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개선된 SSTDR을 이용한 케이블 고장 검출과 위치 계산

Detection and Location of Cable Fault Using Improved SSTDR

전정채* · 김재진* · 최명일*†
(Jeong-Chay Jeon · Jae-Jin Kim · Myeong-Il Choi)

Abstract – This paper proposes an improved spread spectrum time domain reflectometry (ISSTDR) using time-frequency correlation and reference signal elimination method in order to have more accurate fault determination and location detection than conventional (SSTDR) despite increased signal attenuation due to the long distance to cable fault location. The proposed method has a two-step process: the first step is to detect a peak location of the reference signal using time-frequency correlation analysis, and the second step is to detect a peak location of the correlation coefficient of the reflected signal by removing the reference signal. The proposed method was validated through comparison with existing SSTDR methods in open- and short-circuit fault detection experiments of low voltage power cables. The experimental results showed that the proposed method can detect correlation coefficients at fault locations accurately despite reflected signal attenuation so that cable faults can be detected more accurately and clearly in comparison to existing methods.

Key Words : SSTDR, Cable fault location, Time-frequency correlation, Reference signal elimination

1. Introduction

Power cables are susceptible to many faults such as insulation damage, open fault, or short circuit due to inappropriate installation and other various physical, electrical, or environmental factors, which could lead to electrical fires. According to the electrical accident statistics published by the Korea Electrical Safety Corporation, 20% of electric facility accidents are caused by cables, and most electrical fires are related to cables[1].

Cable fault can result in power outage and fire, causing a number of problems such as property damage, information loss, or production delay. Therefore, it is necessary to prevent such accidents through accurate detection of fault locations and rapid restoration as soon as a cable fault is detected. Furthermore, it is also important to reduce cost and shorten the restoration time through accurate location measurement.

Many methods have been proposed to diagnose cable faults and detect their locations such as partial discharge measurement. Among them, reflectometry has been most commonly used for fault detection, in which a specific pulse such as radar is injected into a cable, thereby measuring a reflected signal produced due to the mismatch of characteristic impedance from fault location.

Reflectometry utilizes the principle of reflection of electromagnetic waves flowing through a cable when characteristic impedance changes. A fault caused by open fault can be identified due to the fact that a generated reflected wave has in-phase with the injected signal (or reference signal) due to larger impedance than the characteristic impedance of the transmission line. On the other hand, out-of-phase is generated in case of a fault caused by short circuit due to smaller impedance than characteristic impedance. The location to the fault can be calculated by measuring the time elapsed to detect a reflected signal.

Typically, reflectometry can be divided into two categories: TDR (Time Domain Reflectometry), in which signals reflected using a pulse after injected signals are analyzed in the time domain, and FDR (Frequency Domain Reflectometry), in which frequency signals are employed and reflected signals are analyzed in the frequency domain[2-3].

As for the TDR, it is difficult to extract reflected waves accurately in a noisy environment, and its performance is dependent on the resolution in the time domain of related equipment. As for the FDR, its performance is dependent on the size of measurable frequency bandwidth. In addition, the disadvantage is the high error rate in phase measurement when there is noise[4].

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† Corresponding Author : Electrical safety Research Institute, Korea Electrical Safety Co., Korea
E-mail: ken2003@kesco.or.kr
* Electrical Safety Research Institute, Korea Electrical Safety Co., Korea

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TFDR (Time Frequency Domain Reflecometry), STDR (Sequence Time Domain Reflectometry) and SSTDR (Spread Spectrum Time Domain Reflectometry) have been studied to minimize measurement error and facilitate easy fault detection [5]-[10]. SSTDR among these methods is known to be robust to noisy environments and can detect intermittent fault including open fault and short circuits in dead and live wires [4]. However, if a sequence of specific length is used in the SSTDR, the attenuation of injected signal becomes larger thereby reducing reflected signals as the fault location becomes more remote, which makes fault detection difficult and measurement error larger.

Therefore, this paper proposes an improved SSTDR technique consisting of two steps: peak value of the correlation coefficient of the reference signal is detected using time-frequency correlation analysis, and then a peak value of the correlation coefficient of the reflected signal is detected after removing the reference signal to solve the problem of inaccurate fault detection due to signal attenuation. The performance of the proposed method was evaluated via comparison of existing methods during an experiment involving low-voltage cables. The performance evaluation showed that the proposed method can identify whether a fault occurred more accurately and can track fault locations better than existing methods despite signal attenuation.

2. Conventional SSTDR

The SSTDR was developed by P. Smith and Professor Cynthia Furse at the University of Utah in the USA, as the Direct Sequence Spread Spectrum (DSSS) technique was used in digital communication cables for the purpose of fault location detection in communication lines[7]. Here, the Spread Spectrum (SS) technique has mainly been used in communication systems, which has an advantage of improving resolution or suppressing interference using a wider bandwidth of actual transferred signals than that which is required for information transmission.

SSTDR determines fault location and type by dispersing a band using a pseudo-noise sequence (PN sequence), which has reasonable auto-correlation properties, applying phase-shift keying signals into power lines, and detecting an arrival time and phase of the signal returned via reflection from the fault location as shown in Fig. 1.

A sequence used to detect a cable fault in the SSTDR is mostly a Maximum Length Sequence (MLS), which has been known to have superior detection performance of fault location[8]. An MLS is a binary pseudo-noise sequence whose maximum length is $N=2^m-1$, which can be produced by using a primitive polynomial whose maximum degree is m. When the auto-correlation value at a periodically repeated sequence is $\tau \neq 0$, it has a value below $1/N$.

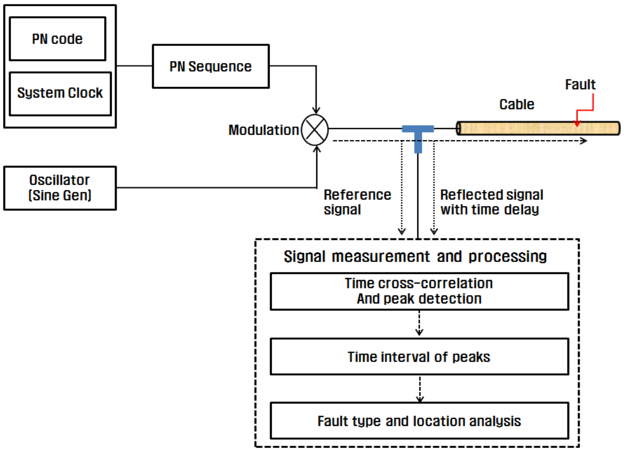


Fig. 1 The principle of SSTDR

In the SSTDR, the reference signal $s(t)$, which is applied to a cable, is produced by a product of MLS $\mathrm{c}=[c_0, c_1, \cdots, c_{N-1}]$, $c_i \in \{-1, 1\}$ whose length is and carrier signal. So, $s(t)$ can be expressed by

$$s(t)=\sum_{n=0}^{N-1} c_n p_{T_c}(t-nT_c) \tag{1}$$

where c_n is the sequence length K containing the amplitude of +1 and -1 Loop Linear Recursive Sequence (RLS) and carrier signal $p_{T_c}(t)$ can be expressed by

$$p_{T_c}(t)=\begin{cases}\cos(2\pi f_c t), & 0 \leqq t < T_c \\ 0, & otherwise\end{cases} \tag{2}$$

Therefore, the cycle of $s(t)$ is a recursive linear signal (RLS) of period $T_s = T_c$ consisting of 1s and -1s, T_c is the minimum duration of a 1 or -1 known as a “chip”, and

$$f_c = \frac{1}{T_c}.$$

If a signal in Eq. (1) is applied to a cable, reflection occurs at the change point of cable impedance. The reflected signal experiences a certain time delay, so the reflected signal $r(t)$ can be expressed as

$$r(t)=\sum_{n=0}^{N-1} a_k s(t-\tau_k)+g(t) \tag{3}$$

where a_k is the amplitude of reflected signal $a_k s(t-\tau_k)$, τ_k is the time delay before receiving reflection k and $g(t)$ is a noise signal.

To calculate the distance to the cable fault location in the SSTDR, a time difference of maximum values of the time cross-correlation function $C_t(\tau)$ is calculated first using an applied signal $s(t)$ and a reflected signal $r(t)$. So, the time cross-correlation output is

$$\begin{aligned} C_{time,sr}(\tau) &= \frac{1}{T_s}\int_0^{T_s} s(t-\tau) r^*(t)dt \\ &= \frac{1}{T_s}\int_0^{T_s} s(t-\tau)\sum_{n=0}^{N-1} a_k s(t-\tau_k)dt \\ &\quad + \frac{1}{T_s}\int_0^{T_s} s(t-\tau) g(t)dt \end{aligned} \tag{4}$$

where $*$ refers to a complex conjugate.

Cable fault location using a time difference obtained via Eq. (4) and VOP (Velocity of Propagation) which is a variable that represents the propagation velocity of the electro-magnetic wave in a corresponding cable is given by

$$D = \frac{V_P \times (t_r - T_s)}{2} \tag{5}$$

where V_p is VOP, t_r is detection time of reflection signal, and t_s is start time of reference signal.

3. Proposed Method

In general, a time difference is obtained via time correlation functions, thereby calculating a fault location in the SSTDR. Since it analyzes signals in the time domain in the time correlation function, it has difficulties in detecting the accurate location of reflected signals because a side lobe in the correlation function with respect to applied signals is larger than the main lobe in the correlation function with respect to reflected signals when a fault location is far, thereby leading to large signal attenuation or to weakness in reflected signal due to a minor fault[11].

To solve this problem, this paper aims to improve cable fault distance detection performance in the conventional SSTDR by using time-frequency correlation analysis and removing the reference signals as shown in Fig. 2.

The proposed method in this study searches the maximum value location τ_1 of the reference signal from the time-frequency correlation function $|C_{sr}(\tau)|$ of reference and reflected signals to find a $s(t)$ is removed from the measured signal $r(t)$ to make $e(t)=r(t)-s(t-\tau_1)$, and the peak τ_2 value of the correlation function of the reflected signal is found via the second time-frequency correlation function $|C_{se}(\tau)|$of $e(t)$ and $s(t)$. Finally, a time difference $\tau_d = \tau_1 - \tau_2$ between the peak values is calculated to obtain the distance to the cable fault location.

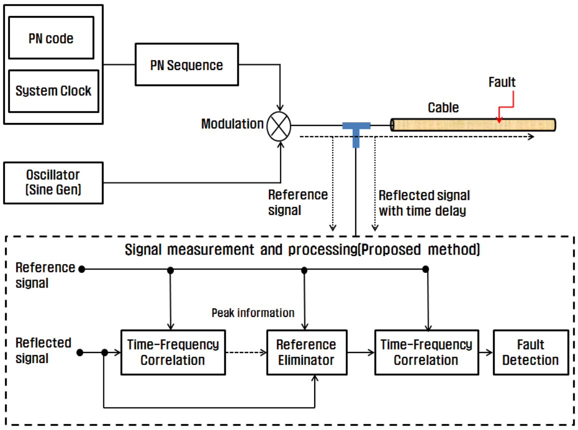


Fig. 2 The proposed SSTDR

The time-frequency correlation analysis in the SSTDR proposed in this study employs the Wigner Ville Distribution (WVD) to analyze the reference and reflected signals in the time-frequency domain[5], [10]. First, the reference signal (1) and reflected signal (3) are transformed into the WVD for the time-frequency correlation analysis, thereby producing Eq. (6) and Eq. (7).

$$W_s(n,m) = \sum_{n=0}^{N-1} s(p_{n,k}) s^*(q_{n,k}) \exp\left(-j\frac{2\pi km}{2N}\right) \tag{6}$$

$$W_r(n,m) = \sum_{n=0}^{N-1} r(p_{n,k}) r^*(q_{n,k}) \exp\left(-j\frac{2\pi km}{2N}\right) \tag{7}$$

where $*$ refers to a complex conjugate, and it satisfies $n=0,1,\ldots,N-1, m=0,1,2N-1, k_n = \min(2n, 2N-1-2n)$, and $p_{n,k} = \lfloor n+\frac{k}{2} \rfloor$, $q_{n,k} = \lfloor n-\frac{k}{2} \rfloor$, where $\lfloor z \rfloor$ refers to the largest integer that does not exceed z.

Next, the time-frequency correlation analysis of the reference and reflected signals with respect to the WVD can be calculated via the following equation to identify the cable fault location[5].

$$C_{tf}(\tau) = \frac{1}{2N\sqrt{E_s E_{r,\tau}}} \sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} W_s(n,m) W_r^*(n,m) \tag{8}$$

where and are the normalization factors that refer to energies of the reference and reflected signals in the time-frequency domain, respectively, which are expressed below[5]:

$$W_s = \frac{1}{2N}\sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} W_s|(n,m)|^2 \qquad (9)$$

$$W_{r,\tau} = \frac{1}{2N}\sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} W_{r,\tau}|(n,m)|^2 \qquad (10)$$

The maximum value of the time-frequency correlation function for the reflected signal $e(t)=r(t)-s(t-\tau_1)$ that removes reference signal using Eq. (8) has a value 1 because of normalization and reference signal elimination. A time difference between peak values of the correlation function of the reference and reflected signals is obtained and a distance to the cable fault location is calculated using Eq. (5).

4. Experimental Results

4.1 Experimental Setup

To validate the performance of the proposed SSTDR, an experiment was conducted as shown in Fig. 3. An F-CV2C6SQ cable was used for the experimental target cable because it has been most widely used in low-voltage power systems. The SSTDR experimental setup in Fig. 3 consists of a control unit, an arbitrary waveform generator, a digital oscilloscope, and "T" connector. To automatically control the Arbitrary Waveform Generator (NI PXI 5422, 16bits, 200 MS/s) that generates a signal injected into a cable and digital oscilloscope (NI PXIe-5162, 10bits, 5 GS/s, 1.5 GHz) that acquires a signal reflected from the cable fault point, the NI LabVIEW program was developed and MATLAB was used to analyze correlations between reference and measured signals. In the experiment, the reference and measurement signals were injected and measured through the T connector and RG58 cables.

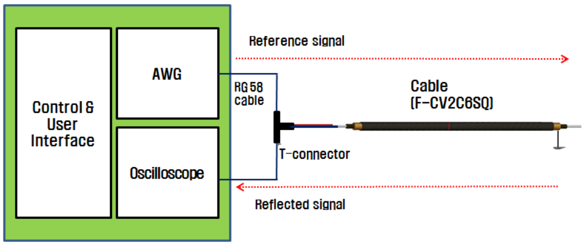


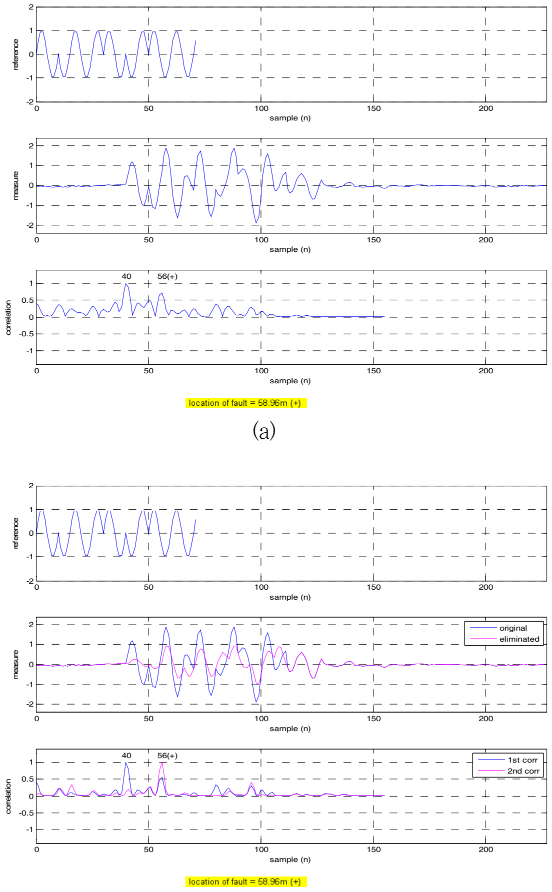
Fig. 3. Experimental setup for the proposed SSTDR

As described previously, accurate VOP is needed to calculate cable fault location. In reflectometry, calculation of fault locations can be affected by the measured time as well as the accuracy of the VOP. In general, communication cables that can maintain characteristic impedance uniformly such as coaxial cables have relatively stable VOP. On the other hand, power cables, which are vulnerable to external environments, have less uniformed VOP, thereby causing error in distance calculation.

In this paper, VOP was measured first with respect to the experimental target cables prior to the SSTDR experiment. To minimize measurement error as much as possible, a pulse signal of 10, 100, 200, and 1000ns was injected into the experimental target cable and averages of tenfold measurement were computed. As a result, a VOP of 1.905×108m/s for the target cable was obtained.

4.2 Results

This paper select the length of MLS is N=7, modulated by sinusoidal signal in the same frequency, as the test signal for SSTDR. The amplitude of the reference signal is set to 5 V and the sampling rate for reflected signal acquisition of the SSTDR is 25 MS/s.



(a)

(b)

Fig. 4. The results of F-CV2C6SQ 60 m open fault (a) The conventional SSTDR method (b) The proposed method

Fig. 4 shows the measurement result of the open fault of the 60 m cable. Fig. 4 (a) shows the measurement result using the existing SSTDR in which accurate measurement of the reflected signal at the open fault point was difficult due to the side lobe of the reference signal. Fig. 4 (b) shows the analysis result using the proposed method in this study, in which accurate fault measurement and distance calculation can be achieved, as the correlation coefficient at the fault location was close to 1.

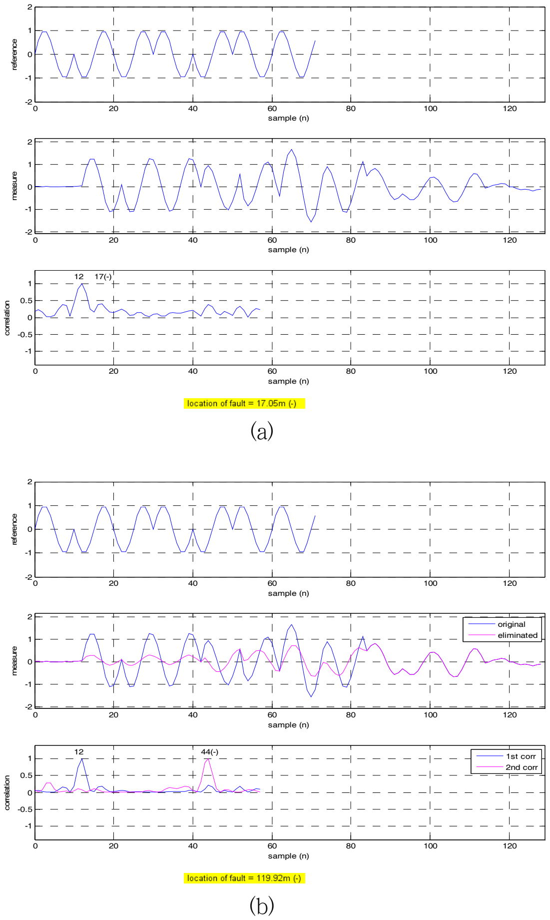
To calculate the distance to the fault location in Fig. 4, a sample difference between peak values of the correlation coefficient was divided by the sampling rate. That is, a difference of one sample is 1/25MS/s=0.04. In Fig. 3, the sample difference is 16(56-40), so the time difference can be calculated as 16/25MS/s=0.64, and the distance to the fault location using Equations (5) can also be computed as

$$D=\frac{(1.905\times 10^{8}\ m/s)\times(0.64\times 10^{-6}s)}{2}-2m\ =\ 58.96\,[m] \quad (11)$$

Note that the connector cable length for signal injection should be subtracted from the measured length (in this paper, it was 2 m).

Fig. 5 and 6 show the measurement results of the short circuit fault using existing and improved SSTRD methods at distances of 120m and 153m. As shown in Fig. 5(a) and 6(a), in the conventional SSTDR, the further the fault location, the smaller the reflected signal and, as a result, the correlation coefficient became smaller, which made it difficult to distinguish the side lobe of the reference signal and other noises. This inability to discriminate the signal, in turn, led to difficulty in fault detection and high error detection rate.

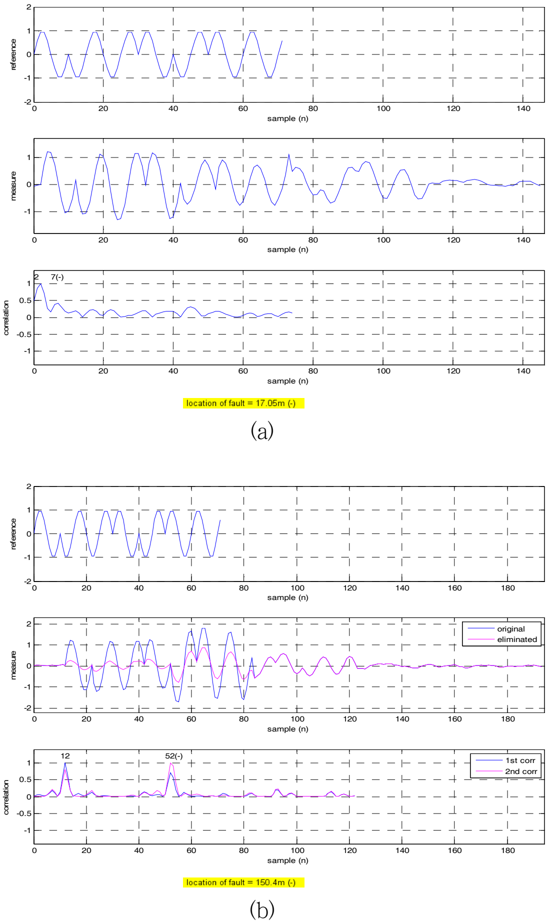
On the other hand, the proposed method in this paper removes the reference signal and employs the time-frequency correlation analysis using a larger correlation coefficient at the fault location as shown in Fig. 5(b) and 6(b), thereby providing more accurate fault detection and easier distance calculation. The location of the fault can be estimated to be 119.92m and 150.4m (an error is within 1 %) respectively.



(a)

(b)

Fig. 5. The results of F-CV2C6SQ 120m short fault (a) The conventional SSTDR method (b) The proposed method



(a)

(b)

Fig. 6. The results of F-CV2C6SQ 153m short fault (a) The conventional SSTDR method (b) The proposed method

The experimental results(Table 1) showed that the proposed method can identify whether a fault occurred more accurately and can track fault locations better than conventional SSTDR despite signal attenuation. Also, an error of automatic fault type and location determination by detection of phase and peak value because of elimination of the reference signal and normalization of correlation coefficient not occurred.

Table 1. Experimental results of cable fault detection through SSTDR and ISSTDR

Cable	Fault Type	SSTDR		ISSTDR	
		measurement (m)	Error rate(%)	measurement (m)	Error rate(%)
CV2C6SQ_60m	Open	58.96	1.57	58.96	1.57
	Short	58.96	1.57	58.96	1.57
CV2C6SQ_120m	Open	116.11	3.7	119.92	0.07
	Short	Error	Error	119.92	0.07
CV2C6SQ_153m	Open	Error	Error	154.21	1.12
	Short	Error	Error	150.4	1.38
CV3C10SQ_200m	Open	Error	Error	198.824	0.59
	Short	Error	Error	202.686	1.34

5. Conclusion

This paper proposed employed the reference signal elimination and time-frequency correlation analysis in order to reduce the measurement error of cable fault detection and distance calculation due to signal attenuation in SSTDR. The performance of the proposed method was evaluated through open- and short-circuit fault detection experiments using 60m, 120m and 153m low-voltage power cables. The results validated the superior performance of the proposed method. The proposed method is expected to play an important role in resolving the difficulties of cable fault detection due to various noises and reflected waveform distortion in real cable fault detection sites when SSTDR devices, in addition to other reflected wave measurement equipment, are utilized. In the future, studies on cable fault detection performance according to the type and length of various sequences, such as Baker and Frank code used in digital communication and radar systems, will be conducted in order to develop better reflectometry that provides easy fault detection and less error.

감사의 글

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저자소개

전 정 채(Jeong-Chay Jeon)

1997년 2월 원광대학교 전기공학과 졸업. 1999년 2월 동 대학원 전기공학과 졸업(석사). 2015년 8월 동 대학원 전기공학과 박사(졸업). 현재 한국전기안전공사 전기안전연구원 책임연구원/팀장

E-mail : cameleon@kesco.or.kr

김 재 진(Jae-Jin Kim)

2001년 2월 원광대학교 전기공학과 졸업. 2010년 2월 동 대학원 전기공학과 졸업(석사). 현재 한국전기안전공사 전기안전연구원 선임연구원

E-mail : glory@kesco.or.kr

최 명 일(Myeong-Il Choi)

2002년 2월 창원대학교 전기공학과 졸업. 2004년 2월 동 대학원 전기공학과 졸업(석사). 현재 한국전기안전공사 전기안전연구원 선임연구원. 2014년 8월 숭실대학교 대학원 전기공학과 박사(졸업).

E-mail : ken2003@kesco.or.kr