International Journal of Engineering & Technology, 7 (4.39) (2018) 589-593

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Performance Improvement of the SSTDR for Partial Disconnection Fault Detection of Low Voltage Cable

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Abstract

Background/Objectives: The Spread spectrum time domain reflectometry (SSTDR) among the reflectometry methods is superior to detect cable fault and find its location. But it is hard to find the location of partial disconnection fault.
Methods/Statistical analysis: This paper usesthe improvedSSTDR, which employs the Wigner Ville Distribution (WVD) based time-frequency correlation analysis (TFCA) and removes the injection signals, in order to detect and locate partial disconnection fault of low voltage cable. The proposed method was validated in partial disconnection cable fault detection and location experiments of F-CV cable used for low voltage power supply in Korea.
Findings: The improved SSTDR method in the experiment scan find partial disconnection faults accurately and clearly than the existing SSTDR. The proposed method has superior performance to detect and locate soft fault in cable because the maximum value of correlation function for the reflection signal, which injection signal is eliminated, has a value 1 vianormalization and elimination of injection signal.
Improvements/Applications: The proposed method is looking forward to playing an important role in solving the problem to detect soft cable fault like as partial disconnection and insulation damage. Also, it can be applied to SSTDR devices or other reflectometry equipment used in real cable fault detection sites.

Keywords: *Power cable, Fault, Insulation damage, Partial disconnection, Reflectometry*

1. Introduction

Cable is critical to the operation of commercial and industrial buildings or factory, power plants and so on with electrical power system. Cable fault in these facilities can result in interruption of electric service and electric fire, causing many problems such as production failure and property damage. So, it is required to reduce cable fault damage cost by accurate fault location measurement.
Reflectometry-based techniques are the most commonly used method for detecting and locating cable fault [1]. Reflectometry methods uses the principle that the reflection of electromagnetic waves flowing in cable at the point at which the characteristic impedance of the cable changes. Namely, an electrical signal is sent to the cable, and refection wave is generated at the point of characteristic impedance change [2]. The reflection signal in open fault point is the same phase with the injection signal. And the reflection signal in short fault point is reverse phase of the applied signal (equals to injection signal) in the cable because of the fault impedance smaller than characteristic impedance of the tested cable. The cable fault location can be computed by measuring the time difference the injection signal and the reflection signal at the fault point.
There are many reflectometry-based methods for cable fault detection and location such as Time Domain Reflectometry (TDR), Frequency Domain Reflectometry(FDR),Sequence Time Domain Reflectometry (STDR), Spread Spectrum TDR (SSTDR) [3-5]. SSTDR among the reflectometry-based techniques is known to robust to detect open, short and intermittent fault in a cable [6]. This traditional SSTDR determines type and location of cable fault by using sinusoidal signal modulated maximum length sequence (m sequence) as injection signal and detecting a time and phase of reflection signal at the cable fault location[7, 8].
However, if there is soft fault like as partial connection fault that a part of cable core is cut, SSTDR has difficulties in detecting and locating soft cable fault because reflected signal in the fault point is very small and a correlation coefficient to injection signal is difficult to be calculated.
This paper describes on performance improvement of partial disconnection cable fault detection and location of the traditional SSTDR by using TFCA and removal of the injection signal. The performance of the improved SSTDR was presented by comparing with the traditional SSTDR through partial disconnection fault detection experiment. The experimental results illustrated that the improved SSTDR can correctly distinguish that a cable fault type and can trace a cable fault point rather than the traditional SSTDR despite of the attenuation of the measured signal in partial disconnection fault location.

2. Improved SSTDR

The signal $s(t)$ injected to the target cable in the traditional SSTDR is a product of m sequence $c = [c_0, c_1, \cdots c_{N-1}]$, $c_i \in \{-1,1\}$ and carrier signal [7, 8]. So, the injection signals(t)c is expressed by

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

where $C_n$is the m sequence that length is$N$and the amplitude is +1 and -1 and $P_{T_c}(t)$ is carrier signal. And the carrier signal $P_{T_c}(t)$iswritten as

$$P_{T_c}(t) = \begin{cases} \cos(2\mu f_c t), & 0 \le t \le T_c \\ 0, & otherwise \end{cases} \tag{2}$$

The cycle of s(t) is $T_s = T_c$ consisting of 1s and -1s, andT_c is the minimum duration of a 1 or -1[8, 9].
If a sinusoidal modulated m sequence signal used in equation (1) is injected to a cable, reflection occurs at the impedance mismatched point (fault point) of cable be tested. The reflection signalr_t has time lag, so it can be written as

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

Where$a_k$isthe amplitude of the reflection signal, $\tau_k$is the time lag before receiving signal reflectionk, and $g_t$is a noise signal.
The time correlation function $C_t(\tau)$ of the injection and the reflection signal will be calculated as

$$C_t(\tau) = \frac{1}{T}\int_0^T s(t)r^*(t-\tau)d\tau = \frac{1}{T}\int_0^T s(t)\sum_{n=0}^{N-1} a_k s(t - \tau - \tau_k) + \int_0^T s(t)n(t-\tau)dt \tag{4}$$

where* is a complex conjugate[7].
Finally, fault location D of the test cable is calculated by

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

WhereV_P is VOP, $t_r$is the injection time, and$t_s$is the detection time of reflection signal.
This traditional SSTDR has difficulties in detecting soft fault of cable like as partial disconnection because reflection signal in the cable fault point is very small due to a small impedance variation and time correlation value with respect to injection signal is not calculated.
This paper use the improved SSTDR to calculate peak value of the injection signal from the TFCA values of injection and reflection signal to trace a cable fault point as shown in figure1. In the improved SSTDR, the injection signal is eliminated from the measured signal and the peak value of the reflection signal is found by using the TFCA.A time difference between the peak values of time-frequency correlation of injection signal and refection signal is computed to acquire the distance to the cable fault point.

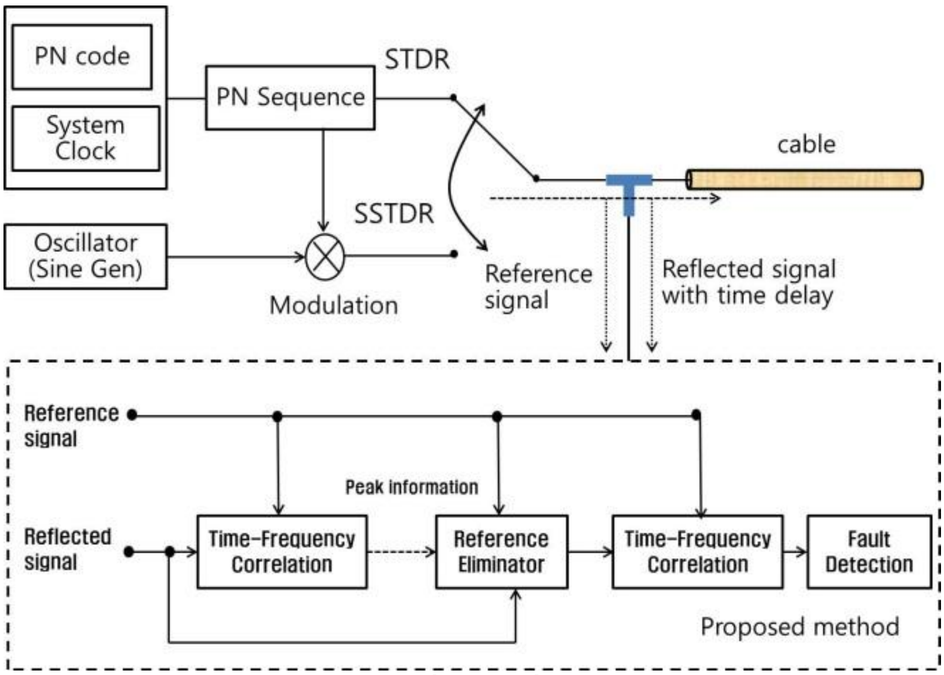

Figure 1: The improved SSTDR

The TFCA in the improved SSTDR uses the WVD to analyze the injection and reflection signals in the time-frequency domain [10]. First, the injection signal of equation (1) and reflected signal of equation (3) are converted into the WVD for the TFCA. Next, TFCA of the injection and reflection signals about the WVD can be calculated as [9]

$$C_{tf}(\tau) = \frac{1}{2N\sqrt{E_s E_{r,\tau}}} \sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} W_s(n,m) W_f^*(n,m) \tag{6}$$

WhereE_s and E_r are the normalization factors of the injection and reflection signals in the time-frequency domain, respectively, which are written following [10]:

$$E_s = \frac{1}{2N}\sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} |W_s(n,m)|^2 \tag{7}$$

$$E_{r,\tau} = \frac{1}{2N}\sum_{n=0}^{N-1}\sum_{m=0}^{2N-1} \left|W_{r,\tau}(n,m)\right|^2 \tag{8}$$

The normalization factors make time frequency correlation coefficient close to 1 at the fault location. And $W_s(n,m)$ and $W_s(n,m)$ are the WVD of the injection and reflection signals respectively, can be written as

$$W_s(n,m) = \sum_{n=0}^{N-1} s(p_{n,k}) s^*(q_{n,k}) exp\left(-j\frac{2\pi nkm}{2N}\right) \tag{9}$$

$$W_r(n,m) = \sum_{n=0}^{N-1} r(p_{n,k}) r^*(q_{n,k}) exp\left(-j\frac{2\pi nkm}{2N}\right) \tag{10}$$

The time-frequency correlation function in equation (6) has a value between 0 and 1. The closer to 1 the value is, the closer the signal to the injection signal. A time difference between peak values of the TFCA coefficient of the injection and reflection signals is found and the distance to cable fault location is computed by equation (5).

3. Experimental Method

The experiment shown in figure 2 was carried out to demonstrate the performance of the improved SSTDR. The experimental devices of figure 2 consist of a control module with personal computer (PC), an arbitrary waveform generator (AWG) module and an oscilloscope module. The National Instrument (NI) Lab VIEW-based program was developed to control the NI PXI 5422AWG that generates injection signal. The NI PXIe-5162oscilloscope obtains an injection signal from AWG and a reflection signal. The MATLAB-based program was used to implement TFCA between injection and reflection signals that are obtained through the RG58 cable and T connector.

A 200m F-CV cable used for low voltage power supply in Korea was chosen in the experiment. The partial disconnect fault of 130m, which core from one to six out of seven was cut, was produced to test soft fault and the fault point of the cable was buried in soil as shown figure 3.

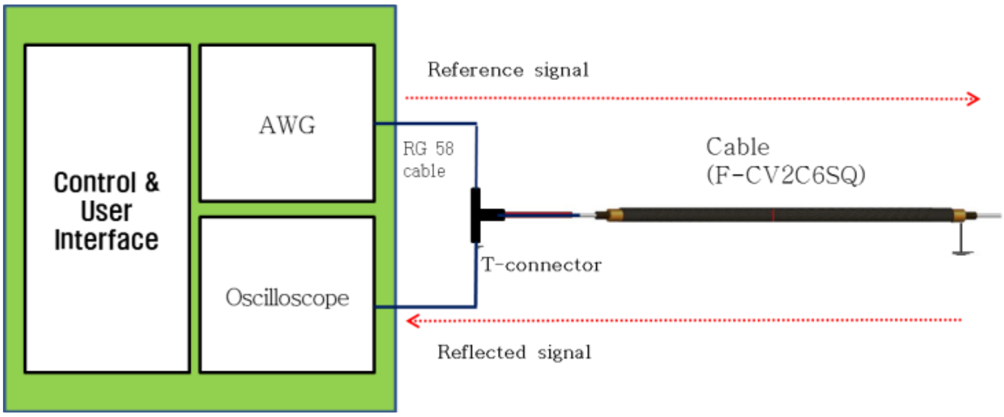

Figure 2: Experimental setup

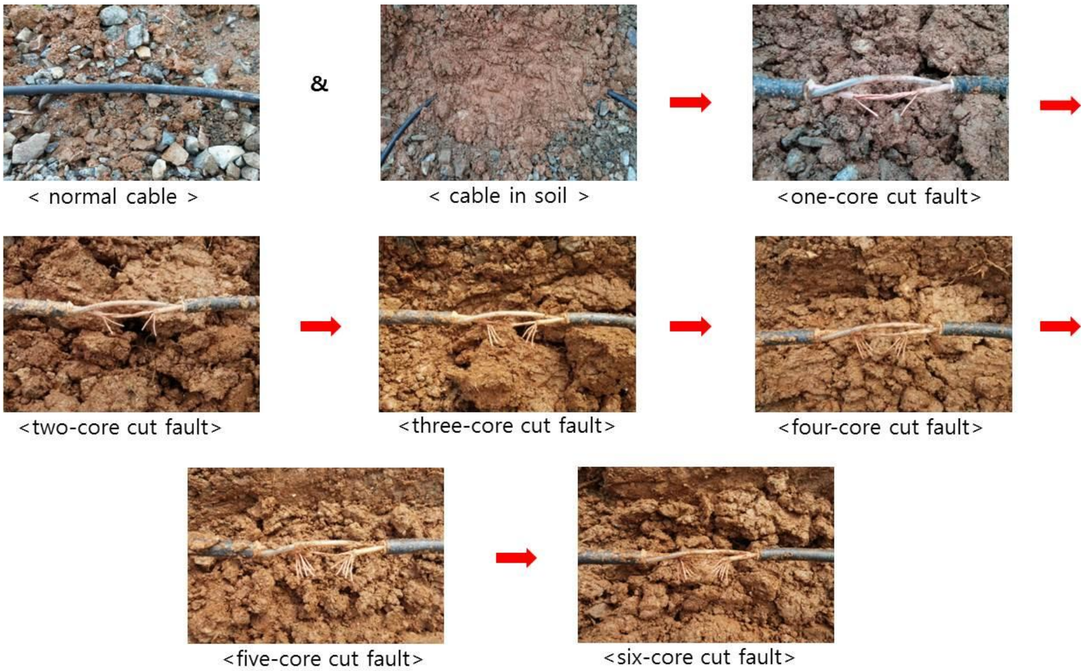

Figure 3: Partial disconnection fault of the target power cable

In reflectometry methods, in order to reduce calculation error of cable fault location, an accurate VOP is required as equation (5).Generally, communication cables such as RB 58 coaxial cables, which characteristic impedance of the cable uniformly is maintained, have relatively stable VOP. However, electrical power cables have comparatively inconsistent VOP. In this paper, a VOP of the target cable was measured before experiment. In order to reduce measurement error, a various pulse signal that pulse width is 10, 100, and 200ns was used in the VOP measurement of the test cable and the average of the measured values was calculated. The VOP of the F-CV low voltage power cable was measured as 1.905×10^8m/s

This paper uses sequence signal modulated by sinusoidal signal in the same frequency as the injection signal for the existing and improved SSTDR. The m sequence length is 7 (N=7) and the amplitude of the injection signal is 5 V. The signal sampling rate of the oscilloscope for reflection signal is 125 MS/s.

4. Experimental Results

Figure4 shows the test result by the traditional SSTDR using time correlation. The target cable length is 200m and six-core cut fault in 130m was produced and end was opened. The traditional SSTDR cannot detect and locate the partial disconnection fault as shown figure 4. There is little reflected signal in the partial disconnect fault point of the test cable and time correlation results has no peak value or little peak in the fault point as shown measured signal and correlation result wave of figure 4.

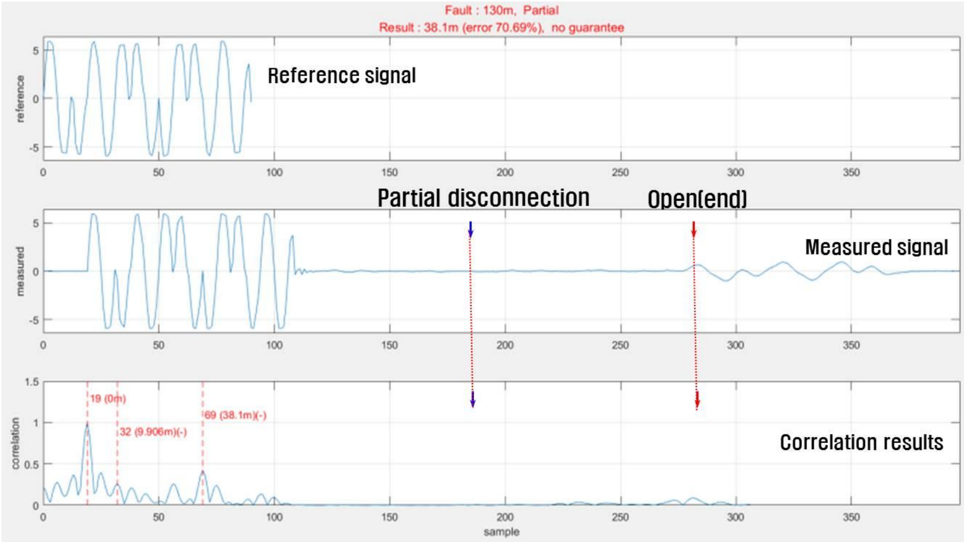

Figure 4: The test result of six-core cut cable using the traditional SSTDR

Figure5, 6, 7 and 8 show results to experiment one-core cut, two-core cut, three-core cut and six-core cut fault of the 200m test cable using improved SSTDR. The fault location was generated in 130m and end was opened. Correlation result wave using the improved SSTDR as shown in figure 5, 6, 7 and 8, which employs the TFCA and the method removing the injection signal, can exactly detect cable fault and find fault location because time-frequency correlation coefficient was near to 1at the partial disconnection fault point. A difference of one sample to calculate the distance to the fault location by MATLAB program for the developed TFCA and distance calculation in figure 5 is calculated as 1/125MS/s=0.008μs. In figure5, the sample difference is169 (185-16) and the time difference is calculated as 169/125MS/s=1.352 μs . So, the distance to the partial disconnection fault location by equations (5) is calculated as

$$\mathrm{D} = \frac{(1.905\times10^{8} m/s)\times(1.352\times10^{6} m/s)}{2} = 128.778m. \quad (11)$$

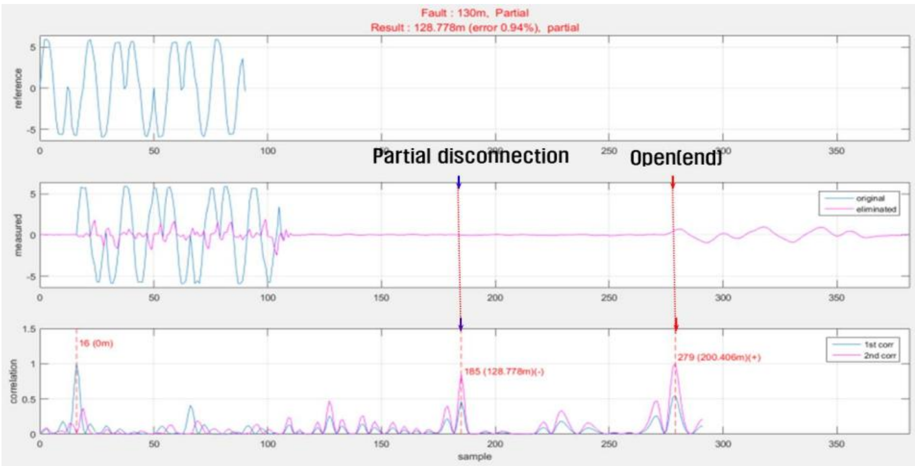

Figure 5: The test result of one-core cut cable using the improved SSTDR

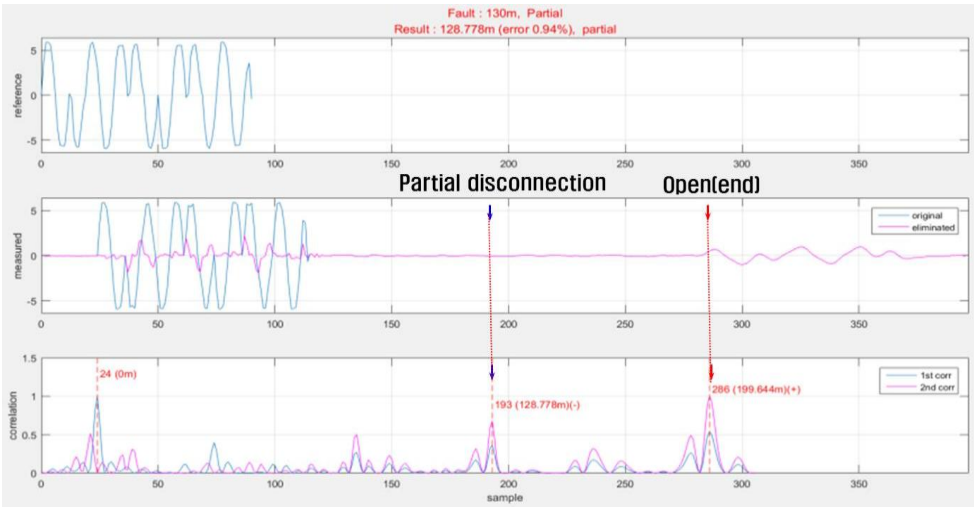

Figure 6: The test result of two-core cut cable using the improved SSTDR

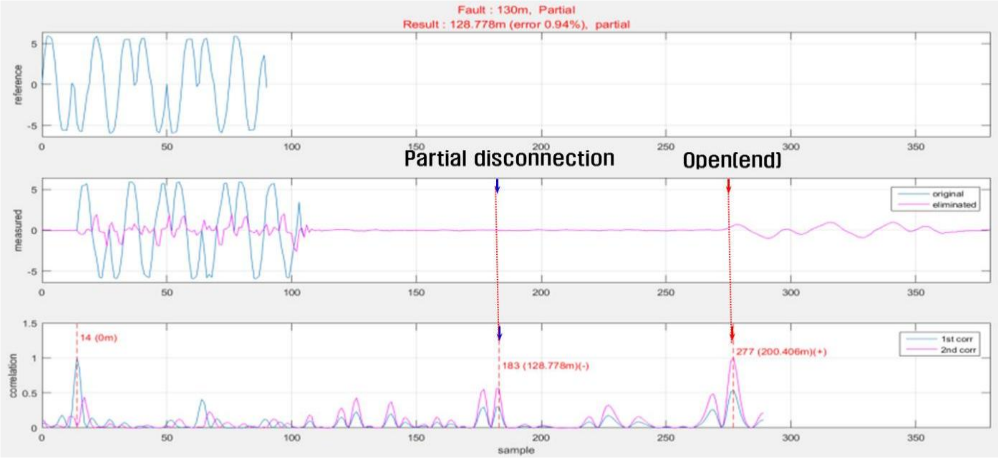

Figure 7: The test result of five-core cut cable using the improved SSTDR

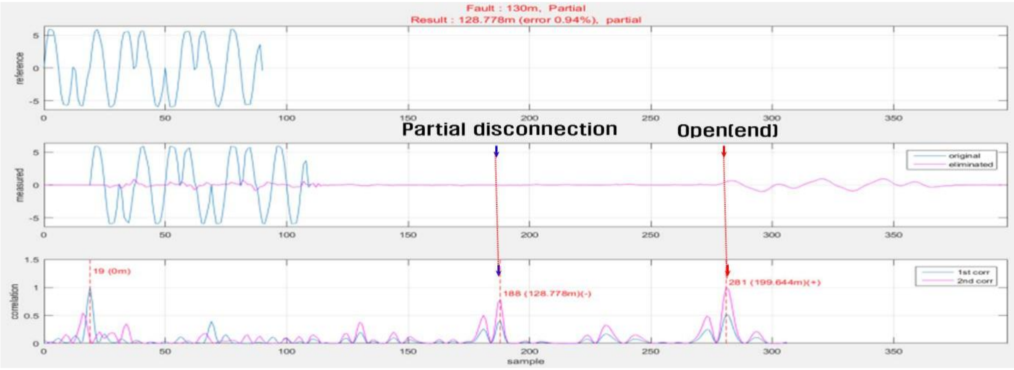

Figure 8: The test result of six-core cut cable using the improved SSTDR

The results of the experiment showed that the improved SSTDR can correctly distinguish whether cable fault occurred or not and can trace cable fault point rather than the traditional SSTDR despite of the attenuation of the measured signal in partial disconnection fault location. Also, there were no errors in the automatic calculation of the cable fault location.

5. Conclusion

The improved SSTDR was used and tested to detect and locate of partial disconnection fault of low-voltage electrical power cable. The improved SSTDR provides more accurate partial disconnection fault detection and distance calculation than the existing SSTDR because it has a time frequency correlation coefficient close to 1 at the fault location. The improved SSTDR is looking forward to playing a major role in solving the problem of detection and location soft cable fault with small impedance variation. And the proposed method can be applied to reflectometry equipment used in real cable fault detection sites.

Acknowledgment

This work was supported by the research grant of Wonkwang University in 2018.

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