Usability of arc fault circuit interrupters with network function

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Abstract. The existing arc fault circuit interrupters have the function to interrupt overloads, ground fault, arc fault and all but neither is there the monitoring function to allow external monitoring nor the notification function to notify the fire safety manager. This is a study on arc fault circuit interrupters with the network function that have not been studied so far. We intend to install these arc fault circuit interrupters in places such as server rooms, pigsties, chicken farms, markets, cultural assets, skyscrapers, and factories where large loss may occur if the fire safety managers do not recognize the electricity shutdown in order to increase the efficiency of electricity management. If an overload, a short circuit or an arc is detected while power is supplied to the load, the microprocessor generates a trip signal and cuts off the power by this trip signal. This situation is monitored in real time by external monitoring and notified to the fire safety manager. The fire safety manager can immediately recognize the situation where the arc fault circuit interrupter interrupts the circuit and take the necessary action to manage the electricity efficiently.

KEYWORDS Network; Arc fault circuit interrupter (AFCI); Electricity management; External monitoring; Interruption cause analysis

1. Introduction

According to the statistics of Korea Electric Safety Corporation in 2015, 7,500 ~ 9,000 electric fires occur each year, accounting for about 20% of the total 40,000 ~ 45,000 fire counts in Korea. In terms of the causes of electric fires, it showed that electric sparks (arc fault) were the main cause of electrical fires as arc fault accounted for 78% of the causes of electric fires, followed by overloads accounting for 10.2% and ground fault accounting for 3.9% respectively while other causes accounted for 7.8% of the causes of electric fires [1]. Therefore, it is necessary to detect and interrupt the electric spark effectively in order to prevent electric fire. The electric spark can be caused by various reasons such as the electric wire's deterioration, the defective electric product and the electric wire's faulty contact. In the case of the electric spark, the temperature rises instantaneously to several thousands to tens of thousands Celsius degrees. It is very dangerous as it can cause fire in a few seconds. In the arc fire simulation results of the National Institute of Standards and Technology (NIST), it was observed that one room was burned in 40 seconds after leaving an arc fault without interrupting it [2]. There is a need to introduce arc fault circuit interrupters in Korea to prevent fire caused by electric sparks in advance. It is considered possible to secure safe electricity management if it is made possible to monitor the identification and the analysis of the interruption causes externally through the network.

Previous studies on arc fault or arc fault circuit interrupters include the work of Qi, P., Jovanovic, S., Lezama, J. and Schweitzer, P. (2017). They provided an in-depth analysis of the parameters for discrete wavelet transform (DWT) applied to detection of arc faults that

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could greatly improve arc defect detection performance. In their work, "Discrete wavelet transform optimal parameters estimation for arc fault detection in low-voltage residential power networks." The influence of three parameters was investigated: the choice of mother wavelet, level of decomposition and sampling frequency. A performance criterion was defined and used to compare the influence of 550 combinations of these three parameters on the arc fault detection performances for different loads, including two household appliances. The study showed that the right choice of these three parameters greatly influences the arc fault detection performances [3].

Guo, F., Li, K., Chen, C., Liu, Y., Wang, X. and Wang, Z. (2016) built a series arc fault generator according to UL1699 in their study on "Series Arc Fault Identification Method Based on Wavelet Approximate Entropy." Experiments were carried out under different load conditions. Loop current waveforms with and without series arc fault were obtained. Firstly, the current signal was decomposed and reconstructed by wavelet transform. Then the irregular degrees of signals in each frequency band were quantified with approximate entropy algorithm and the feature vectors of current signals were obtained. Finally, all the feature vectors were used as input variables of support vector machine (SVM). The series arc fault could be recognized by classifying those feature vectors with SVM. It was shown that the feature vectors obtained by wavelet approximate entropy algorithm could diagnose series arc fault [4].

Chae, S., Park, J. and Oh, S. (2016) described a detection algorithm for series DC arc faults to improve safety issues in DC microgrids in their paper, "Series DC Arc Fault Detection Algorithm for DC Microgrids Using Relative Magnitude Comparison." To identify series arc faults accurately and quickly in DC microgrids, a series DC arc fault detection algorithm using relative magnitude comparison is proposed. The proposed algorithm detects the time of occurrence of an arc fault based on the magnitudes of the load current in both the time and frequency domains simultaneously. The algorithm accurately works in a DC microgrid with multiple switching converters, as it relies only on relative current information [5].

Jovanovic, S., Chahid, A., Lezama, J. and Schweitzer, P. (2016) presented a novel method based on a single-phase active power filter (APF) for series arc faults detection in an AC electrical installation in their paper, "Shunt Active Power Filter-based Approach for Arc Fault Detection." The APF's reference current was used as the starting point for their method tested on a large variety of loads. The proposed method is validated at the simulation level using the Matlab software and then experimentally using the Hardware-In-the-Loop (HIL) approach with an FPGA Altera Stratix III prototyping board. The results obtained in this work showed that series arc faults could be successfully detected with an APF, only by updating its digital control with the arc fault detection functionality, instead of designing from the very beginning an arc-fault detection specific device [6].

Liu, Y. -W., Wu, C. -J. and Wang, Y. -C. (2016) used the approach of a radial basis function neural network (DRBFNN) to identify the occurrence of serial arc faults in their paper, "Detection of Serial Arc Fault on Low-voltage Indoor Power Lines by Using Radial Basis Function Neural Network." The discrete wavelet transform (DWT) was employed to obtain the time–frequency domain characteristics of line current waveforms to reflect the serial arc fault patterns. This study compared the detection results with other two methods, detection of sub-spectrum energy (DSE) and high frequency detection by wavelet transform (HFDWT). It could be observed that DRBFNN has better ability than DSE and HFDWT to detect serial arc faults [7].

Hatton, P.C., Bathaniah, M., Wang, Z. and Balog, R.S. (2016) reported on the results of a project to develop a DC arc generator (AG) suitable for use in the development and testing
of DC arc fault detectors in their paper, "Arc Generator for Photovoltaic Arc Fault Detector Testing [8]."

Zhu, H., Wang, Z., McConnell, S., Balog, R.S. and Johnson, J. (2016) discussed a testbed that had been developed for the purpose of testing arc fault detectors in a laboratory environment using precise-reproduction, or replay, of pre-recorded arc signals in their paper, "High Fidelity 'Replay' Arc Fault Detection Testbed." The testbed was capable of replaying both the arc signature and the noise from the power electronic circuits at proper amplitude to represent real-world conditions. Utilization of such a testbed would facilitate the study of reliable detection algorithms [9].

Zhu, H., Wang, Z. and Balog, R.S. (2016) reported on results from the development of a real time arc fault detection technique that was built as a wavelet decomposition based arc detector using a TI C2000 platform DSP in their paper, "Real Time Arc Fault Detection in PV Systems Using Wavelet Decomposition." The arc fault detector was tested on a composite arc signal constructed from recordings of real-world inverter noise and real-world arc events replayed through a high-fidelity test bed to compare the ability to differentiate inverter only and inverter plus arcing signals. The results demonstrated that the wavelet decomposition and arc discrimination algorithms could be implemented in real-time on a low-cost DSP [10].

Wang, Z. and Balog, R.S. (2016) presented an effective method based on wavelet transform and support vector machines (SVM) for detection of arc faults in DC PV systems in their paper, "Arc Fault and Flash Detection in Photovoltaic Systems Using Wavelet Transform and Support Vector Machines." Because of its advantages in time-frequency signal processing, wavelet transform was applied to extract the characteristic features from system voltage/current signals. SVM was then used to identify arc faults. The performance of the proposed technique was compared with traditional Fourier transform based approaches [11].

Zhao, Y., Zhang, X., Dong, Y. and Li, W. (2016) first introduced the discharge characteristics and classification of arc faults in their paper, "Characteristics Analysis and Detection of AC Arc Fault in SSPC Based on Wavelet Transform." Then, the research status of AC AFD methods were summarized; meanwhile, this paper analyzed those methods advantages and disadvantages, and a new method for arc fault detection based on arc fault difference signal analysis and wavelet transform was proposed. The fundamental waves of the collected current signals were removed, then the obtained difference signal was analyzed by the stationary wavelet transform in matlab, and then the modulus maxima of a layer of detail waveform were selected as the feature for detection. The experimental results showed that this method could improve the accuracy of fault arc detection [12].

Liu, W., Zhang, X., Ji, R., Dong, Y. and Li, W. (2016) proposed a method based on Hilbert-Huang transform (HHT) and artificial neural networks (ANN) for AC SSPC arc fault detection in their paper, "Arc Fault Detection for AC SSPC in MEA with HHT and ANN." Numerical simulation results together with discussions had also been provided which indicated the effectiveness of the proposed fault detection method. Specifically, Hilbert-Huang transform based multi-resolution analysis was adopted to obtain the features of the AC SSPC arc current in the measured signal, artificial neural networks was adopted to identify the faults based on the extracted features [13].

Jay J., Birger P., Charles L., Tom P. and Theodore M. (2011) stated that manufacturers were developing new Arc Fault Circuit Interrupters (AFCIs) in their study, "Photovoltaic DC Arc Fault Detector Testing at Sandia National Laboratories." The Distributed Energy Technologies Laboratory (DETL) at Sandia National Laboratories (SNL) had used multiple reconfigurable arrays with a variety of module technologies, inverters, and balance of system (BOS) components to characterize new Photovoltaic (PV) DC AFCIs and Arc Fault Detectors (AFDs). The device’s detection capabilities, characteristics and nuisance tripping avoidance had been the primary purpose of the testing. Results showed significant noise was injected
Christian S. and Peter M. (2010) showed the following through the analysis of the measured signals in time and frequency domain: Parallel arcing involved significant changes in the current at the primary side of the converter and was therefore easily detectable. Serial arc faults, however, could usually not be detected by a low frequency analysis of current and voltage signals due to the specific characteristic curve of the photovoltaic modules, the control-concept of the converter for maximum power tracking, and possibly changing solar irradiance [15].

Xiu Yao, Luis Herrera, Yi Huang and Jin Wang (2012) designed an experimental system to study the characteristics of series DC arc in their paper, "The Detection of DC Arc Fault: Experimental Study and Fault Recognition." Different tests were conducted in order to determine the influence of different factors to the arc such as gap length, current, etc. [16].

Jay J. and Kenneth A. (2014) discussed the differences in establishing and sustaining arc-faults for a number of different test configurations and compared the variability in arc-fault spectral content for each respective test and analyzed the evolution of the RF signature over the duration of the fault in their investigation, "Parametric Study of PV Arc-Fault Generation Methods and Analysis of Conducted DC Spectrum." Their ultimate goal was to determine the most repeatable, ‘worst case’ tests for adoption by UL [17].

Sidhu, T.S., Sagoo, G.S. and Sachdev, M.S. (2002) described the development of a multisensor device, based on four different physical phenomena, for reliable detection of low-level arcing faults in metal-clad switchgear in their paper, "Multisensor Secondary Device for Detection of Low-level Arcing Faults in Metal-clad MCC Switchgear Panel." The device could also be applied for detection of arcing in power electronic drives, dry type transformers, gas insulated switchgear, generator bus-ducts, and other metal-clad electrical apparatus [18].

Chen, S. and Li, X. (2016) aimed at providing a joint detection method to arc fault circuit interrupters (AFCI) serving for smart micro grid in their paper, "PV Series Arc Fault Recognition under Different Working Conditions with Joint Detection Method." In this paper, two methods to bring PV series arc fault into the PV system had been recorded by intensified charge-coupled device (ICCD). A relatively satisfying joint algorithm based on two proposed detection variables had been put forward to prevent unwanted nuisance trips from system transient process. To fit constantly varying electric signals in PV system, this detection algorithm also adopted dynamic threshold value [19].

Analysis of existing research shows that most of existing studies have suggested methods of reducing arc fault and testing performance of arc fault circuit interrupters but there is no study on arc fault circuit interrupters with the network function. Therefore, this study aims to improve the usefulness of arc fault circuit interrupter management by introducing network function into existing arc fault circuit interrupters considering the case of places such as server rooms where large loss may occur if the fire safety manager does not recognize the electric shutdown quickly.

2. Structure of an Existing AFCI without the Network Function

2.1 Appearance and Block Diagram

Figure 1 (a) shows the appearance of an arc fault circuit interrupter. The test button is located on the front of the arc fault circuit interrupter.

Figure 1 (b) is the block diagram of the arc fault circuit interrupter. The arc detection unit, the overload detection unit and the short circuit detection unit detect arc fault, overloads and
ground fault. They send the detection signals to the microprocessor. The microprocessor receives the signals and sends the signals to the trip function unit to turn off the power [20].

Figure 1.

2.2. Operation Mechanism
As shown in Figure 2, when a load is connected to the arc fault circuit interrupter and power is supplied, real-time monitoring of dangerous signals for electrical hazard factors such as arc fault, overloads and ground fault is performed. If a dangerous signal such as an overload, a short circuit or an arc is detected while supplying power to the load, a trip signal is generated to shut off the power.

As shown above, the existing arc fault circuit interrupters have the function to interrupt overloads, ground fault, arc fault and all but neither is there the monitoring function to allow external monitoring nor the notification function to notify the fire safety manager.

Figure 2.

3. Structure of an AFCI with the Network Function

3.1. Block Diagram and Circuit Diagram
Figure 3 (a) shows the appearance of an arc fault circuit interrupter with the network function. The network connection unit is located at the bottom of the arc fault circuit interrupter.

Figure 3 (b) is the block diagram of the arc fault circuit interrupter. The arc detection unit, the overload detection unit and the short circuit detection unit detect arc fault, overloads and ground fault. They send the detection signals to the microprocessor. The microprocessor receives the signals and sends the signals to the trip function unit to turn off the power. At the same time, the microprocessor sends the signals to the network unit.

Figure 3 (c) is a detailed circuit diagram of the network unit. When the network unit receives signals through its Tx and Rx terminals, its output unit generates the RS232 signals at the TTL level. Generally, RS232 is configured with its GND set on "Common" and its Tx and Rx set to select "High" to send and receive signals. The signals from the microprocessor are converted by the insulation elements, i.e., photo couplers (U10 and U11), enabling the communication of the signals without damaging the external network unit connected to the arc fault circuit interrupter.

Figure 3.

3.2. Operation Mechanism
As shown in Figure 4, when the load is connected to the arc fault circuit interrupter and the arc fault circuit interrupter is turned on by supplying the power, the self-diagnosis is made to see whether the arc fault circuit interrupter operates normally. If the arc fault circuit interrupter does not operate normally, an abnormal signal is generated. If the arc fault circuit interrupter operates normally, overloads, ground fault and arc fault are monitored in real time. If an overload, a short circuit or an arc is detected while power is supplied to the load, the arc fault circuit interrupter is tripped to cut off the power and generate a trip signal [21].

This situation is monitored in real time by external monitoring and notified to the fire safety manager. The fire safety manager can immediately recognize the situation where the arc fault circuit interrupter interrupts the circuit and take the necessary action to manage the electricity efficiently. The arc fault circuit interrupters with the network function can be
effectively used in server rooms, pigsties, chicken farms, markets, cultural assets, skyscrapers, and factories etc. that require real-time monitoring of the arc fault circuit interrupters.

Figure 4.

Table 1 shows the comparison between the existing arc fault circuit interrupter and the arc fault circuit interrupter with the network function.

Table 1.

5. Conclusions

An arc fault circuit interrupter with the network function are equipped with the communication function by the microprocessor to determine whether the cause of the interruption is an overload, an arc, or a short circuit and transmit and notify the result to the management system of a remote place through the network. The arc fault circuit interrupter allows the circuit to be interrupted by remote control if necessary. This arc fault circuit interrupter prevents both electrical accidents and fires more accurately and supports the communication function for the network. Through the network, the external monitoring system can identify and analyze the interruption causes and improve the efficiency of electricity management.

Now, the installation of an arc fault circuit interrupter to prevent electric fire must be compulsory, not an option. Especially, it is necessary to actively introduce the arc fault circuit interrupters based on the network because they can be used in places where real-time monitoring of the electricity is required and because the electricity management can be efficiently performed by them.

References


Figure 5. Structure of the Existing AFCI without the Network Function.
Figure 6. Operation Mechanism of the Existing AFCI without the Network Function.

(a) Appearance
Figure 7. AFCI with the Network Function.
Table 2. The Comparison between AFCIs with and without the Network Function.

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<thead>
<tr>
<th>Function</th>
<th>Existing AFCI</th>
<th>AFCI with Network Function</th>
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<tbody>
<tr>
<td>Function of interrupting overloads</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Function of interrupting ground fault</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Function of interrupting arc fault</td>
<td>Yes</td>
<td>Yes</td>
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<td>Function of external monitoring</td>
<td>No</td>
<td>Yes</td>
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<td>Function of remote interruption</td>
<td>No</td>
<td>Yes</td>
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Biographies

Ha-Sung Kong majored in disaster science in the Graduate School of University of Seoul. His main interests are firefighting facilities, safety policies, disaster management and firefighting qualification systems among others. He currently works in the Department of Fire Safety of Kyungil University as an associate professor.
Woong-Jae Ra majored in Electrical & Electronic Engineering and Business Administration in Yonsei University. He worked in KT Corporation (Korea Telecom) and Accenture PLC and performed various IT and energy related projects. Currently, he is the CEO of Arcontek Co., Ltd., which is a leading professional manufacturer of AFCI (Arc Fault Circuit Interrupter) in Korea.