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Hardware implementation of series DC arc fault protection using fast Fourier transform

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ABSTRACT

This paper proposes method of series direct current (DC) arc fault protection using low cost microcontroller. Series DC arc fault occurs when gap between conductor or wire flows a current. Series DC arc fault can cause fire hazard if do not detected and protected. However, Series DC arc fault is difficult to detected using conventional protection. To detect series DC arc fault accurately using fast Fourier transform (FFT). FFT is used to transform signal in time domain to frequency domain. Series DC arc fault has different characteristic compared by normal current in frequency domain. Therefore, the proposed algorithm for protection of series DC arc fault based on magnitudes of the current in frequency domain. Hardware system is implemented by 100 V DC power supply and DC arc fault generator. Test result is conducted experimentally under varying of load current such as 2 A, 2.5 A, 3 A, 3.5 A, 4 A and 5 A. Experimental testing results show that Series DC arc fault protection has time for trip of 0.48 s, 0.26 s, 1.04 s, 0.68 s, 0.44 s and 0.48, respectively. The fastest time for trip is 0.26 s with current of 2.5 A. Therefore, the proposed algorithm for series DC arc fault protection can operate to trip accurately and have the good performance.

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1. INTRODUCTION

Direct current (DC) power supply is used many to industry such as electric vehicles, aerospace industry, solar power plant and energy storage device [1], [2]. Enhancement of load demand causes voltage value of DC power supply increases to some hundred volts such as testing of cable isolation and DC motor for electric vehicle. DC arc fault has types of series and parallel and it occurs in DC distribution system, solar power plant, microgrid and so on. Series DC arc fault is caused by gap of electrical connection and insulation aging of wires. Moreover, series DC arc fault may result of fire accident and system failure in the DC system. Enhancement of DC arc fault is caused by equipment requirements for DC voltage. However, Series DC arc fault more difficult to detect than series AC arc fault becausethe current waveform does not have zero crossing detector [3]. Hence, this paper proposes method to obtain detection accurately of characteristic of series DC arc fault.

Detection has an important role in protects of series DC arc fault [4]. The accurate detection is required to obtain accurate protection from series DC arc fault. There are conventional techniques to detection of series DC arc fault. For example, Physical indication can be seen when arcing process such as light and temperature [5], [6]. However, physical indication difficult to implemented because do not know happen of series DC arc fault and physical indication changes corresponding of series DC arc fault. Many techniques of series DC arc fault detection are developed. Detection of arc fault based on change of current or voltage waveform [7], [8]. However, may be the change of current or voltage waveform is caused by other case as well as load change, motor starting, harmonics, which can lead to wrong judgment. Method often be applied for arc fault detection is frequency domain analysis [9]-[11]. Many methods play in frequency domain analysis, one of them is fast Fourier transform (FFT) [12]-[14]. FFT is used because easy implementation and fast computation [15]-[17]. Moreover, FFT can detect DC arc fault accurately. However, many paper using FFT to arc fault detection but FFT is operated in offline mode [18]-[20]. Therefore, the contribution in this research is detection DC arc fault using FFT in realtime mode.

Arc fault is physical phenomena that can cause significant damage. Solar power plant and DC system are sensitive exposed to arc fault. Moreover, according to national electricity code (NEC) that DC system with value of maximum voltage more than 80 V should be equipped by protection of DC arc fault [21]. Therefore, arc fault protection is very required for safe system [22]. Protection using overcurrent relay is not able to protect DC series arc fault [23]. However, characteristic of series DC arc fault is the current does not rise high. So, overcurrent relay does not detect of series DC arc fault. To prevent arc fault, this paper develops hardware system to protect of series DC arc fault. Hardware system consists of microcontroller, relay and other components. Identification of series DC arc fault using FFT as algorithm to determine events of series DC arc fault. To obtain the good performance of series DC arc fault protection, the proposed algorithm is introduced by input of magnitudes of the current in frequency domain.

2. THE PROPOSED METHOD

Many methods have been proposed to series DC arc fault detection [4]-[10]. Conventional method to detection of series DC arc fault using physical phenomena. This method requires hardware system but difficult to detect of series DC arc fault because does not know when occurs of series DC arc fault. Detection of series DC arc based on the change of voltage and current is introduced in the time domain. However, the change of voltage and current may be caused by overvoltage, harmonic and the other faults, which affects error identification. Series DC arc fault has characteristic with magnitude appears in frequencies other than 50 Hz. To obtain detect accurately of DC series arc fault using FFT, which it can transform signal in time domain to frequency domain. Series DC arc fault in frequency domain becomes easy to be analyzed. In many papers, FFT is operated in offline mode. Therefore, the contribution in this research is detection DC arc fault using FFT in realtime mode.

To prevent series DC arc fault causes fire hazard, fast and accurate protection is required. FFT has characteristics easy implementation, accurate result and fast computation, which suitable as method to protect series DC arc fault. In this paper, protection of series DC arc fault is implemented by hardware system, which consists of microcontroller, series DC arc fault generator, current sensor and relay. Arm STM32F7 is chosen as microcontroller to run the proposed method. Arm STM32F7 is equipped by 12-bit A/D converter and frequency of 167 MHz so that it has good performance for analyze of series DC arc fault. Moreover, Arm STM32F7 supports series DC arc fault protection to be operated in real time mode.

3. RESEARCH METHOD

3.1. Hardware system

Hardware system and algorithm are presented in this section. In this Figure 1, show circuit of series DC arc fault detection. The circuit comprises DC power supply, series DC arc fault generator, load resistor. The series DC arc fault generator consists of two electrodes each other. There are static electrode and active electrode. The active electrode is controlled manually. The active electrode moves to simulate the series DC arc fault. The current of 0.5 A is capable create DC arc fault. Whereas, the current of 2 until 10 A has very high temperature. Therefore, arc generator is designed to capable withstand high temperature.

For emulate of series DC arc fault require materials, which can be represented in Table 1. DC power supply for series DC arc fault is operated 100 V with variations currents of 2 to 5 A. In Figure 2, represent of series DC arc fault generator. Hardware system for protection of series DC arc fault based on NEC standard. In the NEC standard, explaine 4 conditions for protection of series DC arc fault. In the Table 2, show 4 conditions for protection of series DC arc fault.

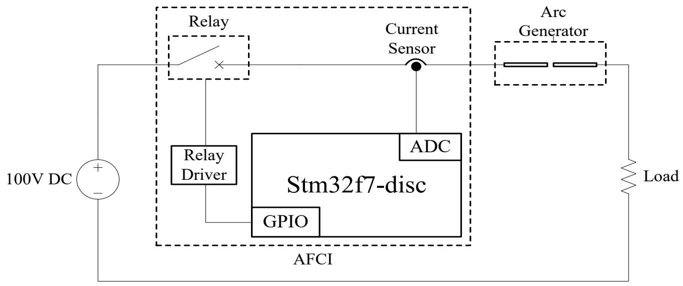


Figure 1. Circuit of series DC arc fault detection

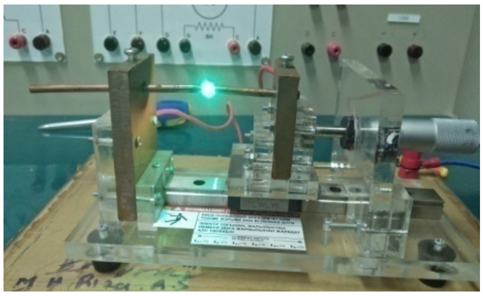


Figure 2. Series DC arc fault generator

Table 1. Materials for DC series arc fault

Electrode material	Copper rod of 3.5 mm
Load	Resistive
Power Supply (V)	100 V
Current (A)	2, 2.5, 3, 3.5, 4, 4.5, 5
Gap Length (mm)	2.5

Table 2. NEC standard of DC arc fault

Current (A)	Arc (Watt)	Electrode gap (mm)	Clearing time (seconds)
7	300	1.6 mm	2
7	500	4.8 mm	1.5
14	650	3.2 mm	1.2
14	900	6.4 mm	0.8

3.2. DC series arc fault detection

Detection has important role to obtain protection accurately. To guarantee protection accurately require three stages detection. The first, detection when the electrode contact is closed. The second, detection when the electrode gap starts to open and occurs arc fault. The third, detection when protection operate to isolate arc fault. In the Figure 3, show three stages detection of series DC arc fault. Fast Fourier transform (FFT) is used to detection of DC series arc fault [24].

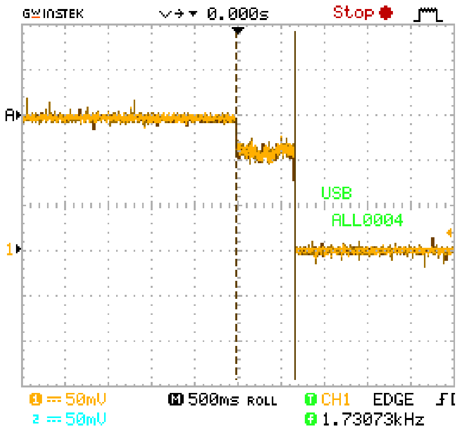


Figure 3. Three stages detection os series arc fault

FFT is method often be used to signal processing because FFT can decrease the computational complexity of discrete Fourier transform (DFT) [25]. FFT convert the sampled DC series arc signals in time domain to frequency domain. Frequency sampling and numbers of data for detection of DC series arc fault are 250 kHz and 100 data, respectively. FFT has windowing is fix with number is 100 data. FFT equation can be obtained from DFT [26]. Equation of DFT can be seen in (1). Signal input is represented by $X(t)$. Whereas, output DFT is represented by $X(f)$.

$$X[f] = \sum_{n=0}^{N-1} x[n] \cdot W_N^{fn} \quad (1)$$

$$W_N = e^{-j(2\pi/N)} \quad (2)$$

DFT equation is divided by two equations namely even equation and odd equation. In (3) and (4) show even and odd equations, respectively.

$$X_{Even}[f] = \sum_{n=0}^{(N/2)-1} x[2n] \cdot W_N^{2nf} \quad (3)$$

$$X_{Odd}[f] = \sum_{n=0}^{(N/2)-1} x[2n+1] \cdot W_N^{(2n+1)f} \quad (4)$$

for n=0,1,2,3,…,N-1

The above equation can be rearranged as follow:

$$X[f] = \sum_{n=0}^{(N/2)-1} x[n] \cdot W_N^{nf} + W_N^{f} \sum_{n=0}^{(N/2)-1} x[n] \cdot W_N^{nf}, for\ n = 0,1,\ldots N/2-1 \quad (5)$$

$$X[f+N/2] = \sum_{n=0}^{(N/2)-1} x[n] \cdot W_N^{nf} - W_N^{f} \sum_{n=0}^{(N/2)-1} x[n] \cdot W_N^{nf}, for\ n = 0,1,\ldots N/2-1 \quad (6)$$

The result of FFT obtains magnitudes of signal in frequency domain [27], [28]. Magnitudes of signal in frequency domain are used to input the proposed algorithm

3.3. Proposed algorithm for protection of series dc arc fault

Protection of series DC arc fault requires identification of differences between normal current and series DC arc fault. Magnitudes of current signal in domain frequency is used to identification of series DC arc fault. In the Figure 4, show the proposed algorithm for series DC arc fault protection. The proposed algorithm operated in range 1-15 kHz. To determine identification of series DC arc fault, the proposed algorithm using average of magnitudes in range 1-15 kHz. The proposed algorithm instructs relay for trip when the average value of 1 mA for a current range of 2-5 A.

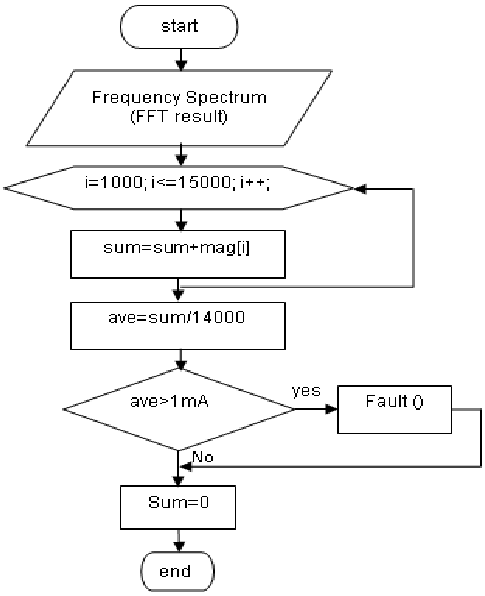
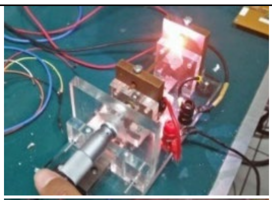
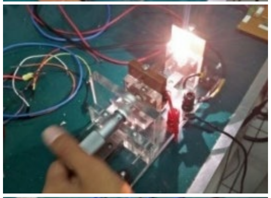
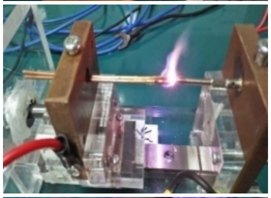
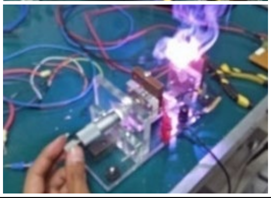


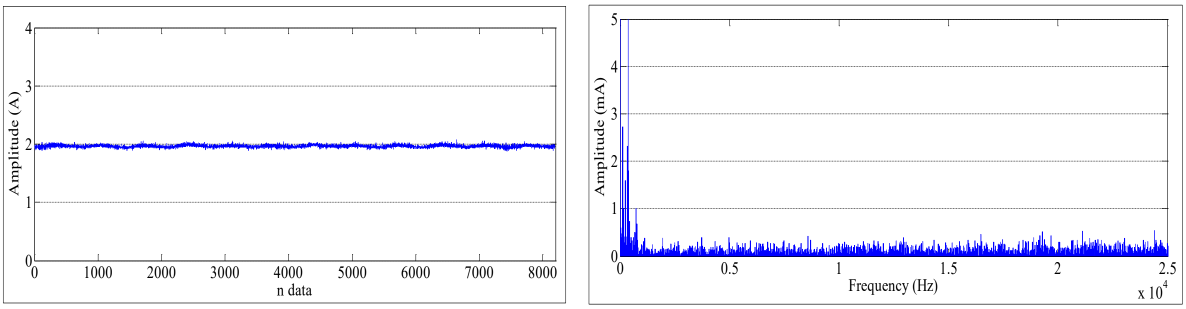
Figure 4. The proposed algorithm for series DC arc fault protection

4. RESULT AND ANALYSIS

In this section, the proposed algorithm for series DC arc fault is evaluated. Experimental is conducted to verify performance of the proposed method, which is implemented in hardware system. Arc fault generator includes main hardware system, which requires testing performance of arc fault generator in emulate of arc fault. In the Table 3, show testing performance of arc fault generator with current variations of 2, 3, 4 and 5 A. Moreover, Experimental Testing to evaluate the performance of the proposed method is conduted by current variations of 2, 2.5, 3, 3.5, 4 and 5 A, respectively. In the Figure 5, show testing of normal condition with current of 2 A. This current waveform is constructed by 8192 samples data in normal condition. The current waveform shows the little ripple of waveform. The current waveform is analyzed by FFT with transform in frequency domain. The result show that magnitudes of current have the value less than 1 mA in range of 1 kHz until 15 kHz. Whereas, in the Figure 6, show testing of series DC arc fault with current of 2 A. Waveform of series DC arc fault show that occurs ripple bigger than the current waveform in normal condition. Series DC arc fault with current of 2 A is analyzed by FFT. The result show that magnitudes of current have the value bigger than 1 mA.

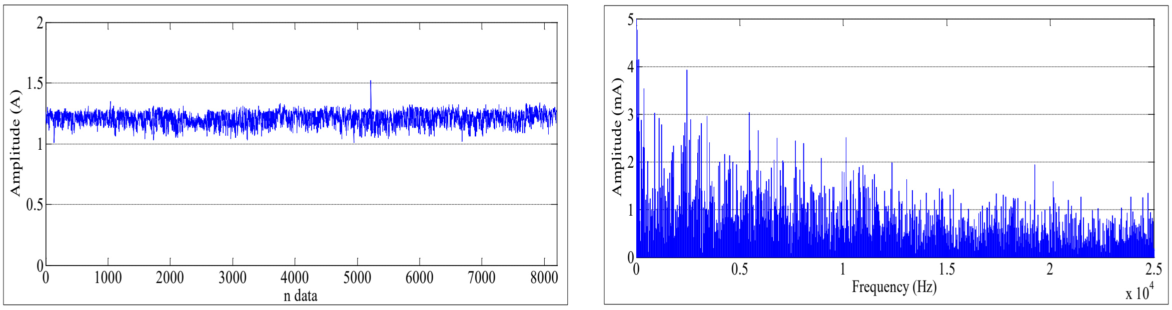
Table 3. Testing of arc fault generator with current variations

No	Current (A)	Arc Fault	Information
1	2		Series DC arc fault
2	3		Series DC arc fault
3	4		Series DC arc fault
4	5		Series DC arc fault



(a) (b)

Figure 5. (a) The current waveform of 2 A in normal condition, (b) The current spectrum of 2 A in normal condition

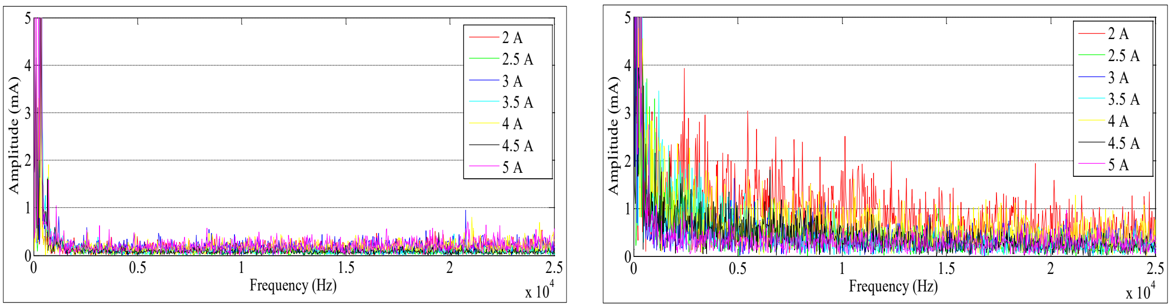


(a) (b)

Figure 6. (a) Series DC arc fault waveform of 2 A, (b) The series DC arc fault waveform spectrum of 2 A

In the Figure 7, the results of the normal current spectrum and series DC arc fault with the magnitudes current of 2 until 5 A show that series DC arc fault has magnitudes are bigger than the normal current waveform in frequency domain. Therefore, characteristic of series DC arc fault has the average values are bigger than 1 mA for a current range of 2 until 5 A in range of 1 kHz until 15 kHz. This characteristic becomes reference to develop the proposed algorithm for series DC arc fault protection.

Experimental testing is carried out to evaluated performance the proposed algorithm of series DC arc fault protection. Experimental testing is demonstrated in Figure 8. Experimental testing is equipped by digital storage oscilloscope for observe the series DC arc fault signal. Then, experimental testing conducts analysis signal when current in normal condition, when series DC arc fault and when relay operate to trip. Hardware system of series DC arc fault protection is operated can be shown in Figure 9. Series DC arc fault protection detects arc fault and operates relay to trip.



(a) (b)

Figure 7. (a) The normal current spectrum of 2 until 5 A, (b) The series DC arc fault spectrum of 2 until 5 A

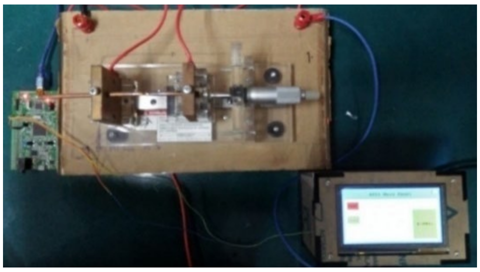


Figure 8. Experimental testing for series DC arc fault protection

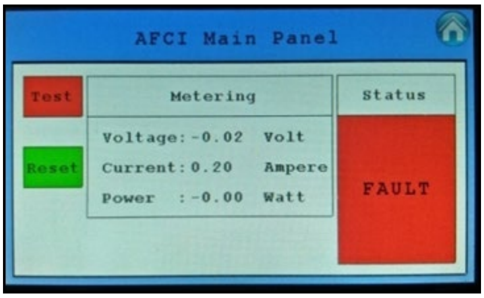


Figure 9. Display of series DC arc fault protection when fault

Experimental testing is conducted with voltage of 100 V and current is varied of 2 until 5 A. Experimental testing results show that the proposed algorithm for series DC arc fault protection can operate to trip accurately and have the good performance. Experimental testing results can be shown in Figures 10 (a)-(f), respectively. Series DC arc fault protection has time for trip of 0.48 s, 0.26 s, 1.04 s, 0.68 s, 0.44 s, 0.48, respectively. The fastest time for trip is 0.26 s with current of 2.5 A. Moreover, series DC arc fault protection using low cost microcontroller compared by NEC standard. The results show that time for trip under NEC standard in the Table 2.

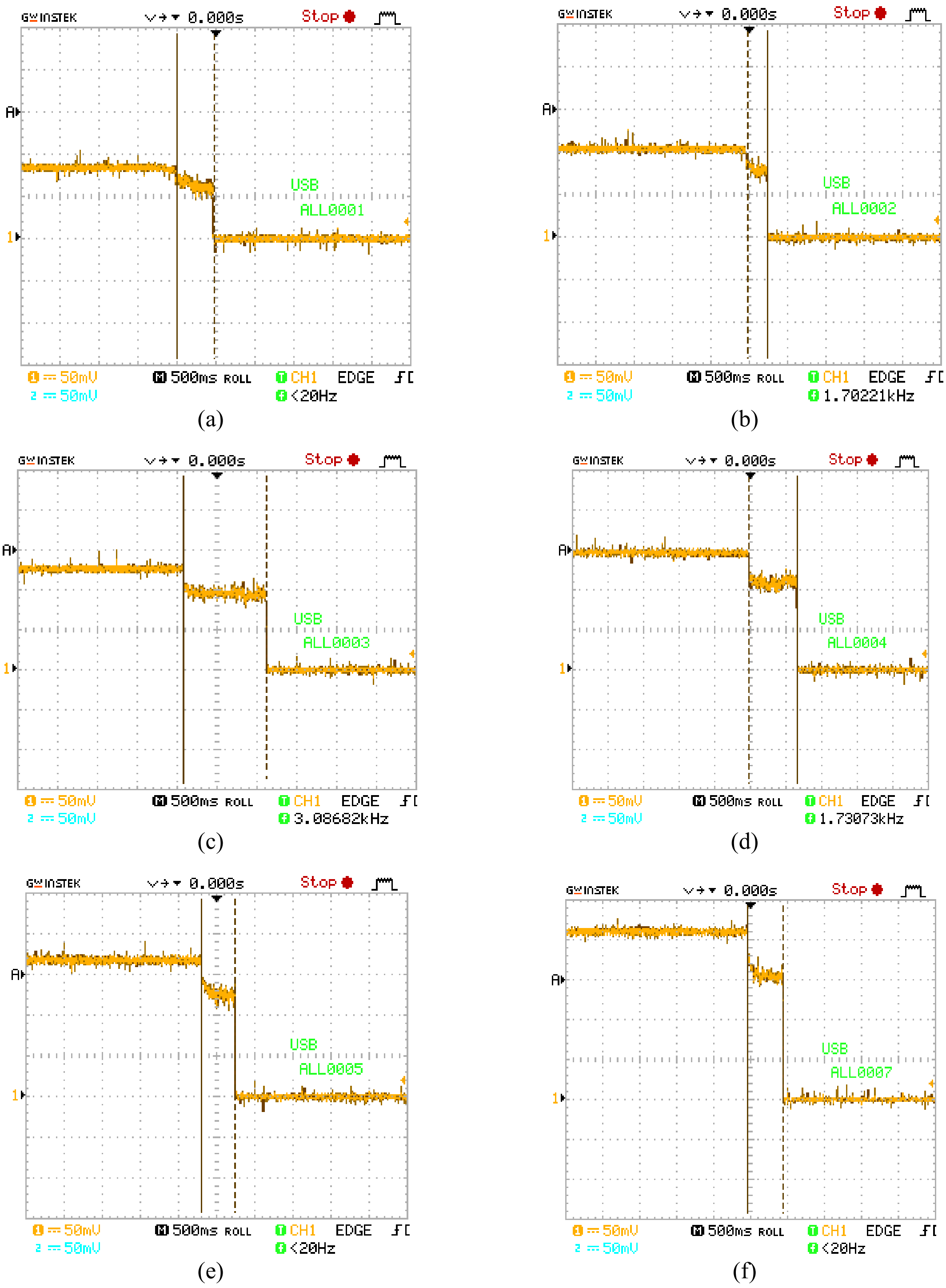


Figure 10. Experimental testing result of series DC arc fault of; (a) 2 A, (b) 2.5 A, (c) 3 A, (d) 3.5 A, (e) 4 A, (f) 5 A, respectively

5. CONCLUSION

This paper presents implementation of a proposed algorithm for series DC arc fault protection using low cost microcontroller. The proposed algorithm detects of series DC arc fault using FFT because series DC arc fault has difference characteristic of current in frequency domain compared by normal current. The proposed algorithm operates to trip when series DC arc fault occurs the average value bigger than 1 mA in range 1 kHZ until 15 kHz for 2 until 5 A. Experimental testing is carried out to evaluated performance the proposed algorithm of series DC arc fault protection with digital storage oscilloscope. Experimental testing conducts analysis signal when current in normal condition, when series DC arc fault and when relay operate to trip with be varied of 2 until 5 A. The experimental testing result show that series DC arc fault protection can operate to trip accurately and have the good performance with time for trip of 0.48 s, 0.26 s, 1.04 s, 0.68 s, 0.44 s, 0.48, respectively. Series DC arc fault protection using low cost microcontroller has time for trip under NEC standard. In the future, research develops hardware to identify of series DC arc fault location.

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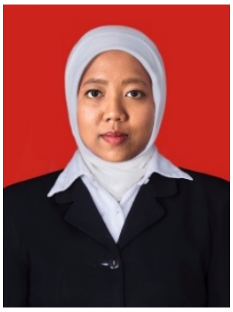

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