Arc Fault Circuit Interruption Requirements for Aircraft Applications

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Abstract

Arc Fault Circuit Interrupting (AFCI) technology has been proposed as a means to improve aircraft wiring system safety. Arc Fault Circuit Breakers that provide supplemental protection against arc fault conditions in addition to the thermal overload protection provided by present generation circuit breakers are being developed, and prototypes have undergone flight-testing.

Although AFCI technology has been in-service in many household applications in the United States for a number of years, the challenges associated with adapting this technology to operate in aircraft electrical systems are significant. Complicating factors include; higher and variable AC line frequencies, the need for DC protection, and lack of ground return wires required for GFI type protection used in most household AFCI technologies.

Whereas households in the US operate at 120 VAC, 60 Hz, aircraft electrical systems operate at 115 VAC, 400 Hz. Also, aircraft electrical systems incorporate both single and three-phase circuits. In addition to AC power, aircraft electrical systems also utilize 28 VDC power. Furthermore, aircraft OEMs have begun to incorporate 270 VDC power and variable frequency power into aircraft electrical systems, with frequency ranges from 200 to 800 Hz. AFCI detection algorithms that rely on the frequency characteristics of a waveform may be affected by aerospace variable frequency systems, complicating the design of arc fault technology.

In total, it is readily apparent that the aircraft electrical system presents a much more complex engineering challenge for arc fault technology than the household application. Fortunately, a significant amount of development work has been accomplished that leads us to believe these challenges can be overcome.

This paper will address the methods for determining and distinguishing between arcing characteristics and normal steady state and transient load conditions on aircraft, and the requirements of arc fault detection algorithms to address these conditions. The paper will discuss methods being implemented to provide robust circuit protection against arc fault conditions on aircraft and the desired product performance attributes of arc fault circuit breakers.

Arc Fault Circuit Interruption Requirements for Aircraft Applications

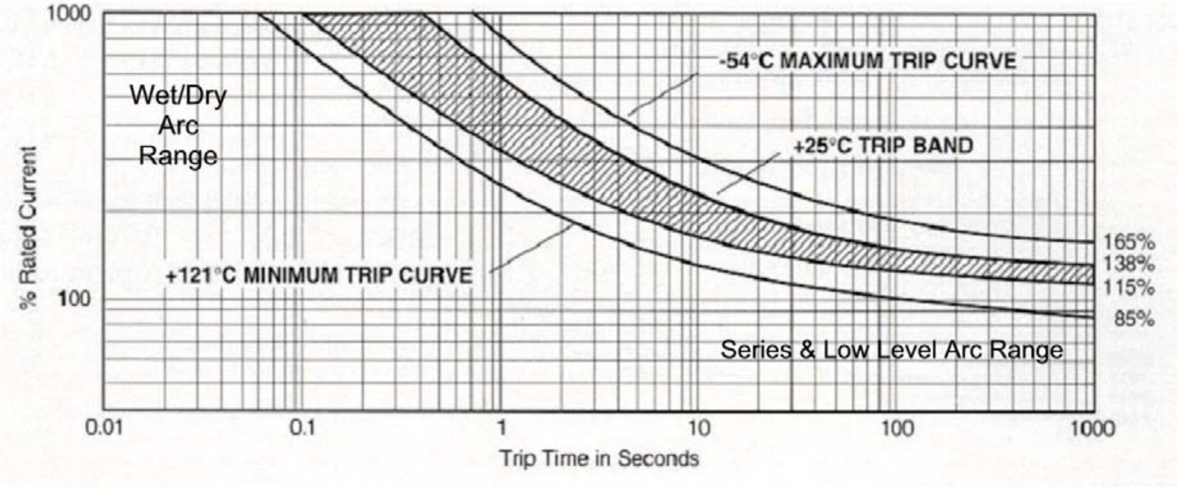
The issue of aircraft wiring safety has received widespread attention in recent years, highlighted by the unfortunate TWA 800 and Swissair 111 tragedies. As a result of these incidents and other concerns, the issue of wiring safety has been taken up by OEMs, regulatory agencies, the military, and is being addressed as part of the Aging Transport Systems Rulemaking Advisory Committee (ATSRAC).

According to industry sources, there is at least one “smoke-in-the-cockpit” incident per week in the United States on commercial aircraft. These can result in unscheduled landings and compromise aircraft safety. The military also has extensive documentation of arcing issues affecting its fleet of planes. Many of these smoke incidents as well as numerous unseen conditions in cargo holds and electronics bays are the result of wiring faults.

As a result of these incidents, a number of recommendations have been made to improve aircraft wiring safety. Included among these is the development of arc fault circuit breakers for enhanced wiring system protection.

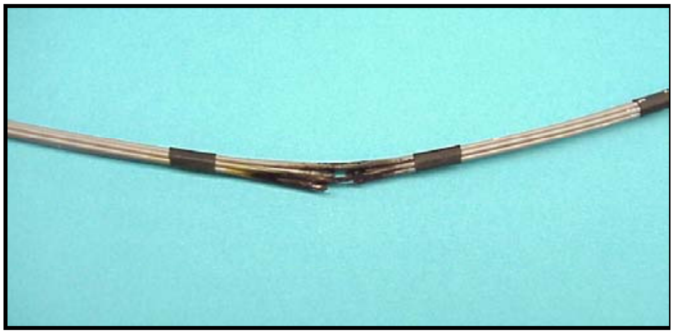
Wiring Safety

Aircraft wiring safety is not a new issue. Thermal circuit breakers were originally developed to protect the wire insulation on aircraft from damage due to overheating conditions caused by excessive over-current conditions. These devices have performed admirably for over 50 years. However, there are other conditions and factors (outlined below) that can damage aircraft wiring. These conditions can manifest themselves in arcing events that cannot be protected solely by thermal devices since the arcing currents do not reach the thresholds for the thermal circuit breaker curves [see graph below].



Typical Time-Current Thermal Overload Curve Showing Arcing Ranges

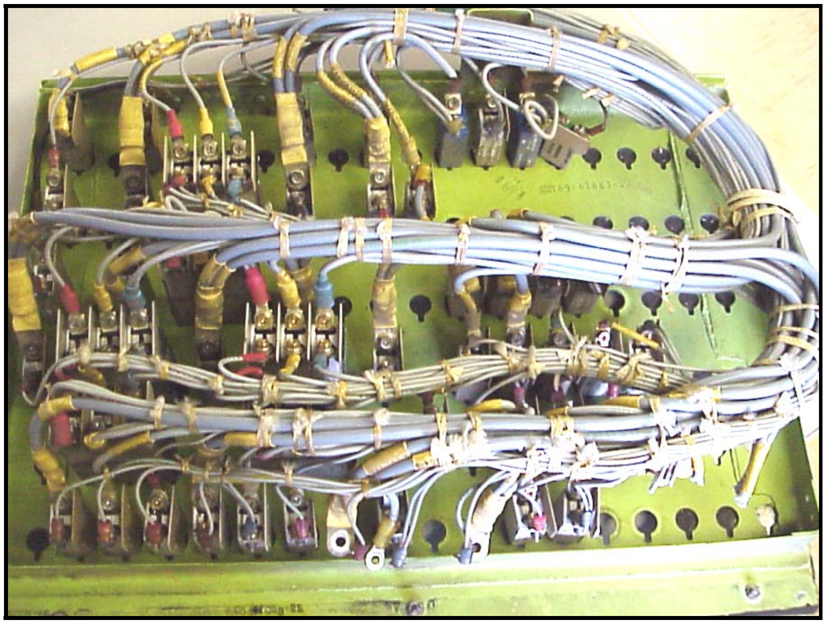
Aromatic polyimide wire insulation material was identified in the 1980s as being susceptible to arc tracking under certain conditions, and as a result was removed from use on most new-production aircraft. However, there are still many aircraft in service utilizing this type of wire insulation in some applications. Other application conditions relating to aging of wire insulation, environmental factors, chemical exposure, location of wiring bundles, and maintenance procedures also contribute to create potential safety conditions that can affect any type of aircraft wiring, whether on commercial or military aircraft. The photograph on the following page vividly shows the extent of damage that can be caused by arcing events. These conditions require a supplemental protection means to improve the overall level of aircraft wiring safety.



Lab Tested Wire Bundle (Wet Arc Test – No Arc Protection)

A relatively new technology – arc fault circuit interruption (AFCI) technology – has been developed to provide this supplemental protection. AFCI technology monitors the electrical circuit for arcing events that are indicative of potentially unsafe wiring conditions that could result in fires or loss of electrical circuit functionality. When coupled with an interruption mechanism, AFCI technology can be utilized to enhance aircraft wiring safety.

Ideally, all circuits on an aircraft ought to be protected with AFCI technology to ensure complete system integrity. Wire bundles on aircraft typically contain wires from many different circuits bundled together – sometime as few as three or four to well over 50 wires in a bundle. Wires for separate circuits are closely coupled and wire bundles are often routed adjacent to each other, resulting in a condition where a catastrophic fault of one wire could damage or impair multiple circuits in common or adjacent wire bundles. Thus, one unprotected circuit could compromise an entire wire bundle(s) of protected circuits.



Boeing 727 Circuit Breaker Panel

Challenges Associated with Arc Fault Circuit Breakers

Arc Fault Circuit Interrupter (AFCI) technology was originally developed for household applications in the 1990s, and has been proposed to improve aircraft wiring safety via retrofit on in-service aircraft and installation in new-production aircraft. Arc fault circuit breakers would replace traditional thermal circuit breakers, providing a dual-function device that augments the traditional over-current protection with electronic arc fault protection packaged in one circuit breaker device. This arc fault circuit breaker would only be slightly larger than today's devices, able to be retrofit into present aircraft circuit breaker panels and installed on new production aircraft. AFCI technology can also be incorporated into solid state power controllers (SSPC's) or remote power controllers (RPC's) for applications on new aircraft that utilize these devices.

Although AFCI technology has been in-service in many household applications in the United States for a few years, the challenges associated with adapting this technology to operate in aircraft electrical systems are significant. Complicating factors include higher and variable AC line frequencies, the need for DC protection, and lack of ground return wires required for GFI type protection used in most household AFCI technologies. Aircraft electrical systems also present a harsh EMI environment not found in the household application.

Whereas households in the US operate at 120 VAC, 60 Hz, aircraft electrical systems operate at 115 VAC, 400 Hz. Aircraft electrical systems also incorporate both single and three-phase circuits. In addition to AC power, aircraft electrical systems also utilize 28 VDC power. Furthermore, aircraft OEMs have begun to incorporate 270 VDC power and variable frequency power into aircraft electrical systems, with frequency ranges from 200 to 800 Hz. AFCI detection algorithms that rely on the frequency characteristics of a waveform may be affected by aerospace variable frequency systems, complicating the design of arc fault technology.

There are also marked differences in the power quality on aircraft platforms [Boeing 737-Classic compared with Boeing 777] and between manufacturers [Boeing compared with McDonnell Douglas compared with Airbus], and power quality has improved as electrical system design has improved and matured on newer generation aircraft. Differences in electrical system design between aircraft platforms can also greatly affect device performance.

In total, it is readily apparent that the aircraft electrical system presents a much more complex engineering challenge for arc fault technology than the household application. Fortunately, a significant amount of development work has been accomplished that has demonstrated that these challenges can be overcome.

Identifying Undesirable Arcing Conditions

There are a number of undesirable arcing conditions that have been identified that the arc fault detection algorithm should be required to protect against. These arcing conditions can be manifested in arcing between parallel conductors, to ground, or in series along the conductor. To demonstrate the capability of an AFCI algorithm to protect against these potentially dangerous conditions, test procedures have been developed that mimic these aircraft and wiring conditions. These include guillotine, wet arc (salt water drip), loose terminal, and carbonized path tests.

In addition to satisfying the test requirements defined below, it is essential that the detection and threshold levels be such that the maximum feasible levels of protection can be provided without resulting in nuisance trips or false indications that unnecessarily disable aircraft electrical circuits. Otherwise, the AFCI functionality is merely a redundant version of protection that does not provide enhanced supplemental protection capability. [This argument was lodged against first generation household AFCI circuit breakers when they were initially introduced.]

The tests that have been identified to define undesired arcing conditions are outlined below.

Guillotine or Point Contact Test.

The guillotine test simulates an arc fault condition between parallel conductors. This represents a condition where the insulation of a wire has been severed or chafed and an intermittent parallel path to ground through an arc has been created resulting in the discharge of a significant amount of energy, capable of igniting adjacent combustible material and/or cutting through adjacent unaffected wires in a bundle. Guillotine, or point contact testing, can be conducted effectively at phase-to-phase voltages as well. This test was developed specifically for arc fault circuit breakers. It is however, based loosely on a dry arc test method used for the testing and qualification of wire insulation material. The test schematic is shown below.

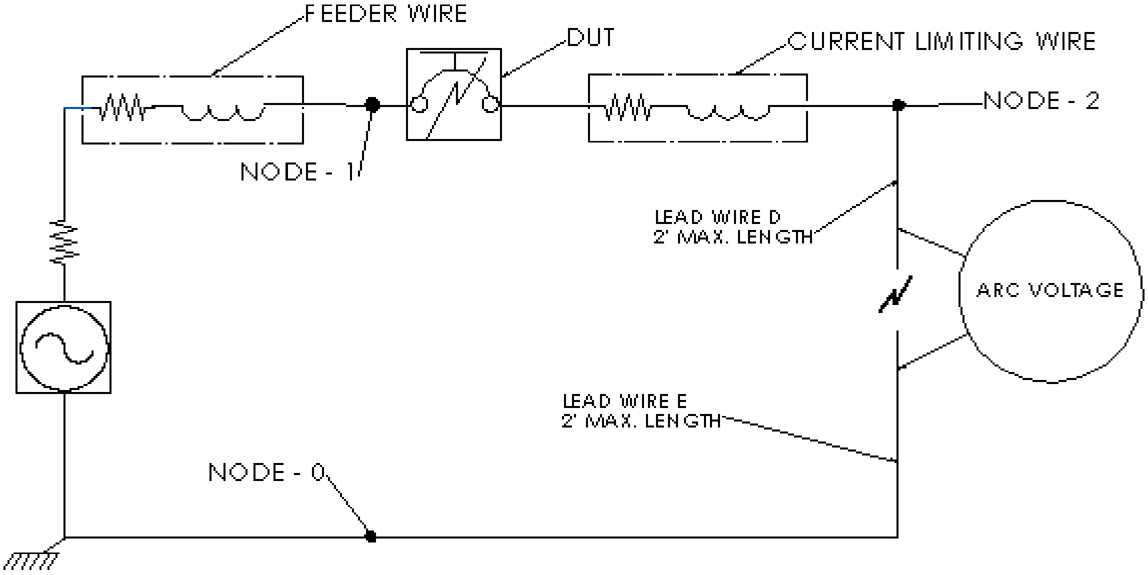


Figure 1

Wet Arc or Salt Water Drip Test.

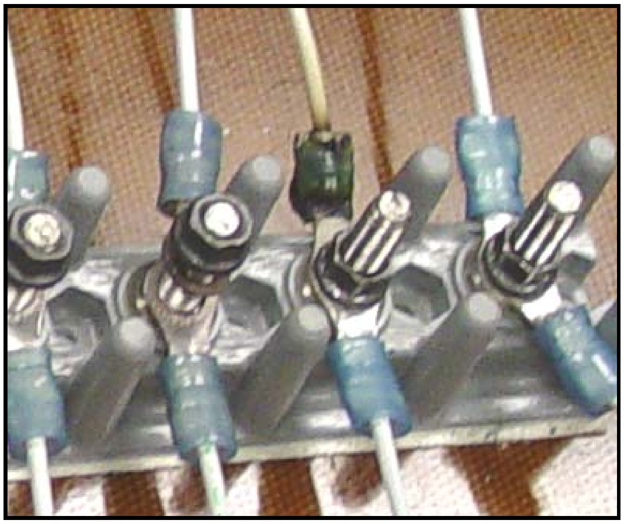
The wet arc (salt water drip) test simulates a condition where wire insulation has been compromised by some means, such as chafing, abrasion, tool marks, or cracking during the natural aging process. The salt water is then used to bridge the gap between two exposed conductors at different potentials simulating the condensation of water carrying contaminants that can occur in an airplane. This test is most commonly performed with conductors at phase-to-phase voltage and with very little resistance in the fault circuit. However, it lends itself to phase-to-ground and higher impedance test setups as well. The wet arc test was originally developed for testing and qualification of wire insulation material.

Low level Arcing (<10 Amps) Before Flashover

High Level Arcing (>100 Amps) After Flashover

Loose Terminal Test.

A loose terminal test was developed to simulate loose connections in the electrical system. These loose connections can occur on terminals to connectors, circuit breakers, relays, and other wiring devices. The arcing from loose terminal conditions has been demonstrated to result in damage not only to the to the pin or lug and associated wiring insulation, but also the wiring device itself, including ignition of adjacent material. Testing has demonstrated that damage can occur at relatively low current levels (< 5 amps). The photo below left is indicative of loose terminal arcing conducted at 4 amps for less than 15 minutes. The photo below right is a circuit breaker that was returned for overheating due to a loose terminal connection. The overheating condition was not sufficient to thermally trip the circuit breaker.



Overheating from loose terminal connection

Burned circuit breaker due to external heating from loose terminal screw

Carbonized Path Test.

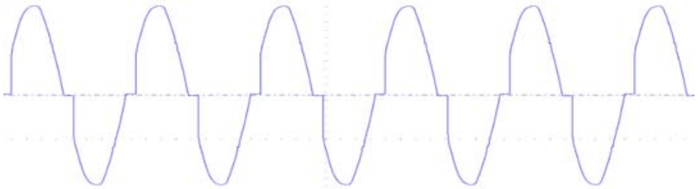
The carbonized path test was developed to simulate wire insulation conditions that have been observed on aging aircraft. Cracking due to maintenance damage, chaffing, aging, chemical exposure, environmental, or other stress related conditions has been shown to form a conductive arc track over time. The application of voltage to this high resistance conductive path burns this track away, thus resulting in arcing. The arcing subsequently re-deposits the carbon resulting in another high resistance path that burns away completing a repetitive cycle of arcing and carbon path conduction. The carbonized path builds up to the point where a flash-over condition can occur, resulting in a potentially catastrophic condition.

Damaged wires prone to arc over

Understanding Normal Steady State and Transient Aircraft Load Characteristics

Detection of arcing events outlined above is actually fairly straightforward. The key challenge in the development of arc fault detection algorithms is to distinguish between normal steady state, as well as transient aircraft load characteristics, and potential fault conditions. Many standard aircraft loads and normal operating conditions on aircraft can exhibit seemingly anomalous waveform signatures. These can include motor start-ups, strobe lights, landing lights, bus transfers, TRU's, incandescent and fluorescent lighting loads, and mechanical switches opening and closing. Moreover, many of the loads and transient conditions can exhibit signatures that mimic or are indicative of an arcing condition.

Arcing Waveform



Typical Aircraft Load

Current traces for numerous aircraft loads on various aircraft types are required to understand and model the normal steady state and transient behavior of the aircraft electrical system. Particular attention should be given to older aircraft electrical systems as these typically exhibit poorer power quality and have harsher waveforms on normal and transient loads. Given the variety and breadth of aircraft variants and loads, the AFCI algorithm must rely on the fundamental characteristics of an arcing event that will cause damage to the aircraft wiring system, without reliance on special case identification of load characteristics. A robust AFCI algorithm should not rely on current level to determine an arcing event, but should distinguish the arcing event based on the arcing content of the signal. The AFCI algorithm must also be flexible, yet robustly designed to distinguish such a wide variety of normal steady state and transient load characteristics from arcing conditions at a low-enough threshold to provide appropriate discrimination and sensitivity levels that justifies this supplemental protection. To provide effective protection, the AFCI technology must recognize normal steady state and transient load conditions and disregard these without causing false indications or nuisance trips.

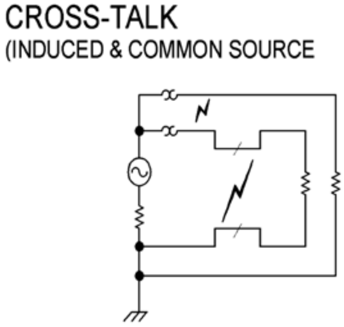
Effects of Masking Loads, EMI, and Cross-Talk

While an arc fault algorithm can be designed to reliably detect and distinguish arcing events from the normal steady state and transient loads conditions outlined in the previous section, it is also essential that the arc fault detection circuit distinguish an undesired arcing condition in the presence of masking loads. It is also imperative that the AFCI circuit be unaffected by EMI conditions (both conducted and radiated), and that the algorithm distinguish between a fault condition on the monitored circuit and a fault condition on an adjacent circuit (cross-talk). Essentially, the AFCI circuit must be unaffected by masking loads and filters while not being susceptible to "noise" that may be present in the electrical system.

The specifications presently under development require that an AFCI circuit demonstrate the capability to detect arcing faults in the present of masking loads. Masking, or operation inhibition, testing requires an AFCI to detect an arc even as it interacts with active capacitive and inductive loads that can and do alter the characteristics of the arcing current signature to varying levels.

AFCI technology in aerospace applications must also meet very stringent electromagnetic interference (EMI) requirements. The arc detection circuit must not be damaged and must not be effected to the extent that it causes a nuisance trip when exposed to radiated and conducted EMI susceptibility testing, as well as lightning burst simulations. The AFCI circuit must also be electro-magnetically quiet such that it does not emit EMI noise into the aircraft environment that will interfere with the sensitive electronic components co-located with the arc fault circuit breaker panels.

In aerospace applications wiring often runs in bundles to take full advantage of the limited space available for running wiring. The sharp current changes due to arcing events on one line can generate a magnetic field that imposes an arc-like signal on wires that are closely coupled to the arcing line. This occurrence is referred to as cross-talk. Many loads are also powered by a common source. When an arc occurs on one branch of a source it can drag down the voltage of that source in rapid successions allowing another type of arc-like signal to be imposed on other circuits that share that source. This occurrence is referred to as common source impedance feedback. Ensuring that loads without arcing remain available is of prime importance when arcing is experienced on one circuit of the airplane.



Desired AFCI Performance Attributes

As can be seen from the previous discussion, the requirements for detecting and protecting against arc fault conditions are onerous. The aviation industry requires enhanced supplemental protection capability with detection thresholds that provide improved levels of safety, but cannot tolerate technology that results in nuisance trips that unnecessarily disable capable circuits. This will especially hold true as aircraft become more electric.

It is imperative that arc fault protection products are designed to address all of the conditions noted above. While there is general agreement on the need for protection against parallel arc faults represented by tests such as the guillotine and wet arc (salt water drip), the need for low level series arc detection and protection against loose terminal and carbonized path conditions are equally important. These conditions have been demonstrated to result in potentially unsafe circumstances that could result in fires and loss of electrical circuits.

The need for low level protection has been recognized in the household market, with changes recently proposed to the National Electrical Code to reflect this. In aircraft applications, conditions that require low level series arc requirements and loose terminal tests include connections that vibrate loose over time or were improperly secured during installation, as well as a severed conductor with intermittent continuity and carbon based contamination. Less obvious, and not applicable to the residential industry, is circuit-to-circuit arcing where the current is still limited by the load on the second circuit. Aerospace wire practice bundles wiring for multiple reasons, including spacing constraints. Wiring for a powered load can be found running along side wiring for an un-powered load that is at frame ground potential and still up stream of the load.

Low level series arcing is particularly insidious because the arc current remains well below the rating of the thermal breaker, and the current sensor will never respond to such low amplitude currents. Since the peak current is never greater than the steady-state load current, series arcing is much more difficult to detect than parallel arcing.

Desired AFCI performance attributes include:

- Fast response to true arcing events
- Ability to discriminate between normal and transient load signatures and arcing events
- Ability to sense arcing events in the presence of masking loads
- Immunity to filters, EMI, cross-talk, and other circuit “noise”
- Low level arc sensitivity

An additional application consideration of the AFCI algorithm for arc fault circuit breaker application is the ability of the AFCI circuit to be powered from either the line or load side (line/load reversible). Today’s thermal aircraft circuit breakers are insensitive to polarity due to their I^2t technology. For retrofit purposes, line/load reversibility is a key application consideration.

Methods Employed by Texas Instruments to Detect Arcs

As outlined in this paper, Texas Instruments has identified a number of key performance objectives for its AFCI algorithm. These include:

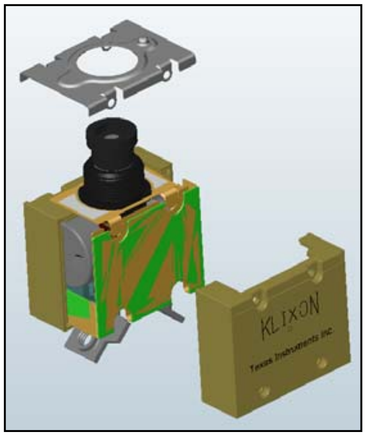
- Robust and versatile
- Low level arc sensitivity
- Fast response to an arc signature
- Ability to see through intervening filters
- No nuisance trips
- Works over a wide range of frequencies

The proprietary TI algorithm is loosely based on sensing di/dt. The key to achieving the performance objectives lay in how the arcing information is extracted from the waveform and how this information is subsequently processed. As a result, TI has developed an AFCI algorithm that does not rely on precise correlation between voltage and current, nor does it rely on the current level. Rather, it relies on the arcing content of the signal. This results in a robust and versatile algorithm that exhibits low level arc sensitivity. Since the algorithm is based on recognition of the fundamental randomness of the arc signature, it has a fast response to an arc signature and the ability to see through intervening filters. Moreover, since the algorithm relies on the fundamental characteristics of the arc, and not on special case recognition, it works over a wide range of frequencies (50 Hz – 1000 Hz) and does not nuisance trip.

As such, the TI arc fault circuit breaker (AFCB) meets the requirements of AS 5692, with excellent immunity to nuisance loads. It detects and interrupts arcing faults with current limited to < 5 amps on the loose terminal test, within 8 half cycles (with current limited to < 70 A) on the guillotine test, prior to damage propagation to adjacent wiring after repeated cold starts cycles on wet arc testing, and within 30 seconds at 50% - 80% of rated current during loose terminal and carbonized path testing. Even higher levels of sensitivity can be achieved on lower rated circuit breakers and application-specific uses.

Arc Fault Circuit Breakers for Aircraft

Texas Instruments (Klixon ®) and other companies have developed prototype Arc Fault Circuit Breakers (AFCBs) that combine supplemental arc fault protection with traditional thermal over-load protection. These have undergone preliminary flight testing and prototypes are presently undergoing in-service flight evaluations. OEMs, regulatory and qualification agencies are adamant that the thermal performance provided by these new AFCB products be identical to the level of protection provided by present generation circuit breakers. This is so as not to degrade the present level of electrical protection provided by thermal circuit breakers in aircraft applications in the event there is an unforeseen anomaly with the new technology. AFCBs currently being designed for aircraft applications are intended to protect wiring from the load terminal of the AFCB to the input of the first active load. This could be the input to ballast for a fluorescent lighting system, a transformer for a strobe light, or it could be the input to a hydraulic motor. In the future, more application-specific AFCBs can be developed to sense arcing after the first active load member (e.g. to detect arcing between that ballast and the fluorescent light bulb). Below, a representative cut-away AFCB is pictured next to a packaged AFCB, alongside a traditional thermal circuit breaker.



Cut-Away AFCB

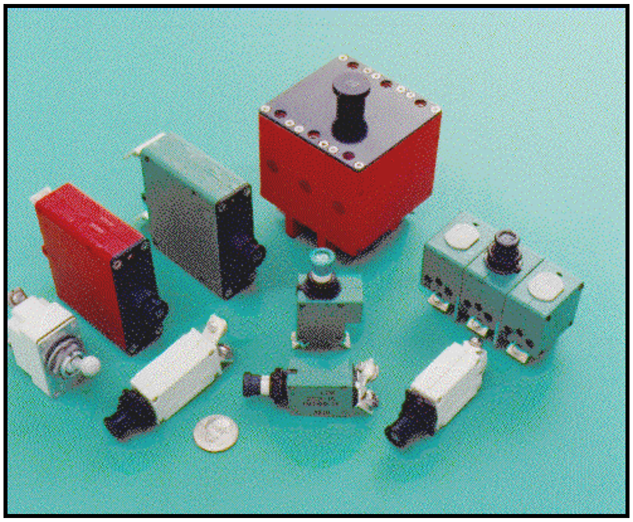
MS 3320 Thermal Circuit Breaker

Early AFCI development has focused on single pole 115 VAC, 400 Hz circuits. This was driven by the relative similarity to existing household technology and load analysis of candidate loads on commercial and military aircraft. Initial applications are planned on non-flight critical circuits [coffee pots, galley circuits, flight entertainment systems, etc.] to build up a performance history on various types of aircraft and aircraft loads. As experience and a satisfactory performance history are amassed, application of these products will be fanned out to virtually all aircraft circuits.

Applying AFCI technology to the breadth of aircraft circuits is a larger challenge than it may appear. Due to the characteristics of thermal circuit protection and the voltages used on aircraft, a portfolio of AFCI products is required to optimally satisfy aircraft circuit protection needs. Ideally, these products must be as small as possible to be interchangeable with the form and fit of present generation circuit breakers to maximize retrofit-ability. The AFCB must also be line/load reversible to satisfy legacy application procedures and circuit breaker panel layouts. This feature will also prevent mis-installation of replacement devices. The required portfolio is outlined in Table 1. Moreover, design of AFCI technology for aircraft must also make future considerations for variable frequency 115 VAC and 270 VDC (military aircraft).

	Ratings		
	1 – 25 A	25 – 50 A	> 50 A
Single Pole 115 VAC	MS 3320 MS 24571	MS 14105 MS 24571 MS 25244	MS 25361
Three Pole 115 VAC	MS 14154	MS 14153	(not widely applied)
28 VDC	MS 3320 MS 24571	MS 14105 MS 24571 MS 25244	MS 25361

Table 1



Representative Portfolio of Klixon ® Aircraft Circuit Breaker Styles Requiring AFCI

Application of AFCI Technology in AFCB's

Although initial development work on AFCI technology for aircraft has focused on maturing single pole AC circuits from 1A - 25A, development has been initiated on three pole 115VAC (400 Hz) and 28 VDC arc fault algorithms. The three pole algorithm should be very similar to the single pole application, although there need to be considerations for powering the circuit either phase to phase or phase to neutral, as well as unbalanced three phase loading.

The algorithms for 28 VDC AFCI technology may or may not differ from the AC technology. This will require the same rigor in comprehending aircraft power quality, normal steady state loads, transient circuit conditions, and load characterization as was undertaken for single pole 115 VAC arc detection development. Due to the lower voltage potential, some of the low level arcing conditions are less problematic at 28 VDC.

The long term objective for the AFCB package is to merge the AC and DC arc detection circuits into one set of electronics that can be packaged in an integral device, such that one device can be interchangeably installed in either AC or DC applications. This would be similar to the thermal circuit breakers used today, which are rated for either 115 VAC (400 Hz) or 28 VDC. However, first generation devices certainly will be voltage specific; but as confidence grows and algorithms are further refined, a universal arc fault protection device will evolve.

Arc fault technology will also be incorporated in solid state power controller (SSPC) and remote power controller (RPC) products used in newer generation electrical distribution systems. SSPC's or RPC's are essentially electronic circuit breakers that combine the over-current protection, as well as a relay function and other diagnostics in an electronic package.

Other AFCB Application Considerations

There are other design and packaging considerations that are also being addressed and will undoubtedly be refined as AFCB manufacturers engage with OEMs and other users. These include:

- Dual indication - differentiation between an arc fault trip and a thermal overload trip
- Built-in-test (BIT) – how do you know the electronics are functioning
- Ground – panel ground is common, but some aircraft use composite panel materials
- Dual voltage (universal) device – Operates at 115 VAC, 400 Hz and/or 28 VDC as do present generation thermal circuit breakers
- Arc Location – Identify location of arcing event (in real time) for maintenance and troubleshooting

These may vary from application to application and may be OEM or system specific.

Future application opportunities may exist to utilize an auxiliary switch or status feature (as are incorporated in some newer aircraft electrical system designs) to provide status indication about an arc fault trip indication. Arc location capability is also a highly desired performance feature to assist maintenance personnel in locating the wiring breach that is creating the arc fault condition the AFCB is responding to.

Summary

Prototype AFCB's have been approved for trial installations on commercial and non-combat military aircraft, while further technology development is ongoing for three pole and DC applications. Texas Instruments has established itself as a leader in the development of this technology, and is distinguished by the low level sensitivity of its algorithm without nuisance trips. This provides truly enhanced supplemental circuit protection against arcing events.

AFCI technology for aircraft requires a robust algorithm that provides:

- Fast response to true arcing events
- Does not result in nuisance trips
- Ability to discriminate between normal and transient load signatures and arcing events
- Ability to sense arcing events in the presence of masking loads
- Immunity to filters, EMI, cross-talk, and other circuit "noise"
- Low level arc sensitivity

Aircraft wiring system safety can be significantly enhanced through the use of arc fault circuit interruption (AFCI) technology. Development work conducted since the late 1990s has validated that the technology is available to produce an enhanced circuit protection product for aircraft. However, development of AFCI protection for aircraft applications is a complex undertaking. There are numerous issues that need to be addressed to satisfy the wiring system application and protection requirements on commercial and military aircraft. Moreover, the detection levels and performance requirements must be such that these new products provide a truly enhanced circuit protection function in the aircraft wiring system.