Comparison Study of Operation Characteristics of AFCI Products

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Abstracts: It is well known that about 80% of electric fire occurs by arc fault. The arc fault can be generated in loose wire connection or damaged wire, outlets, appliances, extension cords, etc. To mitigate the electric fire, US mandated to use Arc Fault Circuit Interrupters (AFCI) since 2002. Before AFCI has been developed, Ground Fault Circuit Interrupters (GFCI) were used for prevention of electric shock accident but GFCIs are not able to detect arc fault that is main cause of electric fire. After AFCI requirement of US established, Canada, Europe, New Zealand also adopted the AFCI as mandatory. It is a worldwide trend to mandate AFCI in their countries. We are living in the era of changing from GFCIs to AFCIs. As the demand for AFCIs increases, many studies regarding development of AFCI products and technologies have been conducted but comparison study of operation characteristics of AFCI has not been done yet, thus in this paper we are going to conduct series of arc experiment with several AFCI products and compare their performance.

Keywords: AFCI, Arc Fault Circuit Interrupter, AFDD, Arc Fault Detection Device

1. INTRODUCTION

Electricity is an essential element for modern society. TVs, Air conditioners, Refrigerators, Microwaves, Heaters, Dehumidifiers, etc., every necessary tool for life is powered from the power grid but a large number of severe property damage and life damage also breaks out from electric fire accident and majority of this disaster occurs from arc fault in these appliances.

According to Statistical Analysis on the Electrical Accident of Korea Electrical Safety Corporation (KESCO), 7,000 to 9,000 fires occur every year, showing no signs of going down. The majority of these fires were typically caused by electrical arc faults in outlets, extension cords, wirings or electrical appliances. To prevent this accident, USA has mandated AFCI installation for households since 2002, and Canada, Europe, New Zealand also adopted the AFCI mandatory followed by USA.

2. RELATED LITERATURE

The demand for AFCIs is growing world-widely and many studies regarding development of AFCI have been conducted by various universities, laboratories, national institutions, and companies. Chee-Hyun Park et al. (2007) [1], analyzed the cause of electric fire and the characteristics of AFCI[2]. Yong-Seo Park et al. proposed that an algorithm that can specify similar arc by removing periodic components from arc signal[3]. Hoonseo Lee et al. studied a system component for arc fault signal detection using 220nm bandwidth of photo multiplier tube[4] Joanna Budzisz et al. (2022) investigated why an AFCI does not detect electric spark in a circuit supplying a switch-mode power supply[5]. Edwin Calderon-Mendoza et al. presented a location algorithm for series arc fault in a low-voltage indoor power line in an AC 230 V 50 Hz home network[6]. Giovanni Artale et al. identified some relevant characteristics of arcing current, which can be obtained by means of low frequency spectral analysis of current signal[7]. Hasung Kong et al. studied usability of network system in AFCI[8]. Edwin Calderon-Mendoza et al. studied a method of Kalman filter for detecting series arcing faults in AC home electrical networks[9]. Joshua E. Siegel et al. examined methods for detecting arc faults, proposing an approach leveraging Internet of Things connectivity, artificial intelligence, and adaptive learning[10].

There are a plenty of studies on analysis and development of AFCI, however, there has not been a comparison study of Operation Characteristics of AFCI Products. Therefore, this paper aims to understand operation characteristics of AFCI products on market by conducting comparison test under IEC 62606 standard environment which is international AFCI product standard.

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3. METHODOLOGY[11]

3.1 Series ARC

A given AFCI should clear the arc fault as the given time specified in Table 1. The AFCI should be tested up to its rated current ampere. The test should be done with cable specimen in series with the AFCI as Figure 1. The test should be conducted at its rated voltage. The clearing time is measured at each arc current level and the measured value should not be exceeded the times in the Table 1. The break time is measured for three times.

With test switches of S1, S3, S4 and the AFCI in the closed position and the test current stabilized, the test arc current is regulated by the resistive load from the lowest arc current value to the rated current of the AFCI. Then the test switch S2 opens. The test switch S4 is then abruptly opened to flow the current to the prepared cable specimen in series with the load. The break time is measured for three times. No measurement shall exceed the limits in Table 1.

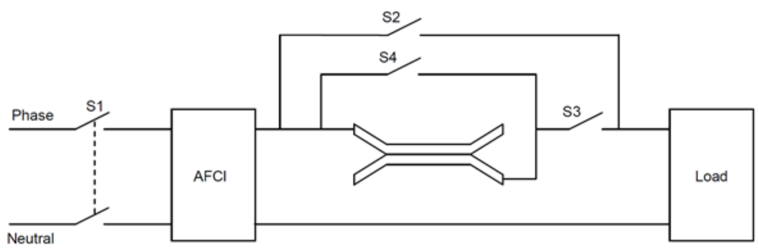


Figure 1. Test circuit for series arc fault tests.

Table 1. Limit values of break time for Un = 230 V AFCIs.

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

3.2 Parallel ARC Test

The AFCI should eliminate arc faults within the number of arc half-cycles mentioned in Table 2 occurs within 0.5 s. For the purposes of these requirements, an arc half-cycle is considered any current trace that occurs within an 8.3 ms period for a 60 Hz rated device. There may be current flow for some within that period.

The test is carried out according to Figure 2. According to the Figure 2, the test apparatus T or equivalent for the cable cutting test shall be prepared. The steel blade of the test apparatus is 3mm nominal thick for 230V AFCI and has approximate dimensions of 32mm x 140mm. During the test, blades of the test apparatus can be replaced or can be sharpened as needed.

The test shall be carried out at the rated voltage of the AFCI and the test arc current in Table 2. The test arc current shall be adjusted with impedance Z and test switches S1, S2, S3 and S4 in the closed position. The AFCI should be tested with 3 wire samples at each current level. One test per each wire sample should be used for one test.

The cutting edge of the lever arm should be positioned at any position along the length of the blade of the blade. With test switches S1 and S3 in the closed position, a slow, constant vertical force must be applied to the lever arm so that the blade can cut through the insulation of the conductor specimen under test. The blade is in hard contact with one conductor and then point contact with another conductor.

The AFCI should break arc faults if the number of arc half-cycles mentioned in Table 2 occurs within 0.5 s.

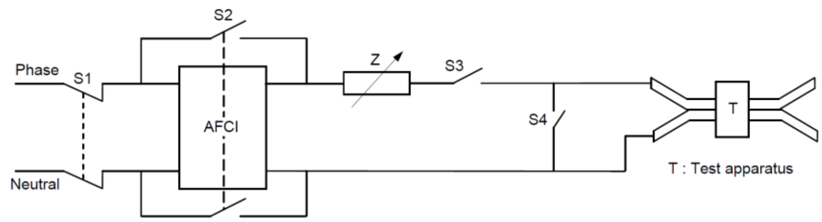


Figure 2. Test for verification of correct operation in case of parallel arc to ground.

Table 2. Maximum allowed number of arcing half-cycles within 0.5 s.

Test arc Currenta (r.m.s. values)	75 A	100 A	150 A	200 A	300 A	500 A
Nb	12	10	8	8	8	8
a This test current is the prospective current before arcing in the testing circuit b N is the number of half cycles at the rated frequency						

3.3 Earth ARC Fault

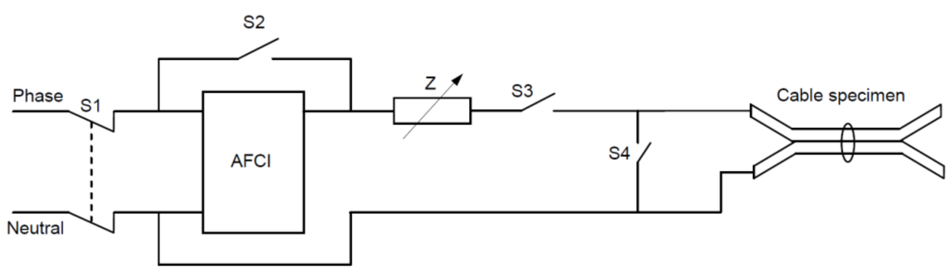


Figure 3. Test for verification of correct operation in case of parallel arc to ground.

The test in 3.1 is repeated at 5A and 75A, but in a way that it creates an arc fault to ground. Figure 3 is the test arrangement for this test. The AFCI must be opened according to Table 1 for 5A and Table 2 for 75A. The AFCI is required to eliminate arcing faults when the arc of the half cycle mentioned in Table 2 occurs. A period of 0.5 seconds is considered to start with the first arc half cycle. If the duration of the arc is shorter than the half-cycle counts in Table 2, the test must be repeated with a new cable specimen.

3.4 Masking ARC Test (CONFIGURATION A, B, C, D)

Without inhibition loads, the first series of tests is performed. According to Figure 9, the AFCI and the arc generator or cable specimen are connected to the circuit. The current is limited and regulated by a resistive load and then open the S1 switch.

The AFCI should be in the rated voltage. Each AFCI must be tested for three times at 2.5A for the rated voltage AFCI. Then perform a second series of tests with inhibition loads using the same resistive load. According to Figure 4, the resistive load, the AFCI, and arc fault testers are connected to each configuration.

The AFCI should be tested with each of the following masking loads:

(a) Vacuum cleaner. (The rated ampere is 5A to 7A. The full load with universal motor of the vacuum cleaner must start and operate.)
(b) A SMPS Power Supply with a minimum total harmonic distortion (THD) of 100% and individual minimum current harmonics having a total load current of at least 2.5A for the rated voltage AFCI, the 3rd being 75% ,

the 5th is 50%, the 7th is 25%. The power supply (or power supply) must be turned on.

(c) A Capacitor-started motors (air compressor type) with a maximum inrush current of 65A ± 10% for the rated voltage. The AFCI must start and run at load. The compressors should not contain any air pressure at the beginning of the test. For the rated voltage AFCI, a 2.2kW capacitor starting (air compressor type) motor must be used.

(d) The electronic lamp dimmer (thyristor type) 600W of the rated voltage with filtering coil controlling 600W tungsten load. The dimmer must be turned on with the dimmer preset turned on to the maximum and with a conduction angle of 60°, 90°, 120° and a minimum setting level to ignite the lamp.

(e) Two 40W fluorescent lamps of the rated voltage and an additional 5A resistive load

(f) The 12V halogen lamps powered by electronic transformers with an additional 5A resistive load with a total power of at least 300W

(g) The powered hand tools such as drills with a minimum output of 600 W of 120V/230V.

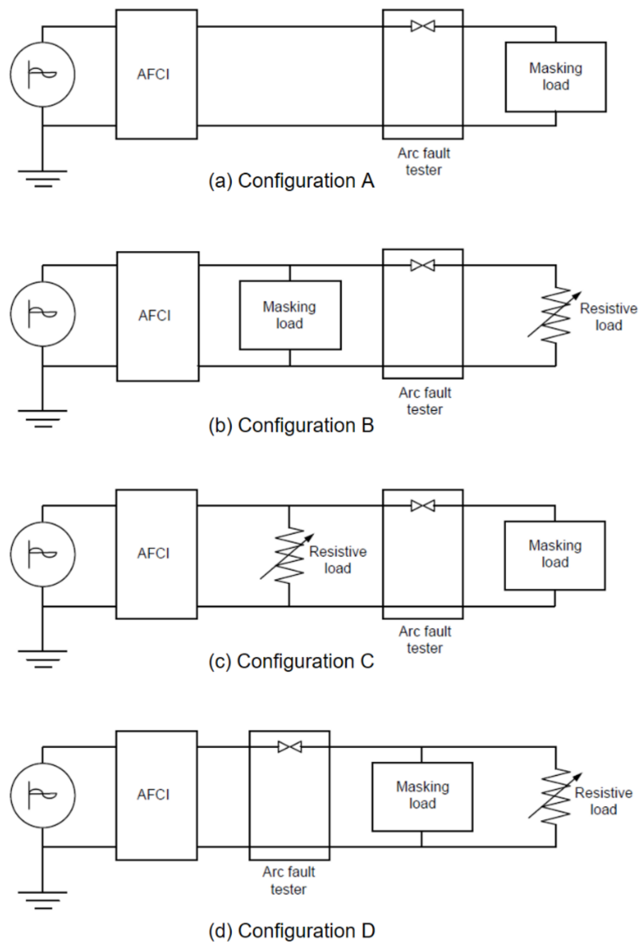


Figure 4. Test configuration for masking tests.

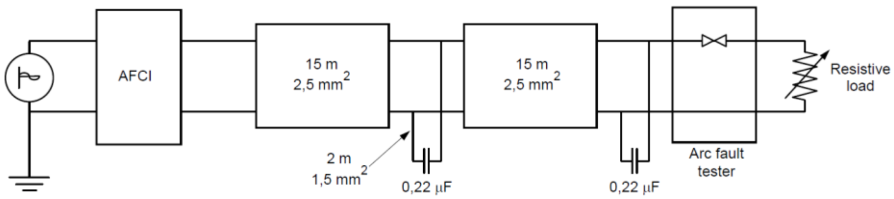
3.5 EMI Filter ARC Test

According to Configuration B of Figure 4, the AFCI must be connected to the circuit. The arc test should be conducted with 2.5A load for 230V rated voltage AFCI.

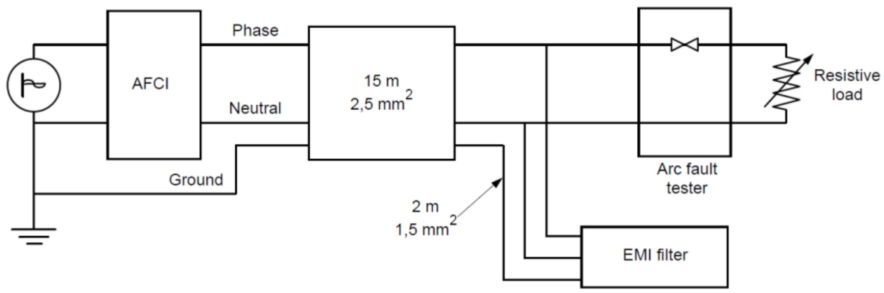
The AFCI must eliminate arc fault as specified in Table 1 when using carbonized cable specimens. When using arc generators, 2.5 times the clearing times in Tables 1 or 2 shall be applied.

(a) Two of 0.22 μF EMI filters are used for the test. One must be installed at one end of two resistive loads that are 15 m (or 50 ft) long and 2.5 mm2 (or 12 AWG) in diameter. Each filter should be approximately 2.0 m (or 6 feet) long and 1.5 mm2 (or 16 AWG) in diameter. The arc fault should be generated as shown in Figure 5(a).

(b) An EMI filter must be installed at the end of 15 m long and 2.5 mm2 diameter. The filter should be at the end of a flexible cable that is 2.0 m long and 1.5 mm2 in diameter. According to Figure 5(b), the AFCI and arc fault should be positioned.



(a) EMI filter 1



(a) EMI filter 2

Figure 5. EMI filters for masking test.

3.6 Line Impedance ARC Test

The AFCI must be installed in branch circuits, and under the following line impedance conditions, the AFCI must operate according to the break times specified in Table 1 when carbonized cable specimens are used, and 2.5 times longer than Table 1 when arc generators are used.

According to Figure 6, 30 m 2.5 mm2 sheathed cable, branch circuit consisting of two conductors with steel sheath is prepared. The arc fault should occur in series with a 2.5A load for a 230V rated voltage AFCI.

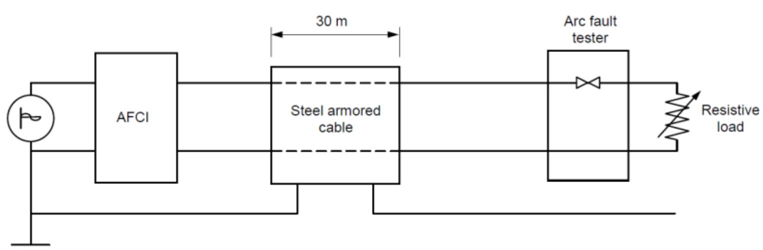


Figure 6. Test circuit for masking tests with line impedance.

3.7 Unwanted Tripping

3.7.1 Cross Talk Test

According to Figure 7, two kinds of branch circuits are installed closely in the same electric panel so that they are fed from the same phase and neutral conductors. These two circuits both have a resistive load that draws a 5 A current. In circuits without AFCI, the arc fault is initiated by the arc generator. The arc fault should have a duration equal to 0.5 seconds for the 230V circuit and AFCI must not be tripped.

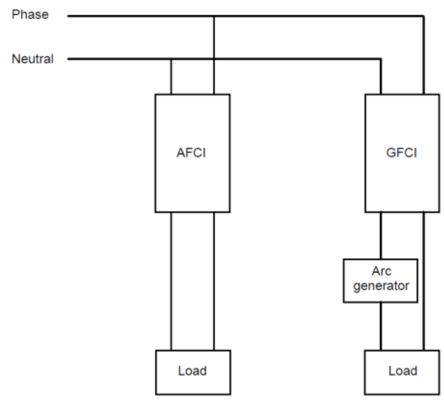


Figure 7. Cross Talk Test.

3.7.2 Test with various disturbing loads

According to 3.2, the AFCI is tested, however, in this time, there is no arc generator or cable specimen as shown in Figure 8. The load is on for at least 5 seconds. There are 5 start/stop operations to be performed and the AFCI should not be tripped.

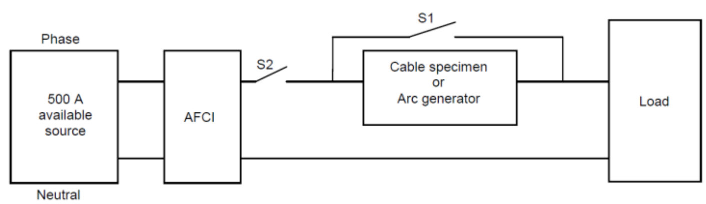


Figure 8. Test circuit for masking tests.

4. RESULTS

4.1. Test Result

In this result, the average trip time for each test item for each AFCI product has been identified as shown in Table 3. As for the test of 2.1 Series Arc Test, average trip times for Product A, B, C are 196.6 ms, 270 ms, 270 ms. As for 2.2 Parallel Arc Test, average trip times for Product A, B, C are 5.9 half-cycles, 6 half-cycles, 10 half-cycles. As for 2.3 Earth Arc Test, average trip times for Product A, B, C are 4.8 half-cycles, 5.5 half-cycles, 6.5 half-cycles. As for the 2.4 Masking Arc Test, average trip times for Product A, B, C are 109.1 ms, 389.7 ms, 391 ms. As for 2.5 EMI Filter Arc Test, average trip times for Product A, B, C are 486.6 ms, 472.1 ms, 471.5 ms. As for 2.6 Line Impedance Arc Test, average trip times for Product A, B, C are 357.3 ms, 345.6 ms, 392.7 ms. And as for 2.7.1 Cross Talk Test and 2.7.2 Test with loads, all 3 products has been passed.

As for test items of 2.1 Series Arc Test, 2.2 Parallel Arc Test and 2.4. Masking Arc Test, Product A shows the fastest operation response. As for test item 2.5 EMI Filter Arc Test, Product C shows the fastest operation response. As for test item 2.6 Line Impedance Arc Test, Product B shows the fastest operation response. In summary, the list in order of fastest operation response, Product A (206.47 ms), Product B (262.23 ms), Product C (277.12 ms) showing that the Product A has the fastest operation characteristic.

Table 3. Test Result for each AFCI.

Test Item	Korean Product A	American Product B	European Product C
Appearance of product		 120V 20A	 230V 20A
2.1 Series Arc	196.6 ms	270.2 ms	270 ms
2.2 Parallel Arc	5.9 half-cycles (49.2 ms)	6 half-cycles (50 ms)	10 half-cycles (83.3 ms)
2.3 Earth Arc	4.8 half-cycles (40 ms)	5.5 half-cycles (45.8 ms)	6.5 half-cycles (54.2 ms)
2.4 Masking Arc	109.1 ms	389.7 ms	391 ms
2.5 EMI Filter Arc	486.6 ms	472.1 ms	471.5 ms
2.6 Line Impedance Arc	357.3 ms	345.6 ms	392.7 ms
2.7 Unwanted Tripping	Pass	Pass	Pass
Summary (Average)	206.47 ms	262.23 ms	277.12 ms

5. DISCUSSIONS

Joanna Budzisz et al. studied a special case study of ineffective protection with arc fault detection Device. [12] In the study, they found out that AFCI can be ineffective when detecting sparking are in the circuit with a switched-mode power supply. AFCI in the laboratory tests according to IEC 62606 and tests under real operating conditions performed differently. This means that simply laboratory test of AFCI product does not guarantee that universal use for other countries. The tests conclude that some of the test loads as capacitive loads negatively influence the spark detection efficiency. From this paper it is assumed that AFCI that is developed for a target country should be used in that country mainly.

The work of Qi Zi-bo et al. [13],, which analyzed that any arc fault which is a dangerous and multiple electrical faults that is one of the main reasons to cause electrical fire. This study describes briefly the current situation of researches for prevention of electric arc faults at home and abroad. The researchers developed a simulation test according to the arc fault features device. This device can produce real electric circuit arc fault and present the principle of operation. This equipment can produce real arc fault and it not only can be used for the basic theory research of electric arc faults, but also can be used in the testing of arc fault protection product, supporting that the necessity enhanced device for arc fault test.

Huaijun Zhao et. al.[14] proposed that a series arc fault detection method based on current fluctuation features and zero-current feature fusion. The series arc faults have features of the strong concealment and high randomness, relatively small current amplitude which is easily annihilated by the load current. According the the UL1699 standard, influence of the load properties, a low-voltage single-phase alternating-current (AC) series arc fault experiment were performed. The four-cycle current of the electric circuit is collected and the zero-current time proportional coefficient and normalized mean square error coefficient are calculated. A fuzzy logic device introduced to fuse the two coefficients to obtain the comprehensive feature identification coefficient of the series arc faults. The zero-current time proportional coefficient is combined and compared to the empirical threshold to determine whether there are series arc faults. This explains that detection of arc fault requires more than one detecting algorithm and the element of algorithm can be identified differently depending on electric environment which can be different from country to country.

Through above discussion, we can understand that some of approaches of authors who are concentrated on

AFCI research are aware of difficulty of arc fault detection and importance of arc test method. However, all of them have not performed comparison test of AFCI products of worldwide and failed to present an enhanced method for arc test so, this study will help to understand that suitable AFCI product and necessity of development of an enhanced test method.

6. CONCLUSION

The purpose of this paper is to compare performance of several AFCI products on market and study characteristics of each products by performing test items that are described in IEC 62606, which is a global product standard for Arc Fault Circuit Interrupter product. For the experiment, representative AFCI products of each country were selected. Test environment for each product was set to its rated voltage and frequency and every test item described in the standard was performed.

As a result of the test on each selected AFCI product, average trip time was recorded. The trip time of product C has been observed for the fastest response time of 206.47 ms. Product A has been observed for the second fastest response time of 262.23 ms. Product B has been observed for the third fastest response time of 277.12 ms. All of the product meet specification of standard of Arc Fault Circuit Interrupter but we can see the difference of performance characteristics.

In this paper, we studied operation characteristics of each AFCI product and found out that its performance difference according to the test items in IEC 62606. In real world, however, there are numerous electric appliances and equipment that can produce good arc, which AFCI should not be tripped by. But test items of unwanted tripping in IEC 62606 are only few. For widespread use of AFCIs, more tests regarding unwanted tripping test are required. So it is required to develop more test items regarding unwanted tripping and perform those tests on AFCI products for assurance of more robust operation quality of AFCI products.

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DOI: https://doi.org/10.15379/ijmst.v10i1.1446