AFCI’s – Technology Driven by Codes

by Douglas Hansen

Electrical Hazards

When most of us think of the dangers of electricity, the first thought that comes to mind is the hazard of electrocution. In reality, your chances of being electrocuted in your home are pretty low – only about 200 such deaths occur from electrocution each year in this country. Statistically, the gravest danger posed by electricity in the home is fire. Over 40,000 residential electrical fires occur each year, resulting in over $650 million in property damage. Nearly 400 people a year die from residential electrical fires, and there are thousands of injuries.

Technological advances – specifically GFCI’s - are one of the reasons for the low number of electrocutions. In 1994, the Consumer Product Safety Commission asked Underwriters Laboratories to investigate technologies that could reduce the other major hazard, electrical fires. The resulting report “Technology for Detecting and Monitoring Conditions that Could Cause Electrical Wiring System Failures” contributed to the development of Arc-Fault Circuit Interrupters (AFCI’s).

What is Arcing?

An electrical arc is a sustained electrical discharge between two electrodes. A common example is a spark plug. Electrical arcs can occur in either AC or DC systems, and they can create temperatures in excess of 5,000^{o}C - hotter than the surface of the sun. In our typical household wiring system, we use AC voltage that changes direction 60 times per second, passing through “zero volts” 120 times a second. Household voltage is not high enough to sustain an electrical arc through air when the voltage passes through zero. The only way to sustain the arc is if the conductors are loosely touching or re-striking, or if a carbonized path is available. That carbonized path might be available through pyrolyzed insulation in a cable or cord. Pyrolysis – the slow burning and carbonization of organic materials - results from damaged insulation. It could be the result of driving a cable staple too far, or setting a chair leg on an extension cord, or repeated bending or tugging on a cord. Pyrolyzed material not only sets the stage for arcing sufficient to burst into flame, it also becomes part of the fuel for the fire.

Arcing Fault Detection – Why Breakers aren’t Enough

The current necessary to create this arcing is less than would be needed to trip a breaker. However, arcs have a recognizable “signature” or combination of voltage and current wave forms. Arcing is recognizable if viewed on an oscilloscope, and the characteristics of an arc can also be detected by circuit boards built into circuit breakers and receptacles. In this regard, AFCI’s are similar to GFCI’s, though their purpose is entirely different. An Arc Fault Circuit Interrupter, as defined in the National Electrical Code (NEC) in section 210-12(a), is a “device intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc fault is detected.” These devices can be circuit breakers, receptacle outlet types, or cord types for specific appliances.

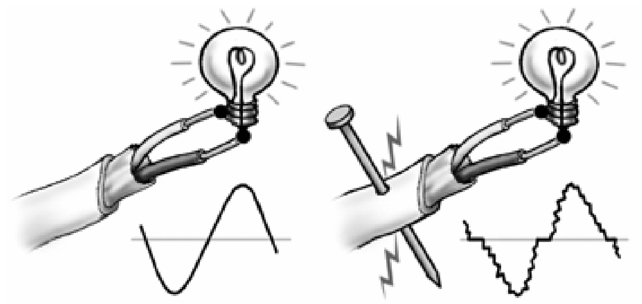

Figure 1 – Normal and Arcing Current Wave Forms

Types of Arcs

There are essentially 3 different types of arcing faults. These are (1) series faults, (2) parallel faults, and (3) ground faults. In a series fault, a single current-carrying conductor is interrupted. An example would be a loose connection or a cable where one conductor is broken by a nail (figure 1). In a parallel fault, there is a connection between the normal current-carrying conductors (usually referred to as hot and neutral). A ground fault requires a ground path, and will behave electrically very similar to a parallel fault. The differences between the various arc types are important because they do not have the same electronic “signature” and are not detected by the same types of devices. A series arc will have a current wave form with “shoulders” and the corresponding voltage wave will have peaks corresponding to the flat spots of the current wave. A parallel or “sputtering” arc will have its voltage and current fluctuations occurring at different frequencies and wave shapes than the series arc.

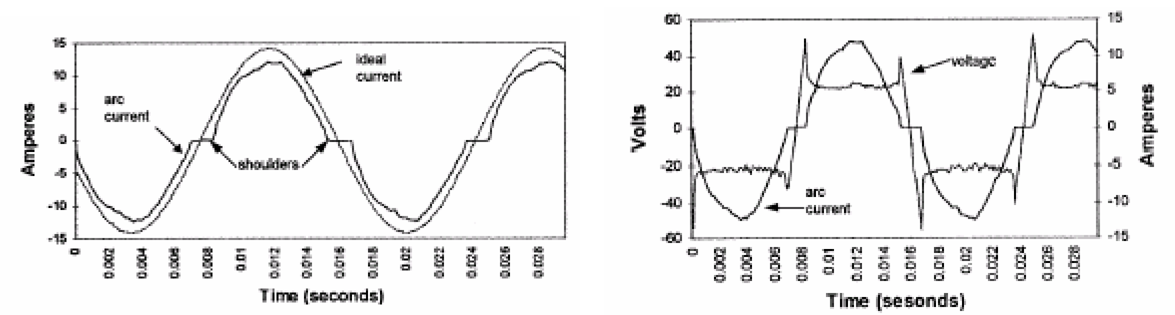

Figure 2a: Series Arc Wave Forms

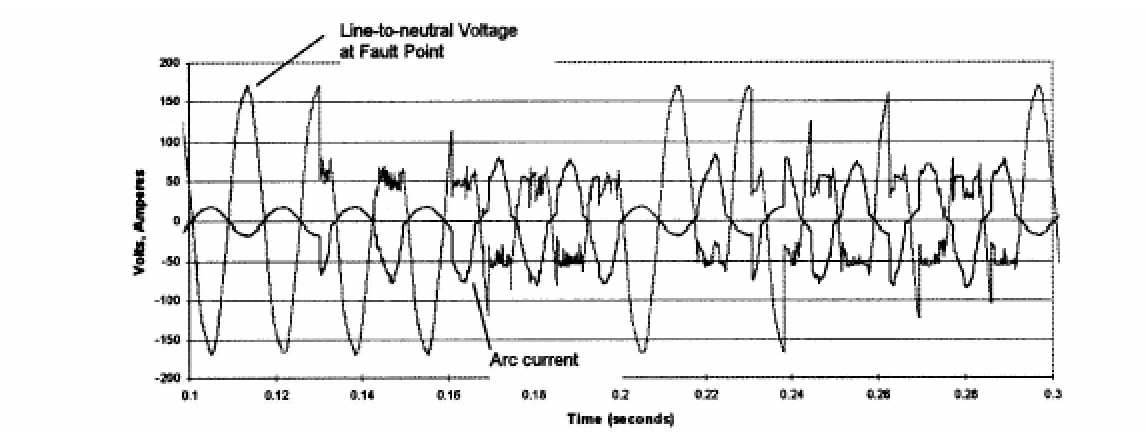

Figure 2b: Sputtering Arc Wave Forms

In addition to arcing *faults*, there are also a number of common everyday arcs. These include the arcing contact of flipping a light switch, the arc when a light bulb burns out, and motors with capacitor starts or with brushes. Additionally, there are many appliances that produce irregular wave forms due to non-sinusoidal currents. These include computers, variable speed shop tools, microwaves, and other common household items. For AFCI protection to be effective, it must avoid nuisance tripping on these everyday items. Generally speaking, arc faults occur at a higher frequency than these acceptable arcs. So far, the reports on AFCI's are good, and there have not been problems with nuisance tripping.

Limitations of Ordinary Breakers

Circuit breakers protect conductors against 3 types of overcurrent. These are (1) ground faults, where a current-carrying conductor contacts a grounded surface or a grounding conductor, (2) short circuits, where a hot conductor contacts another hot conductor of different potential or contacts a grounded (neutral) conductor, and (3) overloads, where the load on the circuit exceeds the rating on the breaker handle for a sufficiently long period of time. Breakers utilize magnetic elements to protect against short circuits and ground faults, and a bimetallic thermal element to protect against overloads. These two separate functions are coordinated. The higher the current, the quicker the breaker will trip. On a dead short, the breaker will open in a fraction of a second, whereas a slight overload could take minutes or even hours to trip the breaker. Breakers will typically allow a momentary "inrush" current of 6 times the rating on the handle without tripping the breaker. In other words, a 15 amp breaker will allow an inrush of up to 90 amps and a 20 amp breaker will allow 120 amps for at least 6 cycles.

In general, breakers do an excellent job of protecting our wiring. However, the inherent nature of arcing faults is such that they do not necessarily draw sufficient current to activate the overload feature of a breaker. There is a window of vulnerability in our breaker design, where the intermittent current peaks of an arc are below the level that would activate the magnetic protection yet within the tolerable time limit before the thermal protection is activated. It is also possible for an arcing fault to draw as little as 5 amps through a breaker, while at the point of arcing the current peaks are enough to produce extremely high temperatures. AFCI breakers are intended to address this vulnerability.

Figure 3 – Square D "QO" AFCI Breaker

AFCI Breakers

At first glance, an AFCI breaker looks exactly like a GFCI breaker. There is a curled white pigtail conductor that is connected to the neutral bus, and the branch circuit hot and neutral conductors both originate from the breaker. There are a total of 3 wires. The label on the breaker will identify it as an AFCI, or there will be a sticker located on the panel cover to identify the AFCI.

Most major manufacturers now have AFCI breakers in their catalogs, including Square D (both “HomeLine” and “QO”), Cutler Hammer (both the “CH” 3/4 in. and “BR” 1 in. sizes), Siemens, GE, Murray, and Pass & Seymour/Legrand. The first manufacturer was Cutler Hammer (their patent application was in 1991) and they marketed their first AFCI breakers in 1997. Early AFCI breakers are labeled “listed as a circuit breaker and also classified to mitigate the effect of arcing faults.” Breakers manufactured after the publication of UL Standard 1699 in February 1999 will say “listed as a branch circuit / feeder arc fault circuit interrupter.”

Multiwire Circuits and AFCI’s

A residential multiwire circuit is a branch circuit that has two hot conductors sharing a neutral, in a similar manner to the way the service has two hot conductors sharing a neutral. When properly installed, the neutral will carry only the difference between the currents on the hot wires. If the currents on the hot wires are identical, the neutral current would be zero. If only one hot wire is carrying current, and the other hot wire has no load, the neutral carries the same current as the active hot wire. The important point here is that the current on the neutral varies depending on what loads are connected to each hot wire, and it is often very different than the load on either individual hot wire.

Because an AFCI breaker needs to compare currents and voltage between hot and neutral conductors, the neutral cannot be shared with another circuit. In other words, AFCI breakers will not work on multiwire circuits, or nuisance tripping would result. The manufacturer instructions warn against using them as replacements in such circuits. A 2-pole AFCI for multiwire circuits is available from Cutler Hammer (figure 4). However, for houses with other panel brands, AFCI’s cannot be retrofit to multiwire circuits.

Figure 4 – 2-pole AFCI for Multiwire Circuits

Electricians prefer multiwire circuits because they save time on installation, reducing the number of cables that need to be run to a given area. In response to the problem with AFCI’s, cable manufacturers will be coming out with nonmetallic sheathed cable containing 2 hot wires, 2 grounded conductors (white wires) and an equipment ground. Because these cables will contain 4 current-carrying conductors, the overcurrent protection for them may require derating to prevent loads that could overheat the wires. In other words, it may sometimes be necessary to use such cable with a smaller breaker than would normally be associated with the wire size, particularly if the cable runs through a hot attic.

Zones of Fire Origin

The CPSC study on electrical fires grouped fire origin into 4 distinct zones:

Zone 0 is the meter, meter socket, and service entrance.
Zone 1 includes the panelboards and fixed wiring of the structure.
Zone 2 is the wiring (cords) between the receptacles and the loads.
Zone 3 is the appliances and other equipment that utilize electricity.

The study found the percentages of fires associated with each zone to be as follows:

Zone 0 – 2%
Zone 1 – 36%
Zone 2 – 12%
Zone 3 – 50%

Based on these statistics, an ideal AFCI protection system would mitigate the hazards of everything connected downstream from the device, and could even provide a limited degree of "upstream" protection of the service (Zone 0) by dropping the load when an arc signature is detected. There are some claims that the branch circuit & feeder type AFCI breakers now being installed only protect against parallel arc faults, and that they only protect against a series arc fault if the faults progresses into a parallel fault or contains peaks above 75 amps. These limitations are relevant when we attempt to use AFCI's to mitigate the hazards of an old knob-and-tube wiring system. A loose connection in series might not be detected by the AFCI, whereas the breaker could detect a parallel arc fault. However, two things mitigate this shortcoming. A series arc will cause the load itself to sputter – such as a flickering light. Also, series arcs have inherently less energy than parallel arcs.

Cables with equipment grounding conductors are more likely to have parallel faults than series faults when a nail is driven into the cable. There appears to also be a limitation to the effectiveness of an AFCI for faulted equipment that does not have a grounding conductor, such as a loose connection in a lamp. In other words, AFCI breakers are best at protecting against arcing faults in Zone 1, in wiring systems with an equipment grounding conductor. Protection of Zones 2 and 3 is very limited.

To provide protection against the fires in Zone 2, another type of AFCI protective device is needed. These are "Outlet Circuit AFCI" devices. They will be receptacle outlets, similar to GFCI outlets, for protection of the cords of connected equipment. Yet another category of AFCI, the "Outlet Branch Circuit AFCI" could be used as the first outlet in a circuit, and would provide downstream protection for other outlets as well as protection for cords of items plugged into it. These receptacle type devices are not yet on the market because the present wording of the code does not create a relevant use, though that may change. UL also categorizes another type of AFCI that could be a combination – capable of protecting both the branch circuit wiring and the connected cords. These devices are not yet commonly available, but may become mandated by current proposals to the National Electrical Code. A full explanation of the types of AFCI devices is available on the Underwriters Laboratories web site at http://www.ul.com/regulators/afci/categories.html

There is one type of equipment failure that is covered by the 2002 NEC, in section 440.65. Room air conditioners are often taken down during the winter months, and their cords are commonly abused. New room air conditioners require Leakage Current Detection and Interruption (LCDI) or AFCI devices to be built into their cords. These devices have yet another category under UL Standard 1699.

Code Requirements

During the development of the 1999 NEC, AFCI's were a hotly contested issue. Many competing proposals for their implementation were put forth. At the time, Cutler Hammer had a large lead on the other manufacturers, and a requirement for AFCI's was seen as an unfair advantage to one manufacturer. There were also a number of concerns expressed over the reliability of AFCI's, and whether it was appropriate for the code to lead the development of technology, rather than to reflect the existing technologies. The Consumer Product Safety Commission was hoping for an immediate requirement for AFCI protection of all 120-volt branch circuits. For a time, the code panel appeared to be at an impasse.

The Code Making Panel, CMP-2, eventually reached a compromise. AFCI's were required in the 1999 NEC in section 210-12 for all 15 and 20 amp 125-volt branch circuits with receptacle outlets in bedrooms. Why bedrooms? In the published materials on the code panel decision, no reason was given for limiting the protection to bedrooms. National Fire Protection Association statistics show that bedrooms are the second most common point of origin (after kitchens) for house fires. While the leading culprit in those fires is smoking materials, electrical equipment is also a major cause. During the code debate, another compromise delayed the implementation date for the AFCI requirement to January 1, 2002. In the 2002 edition of the NEC, another change was made. Coverage was extended to include circuits supplying *all* outlets in bedrooms, not just receptacle outlets. If the circuit supplies a built-in lighting fixture, or a smoke detector, it must be AFCI protected. That code also clarified that the protection was required for the entire branch circuit, not just an individual outlet.

For the 2005 edition, competing proposals have ranged from one that asks for all 120 volt circuits in homes to have AFCI protection, and another that seeks to remove all AFCI requirements from the code. A proposal that received an initial favorable response from the code panel would allow the use of AFCI receptacles to protect the branch circuit if the receptacle was no more than 6 feet from the panel where the circuit originated and the wiring from the panel to the receptacle is a metal-clad cable or raceway system. Another proposal would exempt bedroom receptacles for life support equipment provided the receptacles are labeled "Life Support Equipment Only." Under the 2002 NEC, circuits supplying power to smoke detectors are considered to be the source for "outlets in bedrooms" and that rule does not appear likely to change in 2005.

Adoption of these codes varies widely from one state to another. Vermont adopted the provisions of the 1999 NEC with an early implementation date of January 1, 2001, rather than waiting until 2002. California adopts codes on a more glacial pace, and did not adopt AFCI requirements until November 1, 2002. For work where the building permits were taken out before that date, AFCI's are not required. Nebraska deleted all references to AFCI's in their latest electrical code. Among the reasons cited was the concern that persons adding a bedroom to a house with fuses or an older brand of circuit breaker panel would be forced to upgrade the load center. Some would argue just the opposite, that any excuse to upgrade old equipment should be seen as an opportunity. Massachusetts recently amended their adoption of the 2002 NEC to exempt AFCI requirements in existing construction for panelboards replaced prior to January 1, 2005. In areas where the electrical inspectors interact through organizations such as the International Association of Electrical Inspectors or the International Code Council, they adopt uniform local policies for AFCI's, including the conditions under which they would be required in a retrofit. In some jurisdictions, the addition of a new outlet or circuit may trigger a requirement for AFCI's for that circuit or for all bedroom circuits.

Retrofits in Older Panels

If the panel is a modern style, it may be possible to install AFCI replacement breakers. For certain brands, such as Bulldog, Zinsco, or Federal Pacific, the panel itself would have to be replaced. A Canadian manufacturer makes “Federal Pioneer” breakers that fit in Federal Pacific panels, but they are not UL listed and should not be sold in the United States.

Where are AFCI’s Needed?

AFCI’s can interrupt the source voltage if a loose connection is arcing. However, they offer no protection against a glowing loose connection that is not arcing. Such connections can still generate sufficient heat to ignite adjacent materials without activating the arc fault or the overload protection of a breaker. Do not be misled into thinking that AFCI’s are a general panacea for known wiring defects. The technology is still in its infancy. They are only expected to mitigate – not eliminate - arcing hazards; no manufacturer guarantees that an AFCI can eliminate arcing faults. The type of arc fault that can be detected by the present technology of AFCI’s is precisely the type that could be caused by failing aluminum wire connections. As oxidation forms on aluminum wiring, the contact points gradually become insulated from each other, creating micro-arcing that leads to fires. However, these faults are not the only possible fire hazards associated with old technology aluminum, and inspectors should still recommend complete evaluation by a qualified electrician, not just the installation of AFCI’s.

What about knob & tube wiring? The author must confess to living in a house with 65 year old knob and tube wiring (though I believe it to be in pristine condition). Bad splices in knob and tube can cause series arcs, where the arcing is taking place entirely from one part of a conductor to another part of the same conductor (rather than arcing from hot to neutral, or hot to ground). The lack of sensitivity of some AFCI’s to series arcs might indicate that the AFCI was not needed. I installed an AFCI breaker in a circuit serving the kitchen counters (figure 5). Though the receptacle is supplied by knob & tube wiring, the metal receptacle boxes are grounded independently of the branch circuit wiring. Has anything been accomplished other than transferring $40 from my bank account to the “big box” store? If an arcing fault existed between the knob and tube wiring and the grounded box, the AFCI breaker might function to prevent a fire that might otherwise have gone undetected.

Figure 5 – AFCI breaker (2nd from left) and Test Button Label

AFCI’s and GFCI’s

⇦*Figure 6 – Combination AFCI and GFCI Breaker*

All AFCI’s have a GFCI function, but it is set to 30 milliamps, rather than the 6 milliamp level of a standard class A GFCI. What if AFCI protection is desired on a circuit where class A GFCI protection is also necessary? Combination AFCI/GFCI devices are already available from Cutler Hammer, and other manufacturers may soon be bringing similar devices to the market. The breaker in Figure 5 has a 2-way test button. Sliding the button up tests the ground-fault function, and sliding it down tests the arc-fault function. It is possible that AFCI requirements will be extended beyond just the bedroom outlets in the 2005 code. If they were to include the kitchen receptacles, then a combination device such as the one in Figure 5 could meet both the AFCI and GFCI requirements.

Testing AFCI’s in the Laboratory and the Field

AFCI’s are submitted to specific tests in accordance with UL 1699. They must not only trip under specified fault conditions, they must also avoid nuisance tripping. AFCI’s all incorporate an integral test button. As with GFCI breakers, the breaker handle will trip to a middle position. To reset the breaker, it must be turned all the way to the “off” position, and then to the “on” position. Unlike GFCI’s, the instructions do not state that they should be “tested monthly.” They only recommend testing at time of installation.

AFCI’s can be tested from their built-in test button during a home inspection. However, if the property is occupied, the test might interrupt power to appliances with clocks or timers. The Standards of Practice of ASHI, CREIA, and most other professional associations do not yet address AFCI testing. If an inspector chose to test AFCI’s, they could press the test button and then check to see if the bedroom circuit outlets are off, or for convenience, they may wish to use an external tester.

One such tester, the ETCON AF120, looks very similar to the ETCON GFCI tester, except that the body is green (figure 7). The tester is not UL listed. An early production run of this device did have the UL insignia stamped into the molded body of the tester, and those were recalled as a result. The instructions on this tester indicate that it does not actually simulate an arcing fault – it tests the 30 milliamp level Leakage Trip Function (GFCI) of an AFCI. It can only be used in receptacle outlets with correct polarity and grounding.

Figure 7 – ETCON “AFCI” Tester ⇨

As of this writing, 2 manufacturers make UL listed AFCI testers. These are the Sure Test ST-165, distributed by Ideal, and the Fox Meter. Illustrations of each are shown below (Figure 8). Each of these are true AFCI testers that create a series of 8 pulsed loads on the circuit to simulate an arcing fault.

Figure 8 – UL Listed AFCI Testers

Summary

- AFCI protection is not the same as GFCI protection.
- AFCI's cannot be retrofit to multiwire circuits from other than Cutler Hammer load centers until other manufacturers develop 2-pole AFCI products.
- AFCI protection in its present form is appropriate, though not foolproof, for houses with aluminum wiring.
- The codes, standards, and products for AFCI protection are still evolving.

Resources

A wealth of information (and misinformation) on AFCI's is available on the internet. For further information, a search engine will produce more sites than can possibly be read in a single day. In researching this article, I am indebted to the following sources:

Arc Fault Circuit Interrupters: New Technology for Increased Safety, Engel, Clarey, and Doring, IAEI News, Nov/Dec 1997

IEEE Transactions on Industry Applications, Vol. 34, NO. 5, Sep/Oct 1998

Arc-Fault Circuit Interrupters: The New Residential Electrical Safety Technology, Kimblen, Engel, & Clarey, IAEI News, Jul/Aug 2000

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Arc Fault Circuit Interrupter (AFCI) Fact Sheet, CPSC

Arc Fault Circuit Interrupters: Bringing a new level of protection into the home, Dr. Joseph Engel, NEC Digest, Feb/Mar 2001

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