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Arc Fault Management Using Solid State Switching

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ABSTRACT

In arc fault circuit breakers, the choice of a fault detection sensitivity is generally made as a compromise between speed of detection and avoidance of nuisance trips. By using solid state switching with a variable arc fault detection threshold, the best of both worlds can be obtained. This paper describes baseline experiments on arc fault management through the use of solid state switching. Direct current testing on series arcs and on parallel arcs across carbonized paths suggests that in some cases, an arc event can be actively managed. This allows a reduced level of power to be supplied to a critical system even in the presence of a fault condition. In cases where fault management is not appropriate, solid state fault interruption technology allows the ability to reset a nuisance trip, enabling more sensitive trip thresholds to be used.

1.0 INTRODUCTION

Solid state relays offer advantages over traditional "air gap" mechanical circuit breakers. There are no moving parts, so the response time is generally quicker. The solid state relay is also easily reset by using an electrical signal. Finally, in contrast to a mechanical circuit breaker, rather than binary operation (open or closed), a solid state relay can be controlled to, in effect, have a partial closure with a time averaged resistance other than zero or infinity. These features present some opportunities for electrical fault management in aviation circuit breakers. Since a solid state relay may quickly respond to a sensed fault, it presents the opportunity to implement quick fault interruption. However, the real advantage to solid state technology is not that it interrupts quickly but that it can restore power very quickly. So, in case of a nuisance trip, power may be immediately restored, allowing for a more sensitive fault detection threshold to be used because false (nuisance) trips can be better tolerated. Furthermore, controllable switching may allow the management of electrical faults that occur during flight, allowing an aircraft to maintain enough control to complete a mission or to safely land.

This paper describes some baseline research that was conducted to examine the feasibility of using the reset capability offered by solid state electronics to manage an arc fault situation. In particular, experiments on arc restrike after interruption suggest that only a brief interruption is required to successfully extinguish an arc across separated conductors without restrike. Experiments on arcs across carbonized paths demonstrate that under some conditions, an arc can be managed, allowing the fault condition (but not the arc) to persist, while still maintaining a reduced level of power delivery to the load.

2.0 ELECTRICAL ARCING FAULTS

Electrical system faults are a significant source of aircraft failure. Such faults can arise from causes as diverse as combat damage, insulation aging, loose connections or the damage to electrical wires that can occur during routine maintenance. Insulation breakdown that can impact the conductors used in aircraft wiring has been well documented. Vibration can cause insulation wear as wires rub against each other, against tie downs or against structural members. Maintenance can be rough on wires as wires become damaged by worker's pliers or are pulled through narrow bending radii. Stresses due to thermal and air pressure cycling can prematurely age wire insulation. Condensation and exposure to salt air can create "tracks" where conductive traces are formed. Over time, contaminants can degrade the insulation and penetrate into insulation cracks.

In an aircraft, the skin and airframe form the return for the current in many of the circuits. Electrical leakages to this "ground" may be classified as "ground faults". Whenever there is a luminous discharge (a spark) between two conductors or from one conductor to ground, this is termed as an arcing or arc fault and it is objectionable because heat is produced as a byproduct of this unintended current path. If not immediately detected and interrupted, an arcing fault can lead to electrical fires that can involve other wires, compromising the function of multiple electrical control and power circuits within the aircraft. The heat of an electrical arc can cause the ignition of combustible materials and is the leading cause of electrical fires.

Aging aircraft wiring is particularly problematic as many aircraft are seeing service far beyond their original design life. The ideal situation to maintaining properly functioning electrical wiring is to identify wire damage in its early stages, before small cracks, abrasions and imperfections can become major problem source and lead to electrical fire. However, a given aircraft will have many kilometers of wire that is literally built into the aircraft, making wire replacement both time consuming and expensive. Aside from aging effects, during flight, even new aircraft can experience wire damage due to combat or other factors. For these reasons, arc fault circuit breakers are beginning to see deployment in aircraft for the prevention of electrical fires during flight conditions.

The well known Paschen's law[1] defines the electrical breakdown characteristics of a gap as a function of gas type, gas pressure and gap distance. For air and gaps on the order of 1 mm, the relationship is approximately given by

$$V = (3pd + 1.35) \text{ kV}, \quad (1)$$

Where p is air pressure in atmospheres and d is gap distance in mm. So, for air at one atmosphere, a potential of about 4 kV is needed to establish an arc across a one millimeter gap. Higher voltages are required to establish an arc for greater gaps and greater pressures. However, once established, an arc may be sustained by a much lower voltage because it passes through a heated plasma conductive path where there are many free electrons available for conduction. For example, it is possible to generate an arc (a so-called *drawn arc*) at relatively low voltages by separating two energized conductors. In an environment involving a high level of vibration, there can be a repeated making and breaking of such contact and there can be a concurrent establishment and extinction of an arc.

Arc faults may be broadly characterized as either series or parallel. A series arc fault can occur when one of the current carrying paths in series with the load is unintentionally broken. A series arc fault can also occur when a series connection of two conductors is loose, intermittent or compromised by oxidation, dirt or other contaminants. A parallel arc fault occurs when two distinct conductors, having a different potential, are brought into close proximity or direct contact. Although an electrical arc is thought of as a light and heat producing event, it is possible to have low level, but undesirable, electrical leakages between conductors, that, if left unattended, can develop into higher current, high heat arcs. This is sometimes referred to as tracking.

3.0 ARC FAULT INTERRUPTION

The primary technologies that have been proposed for arc fault detection are based upon an electrical signal analysis of the power delivery conductors. These analysis techniques are based upon the recognition of a signature that is characteristic of the current, voltage or electromagnetic field associated with the chaotic behavior of an arcing fault[2,3,4,5,6]. Arc fault interrupt devices using electromagnetic signature based techniques are available for residential and commercial installations from several sources and are governed under Underwriters Laboratories' 1699 standard [7]. The recently published SAE standard AS-5692 [8] provides a qualification protocol for aviation arc fault circuit breakers that operate at 115 VAC, 400 Hz single phase. Much of the signature sensing technology that has been developed has been dependent upon the detection of the plasma arcing that occurs as the AC waveform makes zero crossings. Arc fault detection systems for DC systems are not as well developed.

4.0 PROBLEMS WITH STATUS QUO DEVICES

There are three significant problems associated with present day signature sensing techniques for the detection of arcing faults. First, the low level electrical leakages that can be precursors to arcing faults (since they may generate carbonized traces that reduce in resistance over time) will not generate the plasma discharge and associated chaotic behavior that are sensed by electromagnetic signature based techniques. That is, small problems must become big ones before they are detected.

A second problem with present day devices is the possible misdiagnosis of a fault condition, leading to nuisance tripping. Many electrical loads generate arcs as part of their normal operation. For example, a DC motor or synchronous AC motor may have brushes that arc continuously as they pass over a commutator. Many switches will exhibit arcing as they interrupt an inductive load. Some loads, such as incandescent light bulbs, will arc toward the end of their life as the filament fails. The inrush currents and/or reaction voltages that occur when a capacitive or inductive load is turned on or off can generate high frequency harmonics that are similar to those produced by arcing. So, there are acceptable arcs (eg: those that occur during normal operation), acceptable arc-like phenomenon (eg: inrush current to a switching power supply) and unacceptable arc faults such as those that result from damaged wiring or loose connections. While it is important to correctly identify the arc faults and to interrupt them, it is equally important not to trip a circuit breaker in the absence of a fault.

A third problem with electromagnetic signature analysis as a means of arc fault detection is the problem of fault location. Unless filtering is provided at the circuit breaker, arc faults that are on the source side of the circuit breaker can look like arc faults that are on the load side of the circuit breaker. This is sometimes referred to as the discrimination problem and is illustrated in Figure 1.

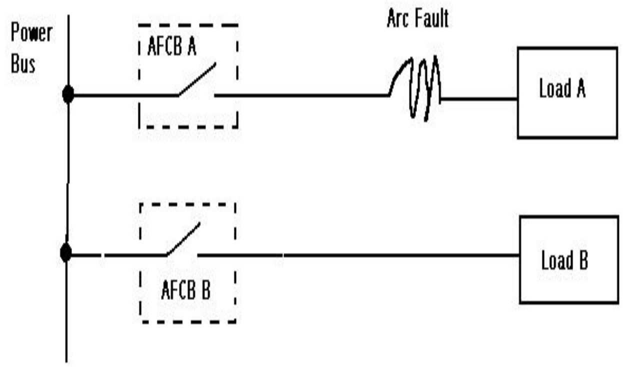

Figure 1 – The Discrimination Problem

Figure 1 depicts two loads that are sourced from the same power bus. Both loads, A and B, are connected to the power bus by an arc fault circuit breaker (AFCB) that uses signal analysis to detect the chaotic behavior that is characteristic of a sputtering arc fault. If a series arc fault, perhaps due to a broken conductor, occurs in the indicated location between AFCB A and Load A, its effect can be sensed at both arc fault interrupters. It is possible that AFCB B would respond first, opening its circuit breaker. However, this would not serve to interrupt the fault and would represent a nuisance trip. This problem is solved in terrestrial installations by adding filtering to the circuit breaker at the source side of each circuit breaker. Such filters generally include an inductive choke. However, this is generally an unacceptable solution in aviation applications due to size and weight constraints.

In statistical analyses, hypothesis tests are generally framed so as to have a binary outcome (accept or reject) and two types of errors are defined. Although for any experiment, the hypothesis may be phrased in different ways, in general terms, a Type 1 error is a false positive (a false alarm) while a Type 2 error is a false negative (an undetected event). By defining the level at which a given hypothesis is accepted, the probability of a Type 2 error can be made arbitrarily low, but this comes at the expense of a greater likelihood of a Type 1 error. In an aircraft, both types of errors can impact safety since a circuit breaker that opens in response to a false positive (a nuisance trip) can cause an in-flight emergency. For this reason, present day arc fault circuit breakers are set to a threshold so that they open in response to a substantial, sustained, no-doubt-about-it arcing fault while ignoring lower level faults or incipient faults. While this avoids the majority of nuisance trip events, it also means that an arc may be allowed to cause substantial damage and involve collateral conductors before interruption occurs.

5.0 ARC EXTINCTION ACROSS AN AIR GAP

The original premise of our investigation was to demonstrate an advantage of solid state circuit interruption over a mechanical breaker. It should be noted that an electrical arc is always associated with an air gap. A short circuit will not generate an arc, an open circuit can. A fundamental question to ask is, “what does it take to extinguish an arc without restrike”. To answer that question, the test configuration depicted in Figure 2 was constructed.

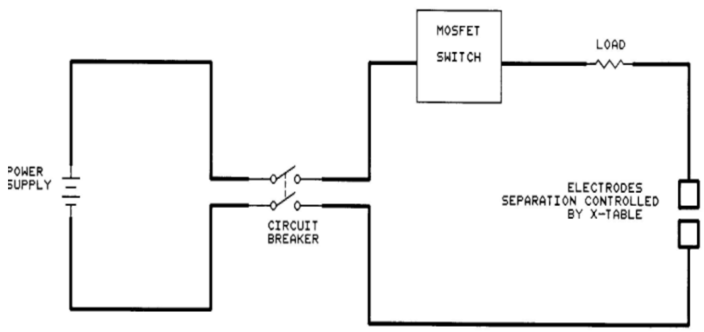

Figure 2 --- Test Bed Schematic for Series Arcing Experiments

A DC power supply was constructed with a series connection of lead acid batteries. Each battery had 22 mohm of source impedance and a 100 ampere short circuit current capacity. The circuit breaker depicted in Figure 2 is a manual breaker that is used to disconnect power during set-up. It was maintained in a closed position during all experiments. Under computer control (not depicted), an N channel MOSFET switch of type IRFPS40N60K was used to control DC current flow into the series circuit. A 2 KW adjustable load (“LOAD” in Figure 2) was used to limit the peak current flow. Two electrodes were used to establish a current through the circuit. At the beginning of each experiment, these electrodes were in electrical contact. The electrodes were then separated under computer control using an X-table to implement a controlled gap. This method allows the generation of a drawn arc.

5.1 FACTORS IMPACTING SERIES ARC TESTING

In a real world setting, a series arc can occur when a wire breaks, or when a connection is loose. Our tests were designed to replicate that event by the controlled simulation of the occurrence of a wire break. The test protocol is to place two copper electrodes in a touching position, establish an electrical current through those electrodes, then separate these electrodes by a known amount to establish an arc. The electrode control was established via an X table having stepper control of 0.0254 mm per step. Some of the variables which were examined were:

1. Electrode composition;
2. Electrode shape;
3. The appropriate electrode separation; and
4. Control of external environmental factors.

Arc extinction and persist tests using copper electrodes demonstrate some dependence upon the electrode composition. For example, the raw stock that was used was 6 gauge (4 mm diameter) copper wire obtained from a local building supply. Surprisingly, while we found good reproducibility of results from within lots, there was a great deal of variability (as much as 30%) in terms of arc persist and extinction times from one lot to another.

Initial experiments used two electrodes, both of which were machined to a 45 degree taper. We quickly found that establishing the initial alignment was difficult (two points had to be on-center and touching). Furthermore, during arcing, the anode quickly degrades. This meant that with a point anode, an initial gap of 1 mm could rapidly become a much larger gap, leading to inconsistent results. We found a solution in using a point on the cathode and a flat on the anode. During experiments, the anode flat experienced minimal degradation and the cathode point maintained its shape. A new set of electrodes was used for each experiment to avoid issues with copper anneal or oxide formation. The electrodes are depicted in Figure 3.

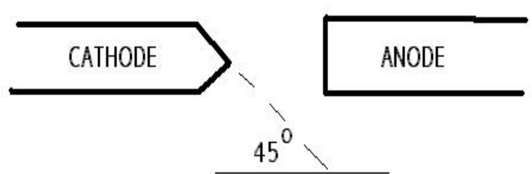

FIGURE 3 ---- The Electrode Shape

The amount by which the electrodes are separated influences the arc characteristics. The farther apart that the electrodes are separated, the harder it is to maintain an arc. In a practical setting, most series arcs are likely to take place with little separation, as broken wires or loose connectors are vibrated back and forth, making and breaking contact. A repeatable gap that is as small as possible is preferable, however, larger gaps are more forgiving to any initial deformations of electrodes and electrode mounts and give better test repeatability. As a compromise, we chose a gap of 1 mm. This represents 39 steps of the X table (each step represents a separation of 0.0254 mm).

Paschen's law as expressed in equation (1) governs the establishment of electrical arcs across an air gap. This law is a function of voltage and barometric pressure. Voltage was controlled in our experiments. Other environmental factors such as temperature and humidity were monitored but not controlled. Barometric pressure was neither monitored nor controlled. Since experiments were conducted in an enclosed laboratory that was tied into a central HVAC unit, ambient pressures were cycling from minute to minute as blowers engaged or turned off. However, we did not find the influences of temperature, humidity, or barometric pressure to be significant factors in series arc tests. One environmental factor that was of major impact was air flow across the gap. In experiments on arc extinction, we obtained quite variable results until we shielded the electrode gap. The shield that was used is a hollow pyrex tube of length 2.5 cm and inside diameter of 1.6 cm. The shield was affixed so that the electrodes were centered. The tube was removed and cleaned prior to each experiment.

5.2 SERIES TEST RESULTS

All series arcing tests made use of the X-Table electrode separation set-up depicted in Figure 4.

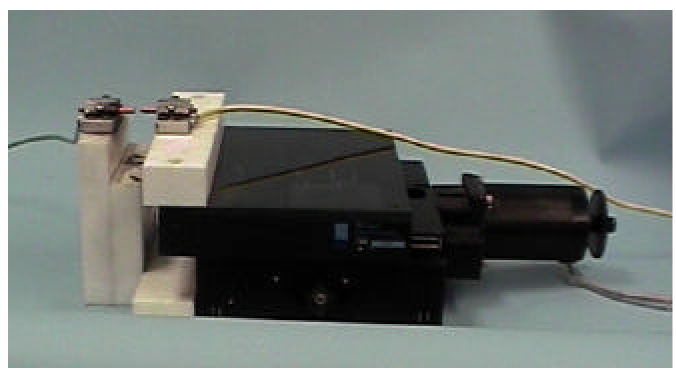

Figure 4 – X-Table Control of Electrodes

The test procedure was as follows:

1. With MOSFET switch off, place the electrodes in contact.

2. Under computer control, energize the MOSFET switch and immediately separate the electrodes to a distance of 1 mm by stepping the X table through 39 steps over a period of 0.4 seconds. This causes a drawn arc to occur across the electrode gap.

3. Allow the arc to persist for 1.0 seconds.

4. Turn off the MOSFET switch for a given amount of time (the notch time), then turn on the MOSFET switch.

5. Check to see if the arc restrikes. This is a binary datum. Either the arc restrikes (persists) or it extinguishes.

So the independent variables are applied voltage, applied current (established by the applied voltage and the series load resistor), and the notch time. The dependent variable is whether the arc extinguishes or persists after a notch is applied. A great deal of experimentation was used to narrow down the time gap parameters for which an arc would usually stay extinguished and for which an arc would usually restrike. Each datum in the following table represents many trials. We defined the minimum extinction time as that amount of off time that would prevent the arc from restriking in four out of five experiments. The maximum persist time was defined as the notch time for which an arc would restrike in four out of five experiments. It is important to note two things. First, our circuit had almost no inductance. Second, the MOSFET switch was controlled as hard on/hard off with a $t_{on} = t_{off} < 600$ nsec. What this means for the series arcing experiments is during the notch times, there is no current flowing between the electrodes. Any restrike occurs because of the persistence of the plasma across the electrode gap.

A summary of results from the series arcing tests is given in Table 1.

Open Circuit Voltage of 150 VDC

Arc Amps	Max. Persist Time	Min.Extinction Time
25 amp	4 µsec	10 µsec
29 amp	19 µsec	25 µsec

Open Circuit Voltage of 200 VDC

Arc Amps	Max. Persist Time	Min.Extinction Time
22 amp	19 µsec	28 µsec
32 amp	30 µsec	33 µsec

Open Circuit Voltage of 250 VDC

Arc Amps	Max. Persist Time	Min.Extinction Time
18 amp	45 µsec	51 µsec
25 amp	141 µsec	151 µsec

TABLE 1 --- Summary of Persist & Extinction Times on Batch Electrodes

The surprising thing about these results is the short time interval required to clear a fault. In all cases that were examined, an arc was extinguished without restrike within a time period of less than one tenth of the 2.5 msec period of a 400 cycle AC waveform and it suggests that by simply interrupting for a half cycle or less, an arc may be extinguished and will not restrike across the plasma path.

5.3 THE INFLUENCE OF INSULATION

In a field setting arcing is most damaging when it involves combustible materials. In particular, since wires are often deployed in wire bundles, a broken wire that produces an arc is likely to involve neighboring conductors as the arc heat ignites the insulation. This led us to consider the impact of insulation on the series arcing set-up. We applied a layer of 0.025 mm polyamide (Kapton®) tape around the conductors in a tube configuration and repeated the series arcing tests described above. The premise is that as the insulation burns it produces carbonized paths that will serve to expedite the rapid evolution of the arc as well as to serve as a path for arc restrike. What we found was that the energy release while drawing out the arc served to completely vaporize the insulating material. For this reason, a parallel arc test set-up was used for examining insulation effects.

6.0 PARALLEL ARCS ACROSS A CARBONIZED PATH

Parallel arcing experiments across a carbonized path were carried out using the test set-up depicted in Figure 5. Initial experiments used a 120 VDC source and a load of a 100 watt light bulb. The resistance labeled "Limit Resistor" is simply the 2 KW adjustable resistive load that was used in the series experiment and which is used to limit the current that is available to be delivered to a fault. Wire samples having the carbonized paths were prepared using the specifications in sections 56.4.2 and 56.4.3 in the Underwriters Laboratories 1699 standard[7]. The samples were all 16 gauge stranded wire with a polyvinyl chloride (PVC) jacket of thickness 1.3 mm. This is a so-called SPT-2, two conductor power cord that is used on most lamps in the U.S. This wire was used for three reasons. First, it is readily available. Second, this is the type of wire that is specified in the U.L. 1699 protocol set for preparing carbonized samples. Finally, in many respects a PVC insulation represents the worst case condition in terms of insulation combustion. PVC is a thermoplastic so it melts and flows when it gets hot, making it less likely to clear a fault, since the insulation material can flow back over the fault. In addition, PVC emits volatile fumes as it melts. In contrast, wire insulation materials such as Kapton® and Teflon are thermoset compounds and less likely to flow or outgas under high heat conditions.

Carbonized samples were inserted in series with the load as shown in Figure 5. If there is no leakage between the two conductors in the carbonized sample, then the load receives full power, and Ia = Ib. Both sides of one of the conductors in the carbonized sample are passed in the same direction through a current sense probe. If Ia = Ib, then there is no net magnetic flux captured by the probe and no sensed current signal. If, on the other hand, Ia > Ib, then this is indicative of a leakage current between the conductors in the carbonized sample and the amount of leakage current is Ia – Ib. The probe that was used was an HP 3114 Hall effect current probe that is rated for 50 amperes and 1 Msamples/sec.

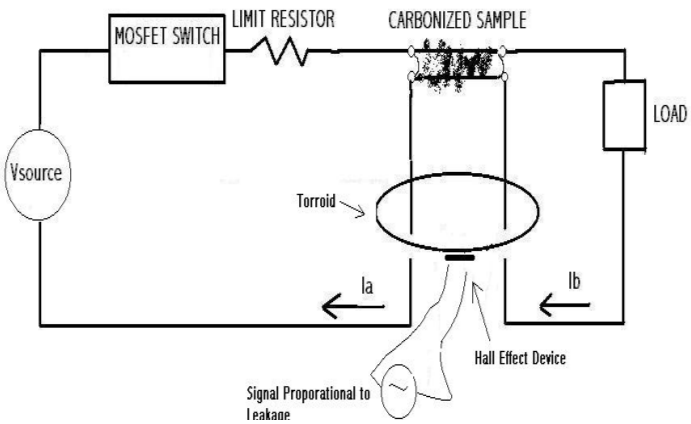

Figure 5 --- Test Bed Schematic for Parallel Arcing Experiments

A computer monitored the voltage from the current sensor. This gave a measure of the leakage across the carbonized sample. When the leakage level exceeded 0.3 A, this was determined to be an arc worthy of interruption. So, using the test set-up in Figure 5, when leakage occurred, it was rapidly sensed and a control action was taken. This defines the best case (immediate arc detection, immediate interruption) and allowed the characterization of fault management with various schemes.

It must be emphasized that our scheme for measuring leakage (and hence arcing phenomenon) using the Figure 5 topology is not suited to field implementations. In actual implementations, arc fault sensing would take place through more standard arc fault detection techniques such as electromagnetic signature matching. However, the Figure 5 scenario allows the examination of what is happening in real time and to implement controls without delays. This makes it possible to establish a best case scenario and to relax this by imposing delays that would be characteristic of an actual fault sensing device.

Our premise was that some level of power can always be provided to the load in spite of the occurrence of an arcing event. The carbonized samples were consumables, that is, each sample was used for only one test. Since the carbonization characteristic is highly variable, it was expected (and was experienced) that there would be great variability among samples. Some samples did not arc at all or immediately cleared when power was applied. In one set of experiments, 58 samples were prepared. These were divided into two groups. In the first group, full power was applied with no control. In the second group, power was controlled. When arcing was experienced, power was momentarily removed, then restored as in the testing protocol described below. The following results were obtained:

GROUP 1 (29 samples, uncontrolled):
- 10 samples – no smoke, no arcing (fault did not develop)
- 19 samples --- flamed, full arcing

GROUP 2 (29 samples, with control applied)
- 22 samples --- no smoke (fault did not develop) or only short term smoking. Visible arcing did not develop.
- 6 samples --- no visible arcing but smokes even after 25 seconds

For this testing, the test set-up was as in Figure 5, with applied voltage of 120 volts DC and limit resistor of 5.5 ohms. An interesting result was that with Group 1 (uncontrolled) when smoke developed, it always led to a runaway condition, that is, a high heat, visible arc. With the Group 2 samples, there was no runaway arcing with any of these samples. On some of these samples, there was light smoke after 25 seconds, so the carbonized path was still present but arcing was prevented from developing. Representative plots from the two cases are depicted in Figures 6 and 8.

In Figure 6 (representative of the uncontrolled Group 1 case), fault current is seen to vary between 0 and about 15 amps with a very chaotic appearance. Note that the limit resistor enforced the 15 ampere limit on fault current. The experiment was manually terminated a little more than 1 second after observing the runaway arcing. Note that a leakage current of 15 amperes across a 120 volt potential represents a fault power of 1.8 KW, all concentrated across a carbonized path. This is the kind of fault that very quickly involves adjacent conductors in a wire bundle and that can cause catastrophic damage in a very short order.

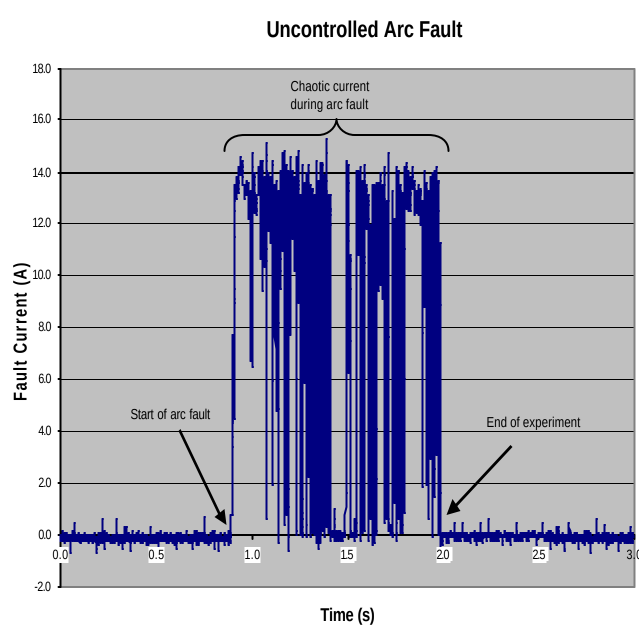

Figure 6 – Uncontrolled Arcing Across a Parallel Carbonized Path

Assuming perfect real time knowledge of the leakage across a carbonized path, a control algorithm was formulated as shown in Figure 7.

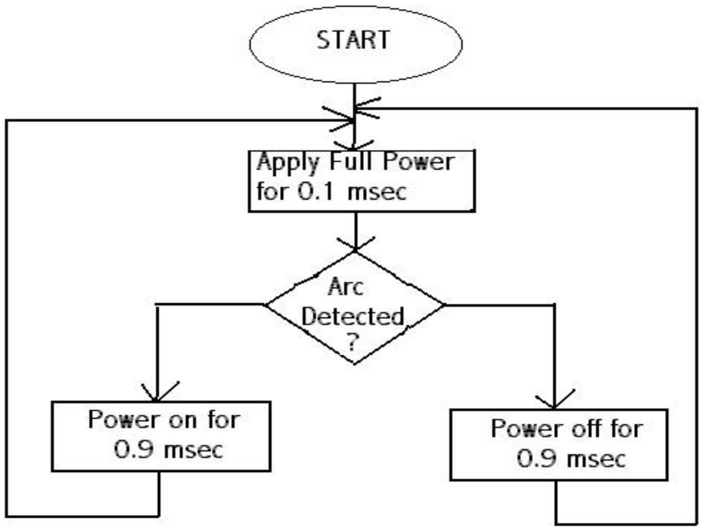

Figure 7 – Control Algorithm Assuming Perfect Knowledge of Arc

Figure 8 portrays the leakage current in a carbonized sample when the control algorithm of Figure 7 is used. From Figure 8 (which is representative of the Group 2 samples), it is seen that under control, the fault current never exceeded 3 amperes. This is one fifth of the amperage experienced in the uncontrolled situation (although it should be noted that even the uncontrolled situation had a current limit imposed by the limit resistor). Under control, the fault was observed to "clear itself". In other words, as in the testing protocol described above, the normal state is to be applying power. Power was removed for only short intervals to try to interrupt the arc. The fact that the arc current dropped to near zero is indicative that the fault path was removed, probably because it was "burned out". It should be noted that many of the controlled samples did smoke, indicating that insulation was being further damaged. But the result of this "damage" appears to be the removal of the carbonized fault paths as they burn out or clear. The main item of interest is that under control, a high heat destructive arc was not observed.

In the above experiments, the load that was used was a 100 watt light bulb. This load represented the load that might be in an aircraft, such as avionics or a fuel pump. By observing the light bulb during control experiments we noted some flicker in the light bulb but the bulb still received substantial power. In other words, in this simple experiment, some level of power was always delivered to the load in spite of the presence of a fault condition.

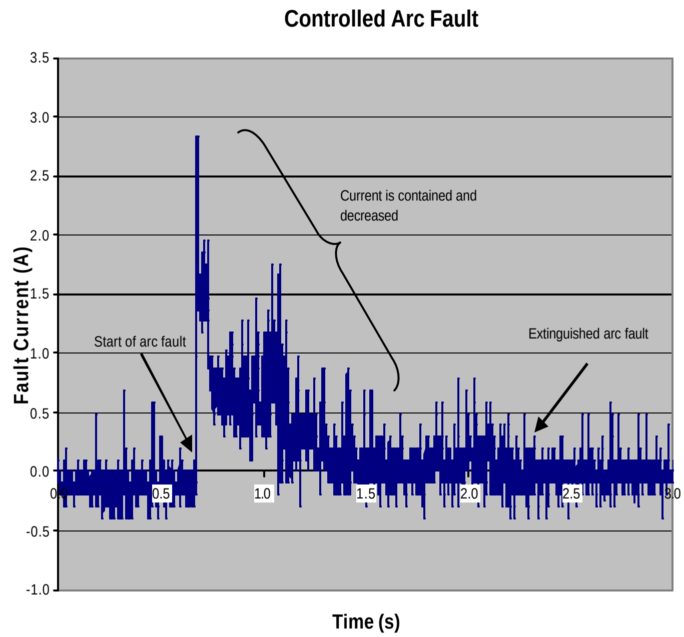

Figure 8 – Fault Current to a Carbonized Parallel Path Under Control *(Note that the current scale is different than that of Figure 6)*

6.1 CONTROL WITH ASSUMED DELAYS

The experiment described in the preceding section describes control actions taken when the controller has perfect knowledge of the fault. Perfect knowledge of the fault is possible because our test configuration allows us to measure the leakage current in real time. In practice, this is unrealistic as it is impossible to measure the leakage current directly. Instead, an estimation of fault current must be made from a remote location. The most common technique is to use electromagnetic signature analysis to identify the chaotic behavior that is characteristic of an arcing fault condition. This takes some time. For example, the SAE AS-5692[8] standard that governs arc fault circuit breakers, states that if arcing behavior is detected in eight half cycles (of 400 Hz AC) during any 100 msec interval, then the circuit breaker must trip. This suggests a required maximum fault detect time of 10 msec.

Accordingly, we modified the algorithm depicted in Figure 7 to incorporate the delays that are characteristic of remote arc fault detection algorithms. We considered two levels of sensitivity. First, we detect a fault with a normal level of sensitivity. This corresponds to a delay time of C1 seconds. That is, we simulate the delays that are inherent in practical fault detection technologies by incorporating a delay of C1 seconds after we detect a fault using the current imbalance sensor depicted in Figure 5. Again, our parallel test bed allows us to detect a fault in real time. In order to incorporate the realistic delays that are exhibited by practical remotely located arc detection technologies, we artificially introduced a delay between the time of arc detection and the time that we took a control action.

When a fault is sensed for the first time, power is removed for an amount of time, C2. C2 was chosen as a time that is sufficiently long to clear a fault but that would not result in an undue power interruption at the load. Then power was restored and checking resumed. This time, if a fault is detected, we delayed taking a control action for C3 seconds, where C3 was chosen to be less than C1. This reflects the fact that, since we already know that a fault was present, we want to use a more sensitive threshold. If a fault is detected, we remove power for an amount C4, which would nominally be chosen to be greater than C2. After all, if we detected a fault and it persists, we need to ensure extinction. At any time that a fault is detected, remove power, restore power and then if no fault is subsequently detected, the algorithm is reinitialized. The complete algorithm is depicted in Figure 9.

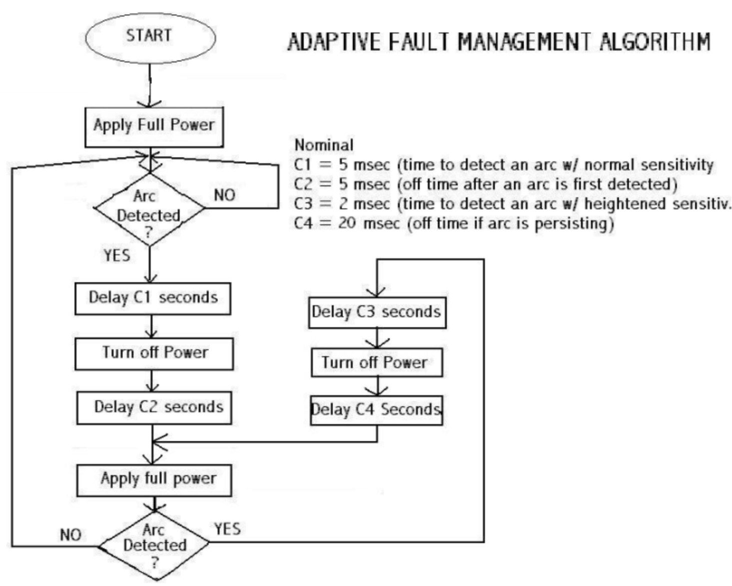

Figure 9 – Algorithm Assuming Delays that are Characteristic of Remote Arc Detection Technologies

Figure 10 depicts a control experiment using the adaptive algorithm of Figure 9. Again, the test figure is that depicted in Figure 8, where the load is a 100 watt light bulb. The applied power is 120 volts DC and the current is limited to 15 amperes. As seen in Figure 10, using the adaptive control, the fault current never exceeds 6 amperes even though the available current is 15 amperes. This was typical of the behaviors seen in all experiments. The fault current is seen to be somewhat chaotic but this is not so much due to the chaotic behavior of an arcing fault as it is to the fact that the MOSFET switch is being controlled to rapidly apply and remove power to the fault and load. The experiment started at time 16.0. As seen in Figure 10, the fault started to clear by about time 18.5 seconds and was largely cleared by 19.2 seconds. Complete arc extinction was deemed to occur at approximately 21 seconds.

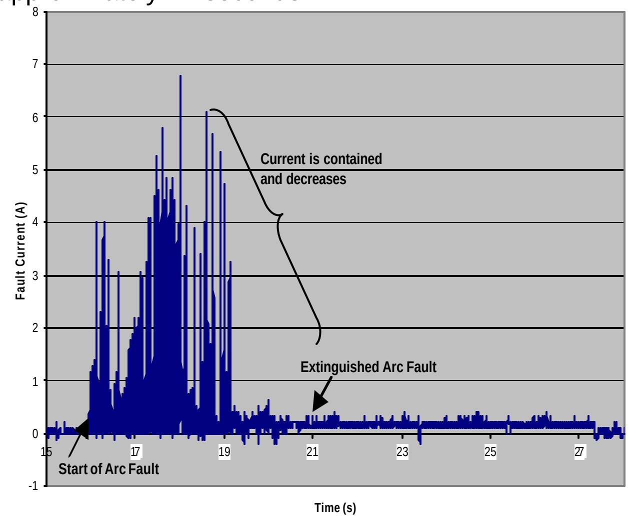

Figure 10 – Fault Current Under Adaptive Control and Assuming Realistic Delays

Figure 11 depicts the same experiment but shows both the fault current as well as the MOSFET gate control. A substantial amount of switching occurs between the start of the arc (time 16.0 seconds) to time 19.2. Then as the fault starts to clear, there is less switching. By about time 20.2 seconds, the control action goes to a fully on status. The momentary turn-off at times 23.2 and 23.9 are probably due to noise but might be due to a incipient arc. In either case, they are immediately reset and the load would experience a negligible reduction in power. At time 27.5 seconds, the experiment was terminated.

The gate control in Figure 11 gives an indication of how much power was delivered to the load (a 100 watt light bulb). As would be expected, the rapid on/off switching of the MOSFET gate that is depicted between time 16.5 seconds and 20.2 seconds, served to cause flickering and dimming in the light as the received power was switched on and off. However, after the fault cleared at time 20.2, the light was observed to maintain full brightness.

The plot in Figure 11 is representative of the behaviors obtained during testing with the adaptive algorithm of Figure 9. In many cases, a slight amount of smoke was observed to come from the carbonized path. Over time, the smoke stopped. In some cases, the fault would continue to smoke and the carbonized path would creep. That is, the process of carbonization appeared to be ongoing, even though there was not sufficient energy across the fault path to result in an arcing fault. Note that in these cases, the power delivered to the load (the light bulb) was highly discontinuous and the light bulb flickered a great deal. The implications of this are twofold. First, as described previously, the insulation on the wire samples was PVC which is a thermoplastic material. With an alternative insulation material such as polyimide, it is likely that the high temperatures necessary to pyrolize the insulation would not be met and arc creep could be avoided. This remains to be tested. Second, the high degree of control interruption, as observed through the dimmed and flickering light bulb load, might be so objectionable that the best control action would be to remove power permanently as this might be judged to be an uncontrollable fault.

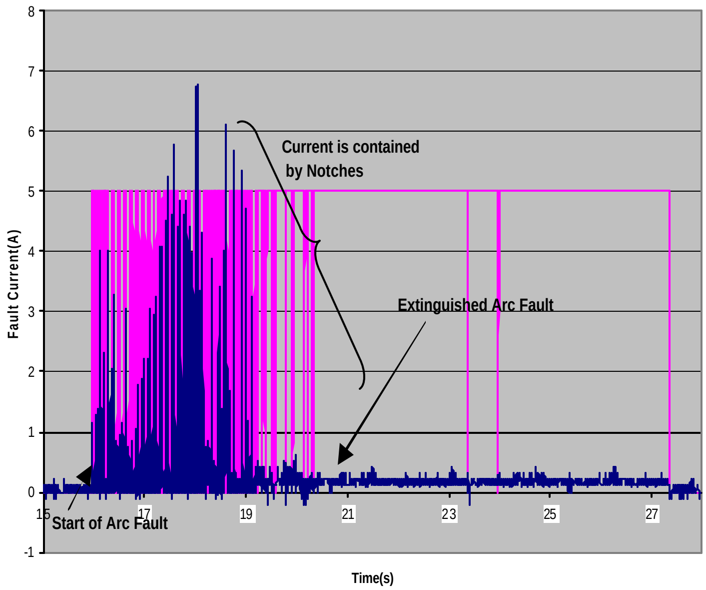

Figure 11 – Fault Current and Gate Signals for Adaptive Control

7.0 ARC FAULT MANAGEMENT WITH AC

As discussed in sections 5 and 6, initial experiments in series and parallel arc fault management were carried out using DC excitation. The reasons were threefold: availability, removal of phase as a consideration in timing experiments, and the fact that DC arcing is considered harder to manage than AC.

The premise that resets may be used to restore power to a system after a nuisance trip allows a higher degree of fault sensitivity. This premise will be true for AC or DC systems. However, delivering power to a load, even in the presence of a parallel arc fault is different for AC conditions than for DC. This point is illustrated by an examination of a parallel arcing situation as portrayed in Figure 12.

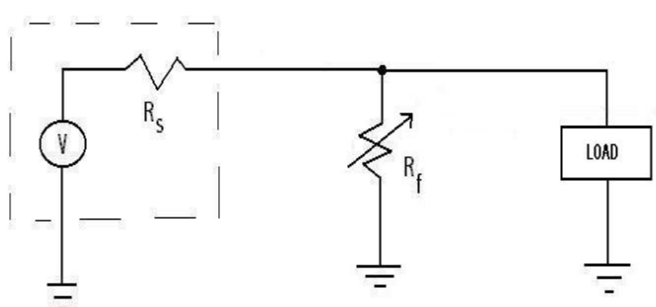

Figure 12 – The Parallel Arcing Case

In Figure 12, the parameter Rs represents all impedance in the wires, plus source impedance, plus any impedance contributed by the switching means (such as a MOSFET or a traditional circuit breaker). The box that is labeled "Load" may represent any general load having resistive, capacitive or inductive elements and may also include nonlinear elements. The fault resistance, Rf, is shown as being variable. This is because an arc fault is never a constant but will vary. In fact, the arc fault may be modeled as a resistance that is a nonlinear function of a number of variables:

$$R_f = f(V,E,G,C), \qquad (2)$$

where V is voltage, E is energy, G is geometry and C is the chemistry of the insulation. The dependence on voltage is well known (witness Paschen's law in equation (1)). Certainly, arcing cannot occur without a voltage potential and the greater potential, the more likely that an arcing event will occur and this results in a sharp reduction in the value of resistance. The energy across a fault is a means for retaining some memory of the immediate past occurrences at that fault location. As demonstrated by the series arcing tests described in Section 5, once struck, an arc can be drawn out over a gap. This is because the hot plasma serves as a low resistance path for electron flow. The plasma is generated when energy is expended into the fault. Geometry influences fault resistance because the fault may arise from multiple sources. For example, if the fault occurs because wire strands from broken conductors impinge upon one another, the resulting fault resistance will be quite different from the case where the fault occurs because of a carbonized path. Finally, chemistry plays a role through the composition of the wire and the insulating material and the outgasing during combustion..

An examination of Figure 12 makes clear how difficult it is to simultaneously furnish power to the load while preventing the fault from getting out of control. Clearly, fault R_f, is in parallel with the load! We anticipated some benefit from the AC case since as the voltage passes through zero, the arc is periodically extinguished and, as we discovered in the series experiments of section 5, it requires only a brief interruption of current flow to extinguish an arc across an air gap. We found that this was not the case when insulation was involved and that the AC case was harder to control than the DC case.

As described in Section 6, under DC conditions there were some circumstances under which an arc fault could be managed by controlling power into the arc and load. However, for the equivalent (in terms of applied voltage and current limit) AC case, we were unable to obtain a controllable arc while using the same control algorithm. There are two possible reasons for this result. First, at times, the applied voltage under RMS AC conditions exceeds the equivalent DC voltage by a factor of 1.414. That is, the peak voltage under AC conditions is greater than the RMS (or DC) value by the square root of two.

According to Paschen's thereom (eq. (1)), the arc strike voltage is proportional to the voltage magnitude, so it is reasonable that an arc would restrike under AC conditions when it might not be as likely to do so at the equivalent DC case. Of probably more significance, at times, the instantaneous power available to an arc under AC conditions will be double that of the DC case. So, even though the AC instantaneous arc power goes to zero at times, it also exceeds the RMS value by a factor of two at other times.

8.0 DISCUSSION

The inherently chaotic nature of an arcing fault makes its characterization difficult and the evaluation of different control and sensing algorithms cannot take place via either pure analysis or pure simulation. There is substantial variability from one fault condition to the next. Although it is possible to simulate open loop behavior, when a closed loop control is attempted, it changes the energy available to the arc which affects the way in which the arc ultimately develops. As such, control schemes must be tested empirically.

One advantage to using solid state fault interruption is that it allows power to be quickly restored to an electrical branch in the case of a nuisance trip so that nuisance trips can be better tolerated. *When nuisance trips can be better tolerated, this allows the use of a more sensitive arc fault sensing threshold.* This result is algorithm independent, that is, it is true regardless of the particular fault detection methodology. For example, suppose that with some known arc detection window, a given algorithm will identify a fault at a 99.99% significance level. Using a reset capability, this window might be set to a shorter period so that it would yield arc fault results at a 90% significance, implementing a brief power restoration after each interruption to confirm arc clearance and maintaining power if no further arcing is detected. This would result in both (1) a reduction in the average fault sense/interruption window and (2) a reduction in nuisance tripping.

The circumstances under which power to faulted electrical branches can be managed is still under investigation. The experiments reported in this paper used a resistive load but more testing must be carried out before we can claim that the results will generalize to loads having an arbitrary impedance characteristic. Furthermore, some loads, particularly avionics, have strict requirements on the quality of applied power and this may restrict the ways in which power may be delivered to a faulted electrical branch.

Allowing a reduced level of power to a faulted branch will never be appropriate for all applications within an aircraft. For example, arc fault protection is an asset for safeguarding the electrical branch that services the entertainment system in a commercial airliner, but trying to manage a fault or to deliver power to possibly faulted conductors for this system, represents an unnecessary risk. For an entertainment system branch, if an arcing fault is sensed, power should be removed and latched in an off condition until the electrical system can be evaluated after landing.

In contrast, there are certain life critical subsystems, such as radar, for which the risk of allowing a continuing low level of damage to wire insulation while trying to manage an arc is preferable to simply removing power from that life critical subsystem. For a military aircraft that sustains combat damage, having an extra five minutes of functioning radar may represent the difference between completing a mission or crashing the plane.

9.0 CONCLUSION

The application of solid state control to manage the power supplied to an arc fault demonstrates some potential for doing more than just a simple interruption upon fault detection. Experiments on arc extinction across an air gap demonstrate that a short duration interruption in power is sufficient to terminate an arc across an air gap without restrike upon power reapplication. When there is intervening insulation to furnish a carbonized path for arcing and to furnish fuel to the arc, a brief interruption is not sufficient to extinguish an arc but in some cases, the arc may be controlled through a managed application of power. In this regard, DC arcs were found to be more manageable than the equivalent power AC arcs.

For an aviation environment, when a mission-critical system is involved, the implications are clear – the best fault management strategy may not be to simply shut off power if a fault is sensed. Instead, it may be preferable to tolerate a reduced level of power, turning off power if a fault is sensed, then restoring power briefly to see if the fault has cleared. The reset feature has the advantage that the system will be more tolerant to a sensitive fault setpoint without nuisance trip issues. Furthermore, in some cases, if an arc is prevented from avalanching out of control, it will "burn itself out", essentially clearing the carbonized path that led to the arcing fault in the first place and allowing full power to be restored to the subsystem until the aircraft can safely land.

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REFERENCES

[1] M.A. Lieverman and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, New York, Wiley, 1994.

[2] J.H. Cooper and W.H. South, *Protective Relay Circuit for Detecting Arcing Faults on Low Voltage Spot Networks*, U.S. Patent 4,639,817, January 27, 1987.

[3] J.Boksinger and M. Parente, *Power Cable Arcing Fault Detection System*, U.S. Patent 5,047,724, September 10, 1991.

[4] C.W. Ragsdale, *Arc Detection System*, U.S. Patent 5,280,404, January 18, 1994.

[5] B.C. Beihoff, C.J. Tennies, F.S. Richards, W.K. O'Neal, *Frequency Selective Arc Detection*, U.S. Patent 5,185,684, February 9, 1993.

[6] B.B. Neiger, R.M. Bradley, J.N. Pearse and W.J. Rose, *Arc Fault Detector with Circuit Interrupter and Early Arc Fault Detection*, U.S. Patent 6,407,893 B1, June 18, 2002.

[7] Underwriters Laboratories, *UL 1699 – Standard for Arc-Fault Circuit Interrupters*, May, 2003.

[8] SAE, *AS-5692 – Arc Fault Circuit Breaker (AFCB), Aircraft, Trip Free Single Phase 115 VAC, 400 Hz – Constant Frequency*, Proposed draft December 12, 2003.

[9] R. Bartnikas and E.S. McMahon, *Engineering Dielectrics, Vol 1, Corona Measurement and Interpretation*, ASTM, STP 669, Philadelphia, 1979.

[10] P. Meckler, K.F. Eichhorn and W. Ho, "Detecting and Extinguishing of Arcs in Aircraft Electrical Systems", *Proc. 2001 Aerospace Congress*, SAE-2001-01-2657, Sept. 10-14, 2001.

[11] C. Furse and R. Haupt, "Down to the Wire", *IEEE Spectrum*, vol 38, no. 2, Feb. 2001, pp 35-39.

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