taken to be the baseline (averaging several early steps can be used to improve this baseline, but this has not been found to be critical). Subsequent time steps are compared to the baseline and stored only if they are sufficiently different (10% in our case) from the baseline. When the arc occurs, there is a significant change in the signal, indicating an event worth noting. The algorithm for location of

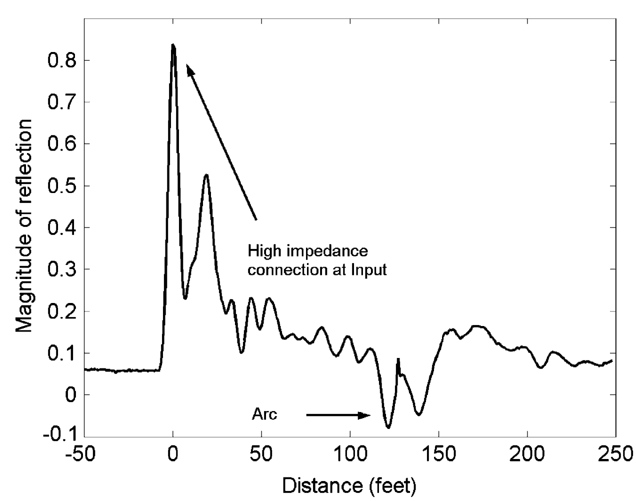

Fig. 6. STDR traces showing the instantaneous near short circuits caused when saline solution is dripped on a wire with damaged insulation, making a partial path for conduction.

a short circuit can then be as simple as searching for the maximum negative peak when the significant event occurs.

Fig. 6 shows similar results when the load is a retractable landing light with its retraction motor. The short circuit is clearly

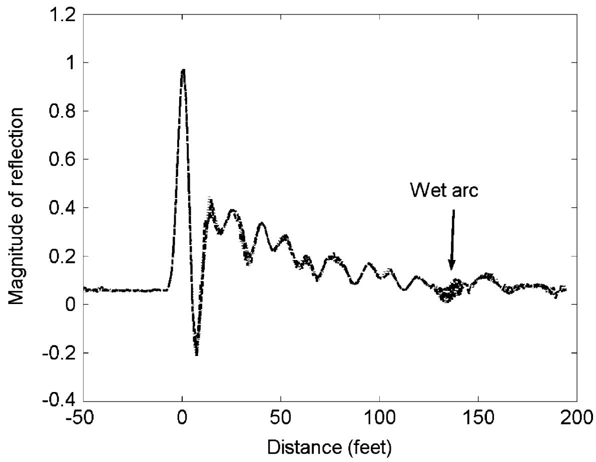

Fig. 7. STDR traces showing the instantaneous near short circuits caused when saline solution is dripped on a wire with damaged insulation, making a partial path for conduction. Several time samples are superimposed to show the location of the wet arc.

seen at 120 ft, and the change in RMS indicates the fault event. These two plots are good examples of arcs identified and located by the STDR method. Unfortunately, the data collection system (utilizing the parallel port on a PC, and requiring about 20 ms) was not fast enough to catch all of the arcs we tested before current was removed by the SCB (which tripped in about 5 ms in many cases).

B. Wet Arcs

Wet arcs were simulated using a saline drip test. An example of this is shown in Fig. 7, with the strobe light connected as load. Several different time steps are superimposed in this figure, showing the range of values over time. The time steps in the figure are the ten out of 200 samples that have the largest difference from the initial baseline, since these will be the samples representing the wet arc. The location of the arc is clearly seen as an area with substantial change. When this is observed sequentially, the dripping/drying and the resultant activity/inactivity can be seen. When the water is present, the low peaks are seen. When the water is not present, the curve is flatter in that location. The combination gives a region of substantial noise that can be identified as the wet arc location.

V. Summary and Conclusions

Previous work [16] has shown that spread spectrum methods are able to locate hard faults (open and short circuits) on both energized (live) and de-energized (dead) wires. This paper demonstrates the feasibility of detecting and locating intermittent shorts (arcs) on live wires running 400-Hz 115-V with live loads and either a paired wire or aircraft chassis as the return path for current. The STDR correlation plots show the arcs as low-impedance peaks. The location of these arcs (distance on the wire from source or load end) could be automatically calculated and displayed by a computer using a peak detection or pattern-matching algorithm.

Our present system collects one complete data set in about 20 ms, so we need to increase the speed with which the system gathers data in order to locate every arc and analyze the statistical accuracy of the system, probability of false positives and negatives, etc. For accurate location, the system must correlate the PN code with the signal on the line, process and store it fast enough to catch the arc before it goes away (either because it is physically removed or because the circuit breaker trips), which is feasible with today's technology. This paper demonstrates the feasibility of a fault location system that is of critical importance in the widespread deployment of smart circuit breakers.

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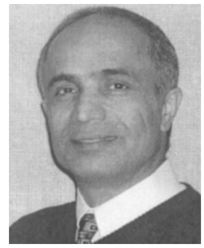

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