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Detection and analysis of series arc using non-conventional methods in low-voltage switchboards

Guoming Wang*, **Woo-Hyun Kim***, **Hong-Keun Ji****, **Gyung-Suk Kil***

Detection and analysis of series arc in low-voltage switchboards have significant meaning for preventing the electrical fires. However, the conventional current and voltage methods have low a sensitivity to sense the minute arc discharge, leading to the fail operation of arc fault circuit interrupter. Therefore, this paper dealt with the application of non-conventional methods, including the ultra-violet (UV), acoustic emission (AE), and transient earth voltage (TEV) sensor in arc detection, for the purpose of improving the detection sensitivity and reducing the potential electric fires. Three types of typical arc faults in low-voltage switchboards were simulated and the actual detection environment was configured. From the results, the wavelength of UV light emitted from arc was 200–400 nm and the arc-induced AE signal had a frequency range of 40–600 kHz. The TEV signals generated from three types of arc faults presented different frequency spectrums, based on which the time-frequency map was used to classify the fault type.

K e y w o r d s: series arc, non-conventional methods, ultra-violet, acoustic emission, transient earth voltage, time-frequency map

1 Introduction

According to the Underwriters Laboratories (UL) Standard UL 1699 and the International Electrical Commission (IEC) Standard IEC 62606, an arc is defined as a luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes [1, 2]. Arc is one of the main causes of electrical fires in low-voltage switchboards. It was reported by the National Fire Protection Associate that 16 % of the home structure fires from 2010 to 2014 that led civilian death were electrical reasons [3]. It was also presented by the National Fire Data System that electrical fires caused by the arc accounted for 39.3 % of the total 9 256 accidents in 2017 in Korea [4].

The three typical types of arc faults include series arc, parallel arc, and earth arc, among which the parallel and earth arc can be easily detected and the series arc occurs the most frequently [2, 5–7]. Although protection devices such as circuit breakers, fuses, and ground fault circuit interrupters are installed in low-voltage switchboards, they are not intended to protect the circuits from series arc faults [7–9]. An arc fault circuit interrupter (AFCI), which is intended to mitigate the effects of arc faults by recognizing characteristics unique to arc and by functioning to de-energize the circuit when an arc fault is detected, is required to be installed in residences for preventing fires [1, 10, 11]. The AFCI works based on discriminating the waveforms detected using the current and voltage sensors and by tripping the circuit when arc-related characteristics are monitored. However, the commercial AFCI performs correctly with a low reliability of 50 % [7, 8]. In addition, in case of the occurrence of minute arc, the arc features are usually easily masked when the conventional current and voltage methods are implemented owning to their low sensitivity. Consequently, the AFCI fails to trip and to protect from electrical fires.

In this paper, we discussed the detection and analysis of series arc faults using the non-conventional methods, as the ultra-violet (UV) detection, acoustic emission (AE) detection, and transient earth voltage (TEV) detection, for the purpose of improving the arc detection sensitivity and reducing the potential electric fires in advance.

2 Detection of series arc faults

In low-voltage switchboards, series arcs occur owning to the frayed cords or the loose connection, such as damaged cords (cord-cord), poor connection between termination and terminal block (termination-block), and point contact between plug and receptacle (plug-receptacle). Owing to the series connection of this type of arc faults with the loads and the existence of arc impedance, the arc current is lower than the rated current of loads. However, the heat released from arc reaches a temperature up to 13 000 K and the energy is sufficient to cause ignition of the combustible material. Arc may cause fire by the means of the formation of a carbonized path between electrodes or the point contact of electrodes [12, 13].

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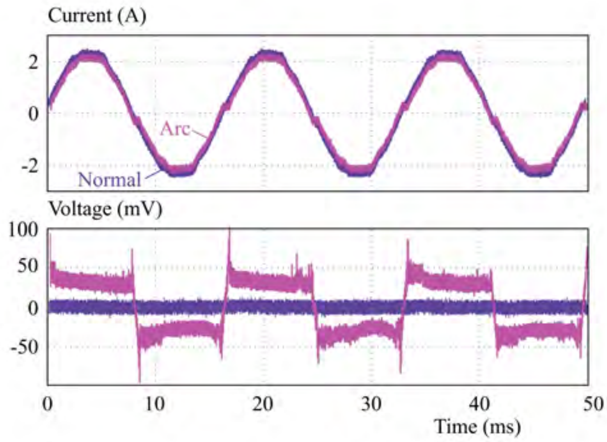

Fig. 1. Current and voltage waveforms of normal condition and arc fault

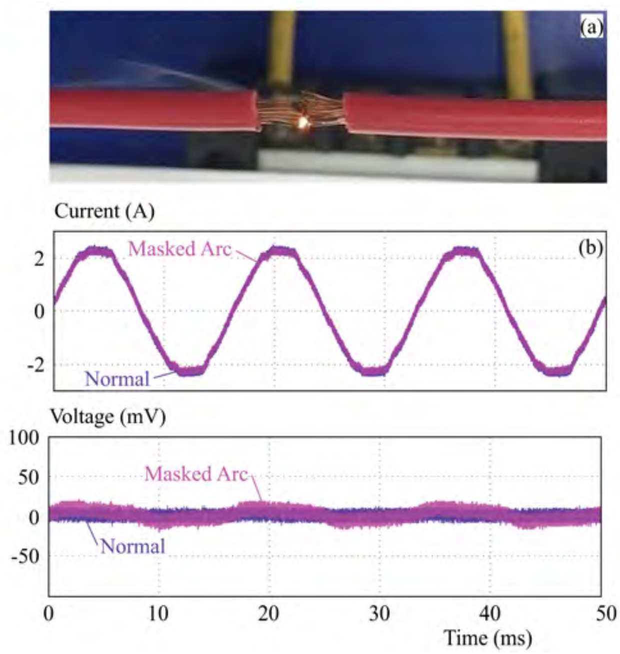

Fig. 2. Masked arc: (a) – occurrence of minute arc with smoke and high temperature, (b) – current and voltage waveforms

Aiming to prevent electrical fires, there have been many studies about arc detection, most of which are conventionally based on the current and voltage methods and fail to sense the masked arc [10, 14, 15]. With the increasing demand of safety in residential area and the rapid development of sensing technology, the non-conventional methods are expected to be applied for arc detection. Compared with the current and voltage methods, the non-conventional methods have advantages of high sensitivity, potential free measurement, and easy installation.

2.1 Current and voltage methods

Figure 1 shows the current and voltage waveforms of normal condition and common arc fault in a low-voltage circuit. It can be seen that the arc current is somewhat lower than the normal current as there is a voltage drop across the arc impedance. Shoulders appear near the zero crossing points of arc current waveform, where arc extinguishes owing to the insufficient voltage for sustaining the discharge. The voltage of normal condition is almost zero, whereas the arc voltage waveform appears nearly as a square wave and has a jumping increasing rate around the zero crossing point [10]. In addition, due to the distortion of waveforms, both the arc current and voltage signals contain high frequency components. The AFCI has the ability to identify the above electrical signatures related with the abnormal arc and to interrupt the circuit to avoid fires.

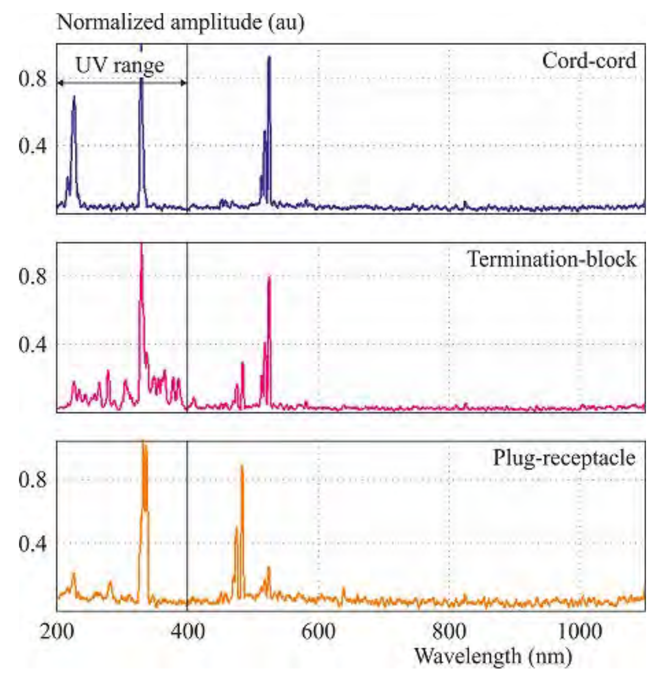

Fig. 3. Spectral distribution of light emitted from arc fault

However, in case the arc is very minute, the conventional current and voltage methods may fail to sense the arc fault and to trigger the AFCI. As shown in Fig. 2(a), arc occurs in a cord-cord, with a temperature high enough to burn the nearby combustible materials, whereas the arc waveforms detected by the current and voltage transformers shown in Fig. 2(b) are similar to that of the normal condition, where the unique arc signatures are masked. As a result, the AFCI cannot identify the arc signatures or trip the circuit.

2.2 Non-conventional methods

When arc occurs, it usually accompanies with various physical phenomena such as light, sound, and electromagnetic radiation, based on which the non-conventional sensors can be implemented [16].

Figure 3 shows the spectral distribution of light emitted from the cord-cord fault. It was detected using a high resolution spectrometer (AvaSpec-ULS3648) with a wavelength range of 200–1100 nm. The arc discharge is mainly in the UV spectrum with a wavelength of 200–400 nm.

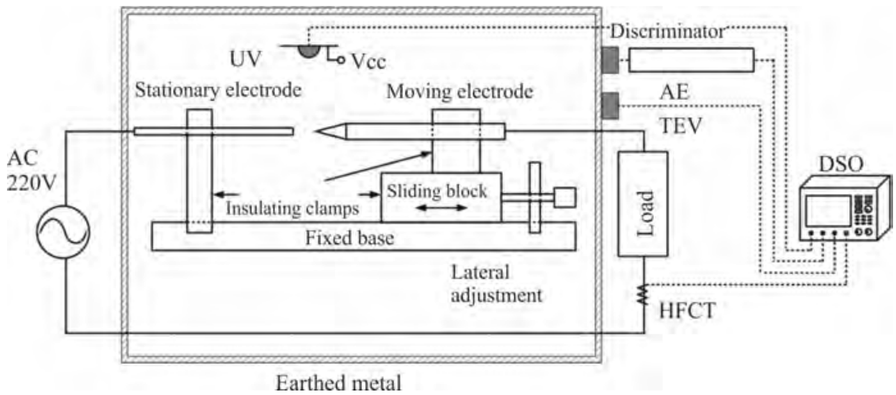

Fig. 4. Experimental setup

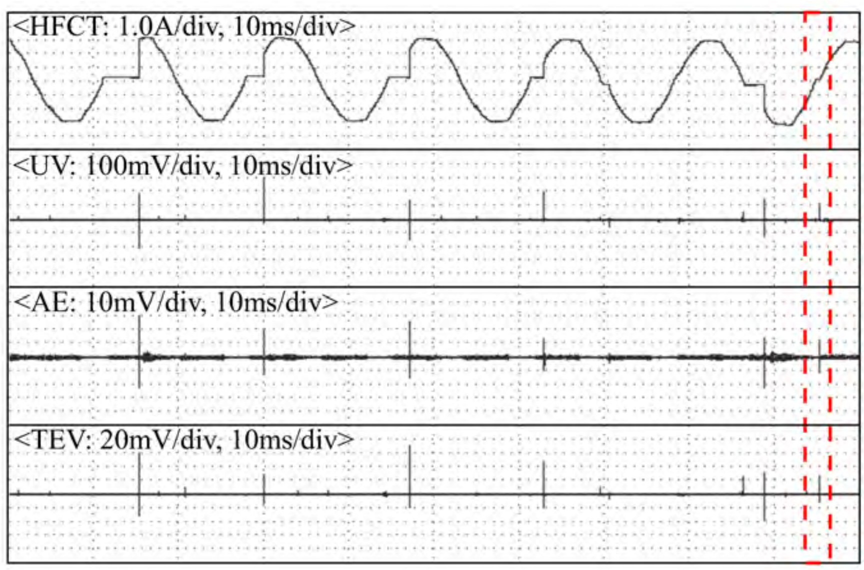

Fig. 5. Arc signals detected by HFCT, UV, AE, and TEV sensor

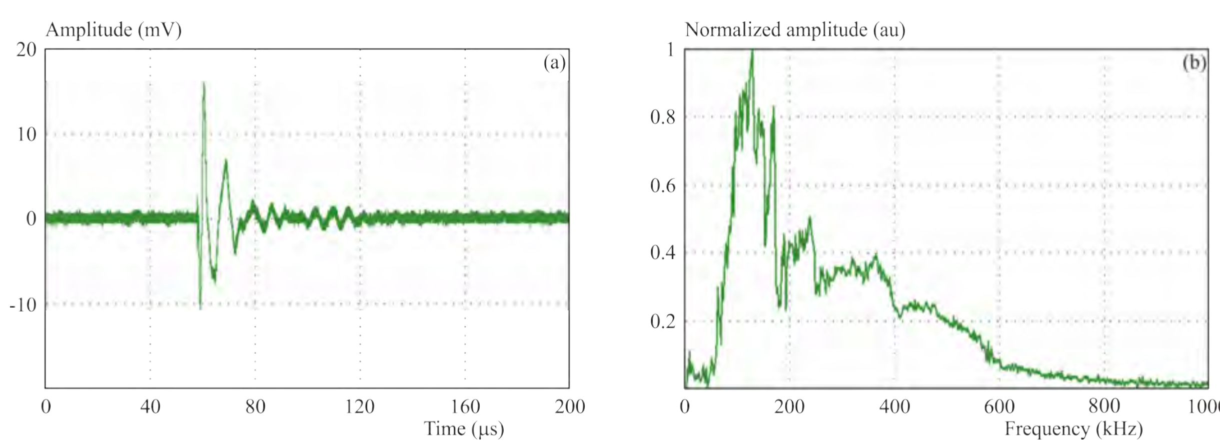

Fig. 6. Arc-induced AE signal: (a) – time-domain signal, (b) – frequency spectrum

Therefore, a UV sensor with a photoelectric element can detected arc discharge and the daylight blocking filter is preferable to improve its detection sensitivity.

The AE method has been widely used for fault detection [17, 18]. Its piezoelectric element can detect the ultrasonic waves generated by the rapid release of energy from arc discharge. Acoustic couplant is necessary to improve the transmission of acoustic energy across the interface. As the AE sensor is designed with only one bayonet but connector (BNC), a discriminator is needed, which consists of a decoupler to separate acoustic signal from power source and a low-noise amplifier to amplify the minute arc-induced AE signal.

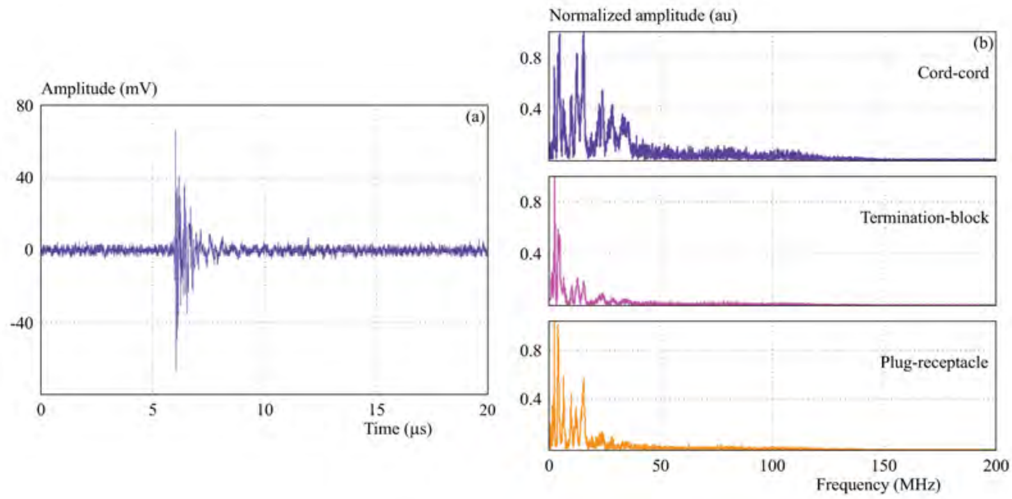

Fig. 7. Arc-induced TEV signal: (a) – time-domain signal in the cord-cord, (b) – frequency spectrums

When the electromagnetic wave propagates away from the arc discharge, it couples onto earthed metal surfaces of the switchboard and induces the TEV signal. Such signal can be detected by the TEV sensor mounted on the metal surface using the magnetic clamp. As the high frequency radiation has a range up to MHz, the TEV sensor is immunity against the low frequency noise.

3 Experiments and results

3.1 Experimental setup

The experimental setup is shown in Fig. 4. Three types of electrodes, including the cord-cord, termination-block, and plug-receptacle were fabricated to simulate the most frequent arc faults in the low-voltage switchboards. A 220 V AC mains and an arc generator were connected in series with a load. The arc generator designed according to UL 1699 was composed of a stationary and a moving electrode, which were used to fix the simulated arc source. The lateral adjustment was used to control the distance between the two electrodes such that current can flow in this circuit. The arc current signal was detected by a high-frequency current transformer (HFCT) with a frequency range up to 20 MHz. A UV sensor with a wavelength of 200–400 nm was used. An AE sensor with an operating frequency range of 20 kHz–1 MHz and a TEV sensor that has a frequency response of 1–200 MHz were attached to a earthed metal to detect the acoustic and TEV signals, respectively. This configuration was the same as the detection environment of arc in a switchboard, where the sensors can be easily installed. The signals were acquired using a digital storage oscilloscope (DSO) and further analyzed by LabVIEW program.

3.2 Result and analysis

Figure 5 shows the signals detected from cord-cord using HFCT, UV, AE, and TEV sensor in 6 cycles of the power-frequency voltage. It can be seen that the arc current waveform contains shoulders near the zero crossing points, where the non-conventional sensors also response to the arc discharge. However, very minute shoulder was observed on the last rising edge of the current waveform, which is too small to trigger the AFCI. On the contrary, arc was sufficiently detected by the non-conventional sensors.

An example of the arc-induced AE signal in the cord-cord is shown in Fig. 6. From the experimental results, the similar waveform and frequency spectrum were acquired in the termination-block and the plug-receptacle fault. This can attribute to the propagation path of arc-induced acoustic signal, all of which propagates through air in the switchboard. The AE signal generated from arc discharge has a frequency range of 40–600 kHz.

The arc-induced TEV signal in time-domain in the cord–cord is shown in Fig. 7(a). It was difficult to identify the difference between time-domain signals in the three types of faults. However, the frequency spectrums shown in Fig. 7(b) present distinguishable distributions. Arc TEV signal in the cord-cord has a frequency range of 1.4–37 MHz. The frequency ranges in the termination-block and the plug-receptacle are 4–17 MHz and 4–16 MHz, respectively. Due to the specific frequency spectrum of each arc fault, the TEV signals were further used to classify the type of fault using the time-frequency (TF) map.

4 Faults classification

Figure 8 shows the TF spectrograms of TEV signals that indicate the distribution of signal energy along with time and frequency [19, 20].

The signal energy (E) is defined as

$$E = \int_0^T |s)t)|^2 \mathrm{d}t \tag{1}$$

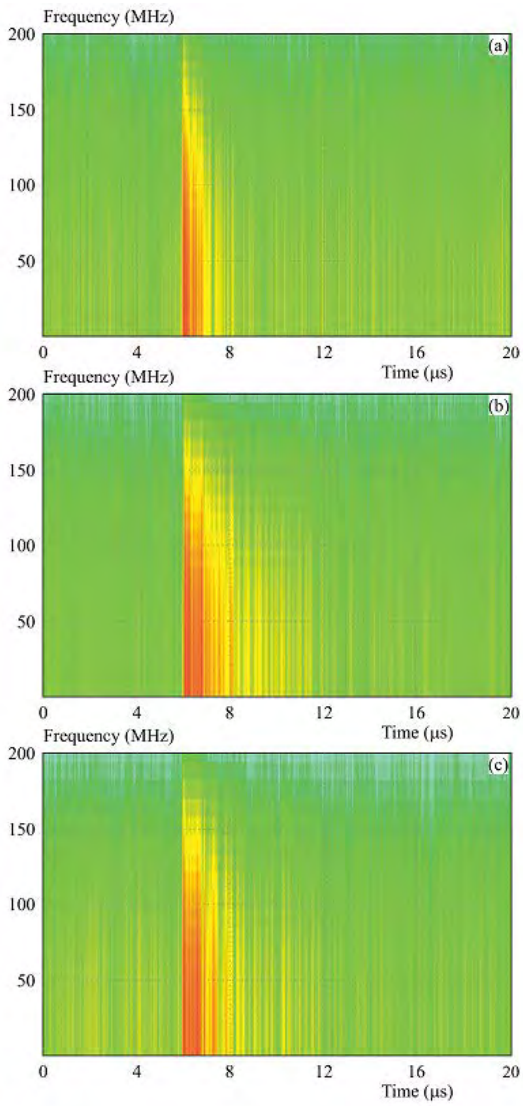

Fig. 8. TF spectrograms of TEV signals: (a) – cord-cord, (b) – termination-block, (c) – plug-receptacle

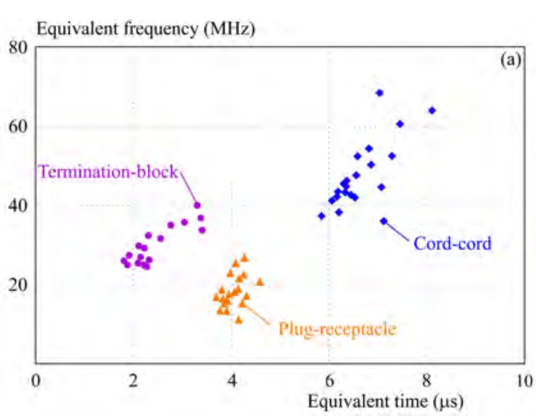

Fig. 9. TF map of TEV signals induced from series arc

where $s(t)$ is the acquired TEV signal. The central time (t_0) and central frequency (f_0) can be calculated by

$$t_0 = \frac{1}{E}\int_0^T t|s)t)|^2\mathrm{d}t, \tag{2}$$

$$f_0 = \frac{1}{2\pi E}\int_0^F f|S(f)|^2\mathrm{d}f \tag{3}$$

where $S(f)$ is the Fourier transform of the signal $s(t)$.

The TF map is the analysis of TEV signal in time and frequency domain by extracting the equivalent time (σ_T) and the equivalent frequency (σ_F) from each signal. σ_T and σ_F are the standard deviations which mean the effective range of time around the central time and the effective range of frequency around the central frequency, respectively. They are given by

$$\sigma_T = \sqrt{\int_0^T (t-t_)0)^2 s(t)^2\mathrm{d}t}\,, \tag{4}$$

$$\sigma_F = \sqrt{\int_0^T f^2|S(f)|^2\mathrm{d}f}\,. \tag{5}$$

Using the above equations, the σ_T and (σ_F) distribution of TEV signals induced from three types of faults can be presented in the TF map, which is shown in Fig. 9. Unique cluster was formed for a specific fault, therefore, the TF map can be used for classification of the type of arc fault.

5 Conclusions

In this paper, three non-conventional methods were used to detect the series arc in low-voltage switchboards, aiming to prevent the potential electrical fires. The UV, AE, and TEV sensor responded to the shoulder of arc current waveform. The light emitted from arc discharge distributed in the UV range with a wavelength of 200–400 nm. The AE signals generated from three types of arc faults had a similar frequency range of 40–600 kHz. The arc-induced TEV signals had distinguishable frequency spectrums depending on the type of fault with a frequency range of 4–37 MHz. By analyzing the TF map of TEV signal, the unique cluster can be used for classification the type of fault, which is helpful to find the existence of arc discharge promptly.

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