Arc Fault Circuit Breaker Development and Implementation

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ABSTRACT

About one and a half years ago, the Federal Aviation Administration (FAA), the Naval Air Systems Command (NAVAIRSYSCOM), and the Office of Naval Research (ONR) began a joint program to develop arc fault circuit breakers (AFCB). Since that time, there has been an unprecedented level of interest in the technology from all corners of the military and commercial aviation communities within the United States and internationally. This paper will provide an overview of the progress of AFCB development to date, and address newly emerging issues concerning the deployment, operation, and support, of AFCB's aboard operational aircraft.

PRESENT STATUS OF ARC FAULT CIRCUIT BREAKER PROGRAM

In December 1999, the Federal Aviation Administration (FAA), the Naval Air Systems Command (NAVAIR), and the Office of Naval Research (ONR) initiated a joint research and development program aimed at the development of arc fault circuit breakers (AFCBs) suitable for the protection of aircraft electrical wiring. The program began with contract awards to Eaton Aerospace Corporation and Hendry Telephone Company. Both companies were contracted to independently develop 115V, 400-Hz AFCBs. The goal was to add arc-fault protection to existing thermal protection in a package not to exceed an MS24571 size circuit breaker. Figures 1 and 2 are photographs of the Eaton and Hendry prototype AFCBs, respectively.

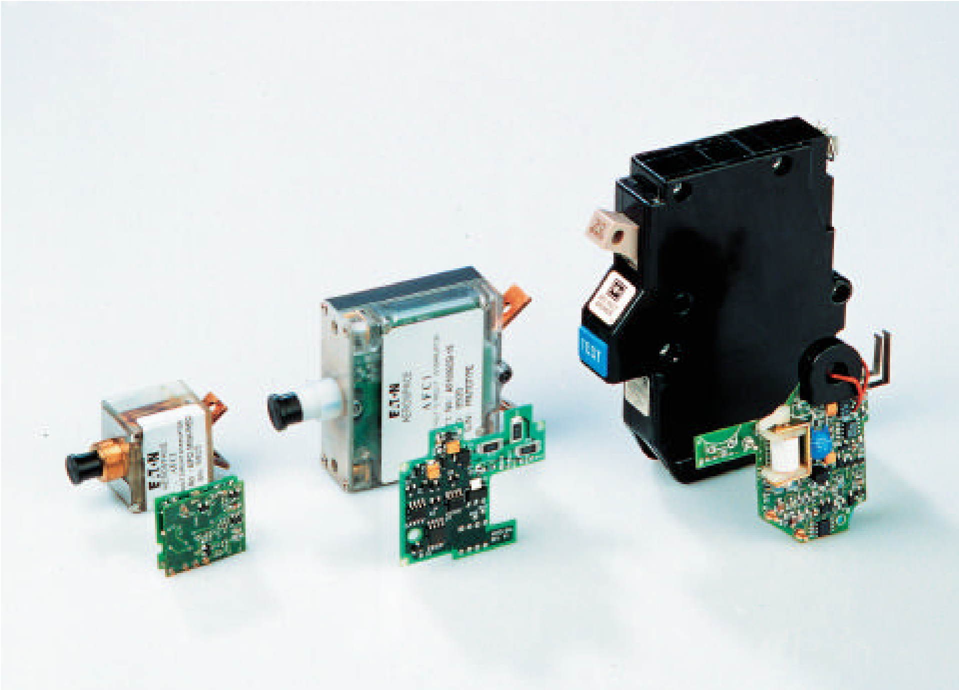

Figure 1. Eaton Aerospace Corporation Prototype AFCBs
(Two left breakers are 400-Hz prototypes. Right breaker is a 60-Hz residential breaker.)

Figure 2. Hendry Telephone Products/Texas Instruments Prototype 400-Hz AFCB

The AFCB contracts were developed around the vendor's proposals. The Eaton contract duration is 24 months and is scheduled for completion in December 2001. Hendry, which has since teamed with Texas Instruments, is operating under a 33-month contract and is scheduled for completion in September 2002. Each program will be complete upon delivery of 20 prototype AFCBs that will undergo flight-testing aboard FAA and NAVAIR aircraft.

Each vendor proposed various designs for detecting an arcing fault. Existing detecting methods developed for 60-Hz residential applications and 48 Vdc telephone systems had to be modified to work on aircraft 115/200 volt, 400-Hz electrical systems. AFCB detection algorithms must be sensitive enough to rapidly identify an arc condition and conversely, not so sensitive that the device trips on normal electrical transients associated with various load equipment current signatures and electrical power systems operations such as bus transfers. These unintended trips are referred to as nuisance trips.

Development of effective arc-fault detection algorithms is only one of two major developmental challenges. The other is packaging the arc-fault components along with the components for thermal overcurrent protection into a standard aircraft circuit breaker package. The difficulty posed by this requirement is best illustrated by example. Repackaging an average residential AFCB into an MS24571 package or smaller requires at least a 50% reduction in packaging volume. Exacerbating this challenge is the requirement to operate in an aircraft environment at temperature ranges between -20^{o} and $+71^{o}$C, altitudes of 0-45,000 feet, with vibration, electro-magnetic interference (EMI), and operating on electrical systems with many unusual electrical transients.

The need for an AFCB performance specification became evident early in the program. Consequently, the Society of Automotive Engineers (SAE) AE8B-1 Committee began drafting an AFCB performance specification for approval and publication by the SAE. The AE8B-1 Committee has met several times and anticipates completing the draft specification in October 2001.

ADVANTAGES AND DISADVANTAGES OF INSTALLING AFCBS INTO CIRCUITS

The use of AFCBs aboard aircraft represents a major, even revolutionary, shift in aircraft electrical system protection. Laboratory demonstrations show conclusively that thermal circuit breakers will not react to intermittent arcing conditions until the arcing develops into a serious hazardous condition. AFCBs provide a simple means for mitigating the effects of electrical arcing before the arc develops into a serious condition, preventing potentially catastrophic damage to electrical wire bundles. Second, AFCBs will limit the energy expended by the arc fault thereby reducing the potential to ignite surrounding materials (i.e., wire insulation, lint, cleaning fluids, etc.) and the associated smoke and fire that can occur. Third, a tripped AFCB will naturally identify on which wire the fault is located.

Active monitoring versus passive electro-thermal reaction to system faults separates AFCBs from their thermal counterparts. Thermal circuit breakers are designed and calibrated to trip at prescribed levels of current over a particular period of time. In the case of many arc faults, though the currents can be high, the durations are intermittent, and the thermal bimetallic element does not heat enough to interrupt the circuit until the arcing has become much more severe. On the other hand, an AFCB, whether digital or analog, actively monitors the current waveforms of the circuit being protected. The active monitoring is what enables the successful identification of an arc fault condition. Active monitoring also introduces new failure modes that must be properly considered in the design of the AFCB and its installation on aircraft.

One of these failure modes is nuisance tripping and/or common mode failure. There are several modes in which nuisance tripping may occur. The occurrence of an arc fault on one circuit must not trip AFCBs on other circuits. Additionally, the occurrence of a transient or other electrical system upset must not cause multiple AFCB trips or failures. Detection algorithms must be carefully designed to eliminate this potential problem. A variety of rigorous qualification tests are being incorporated into the SAE performance specification that will insure that the probability of nuisance tripping has been controlled to an acceptable level.

Present AFCB prototypes do not provide a means for monitoring the performance of the AFCB functional status. In other words, it may not be apparent to the operator that an AFCB circuit has failed. This is a second potential failure mode that must be considered. It is very important to note that all AFCB designs continue to provide thermal protection in the event of a failure of the AFCB portion of the breaker so existing levels of circuit protection are never compromised. However, an assumption that the AFCBs are functional may prove wrong. In the absence of an active status indication, some AFCB surveillance programs may be necessary to provide assurance that the AFCBs are fully functional.

Another potential concern is associated with the rate of AFCB tripping versus thermal circuit breakers. If an assumption is made that some level of arc faults presently exists and occurs undetected, then it follows that upon installation of AFCBs, the rate of AFCB trips will be greater than that of the thermal breakers being replaced. There is a catch-22 at work here. Obviously, everyone benefits through the timely identification and repair of potentially serious arc faults. However, this increase in the trip rate must be planned for in advance so suitable resources and processes are put in place to address these newly occurring trips efficiently.

Lastly, there is the problem of determining the location of the arc fault along the length of the circuit. AFCBs are designed to mitigate the wiring damage caused by electrical arcing. In some instances, the trip time is so fast that visible arcing damage is nearly nonexistent. This is compounded by some of the inherent weaknesses associated with visual inspection of wiring that has been identified in other programs. There is a strong need for the development of nondestructive technologies which can determine the location at which the arc fault occurred or determine with a very high degree of confidence that an arc fault did not occur, thus concluding that the AFCB nuisance tripped.

There are a variety of technologies that can potentially assist with this problem. Ideally, these technologies will be packaged in a small hand-held device with the ability to test the AFCB and determine the location of the arc fault in the circuit.

Some of the disadvantages of AFCB installation include not being able to identify where on the wire the fault occurred and the current lack of test equipment to verify if the AFCB protection is working. Various companies are developing tools to address these disadvantages.

IMPLEMENTING CONSIDERATIONS AND APPROACHES

Maximum arc fault protection can be achieved by the complete retrofit of existing thermal circuit breakers with arc fault-equipped breakers. This approach may not always be possible. Short of a complete replacement, what factors should be considered when retrofitting less than all of the thermal breakers with AFCBs?

There are many factors to consider when choosing how and where to implement AFCBs into aircraft. These factors must be considered together in some form of risk assessment that will point out which circuits are most susceptible to arcing and/or which have the highest potential hazard severity. At this point, for each circuit, it is essential to consider if an AFCB provides an adequate level of mitigation for the identified hazard. The collocation of critical subsystem wiring within the same wiring harness as the circuit being analyzed for AFCB installation must also be considered.

Incident reports and repair records can assist in determining the locations where wire problems are occurring most frequently. These can be categorized in terms of location and zone; was there a fire and/or smoke, etc.

Smoke and fire data can be collected through the review of incident reports. Incident reports provide a written account of the incident and the associated corrective actions. Some reports will include data such as type of aircraft, location of event, and corrective action; however, many times the data is incomplete or needs an expert on the aircraft wiring location and what equipment it is attached to identify the wires involved in the incident. This process can find the locations of the most frequently occurring incidences that should be considered for AFCB.

Additionally, areas of the aircraft that are not environmentally controlled are possible locations for arcing incidences. Severe weather and moisture prone (SWAMP) areas should be evaluated to determine if these wires are candidates for arcing. SWAMP areas include leading edge flaps, trailing edge flaps, wheel wells, and unpressurized compartments. SWAMP areas and areas subject to high temperature and vibration may be more susceptible to the occurrence of arc faults. Other areas should also be considered, including high-maintenance areas such as avionics bays, passenger cabins, and other environmentally controlled areas.

The criticality of the circuit under evaluation is another consideration. Not much consideration is needed for nonflight essential equipment, since the avoidance of arc faults outweighs the need to have the equipment operational. However, for flight critical systems, what happens if the equipment is lost to a circuit breaker trip, especially a common mode nuisance trip. Obviously, redundancy is included in aircraft systems but disabling systems due to an arc fault and the need to have flight essential equipment operational is an important consideration.

What equipment should stay energized even in the event of a possible arcing condition? Most flight essential equipment is on the emergency bus feed from a 24-volt battery. Equipment on this bus should have some review, since this is usually the last chance to keep the aircraft flying. Flight critical equipment on other electrical systems (115V, 400-Hz, and 28Vdc systems) deserves review, too. While a 115V/400-Hz fuel pump may be vital to operating the aircraft, the fuel system may have enough fuel pump redundancy to keep it off until after landing if an AFCB tripped during flight. However, if the AFCB trips on the primary longitudinal trim motor, is there redundancy to operate the aircraft safely? The functional criticality of each circuit must be considered when evaluating circuits for AFCB installation.

TROUBLESHOOTING ARCS AND NUISANCE TRIPS

The trade between detecting arcs and nuisance tripping the AFCB is a classic engineering trade-off. The need to detect arcs is critical to the prevention of potential fire and smoke conditions. However, the difference can be hard to distinguish. Many electronic load currents are similar to arc fault currents. Maintenance personnel need to know if either the AFCB is working or where the arc occurred. The development of the AFCB is only one in a series of developments that must occur to make AFCB viable in the commercial and military aircraft industry. At least three developments are presently being pursued. The first is an AFCB tester that can be internal or clipped onto the AFCB and test the electronics in the AFCB. This is being worked on by the manufactures of AFCBs. The second development is a device for the maintainer to locate where the arc occurred so the wire can be rapidly repaired. Several manufacturers have proposed various concepts to find where the arc occurred. This is challenging because little work has been done in wire damage characteristics after an AFCB trip. The third development is an onboard diagnostic for wiring systems to further reduce downtime of aircraft. Various vendors are also pursuing this development.

FUTURE ARC FAULT PROTECTION

AFCBs improve upon thermal circuit breakers by adding electronic arc fault sensing. The FAA-NAVAIR program is aimed at the development of 115V, 400-Hz circuit breakers in the 1A to 25A range. Although this is a major step forward, there are additional requirements yet to be addressed. Additional improvements that would greatly improve the utility of the devices are being considered. Some of these will be discussed below. Incorporation of arc-fault detection into other circuit protective devices and into components also requires consideration.

Arc-fault detection can be incorporated into other circuit protection. These include three-phase 115/200 volt breakers; 115V, 400 Hz, 25-50 amp circuit breakers; 28Vdc, 1-50 amps; ac and dc equipment contactors/bus tie contactors; and ac and dc generator control units. Integration of arc fault detection in load equipment may also prove feasible.

Miniaturized AFCBS

The packaging goal of the FAA-NAVAIR program was a circuit breaker that would not exceed the size of an MS24571 thermal circuit breaker. This is a relatively large aircraft circuit breaker and an uncommon size not frequently used. However, at the time the project began, the MS24571 package appeared to be an ambitious goal. A number of AFCB developers have exceeded this goal by a good margin. Smaller package sizes will allow for the easy swapping of current thermal circuit breakers with AFCBs.

Nevertheless, even smaller AFCBs are required, especially for military aircraft. Military aircraft commonly use MS3320 size circuit breakers. The breakers are packed tightly into circuit breaker boxes leaving little or no room for growth in the package size. Development of MS3320 AFCBs is, therefore, very important to the military. The Air Force is currently exploring options to develop 115V/400-Hz AFCBs in the MS3320 configuration.

Commercial transport aircraft also use a fairly large number of MS3320 size circuit breakers. Unlike military aircraft, commercial aircraft have varying degrees of additional room in the circuit breaker panels, easing the requirement for an MS3320 package. However, miniaturization of the AFCB can potentially create free space. This free space is a must if additional features are to be integrated into the AFCB designs.

28Vdc AFCBs

Although development of 115V/400-Hz AFCBs is a major step forward in circuit protection, there are still a large number of 28Vdc circuits aboard transport category aircraft that are susceptible to arc faults. Smaller aircraft have an even higher percentage of 28Vdc circuits than transport category aircraft. Navy data indicates that nearly one-third of incidents involving the wire on its aircraft are on 28Vdc circuits. Laboratory testing confirms that 28Vdc arcing can occur quite readily, resulting in arcing of significant energy and temperatures. Consequently, development of 28Vdc AFCBs is an important requirement for military and commercial aircraft in all categories.

The FAA and NAVAIR are currently establishing the performance requirements for an R&D program to develop these devices. Extensive knowledge and experience has been gained through the 115V/400-Hz program that will benefit 28Vdc development. However, a great deal of work must be done to determine how dc arcing characteristics differ from ac. The effect of the lower voltage must also be understood.

Extensive data collection of ac power and load characteristics was conducted during the 115V/400-Hz development process. In fact, this effort continues. Similar efforts must be conducted for 28Vdc power and load characteristics. This data is required for the successful development of effective dc algorithms that will be resistant to nuisance tripping. The data is also necessary to develop performance standards and test methods.

Three-Phase AFCBs

The development of three-phase AFCB ranging from 5-50 amps is required to protect the wiring feeding the three-phase equipment. The development differs from the single-phase development because of the detection of three-phase arc fault and three-phase to ground arc fault. Chafing and water dripping into cracks in the insulation cause the arcing faults. The need to protect three-phase motor windings from arcing as well as arcing in three-phase power supplies would be an added protection for the aircraft.

Solid-State AFCBs

Solid-state circuit breakers (SSCB) are fast switching metal oxide semiconductor field effect transistors (MOSFETS) programmed to emulate a circuit breaker time current curve. These devices are presently used in various applications including F-22, C-130J aircraft, the Space Shuttle, and the Abrams tank. The SSCB offers many switching and diagnostic features that are presently not available in conventional thermal circuit breakers. These include switching in 50 microseconds, remote control switching, known status of the breaker, and trip indication. Incorporating arc-fault detection in the SSCB will enhance wire protection. The ability to switch fast will reduce the arc energy in areas with fuel vapors and atomized hydraulic fluid, though they may not be fast enough to prevent an ignition. Presently, SSCBs are only used in new designs, as the present packaging does not allow easy retrofit in existing applications. The small leakage current through the turned-off MOSFETS needs to be addressed from a maintenance personnel safety perspective as the currents grow from 1-25 amps up to 50 amps. The mechanical AFCB will isolate the feeder to equipment.

Advanced Diagnostic and Protection Features

Built in diagnostics (BIT) for the circuit breaker can also improve the electrical systems reliability. The use of self-test and self-monitoring is used routinely in avionics to help troubleshoot and maintain this equipment. Additional diagnostics for troubleshooting wire faults, such as Time Domain Reflectometry (TDR) may possibly be incorporated into future circuit protection. In the future, it may also be useful to record electrical waveforms for operation, maintenance, and accident investigations. Since the circuit breakers have electronics sampling the waveforms for arc detection, this information could be communicated to the aircraft flight data recorders for later playback. The promising concept of power management of electrical distribution systems could become reality through the incorporation of electronics into existing circuit breaker packages.

Circuit Breaker Coordination

Incorporating the arc detection algorithm in many of these devices may prove easier than making the systems work together or coordinate. The idea of coordinating the devices is a known concept and is currently designed into thermal circuit breakers. However, getting arc-fault detection to coordinate is a challenge. It will be incumbent upon the electrical aviation community to work with the SAE to develop a specification for coordination of electrical devices.

AFCB SPECIFICATION DEVELOPMENT

The need for an AFCB performance specification became evident early in the program. A high degree of interest in the development of the specification was expressed from all corners of the aviation community. The effort to develop the specification is being managed by the Society of Automotive Engineers, SAE-8B1 - Protective Devices Subcommittee. Several meetings have been held to date and a final draft of the specification will be submitted to the SAE in October.

Development of the specification requires combining existing thermal circuit breaker requirements together with new requirements for the arc fault portion of the AFCB. In addition, portions of MIL-PRF-83383 (Remote Control Circuit Breakers), which address the electronic components, will be incorporated into the AFCB specification.

To accomplish the development of the specification, two groups were established. The first group is combining all thermal requirements and electronics requirements together. The second group is establishing the arc-fault performance requirements and test methods. Development of arc-fault performance requirements has proven to be difficult. Progress has been made and current efforts are focusing on two arc fault test requirements: the Guillotine Test and a Wet Arc Fault Test. Other test methods for evaluating nuisance tripping, crosstalk susceptibility, feedback susceptibility, and others are being fine-tuned.

Copies of the draft specification are available for review on the SAE web site (www.sae.org), AE8B-1 Subcommittee page.

CONCLUDING REMARKS

AFCB development continues to progress quite rapidly. Over the next 12 months much more technical guidance will be developed that will clarify and guide all parties with an interest in AFCBs. Flight-testing will accelerate and produce a substantial number of flight hours and in-service experience. It is expected that operators, civilian and military, and aircraft manufacturers will begin installing AFCBs on a limited basis.

Research and development in arc-fault protection and troubleshooting technologies will continue to grow. Development of 28V and three-phase AFCBs will begin. Efforts to miniaturize AFCB packaging will also begin. Development of effective and efficient tools for AFCB troubleshooting will also be developed. Incorporation of arc detection algorithms and self-diagnostics throughout the aircraft's electrical system will allow users and maintainers to mitigate the electrical fire risk, diagnose where the event occurred, and fix the problem. This will provide increased safety and reliability for the aviation community.

The development and use of AFCBs and other technologies will continue to improve the safety of aircraft electrical systems as well as electrical systems in other modes of transportation and daily life.