The Arc-Fault Circuit Interrupter: An Emerging Product

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***Abstract*— The arc-fault circuit interrupter is beginning to emerge as a new product in residential applications in the U.S. to protect against conditions that may cause fire. This paper provides some of the background regarding its emergence as a product and the function it is intended to provide. The evolving technology may also lend itself to industrial applications, as the potential applications become sufficiently well understood.**

***Index Terms*—Arc-fault circuit interrupter, arc-fault detection.**

I. Introduction

A DESCRIPTION of an arc-fault circuit interrupter (AFCI) is *a device intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to deenergize the circuit when an arc fault is detected.* The presently available devices were developed specifically for 120 Vac residential applications to address arc faults as one of the primary causes of electrical fires.

This paper provides background relating the AFCI to its intended function of detecting arcs that may lead to fire causes. It contrasts the AFCI with overcurrent protective devices and with ground-fault circuit interrupters. It also discusses elements of the certification testing required by Underwriters Laboratories (UL). Finally, it briefly discusses the potential application of the technology in commercial and industrial applications.

II. What Is An Arc?

An arc is defined as "a continuous luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes" [1]. Typically, a cathode and an anode are separated by an air space across which the arc forms. Temperatures at the center of the arc are between 5000 °C–15 000 °C. High ionized gas pressure is produced in the region of the arc that will result in expulsion of hot gas and electrode material from any location in which the arc is confined.

III. How Do Electrical Arcs Relate To Fire?

In 120-Vac circuits, it is very difficult for an arc to ignite or to be sustained as more than a spark unless: 1) it is tracking across a partially conductive surface or 2) electrodes are so close together as to be loosely touching. The most available surface that may become partially conductive is organic, electrical insulation. Insulation is generally excellent in performing its intended function unless it is damaged or the product is misused. A carbonized path on surfaces between electrodes may form as a result of heat developed by I^2R heating, by leakage current tracking, or by occasional sparking over a period of time. The period of time may be moments, months, or even years before a sufficient path has been established to support an arcing condition of sufficient energy to produce a flame.

As leakage current flows across this path or sparking occurs, the surface heats up and becomes pyrolyzed as it builds up conductive carbon. Pyrolyzation prepares it for fire ignition at the same time it is becoming a better conductor, converging over time toward a fire-ignition condition. Also, as a sustained electrical arc is finally produced, extremely high pressures are generated in the arc that will blow hot, ionized gas and perhaps particles onto any nearby materials that may ignite. For low-level arcs, such as below 30 A, at 120 V, this mechanism of carbonized path formation appears to be the most common cause of conditions under which fire ignition occurs. This indication is derived from a study of data from a major insurance company made available to the authors.

Arcs are sometimes generated by electrodes that are loosely touching, such as when a piece of wire touches grounded conduit or tubing. Other examples might be a cord cut by metal furniture or a frayed end of stranded wire contacting grounded metal or another conductor. The impedance of such a path can be relatively high, such that the current flowing would not be of sufficient magnitude or of long enough duration to cause an overcurrent protective device (OCPD) to open. However, the heat from such a contact could be significant enough to cause ignition of wood, sawdust or other nearby materials immediately or over time.

As higher levels of arc current are generated, especially at current levels above about 50 A, at 120 V, it is common for molten metal globules to be expelled from the arc. These globules sometimes contain sufficient energy to cause flaming of nearby materials, especially paper, cloth, or sawdust.

The above paragraphs describe the two basic modes in which arcs occur and may cause fire:

1) formation of a carbonized path between electrodes;
2) point contact and separation of electrodes.

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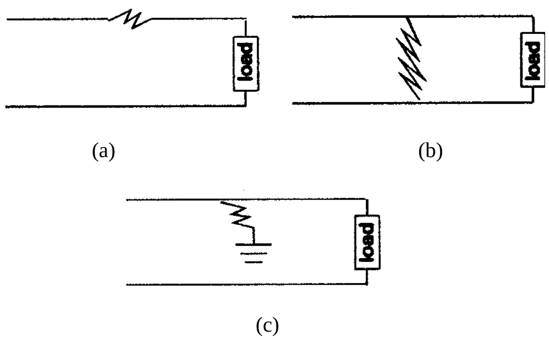

Fig. 1. Three arc-fault types.

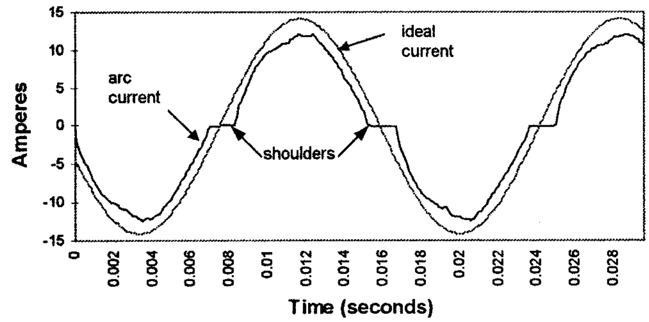

Fig. 2. Series arc current.

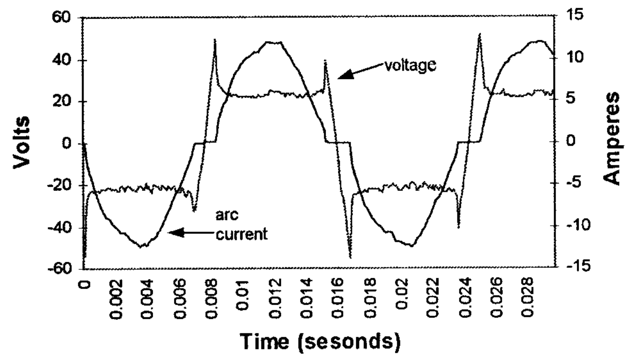

Fig. 3. Series arc voltage and current.

Fire may be ignited by heat directly from the arc, by heat from materials near the arc, from hot gases emanating from the arc, or from molten metal globules ejected from the arc area.

IV. Arc-Fault Types

There are three types of arc faults:

1) series;
2) line-to-line (neutral);
3) line-to-ground.

The series arc depicted in Fig. 1(a) occurs in a single conductor. Examples might be a frayed conductor in a cord that has pulled apart or a loose connection to a receptacle or in a splice. A series arc is load limited, such that arc current cannot be greater than the load the conductor serves.

The line-to-line arc depicted in Fig. 1(b) is a short circuit. Examples might be wire insulation cut by a staple or a cord cut by a metal table placed on it. The line-to-line arc is limited only by the system service impedance and impedance in the fault itself.

The line-to-ground arc depicted in Fig. 1(c) can occur only when a ground path is present. For example, it will not occur in a two-wire appliance or extension cord or within an ungrounded appliance. However, when there is a grounded conductor or enclosure present, other types of arc faults will frequently also include a line-to-ground fault.

V. Arc Characteristics

As might be expected, arc current and voltage waveshapes are generally not simple sinusoids. This section shows several current and voltage traces from arcing conditions. Also shown are nonarcing conditions with characteristics that might seem similar to an arc. These are just examples of the countless loads and conditions that may be encountered in residences. An AFCI must accurately distinguish between an arc and needed energy if it is to be effective.

A. Resistive Load in Series with an Arc

Figs. 2 and 3 show the simple case of arcing current in a resistive circuit. Notice that "shoulders" appear on the current traces around the voltage and current zero locations. The arc ignites only after sufficient voltage across the gap returns following a current zero. It extinguishes when voltage drops below that needed to sustain the arc. Also, notice that arc current is less than the ideal current due to the voltage drop across the arc. Arc voltage is almost a square wave, except for the transient near current zero. The choppiness of the voltage trace indicates another distinct characteristic of the arc which is that of a high-frequency voltage source.

With a series arc present, the rms value of current and I^2t sensed by an overcurrent protective device in the circuit is less than it would sense without the arc. In other words, an overcurrent protective device would be less likely to operate effectively with a series arc in the circuit than without.

B. Sputtering Arc

Fig. 4 shows a trace of current in a cord to a 10-A resistive load when the cord is cut by a "guillotine" similar to a paper cutter. This action might simulate metal furniture cutting the cord, causing a line-to-neutral fault. Voltage shown is that across the cord ahead of the cut. Available short-circuit current is 70 A.

Notice that the arc is not continuous. Once it starts, it is interspersed with segments of normal load current. Again, the rms value of current and I^2t delivered is considerably less than that of a solid fault, especially when viewed over several cycles. Again, in Fig. 4, the shoulders are visible in the arc current trace.

C. Switching-Mode Power Supplies

Fig. 5 shows the current trace of four computers all energized at the same time and then reaching steady-state current. Notice that shoulders similar to those for arcing current are present in both startup and steady-state traces due to the high harmonic content of the load. Startup current has characteris-

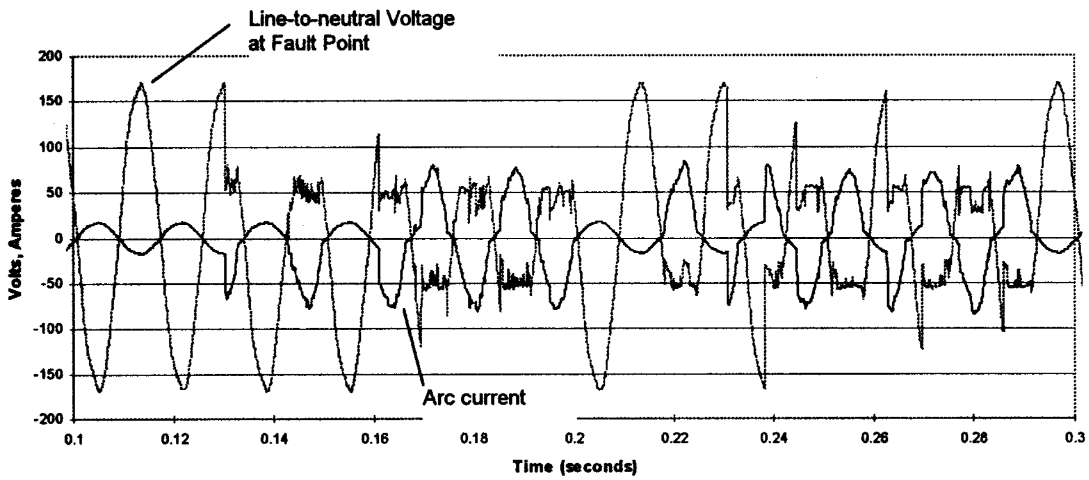

Fig. 4. Voltage and current of a line-to-line sputtering arc in a cord.

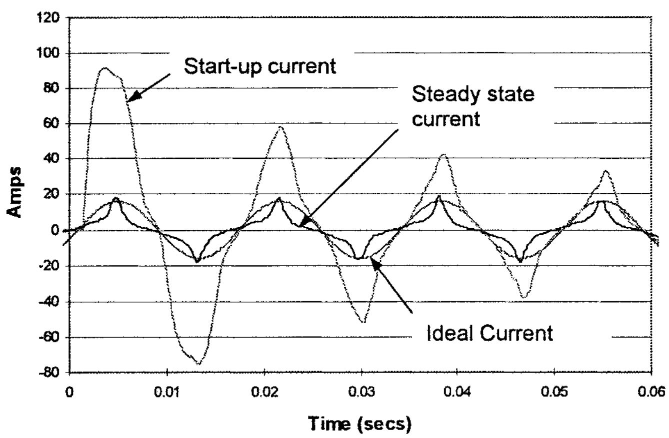

Fig. 5. Current to four computers: startup and steady state.

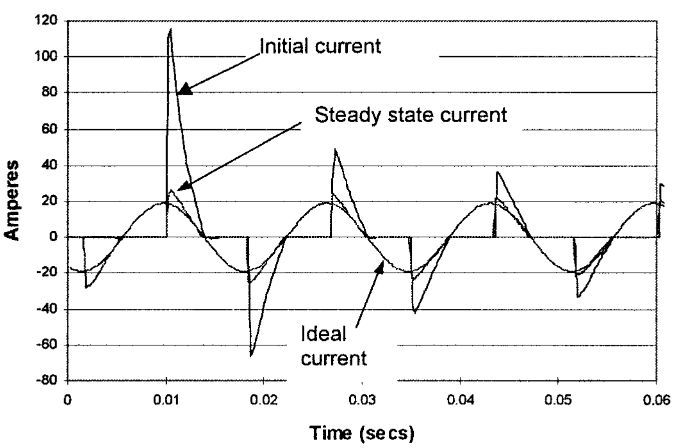

Fig. 6. Current to a 1000-W dimmer: initial and steady state.

tics similar to those of an arcing short circuit. Such loads as this must be allowed to start and run without activating an AFCI.

D. Dimmer

Fig. 6 shows traces of a dimmer with a 1000-W tungsten lamp load. This load waveform also has trace shoulders and high peaks with similarities to a sputtering arc.

Traces of arc current and voltage illustrate the following.

1) Current with an arc in series has a lower rms value than current without the arc due to extinction and reignition around current zero.
2) When a sputtering arc exists in a line-to-line fault, the rms value or I^2t delivered over several cycles is considerably less than that of a solid fault.
3) Voltage across the arc has characteristics of a variable duty cycle square wave with some high-frequency modulation.

VI. Contrast With Traditional Overcurrent Protection

Protection against arcing faults is already provided to a very great extent by the OCPD, a circuit breaker, or a fuse. Many electrical system faults involve arcing, especially where damaged insulation or equipment is involved in the fault. Looking from the residential perspective, the time–current characteristic of Fig. 7 is that of a 20-A circuit breaker. Any arc occurring for a time and current to the right and above the characteristic will be detected as an overcurrent condition and the circuit will be opened. Although the OCPD is intended only to protect good conductors from becoming thermally damaged, a byproduct of this protection is to mitigate potential damage from arcing at the point of the fault. All circuits that complied with the National Electrical Code when they were installed have had this protection all along.

In a study done by UL for the Electronic Industries Association (EIA), data shows that available short-circuit current at receptacles in residences ranges from approximately 75 to 1650 A with an average of 300 A for 15-A branches and 467 A for 20-A branches [2]. This data gives a good idea of the current levels available in branch circuits.

Notice that the instantaneous opening current for the circuit breaker in Fig. 7 begins at 120 A, shown at point *A*. This is about the lowest level at which an OCPD can be designed without nuisance operating on normal circuit occurrences, such as transient inrush current to microwave ovens and burnout of tungsten light bulbs. Most circuit breaker designs in North

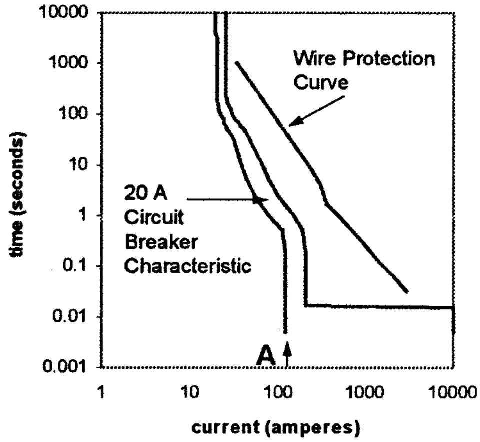

Fig. 7. Time–current characteristic of a 20-A circuit breaker.

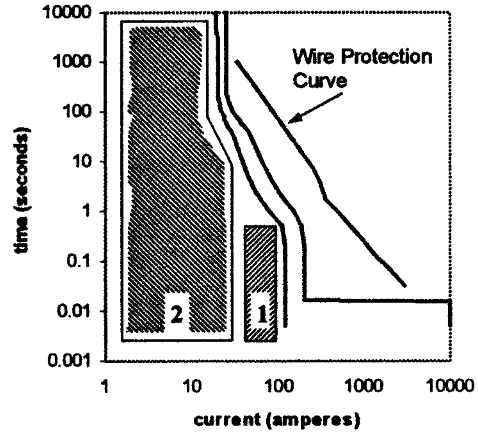

Fig. 8. Regions not protected against arcing fault conditions.

America have an instantaneous opening level significantly above the 120-A level, with perhaps 300 A being the average. In all cases, a gap exists between the 75-A available level in the receptacle study noted above and the instantaneous opening level for the OCPD. This gap is identified as region 1 in Fig. 8.

Looking at points on Fig. 7 below the continuous current rating of 20 A, no circuit protection exists. The circuit breaker must permit branch circuit current to flow. Normal transients and short-time overcurrents are permitted to flow for brief periods at current levels just above the continuous current rating. Arc faults can exist in this region, region 2 in Fig. 8, for long durations with no detection.

In site evaluations following fire occurrences of electrical cause, it is frequently found that the OCPD has not operated. This point indicates that present OCPD's are reasonably effective in mitigating fire causes for conditions under which they are designed to operate. That is, when an OCPD does operate to open, fires are frequently prevented. However, it also indicates that when hazardous, arcing conditions of time and current exist and are too low to cause operation of the OCPD, fires are occurring. Arc-fault protection in these presently unprotected regions 1 and 2 will mitigate fire in a number of causes.

It should be clarified that the OCPD is generally intended to protect the conductor and that mitigation of fire causes by the OCPD is a side benefit.

VII. Contrast With Ground-Fault Circuit Interrupter Protection

If we look at the line-to-ground arc fault mode, we find that ground-fault circuit interrupter (GFCI) protection offers exemplary protection where it is applied for arc faults, as well as any other type of fault to ground. GFCI's protect the circuit for any leakage current to ground 6 mA and higher. It is hard to imagine a form of protection that would be more comprehensive for the line-to-ground fault mode. In an evaluation of technologies available to address home fires done for the Consumer Product Safety Commission (CPSC), UL reported, "Ground-fault interruption technology, due to the low-trip current levels that are possible, coupled with a fast response was shown to be very effective in interrupting arcing-fault currents to ground. This suggests that it should be combined with AFD (Arc Fault Detection) technology, since AFD technology does not require current to ground to operate" [3].

One limitation to be aware of is that a ground path must be present for this protection to be effective. For example, many circuits in older homes are extensions of two-wire circuits with no grounding conductor. Even though a GFCI may be placed in these circuits, it will not detect a fault to a conductor that is not grounded, even though it will be effective in protecting a person who is grounded. A second limitation is that receptacle GFCI's will protect only the cords and equipment connected to the receptacle. It will take a GFCI protecting the entire branch to protect fixed, premises wiring in which a great many of the fire-causing faults occur.

VIII. Contrast With Ground-Fault Protection

Beyond the GFCI, there is another ground fault protective device called an equipment protective device (EPD) that provides ground-fault protection at higher operating levels than the GFCI. For example, the typical EPD operates with ground faults of 30 mA to protect sensitive equipment, while the GFCI operates at 6 mA to protect personnel. As with the GFCI, the EPD would be effective in sensing arcing faults to ground. The EPD has limited application and is used primarily in the protection of heating tapes for pipelines.

IX. Certification Testing

Discussed above were modes of fire ignition from electrical arcs and the need for differentiating between potentially hazardous arcs and needed energy. It would seem that product certification testing must address both of these areas, as well as test a representative sampling of loads and conditions under which arcs will occur. Because the variety of load combinations and conditions is virtually unbounded, no series of tests can be expected to cover every condition, nor will any product known to the authors respond perfectly to every conceivable condition. However, testing must be sufficiently comprehensive to verify safe and correct performance under expected conditions.

The tests discussed below have been applied by UL to 20-A units to be marked as "Listed Circuit Breakers Also Classified for Mitigating the Effects of Arcing Faults." These units consisted of a combination of a standard 20-A circuit breaker pole housed together with the AFCI module. Detection of an unwanted arcing condition causes the circuit breaker to open in these units.

This brief description of the tests is intended only to provide an overview. The outline of investigation being applied by UL requires over 70 tests in the modes covered below. In addition are an extensive series of tests, not described here, that covers extreme circuit and environmental conditions and tests required as part of circuit breaker performance testing.

A. Arc Detection Tests

The above discussion indicates that certification testing of arc detection products should test both arc generation types, carbonized path and point contact and separation. Also, for certification testing, it would seem reasonable to establish a criteria based on limiting arc energy to that below which commonly available materials ignite for sustained arcs. For sputtering arcs in which molten metal globules are expelled almost instantaneously, the circuit must be opened as soon as practical.

In the recent tests by UL, the 20-A units were tested in carbonized path tests at 5, 10, 20, and 30 A. The pass criteria was that surgical cotton placed over the arc area could not ignite. In a point contact test at 75, 100, 150, 200, and 300 A, the AFCI was required to open before eight, half-cycle loops of arcing had occurred. The half-cycle loops were counted because the arc was not continuous for the full period. These tests are being used for present classification of AFCI products and are also being considered for approval in an industry standard for AFCI's.

B. Unwanted Operation Tests

An AFCI must also be able to distinguish between an arc or circuit condition that looks like an arc, which is normal and expected in a circuit, and an unwanted, potentially hazardous arc.

What is an arc that is expected in normal circuit operation? In residential applications, each time a light switch is switched off, an arc appears between the switch contacts. When a plug is pulled out of a receptacle with the appliance operating, an arc appears. Motors with brushes have arcs. Some gas-fired furnaces and clothes dryers use arc igniters. These and similar operations with normal arcs must be permitted without opening the circuit. In industrial applications, the number of normal service arcs increases to include devices from contactors and switches to arc welders and arc furnaces.

Beyond arcs encountered in normal circuit operation are conditions that may look like an arc in their electrical characteristics. Examples might be electronic dimmers or switching-mode power supplies. Further, an unwanted or unsafe arc may occur in a circuit with one or more of the normal service arcs or devices that look like an arc.

To be useful, an AFCI must be capable of distinguishing between normal circuit conditions and unwanted, unsafe conditions.

In the recent UL certification tests, tests were conducted with a variety of equipment in each of six categories to determine that the AFCI correctly distinguishes needed energy. The six categories are as follows.

1) Inrush Current: These are conditions in which the initiating transient is high, such as tungsten filament lamps and capacitor start motors.

2) Normal Operation Arcing: These are conditions in which desirable arcing is normal. Brush motor, thermostatically controlled contacts with heating appliance loads, wall switches, and appliance plugs are example test conditions.

3) Nonsinusoidal Waveform: The unusual waveform loads consist of such items as electronic lamp dimmers, electronic variable-speed electric shop tools, computer switching-mode power supplies, and fluorescent lamps.

4) Cross Talk: This condition examines the ability of the AFCI to avoid operation when the arc is produced in an adjacent circuit under several configurations.

5) Multiple Loads: Under this condition, the AFCI repeats some of the nonsinusoidal waveform tests, but with additional load in the branch circuit.

6) Service Life: Tests in this category are devices that have experienced considerable conditioning under load.

C. Operation Inhibition Tests

This series of tests evaluates whether the AFCI can distinguish an unwanted arc, even in the presence of other loads or conditions in the circuit that might mask, attenuate, hide, or disguise the arc signal. In recent certification tests, multiple tests were conducted in each of the following categories:

1) tests for masking with a variety of equipment in series and parallel with the arc;
2) EMI filter tests;
3) line impedance tests;
4) minimum voltage test.

X. Potential for Commercial and Industrial Applications

Arc-fault detection as a technology is well suited to the detection of arcs in low-voltage, commercial, and industrial applications. However, as one views the range of equipment operated in these environments, it rapidly becomes apparent that a universal device that will distinguish all unwanted arcing conditions from all wanted energy needs may be impractical. For example, there are arc welders, arc furnaces, and induction welders, as well as motors with unusual loads and duty cycles. Arc detection products may be on a circuit with power factor correction capacitors. Office equipment and computers have other special characteristics. Because of this mixture of equipment and the potentially unusual transient, or even continuous current and voltage waveshapes they will produce, it may be prudent to orient individual products to various classes of application or to specific equipment or to otherwise "tune" arc-fault detection to specific applications.

Since there is presently no commercially available device for application above 120 V and 20 A, the definition of "tune" has not been established.

It may be asked whether the residential products are suitable for applications in 120-V 20-A circuits in commercial or industrial applications. The answer is that they have been developed for residential loads. They will detect arcs as readily in commercial and industrial applications as in residential. However, in nonresidential applications, the potential for heavier equipment and unusual loads is greater, which could result in unwanted operation. Experience may indicate an adjustment of the design for commercial and/or industrial applications.

XI. Summary

1) The residential AFCI is intended to mitigate fire causes related to electrical arcs.
2) Presently available AFCI devices are rated 15 and 20 A at 120 V.
3) The function of the AFCI is to detect an arc under various circuit conditions and to disconnect the affected circuit. It must also distinguish between a hazardous arc and needed energy.
4) An AFCI functions within a time–current characteristic below that at which an overcurrent protective device functions.
5) Devices are not yet available for commercial and industrial applications. However, the technology lends itself well to such applications as long as the device is oriented to the load.

References

[1] *IEEE Standard Dictionary of Electrical and Electronics Terms,* IEEE Std. 100-1996.

[2] "Fact-finding report on an evaluation of branch-circuit circuit-breaker instantaneous trip levels," Underwriters Laboratories Inc., Chicago, IL, Oct. 25, 1993.

[3] "Technology for detecting and monitoring conditions that could cause electrical wiring system fires," Underwriters Laboratories Inc., Chicago, IL, Contract CPSC-C-C-94-112, Sept. 1995.

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