Detection of Arc Fault on Low Voltage Power Circuits in Time and Frequency Domain Approach

Shu-Chen Wang, Chi-Jui Wu, and Yi-Jie Wang

***Abstract*—**For the safe use of electric power, it needs to detect the occurring of electric arc faults on the low voltage power circuits and switch off the power source before the occurring of fires. However, many examples reveal the facts that a number of home fires are caused by electric arc faults. The arc-fault circuit interrupter (AFCI) is a device which can detect the occurring of electric arc in the low voltage circuits, and then it can switch off the power source before the occurring of fire caused by series or parallel electric arc faults. The detection approach is the major part in the design of an AFCI. In the paper, it is to investigate series arc fault detection approach of low-voltage power circuits feeding several characteristics of the load. The test data are collected through the arc fault testing platform. The series arc faults will be verified and evaluated their time-frequency characteristics by using the experimental data and compared with relative literature. By combining the time domain-frequency domain techniques, it sums up six detection rules. Then two detecting methods are developed to suppose detecting approaches. Finally, the experimental data with serial arc faults are used to test the detecting methods and compare with the commercial devices. The purposed detecting methods can effectively detect the occurring of series arc faults, and the probability of malfunction is low.

Keywords—Low Voltage Power Circuit, Arc Fault, Detection, Electricity Safety, Spectrum Analysis.

I. INTRODUCTION

According to the reports of the U.S. National Fire Protection Association (NFPA), major part of home fire events were caused by electric arcing faults. Therefore, how to use modern technology to reduce occurring of home fires caused by arc faults has become an important issue.

Defined by UL1699, electric arc is "a luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes" and arcing fault is "an unintentional arcing condition in a circuit" [1]. Temperatures at the center of the arc are between 5,000 and 15,000 ℃. If there are combustible materials around, it may cause fire. General reasons of arcing on lines include (1) wire insulation damage and wear, (2) loose wire connections, (3) overheated wire, and (4) damage or misuse of electrical equipment. So in home electricity usage, it is needed to protect the accident caused by electric arc hazards.

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Shu-Chen Wang is with the Department of Computer and Communication Engineering, Taipei College of Maritime Technology, Taipei, Taiwan. Chi-Jui Wu and Yi-Jie Wang are with the Department of Electrical Engineering, National Taiwan University of Science and Technology. Taipei, Taiwan (cjwu@mail.ntust.edu.tw).

The arc-fault circuit interrupter (AFCI) [1] is a device which can detect the occurring of electric arc in the low voltage circuits, and then it can switch off the power source before the occurring of fire caused by series or parallel electric arc faults. Arc-Fault Circuit Interrupter (AFCI) is able to utilize circuit interrupting to stop power supply when it can detect arcing faults, thus avoiding from fire disaster caused by arcing faults. AFCI will not trip for the normal arc (good arc) on the line, for example, the arc situation when switching on or pulling the plug from socket. According to UL1699 Standard [1], when AFCI perceives 8 times of fault arc with half of cycle length (8x0.5power cycle) on low voltage line within 0.5 second, AFCI will immediately interrupt to cut off AC circuit. Since the detection approach is the major part in the design of an AFCI, so many studies have been presented to investigate the detection technology. The stochastic characteristics of the series arc faults has been investigated, and the phase shift method is used to obtain the arc fault signals [2]. It has been revealed that the noises with wide spectrum will be caused by the arc fault currents [3]. By using the shoulder characteristics, the detection of arc faults can be obtained by wide band radiation frequency. The lifting multiwavelet approach has been used to obtain the high frequency components of the arc fault currents, and the threshold is determined to identify the occurrence of arc faults [4]. The short-time Fourier transform was used in time-frequency analysis. The harmonic components increase during the arc fault [5-6]. The Fourier transform is also used in the time-domain and frequency-domain analysis of the arc fault currents [7-8].

In this paper, the effective detection method of series arc fault will be investigated to improve the electricity safety of low voltage power circuits [9-12]. The artificial arc generator is inserted in a power line which feeders load currents. The current waveforms of a system with normal arc and series arc fault are recorded. It is to investigate whether the arc fault could be successfully detected, while the normal arc will not cause malfunction. The experimental test results presented in this paper to compare the detection approaches to find better detection methods. The test results are compared with the commercial arc fault circuit interrupter (AFCI).

II. AFCI CHARACTERISTICS

The AFCI provides arc fault protection for the branch circuit, as well as protection for cord sets and power-supply cords. When an arcing event is detected, the AFCI analyzes the event and the circuit breaker opens when it determines a hazardous condition. Fig. 1 shows the illustration diagram of a typical AFCI for arc fault detection. There are two current measurement units. The electronic circuits will continuously monitor the current and voltage. The AFCI contacts will be opened if there are currents with typical arc fault characteristics. This paper uses a combination type AFCI for comparison. It can detect series arcs and parallel arcs, and there is leakage circuit breaker with overload protection, as shown in TABLE I.

III. Experimental Method

Arcs in low-voltage circuits can be divided into two types. One is generated under normal operation. For example, the arc in the plugging of electrical plugs. The other is the arc fault. The arc faults include series and parallel types, the latter containing line to line arc and line-to-ground arc, as shown in Fig. 2. The series arc fault tests are investigated in this paper.

The artificial generator for series arc faults according to the UL1699 was used as shown in Fig. 3. Fig. 4 shows the test circuit for series arc fault. The voltage waveforms are measured in CH1, CH2, and CH3. The line current is measured in CH7. It is to use the line current (total load current) to determine whether the series arc fault occurs. The series arc fault occurs between the voltage source and the load. So the

The four test loads are (a) hair dryer (850W), (b) fluorescent lamp (electronic ballast) (23Wx8) and resistor (443W), (c) electrical rice cooker (600W) and resistor (100W), and (d) mixed load, including computer (300W), fluorescent lamp (electronic ballast) (23Wx3), electric rice cooker (600W), fans (60W), and refrigerator (228W).

Experimental procedures include three tests:

A. The test of the load characteristics: The load current waveforms under normal operation are recorded. It is to investigate whether the harmonic currents from nonlinear load would cause malfunction. The fluorescent lamps (electronic ballast) and computers are nonlinear loads.

B. The test of normal arc (good arc): It will generate normal arc during the opening and closing of the switch, and the pulling out and inserting of the plug. These operations are still normal conditions of the circuits. It is examine the malfunction.

C. The test of series arc faults: It is to artificially generator the series arc faults. It is to test the operation of commercial AFCI. The measured current waveforms are also used to test the detection methods in this paper.

TABLE I
TYPICAL COMMERCIAL AFCI PROTECTION CHARACTERISTICS

Types of AFCI / Arc Condition	Branch/ Feeder	Outlet Circuit	Combination
Line-to-neutral	Yes	Yes	Yes
Line-to-ground	Yes	Yes	Yes
Series arcing	No	Yes	Yes
Protects whole branch circuit	Yes	No	Yes

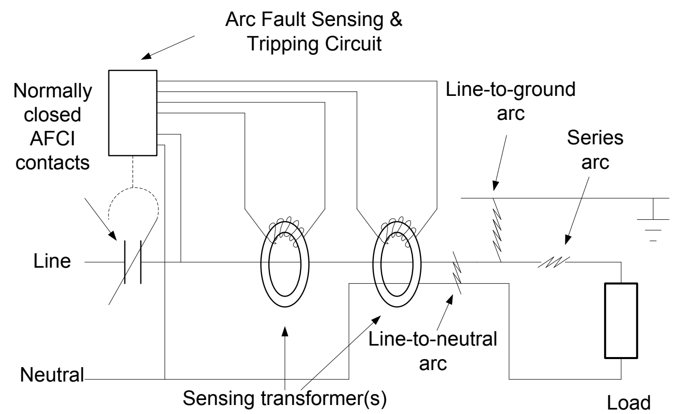


Fig. 1.Typical AFCI sensing arrangement [13].

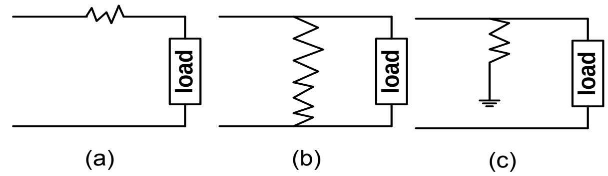


Fig. 2. Three arc fault types(a) series (b) line-to-line (neutral) (c) line-to-ground [14].

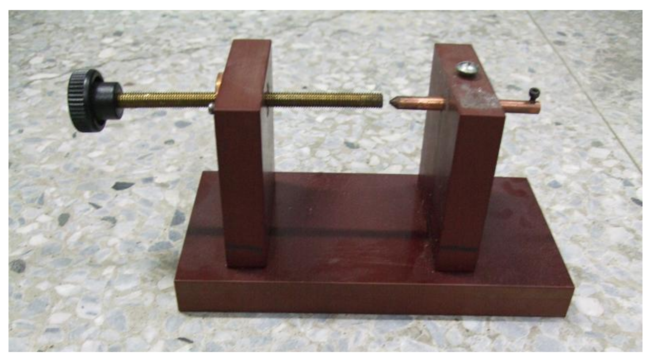


Fig. 3. Photograph of artificial series arc fault generator.

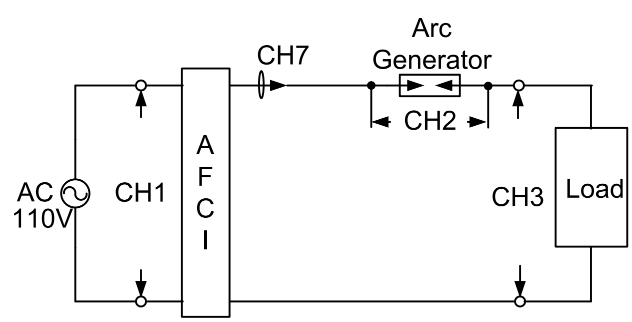


Fig. 4. Test circuit for series arc fault test.

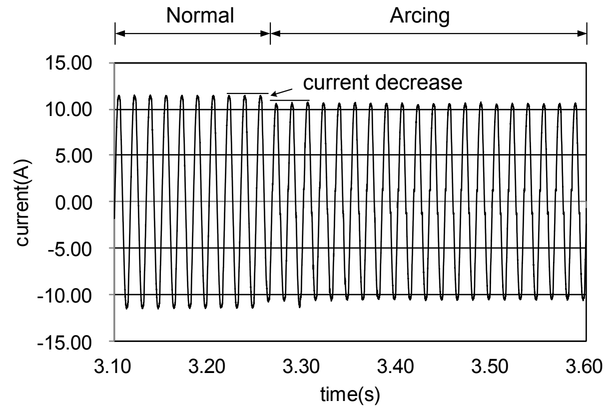


Fig. 5. Measurement of line current under series arc fault of the circuit feeding hair dryer load.

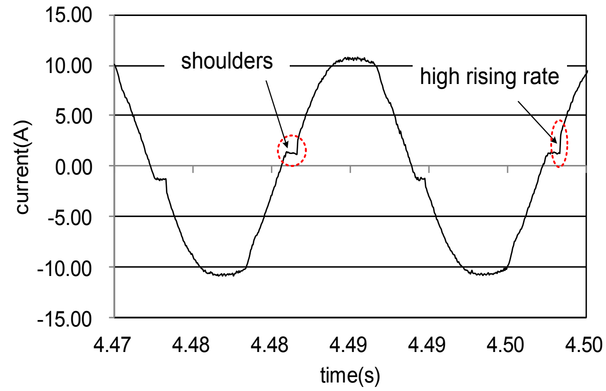


Fig. 6. Typical current waveform with series arc fault.

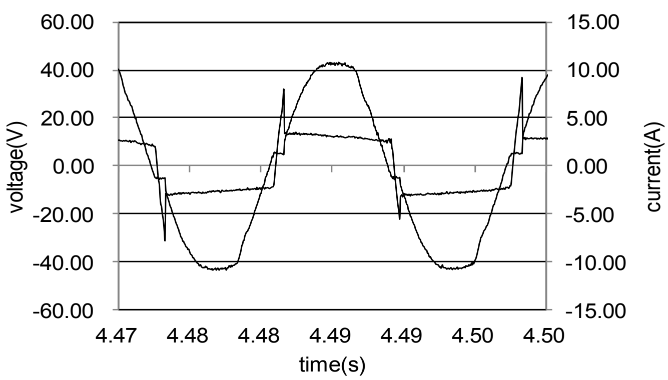


Fig.7. Arc voltage and current of series arc fault.

IV. Characteristics of Series Arc Fault Current

From the literature [13-14] and the experimental data in this paper, the following characteristics of series arc fault currents can be obtained.

1. Compared with the normal current waveform, the peak values of the series arcing current waveform are decreased, as shown in Fig. 5 of a test circuit feeding hair dryer load.
2. When series arc fault occurs, there are a few high-frequency components in the arc voltage and line current waveform.
3. The line current has high rising rate components during the zero-crossing zone as shown in Fig. 6.
4. Every half cycle, line current will present a shoulders phenomenon as shown in Fig. 6.
5. The arc voltage looks like a square-wave as shown in Fig.7.
6. The series arc fault is momentary, that is, arc fault current is interspersed in the normal current.
7. The duration of series arc fault period has several power cycles. In the conditions of switch operation and or the plug operation, the transient time is very short.
8. Arc voltage is not the same in each cycle, therefore when arc fault occurs, the load current in each cycle is changing.
9. The current waveforms of fluorescent lamps with electronic ballasts and computers have distorted components. The distorted characteristics in the normal line current should not cause malfunction. The harmonic currents and series arc fault currents are different.

V. Spectrum Energy of Line Current with Series Arc Faults

Figure 8 reveals the spectral of line current under series arc fault of the circuit feeding fluorescent lamp and resistor load. In the each cycle of the four cycle periods, the high-frequency (above 1k Hz) components of each cycle are changing. But in normal operation, it does not have this phenomenon.

In order to detect the arc fault by the spectrum energy analysis, at first, let us define the spectrum energy E of line current I_n for frequency equal or greater than frequency f_n as

$$E = \sum_{f \ge f_n} I_n^2 \tag{1}$$

The relative changes of the spectrum energy in cycle k, S_k, is

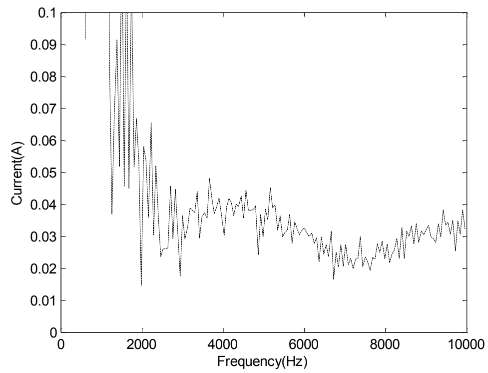
$$S_k = \left| \frac{E_k - E_{k-1}}{E_k} \right| \tag{2}$$

Then the score of cycle k, x_k, is determined by

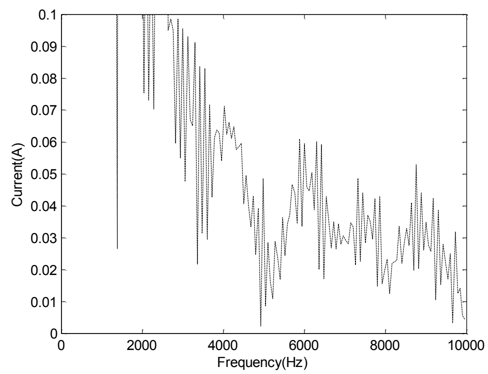
$$\begin{array}{ll} \text{If } S_k \le m_1 & \text{Then } x_k = b_1 \\ \text{If } m_1 < S_k \le m_2 & \text{Then } x_k = b_2 \\ \text{If } m_2 < S_k \le m_3 & \text{Then } x_k = b_3 \\ \text{If } m_3 < S_k & \text{Then } x_k = b_4 \end{array} \tag{3}$$

Where $m_1, m_2, m_3, \beta_1, \beta_2, \beta_3, \beta_4$ are selected coefficients. Then the total score of H cycles is,

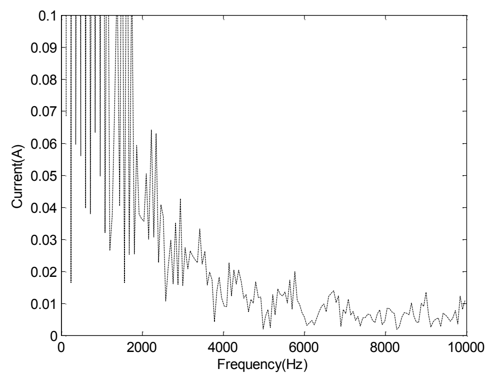
$$X_H = \sum_{k=n}^{H} x_k \tag{4}$$



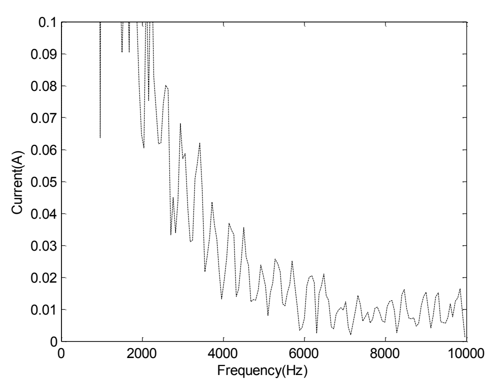
(a) first cycle



(b) second cycle



(c) third cycle



(d) fourth cycle

Fig.8. Spectral of line current under series arc fault of a circuit feeding fluorescent lamp and resistor load.

If 16 cycles are used to determine the total score, the coefficients are as follows:

$$f_n = 1000\,\text{Hz} ,$$

$$E = \sum_{f \geq 1000} I_n^{\ 2} ,$$

$$H = 16 ,$$

$$X_{16} = \sum_{k=1}^{16} x_k$$

$$\begin{array}{l} \text{If } S_k \leq 0.3 \text{ Then } x_k = 0 \\ \text{If } 0.3 < S_k \leq 0.5 \text{ Then } x_k = 1 \\ \text{If } 0.5 < S_k \leq 1 \text{ Then } x_k = 3 \\ \text{If } 1 < S_k \text{ Then } x_k = 5 \end{array}$$

In this paper, if the total score is greater that 25, it indentify that the occurring of series arc fault.

VI. Effect of Filter of Current with Series Arc Fault

It has been reveal in the literature [15] that the rising current edge after arc re-ignition is quite steep with rise time from 10 to 100 μs. The steep rise edge is equivalent to the frequency of about 2kHz to 5kHz.

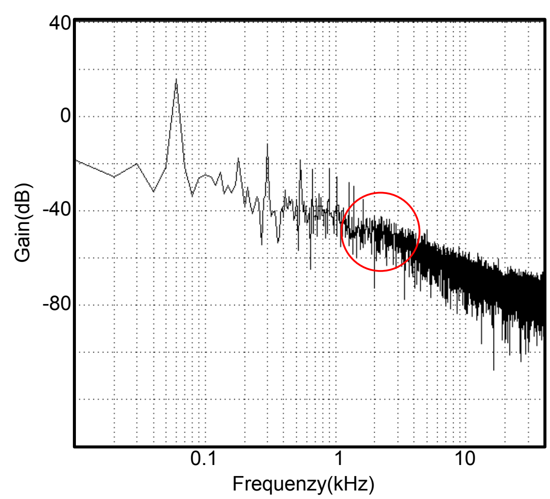
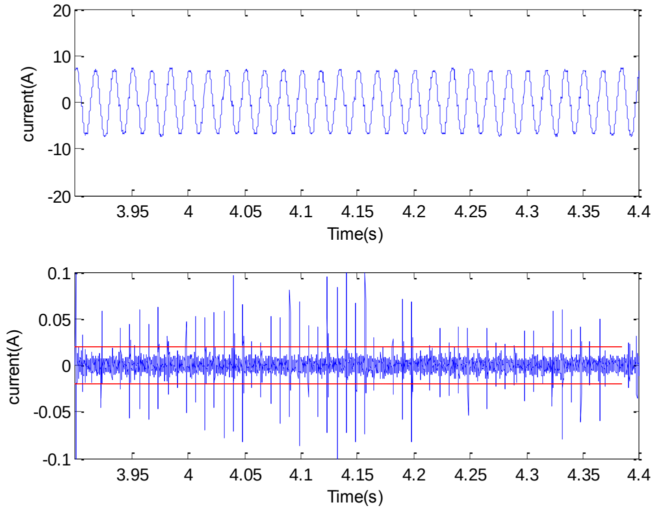
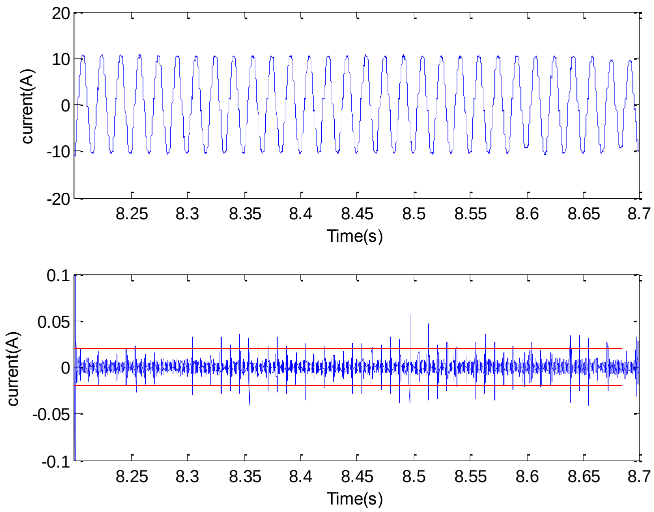


Fig.9. Spectrum of line current with series arc fault of a circuit feeding hair dryer load (the decreasing trend being changed between 2 kHz to 5kHz).



(a) electric cooker + resistor



(b) hairdryer

Fig.10. Original line current waveform with series arc fault and filtered current waveform of a circuit feeding load (dotted line: ±0.02 for border value).

The frequency spectrum of line current with series arc fault of a circuit feeding a hair dryer is shown in Fig. 9. It is observed that the decreasing trend is changed during 2 kHz to 5 kHz. Therefore it is to design a band-pass filter with the low cut-off frequency in 2kHz and the high cut-off frequency in 5kHz. The line current waveforms with series arc fault of a circuit feeding two types of load are given in Fig. 10. The sampling frequency is 20 kHz, and the sampling time is 50 μs. So it is concluded that the number of steep rising edge of the data may be the first sampling to the third sampling. Consider the harmonic components of rice cookers and hair dryers, the current waveform after filtering should be easily to examine the occurring of arc fault. If some peak values of the waveform after filtering are greater than a set value γ, it means that there are steep rising edges after zero crossings in line current waveforms. This characteristics can be used to detect the occurrence of series arc fault.

The current filter detection method is described. For the filtered current waveform A(k), the value of a(k) at the k-th sampling is determined by

$$a(k) = \begin{cases} 1 & \text{if} \quad |A(k)| > \gamma \\ 0 & \text{if} \quad |A(k)| \le \gamma \end{cases} \tag{5}$$

Each power cycle, there are 333 samples. The H_n is cumulative value of a(k) of the n-th cycle.

$$H_n = \sum_{k=[(n-1)\times 333]+1}^{333\times n} a(k) \tag{6}$$

If four cycle is used as a window to determine the score of the m-th window, then

$$W_m = \sum_{n=m}^{m+3} H_n \tag{7}$$

The decision of occurrence of series arc fault is to determine the value of F by

$$F = \begin{cases} 1 \ \text{if} \ \{H_n > \alpha \ \cup \ H_{n+1} > \alpha \ \cup \ H_{n+2} > \alpha \ \cup \ H_{n+3} > \alpha\} \cap W_m > \beta \\ 0 \ , \ \text{others} \end{cases} \tag{8}$$

To use the steep rising edge characteristic, if the H_n is greater than α in any one of the four cycles and the total score of four cycles, W_m, greater than β above, then F is equal to 1. It means the occurrence of series arc fault. In this paper γ =0.02, α=4, and β=15 are chosen.

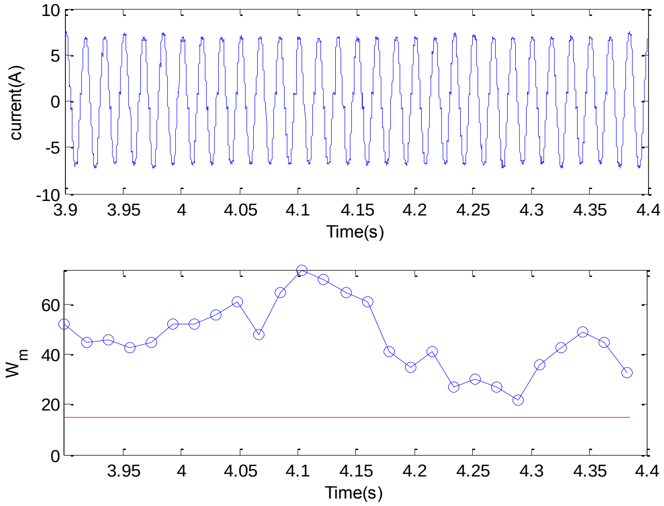
VII. Detection Results

In the test, the circuit feeding load conditions include (a) hair dryer (850W), (b) fluorescent lamp (electronic ballast) (23Wx8) and resistor (443W), (c) electrical rice cooker (600W) and resistor (100W), and (d) mixed load, including computer (300W), fluorescent lamp (electronic ballast) (23Wx3), electric rice cooker (600W), fans (60W), and refrigerator (228W).

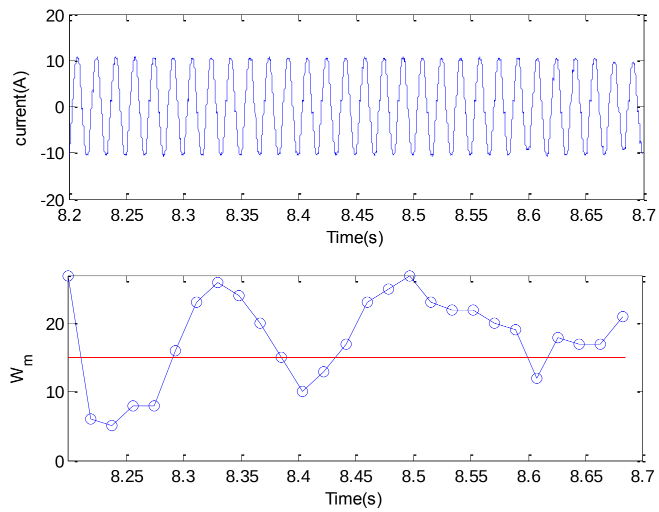
The spectrum energy and current filter approaches are compared with the commercial AFCI. In order to avoid malfunction, the detection method also contains two rules: (1) Load current rms value is greater than 5A. (2) The relative change in RMS current is less than 0.1.

Fig. 11 gives the analysis result of the line current waveforms in time-domain. For the condition feeding the electric rice cooker, it can quickly determine within four cycles the occurrence of series arc fault. Fig. 12 shows analysis result of line current waveform in frequency domain. If the load is fluorescent lamps or mixed load, the X_H value in frequency domain is higher. It was found that the frequency domain approach is more suitable for the conditions feeding harmonic load.

TABLE II-V show the test results of the circuit feeding four difference load. It is found that the purposed method in this paper is better than the commercial AFCI.

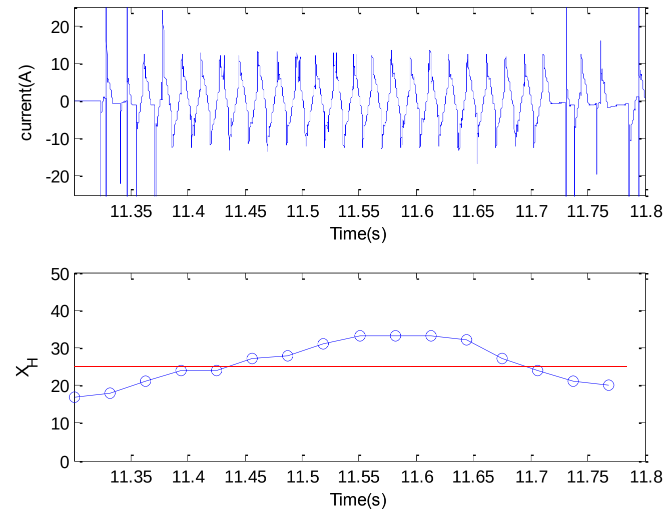


(a) electric cooker + resistor

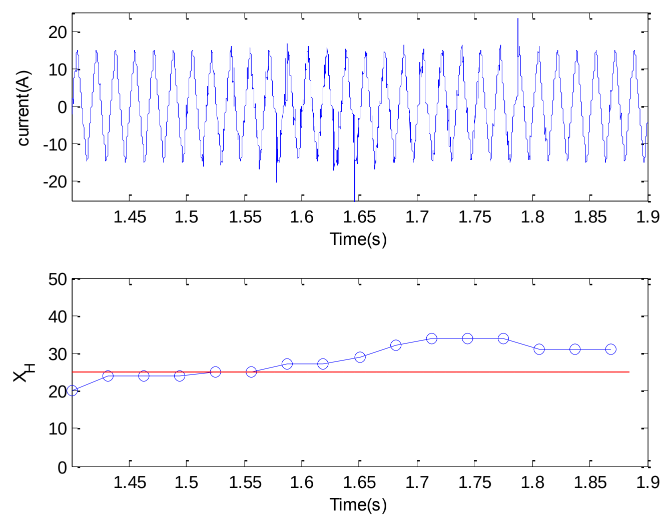


(b) hairdryer

Fig.11. Analysis result of the line current waveforms in time-domain.



(a) fluorescent lamp + resistance



(b) mix load

Fig.12. Analysis result of line current waveform in frequency domain.

VIII. Conclusion

The spectrum energy approach and current filter approach are both used in this paper to detect the occurrence of series arc fault. The variation of spectrum energy is adapted in the frequency domain. And the characteristics of steep rising edge is adapted in the time domain. The characteristics of line current with series arc fault should be well studied at first. The additional rules (1) Load current rms value is greater than 5A, and (2) The relative change in RMS current is less than 0.1 can avoid the malfunction of the detection approach. The experiment results show that the purposed method in this paper is better than commercial AFCI. The malfunction rate is low.

TABLE II
TEST RESULTS OF CIRCUIT FEEDING HAIR DRY

Test condition	Commercial AFCI	Current filter method	Spectrum energy method
Normal load	NO	NO	NO
Switching 1	NO	NO	NO
Switching 2	YES	NO	NO
Pulling or pushing of plug	NO	NO	NO
Series arc fault 1	NO	YES	NO
Series arc fault 2	NO	YES	NO
Series arc fault 3	YES	YES	NO

TABLE III
TEST RESULTS OF CIRCUIT FEEDING FLUORESCENT LAMP AND RESISTOR

Test condition	Commercial AFCI	Current filter method	Spectrum energy method
Normal load	NO	NO	NO
Switching 1	YES	NO	NO
Series arc fault 1	YES	NO	NO
Series arc fault 2	YES	NO	YES
Series arc fault 3	YES	NO	YES

TABLE IV
TEST RESULTS OF CIRCUIT FEEDING RICE COOKER AND RESISTOR

Test condition	Commercial AFCI	Current filter method	Spectrum energy method
Normal load	NO	NO	NO
Switching 1	NO	NO	NO
Series arc fault 1	NO	YES	YES
Series arc fault 2	NO	YES	NO

TABLE V
TEST RESULTS OF CIRCUIT FEEDING MIXED LOAD

Test condition	Commercial AFCI	Current filter method	Spectrum energy method
Normal load	NO	NO	NO
Series arc fault 1	NO	NO	YES
Series arc fault 2	NO	NO	YES
Series arc fault 3	NO	NO	YES

ACKNOWLEDGMENT

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Biographies

Shu-Chen Wang was born in Taiwan, 1969. She received the B. Sc., M. Sc., and Ph.D. degree from the Department of Electrical Engineering, National Taiwan Ocean University in 1992, 1994, and 2007, respectively. Currently she is an associate professor in the Department of Computer and Communication Engineering, Taipei College of Maritime Technology. Her current research interests include fuzzy theory, control system, and power system dynamics.

Chi-Jui Wu received the B. Sc., M. Sc., and Ph.D. degree in electrical engineering all from the National Taiwan University in 1983, 1985, and 1988, respectively. In 1988, he joined the Department of Electrical Engineering, National Taiwan University of Science and Technology as an associate professor. Now he is a full professor. He has been active in practical problems and got many projects from private companies, independent research institutes, and governments. His current research interests lie in electric power quality, power electromagnetic interference, and power system stability.

Yi-Jie Wang was born in Taiwan, R.O.C. in 1988. He received the B. Sc degree in the Department of Industrial Education and Technology from the National Changhua University of Education, Taiwan, R.O.C. in 2010. He is currently a Ms. C. student in the Electrical Engineering Department, National Taiwan University of Science and Technology. His major research fields are power quality analysis and arc fault detection in electric power systems.