Central Power Research Institute

Vol. 16(1)/1-7, January-June 2020
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v16i1.152764

Power Research

Arc Fault Protection and Detection

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Abstract

Arc faults in electric circuits are recognized as an important cause of fire. The first Arc Fault Circuit Interrupter (AFCI) has been patented in 1980 in the United States. AFCI is a device designed to detect electric arc faults which was prescribed for use by the National Electric Code (NEC, US Wiring Regulation) in January 2008. The NEC describes it as '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'. At the beginning of 2012 the Arc Fault Detection Device (AFDD) began to be introduced into the IEC world, culminating in the publication of Technical Product Standards IEC 62606 [1] in August 2013, which sets out the requirements for arc fault protection devices. This paper underlines the importance of preventing electrical fires by using the new technology of AFDDs, which largely extend the protection offered by traditional circuit breakers like MCBs and RCDs. Product standard IEC 62606 and functional tests are reviewed, the functioning of AFDDs is explained and a method to design robust algorithms for arc fault detection is proposed.

Keywords: Arc Faults, Arc Fault Detection Device (AFDD), MCB, RCD

1. Introduction

Fire is the rapid and uncontrolled oxidation of material in the exothermic chemical process of combustion, which releases heat, light, and various reaction products. It requires three basic elements: something combustible (flammable), oxygen, and a suitable temperature. The different phases of a fire are shown in Figure 1.

Three minutes is all it takes for a fire to involve an entire room, because today we use more flammable materials than in the past. In the first ignition stage, vapors from combustible substances begin the combustion process, which is easily controllable. During the propagation phase, heat feeds the fire and determines a slow rise in temperature and the emission of fumes.

At this step the fire is not yet fully developed, but must be managed to avoid flashover. At that stage, there is a sudden rise in temperature and an increase in the amount of material involved in the combustion. The fire in fact reaches very high temperatures (exceeding even 1.000 °C) and combustion becomes uncontrollable as long as there is fuel and oxygen, before it finally reaches the extinction phase. It is therefore essential to control the fire before it reaches the flashover stage.

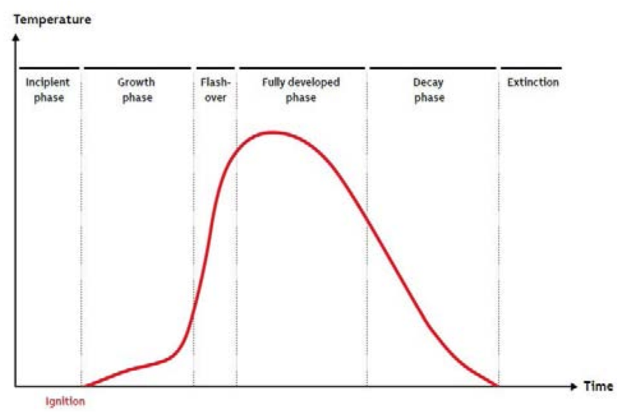

Figure 1. Fire phases.

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1.1 Fire Statistics

Fire outbreak is the third biggest risk to business continuity and operations, according to India Risk Survey (IRS) 2018. In IRS 2016, fire outbreak was ranked eighth biggest risk to businesses.

According to ADSI (Accidental Deaths & Suicides in India) 17,700 Indians died of accidental fire in 2015, an average of 48 deaths a day which is largely avoidable. There was a 300 per cent increase in cases of fire incidents in commercial buildings between 2014 (179 cases) and 2015 (716 cases). Fire outbreaks in government buildings also rose by 218 per cent in the same period (35 cases in 2015 and 11 cases in 2014). The ADSI report shows residential buildings are most prone to fire outbreaks. 7,493 cases of fire outbreaks were reported in residential buildings in 2015, a 100 per cent increase from 2014 (3,736 cases). In fact, 42 per cent of the deaths due to accidental fire in 2015 happened in residential buildings. Just 20 cities recorded 81 per cent of the deaths due to building fires in 2015. Of the 20 cities, 14 are non-metros. Kanpur (147 deaths), Allahabad (134 deaths) and Bengaluru (132 deaths) recorded the highest deaths among 53 major cities monitored by the National Crime Records Bureau.

1.2 Fire due to Electricity – Common Causes

1) Faulty outlets, appliances: Most electrical fires are caused by faulty electrical outlets and old, outdated appliances. Other fires are started by faults in appliance cords, sockets and switches. Never use an appliance with a worn or frayed cord which can send heat onto combustible surfaces like floors, curtains, and rugs that can start a fire.

2) Light fixtures: Light fixtures, lamps and light bulbs are another common reason for electrical fires. Installing a bulb with a wattage that is too high for the lamps and light fixtures is a leading cause of electrical fires. Always check the maximum recommended bulb wattage on any lighting fixture or lamp and never go over the recommended amount. Another cause of fire is placing materials like cloth or paper over a lampshade. The material heats up and ignites, causing a fire. Faulty lamps and light fixtures also frequently result in fires.

3) Extension cords: Misuse of extension cords is another electrical fire cause. Appliances should be plugged directly into outlet and not plugged into an extension cord for any length of time. Only use extension cords as a temporary measure. If you do not have the appropriate type of outlets for your appliances, hire an electrician to install new ones.

4) Space heaters: Because these types of heaters are portable, many times people put them too close to combustible surfaces such as curtains, beds, clothing, chairs, couches and rugs. Coil space heaters are especially dangerous in this regard because the coils become so hot they will almost instantaneously ignite any nearby flammable surface.

5) Wiring: Outdated wiring often causes electrical fires. If a home is over 20 years old, it may not have the wiring capacity to handle the increased amounts of electrical appliances in today's average home, such as computers, wide-screen televisions, video and gaming players, microwaves and air conditioners.

1.3 Faults in Electrical Systems – Classification

Many of the mechanisms described in the previous section (faulty outlets or loads, misuse of extension cords, outdated wiring, too high wattage for light fixtures) together with others (aging of cables, rodents, aggressive environments) may result in a fault of the electrical system that poses a risk of fire. Most common kinds of faults are:

1) Arc Faults: A very common cause of fire due to electricity can be found in the arc faults. "Contact arcs" are generally related to two conductive parts at different voltage placed in direct or indirect contact through low conductive paths. For example, the conductive parts can be the metal contacts of a switch. A damaged conductor could enable the creation of electric arcs between the initial merged contacts.

2) Over Current: Can be differentiated in two types: **Short circuits** occur when two conductors come into contact and quickly create a high current draw that results in an explosion of the conductors, which can then ignite any nearby combustible materials. **Overload** occurs when an electric circuit carries more current than it is designed to handle. An overheated conductor can damage its insulation and cause a fire by igniting any nearby combustible materials.

Leakage current can create fatal electric shocks and also can lead to fire accidents due to insulation faults.

3) Permanent over-voltages: Over-voltages of long duration (from several seconds to several minutes) are voltages that may not be high but are long enough in duration to cause certain components in electrical equipment to overheat and even catch fire, if they have not been sized correctly to operate under such conditions. These over-voltages may be caused by faults in the supply network (break in neutral conductor; short-circuit to earth of high voltage network cable).

4) Transient over-voltages: or surges, related to lightning strikes cause the instant deterioration of certain loads, and can potentially start a fire.

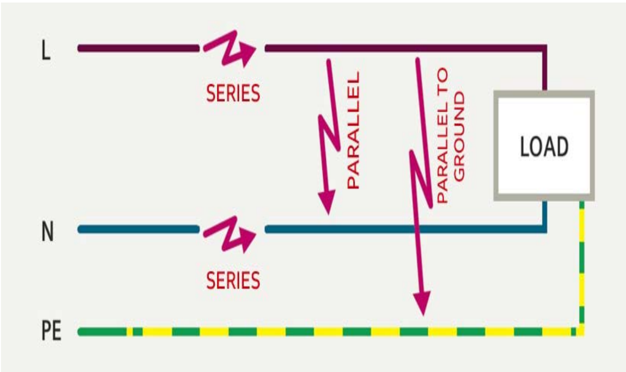


Figure 2. Classification of arc faults.

2. ARC Faults – Classification and Causes

There are two different types of arc fault in electric circuits (Figure 2):

Parallel arc fault - insulation breakdown between the conductive parts that are normally isolated (phase and neutral, or phase and ground). Current of typical parallel arc faults ranges from few tens to few hundreds of Amperes; it is limited only by the length of cable in the circuit and by the arc impedance. Even if high, this current level may be well below the tripping threshold of the MCB protecting the circuit.

Series arc fault - the partial disruption and unintended release of an active conductor not normally interrupted. It can be located along the phase or neutral conductor. Current level during a series arc fault is limited by the presence of the load and hence can range from few Amperes up around to the nominal current of the breaker that protects the circuit.

Possible causes of arc faults include (Figure 3): ageing, lack of maintenance, damaged wires, defective isolation, aggressive environment, vibrations, rodents, faulty devices, multiple sockets, trapped cables in doors, incorrect installation with screw, nails and clips.

Figure 3. Possible causes of arc faults in electric circuits.

3. Protection Devices

Traditional circuit breakers known in the market since many years offer protection against some of the kinds of faults that can lead to a fire. For instance, MCBs protect circuits against overcurrent (short circuits and overloads); RCDs, RCCBs, RCBOs open the circuit in case of leakage current to ground and solutions are known also against permanent (POPs) and transient over-voltages (SPDs).

However, many kinds of arc faults, that are recognized as a common cause of fire in electric circuits, shall go undetected by traditional circuit breakers. In fact, MCBs can detect only some Parallel Arc Faults, those with a current high enough to trip the breaker. RCDs can detect only arc faults that produce a leakage current, like Parallel Arc Faults to Ground. But traditional circuit breakers cannot detect Parallel Arc Faults at currents lower than tripping thresholds of MCBs and moreover they cannot detect Series Arc Faults. This latter kind of fault is particularly dangerous, since, even though series arcs occur at currents as low as few amperes, it is known that they can be stabilized (also in AC voltage) by the presence of a carbonized path (due to charring and melting of insulation), thus leading to a localized source of heat and high temperatures that can quickly lead to ignition of insulations and of nearby material. Specially designed product Arc Fault Detection Device (AFDD), compliant with standard IEC62606 [1], offers a solution and protects against all kinds of arc faults: series, parallel and parallel to ground.

4. Standards

The international reference standard for all Arc Fault Detection Device (AFDD) products is IEC 62606 [1]; it defines requirements, compliance tests and tripping times for these devices. In this section we briefly review more significant functional tests[1,2].

Almost 300 functional tests are foreseen in IEC 62606, including:

- Arc detection tests (with series, parallel or earth arc faults; resistive loads or masking loads; EMI filters and masking due to line impedance; tests at temperature limits).
- Unwanted tripping (with disturbing loads and cross-talk tests).
- EMC tests.

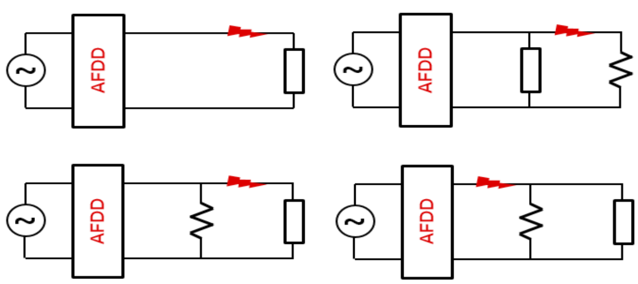


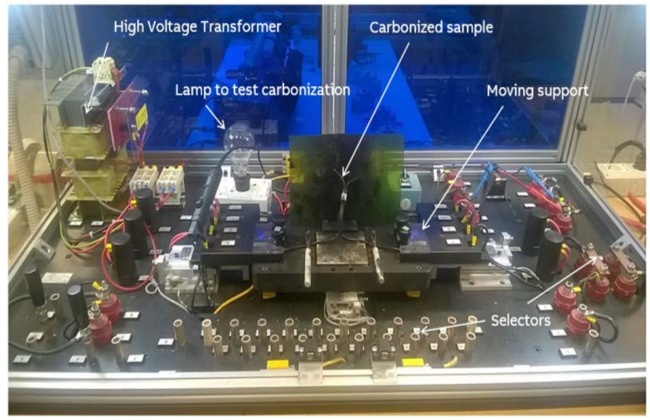
Figure 4. Test equipment for carbonized path tests.

Many Series Arc Detection tests are performed by creating a carbonized path in a suitably damaged sample of wire with application of high voltage (Figure 4). The carbonized sample is placed in series with a lamp to test if it can withstand an arc current.

Subsequently, the sample is placed in a test circuit protected by an AFDD, in one of the configurations shown in Figure 5.

The AFDD must open the circuit within a tripping time specified by the standard (Table 1). As it is evident from Figures 5 and 6 AFDD must recognize an arc fault in presence of many different loads and with many circuit configurations, where a resistor may be added in parallel to the masking load.

Parallel Arc Detection tests are performed both with a carbonized sample, prepared in the same way as for series arc tests, and with the cable cutting test, shown in Figure 7. In this test, a metallic blade is used to cut a sample of wire between phase and neutral to create a parallel arc.



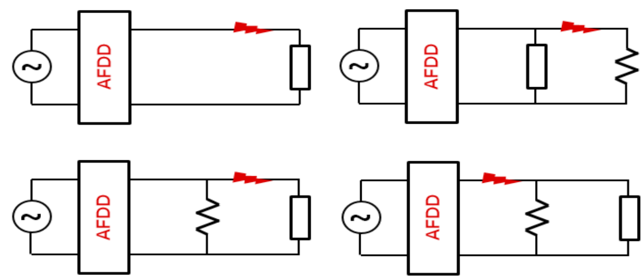


Figure 5. Configurations for carbonized path tests. The arc is created in a pre-carbonized sample of wire (in red). A resistor may be present together with a masking load (shown as a rectangle). Possible masking loads are listed in Figure 6.

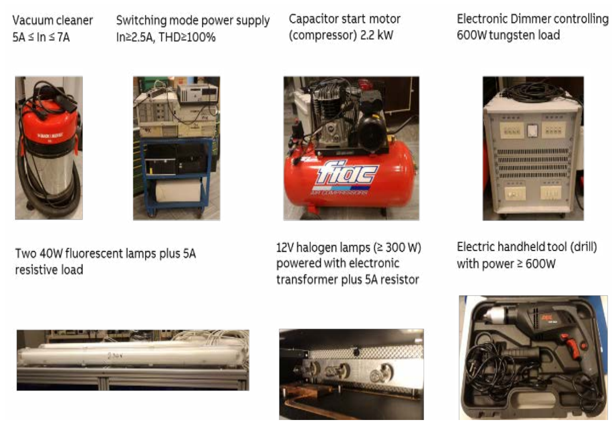


Figure 6. Masking loads in IEC62606.

Table 1:
Tripping time for low current values

Test arc current (r.m.s.values)	2.5 A	5 A	10 A	16 A	32 A	63 A
Maximum break time	1 s	0.5 s	0.25 s	0.15 s	0.12 s	0.12 s

The test current level is set by regulating the length of wire in the test circuit. The AFDD must open the circuit within a specified number of arcing half-waves (Table 2).

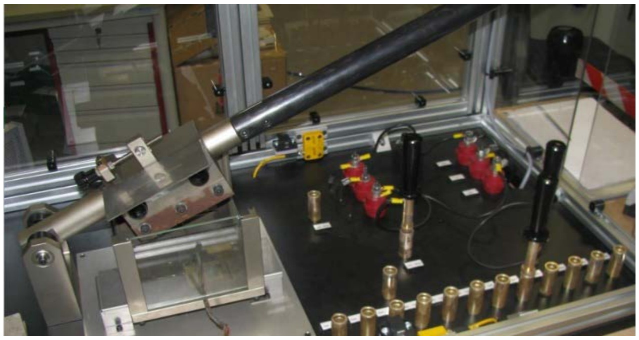


Figure 7. Parallel arc cable cutting test.

Table 2:
Number of half-waveforms declared for high currents

Test arc current (r.m.s.values)	75 A	100 A	150 A	200 A	300 A	500 A
N	12	10	8	8	8	8

The use of AFDD devices is currently specified in Installation Standard IEC 60364-4-42 [3]. Strongly recommended applications according to this standard are:

- Sleeping and common rooms in nurseries, senior and care homes, equipment for disabled persons.
- Places and rooms with existing fire risks and flammable materials, such as production facilities, barns, carpenter workshops, paper manufacturing plants or printing shops where the fire risk is high.
- Places and rooms with prevailingly flammable building materials like wood houses, flammable buildings or forced ventilation systems.
- Places and rooms with irreplaceable goods (cultural assets), such as those in museums, libraries, galleries, archives or architectural monuments.

The use of the AFDD is additionally recommended in any rooms with sleeping facilities in private apartments, houses, hospitals (does not apply in medically use areas) and hotels.

5. ARC Fault Detection Technology

Arc fault detection is performed in a typical AFDD circuit breaker by means of a printed circuit board (PCB) endowed with sensors, analogue front ends and digital processing means to recognize features produced by dangerous arcs inside sensed current or voltage signals. An example of such PCB is shown in Figure 8. The PCB includes a Switched Mode Power Supply stage (SMPS) to power active components inside PCB. There are two main sensing stages to detect a Low Frequency (LF) signal and a High Frequency (HF) signal of the current in main conductor. The LF signal is indicative of current in a frequency band around the voltage frequency (50-60Hz) and is used to compute the rms value of current, that determine also trip times in agreement with product standard[1]. It turns out that arc faults are a good source of broadband high frequency noise (from few kHz up to around a GHz). For this reason, most AFDD circuit breakers include dedicated sensors and amplifiers to extract a signal indicative of noise in a suitable high frequency band. In the example shown in Figure 8, the High Frequency stage is suited to filter and amplify noise signals in a frequency band around 10MHz. A Microcontroller Unit (MCU) receives input signals from the LF and HF sensing stages sampled at around 20kHz and by means of appropriate algorithms continuously analyses the signals in search of unique features indicating the presence of a dangerous arc fault in the line. Figure 9 shows an example of LF and HF signals seen by the MCU of an AFDD during a carbonized path test with a resistive load. The arc fault is introduced slightly before 50ms, with the time reference of the figure. Therefore, signals on the left represent a situation without fault, whereas signals on the right are indicative of an arc fault. It is evident that the arc fault introduces distortions in the LF signals (“shoulders” near the zero of current, high derivatives) and produces a typical waveform in the HF signal, indicative of an AC arc that continuously extinguishes near the zeros of voltage and restrikes soon after. If the algorithm in the MCU detects such features for a suitable amount of time, the MCU energizes an electronic actuator by means of a Silicon Controlled Rectifier (SCR); the actuator trips a mechanism similar to that of an MCB and opens the main contacts. This technology provides proper tripping for both series and parallel arcs. The PCB may include a LED indictor to inform the user of the kind of fault after a tripping. According to standard [1], an AFDD must also contain testing circuitry; in the example of Figure 8, when the MCU detects that a test button has been pressed, it outputs test signals that mimic signals produced by an arc fault. Such signals are injected in the front-end electronics and the MCU must recognize them to trip the circuit breaker.

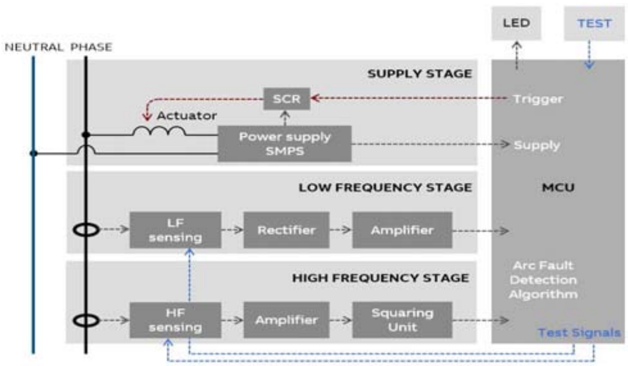


Figure 8. Functioning scheme of an AFDD printed circuit board.

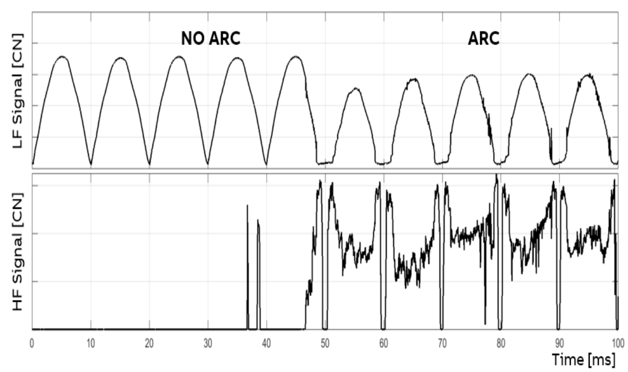


Figure 9. LF and HF signals seen by the MCU of an AFDD during a series arc carbonized path test.

6. Differentiating between ARC Signals and Loads Signals

Differently from MCBs or RCCBs, compliance with standards is not enough to confirm robustness for AFDDs. In fact, many loads and load combinations in real applications are not foreseen by standards and it turns out that some specific brands of specific loads may emit high levels of High Frequency noise, determining in some cases AFDDs unwanted tripping (Figure10). The reason is that low quality electrical appliances, with disputable compliance with EMC standards, can generate significant noise level on the network with HF waveforms very similar to arc fault perturbations. See Figures 11 and 12 for examples of HF signals waveforms recorded in laboratory experiments with arc faults and in field tests during normal behaviour of specific appliances. Therefore, highly sophisticated real time algorithms must be developed in order to discriminate harmful loads versus standard appliances. Intensive field tests and massive data analysis are crucial to develop a successful product. The method we followed to strengthen the performance of AFDDs is summarized in **Error! Reference source not found.**. A library of data has been created by recording LF and HF signals during field tests and laboratory experiments

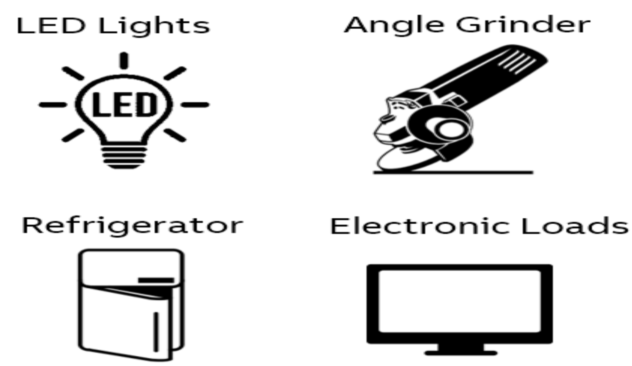


Figure 10. Examples of loads not foreseen by arc fault standards. Specific brands of these load my cause arc fault unwanted tripping.

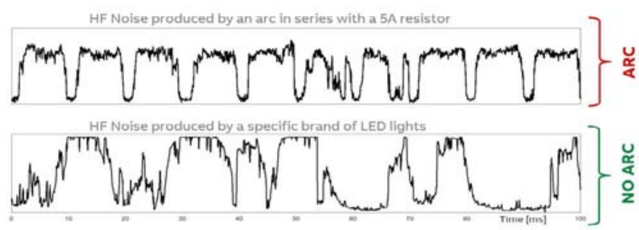


Figure 11. Comparison between the HF signal produced by an arc fault in series with a 5A resistor (above) and the HF signal produced by a specific brand of LED lights during normal functioning (below).

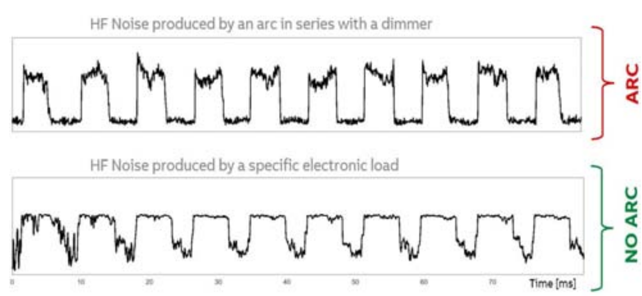


Figure 12. Comparison between the HF signal produced by an arc fault in series with a dimmer (above) and the HF signal produced by a specific electronic load during normal functioning (below).

Figure 14 shows the device that has been developed to record realistic data: it consists of a modified AFDD with the same MCU and analogue front end of a standard AFDD; the MCU outputs through SPI communication sampled data of LF and HF signals to an interface module, which decodes the data and sends them to a laptop, where they are saved. The signals are then processed offline, to improve and strengthen the FW. Most suited features to be extracted are computed and classification algorithms are trained with machine learning techniques. After offline simulation of FW modifications, laboratory and field tests are performed on improved prototypes.

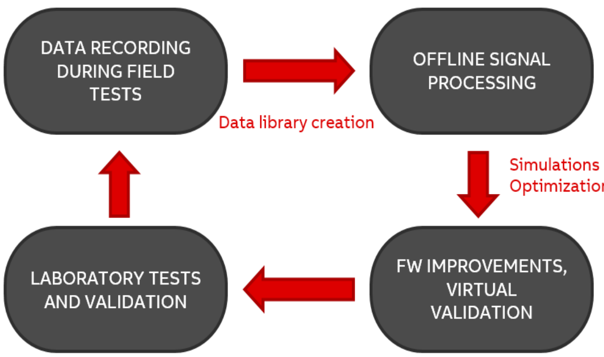


Figure 13. Method to improve arc fault detection algorithms.

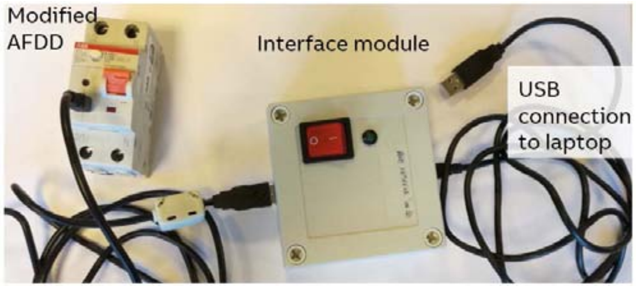


Figure 14. Modified AFDD breaker used to recorder data seen by the MCU during laboratory and field tests.

7. Conclusion

In this paper we have reviewed the importance of arc fault detection for improving protection against fires in electrical circuits. Many mechanisms leading to arc faults and eventually to fire are known in the literature. Moreover, some arc faults, in particular those at low current and without leakage to ground, may go undetected by traditional MCBs or RCDs. A new type of circuit breakers, AFDDs compliant with standard IEC62606, offer enlarged protection against arc faults. After briefly reviewing standard tests and state of the art technology, we have underlined the importance of intensive field tests and data recording of signals and we have shown a method to strengthen the design of arc fault detection algorithms that can discriminate between dangerous faults and signals produced by specific loads in normal behavior.

8. References

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2. ABB. AFDD Technical Guide. Arc fault phenomena and functioning of AFDDs. Document available online.
3. IEC60364-4-42. Protection for safety - Protection against thermal effects.