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Research on SSTDR-based online distance measurement method for single-phase faults in cables

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Abstract: *In order to accurately locate the non-destructive faults of distribution network cables, an extended spectrum time-domain reflectometry method based on the equivalent distribution parameter model of transmission lines was proposed to detect and locate single-phase grounding short-circuit and single-phase disconnection faults online. Firstly, the extended spectrum and time-domain reflectometry are analyzed theoretically. Then through simulink simulation platform to build single-phase grounding and single-phase disconnection fault model of distribution network simulation, verify the correctness of the theory; Finally, the influence of fault distance, fault resistance and signal-to-noise ratio is analyzed.*

Keywords: *SSTDR; Uniform transmission line; On-line ranging; Single-phase fault*

1. Introduction

The proportion of underground cables in the distribution network is increasing, and at the same time, faults in distribution cables are becoming more frequent, mainly single-phase ground faults and single-phase break faults, which account for about 80% of the total faults in distribution cables [1]. At present, most of the power supply companies use fault location detectors to locate fault points in distribution networks, but this method is only effective for destructive faults with low frequency, while for non-destructive faults with high frequency, it not only takes a long time to measure the distance, but also causes very great damage to the cable itself.

In order to solve the problem of accurate location of non-destructive faults in distribution cables, the current methods are mainly impedance and traveling wave methods [2], literature [3] used distributed parameter model to locate faults in single-phase cables using the voltage and current flow at the first and last ends of the cables, and in literature [4], high voltage pulse was injected into the faulty cable, and the Hilbert-Huang transform algorithm was used to de-noise the fault signal, so as to achieve fault location. However, all the above methods are operated in the case of distribution network blackout, which greatly reduces the quality of power supply to the distribution network. In order to ensure the quality of power supply for users, online detection technology has been widely concerned by researchers. Reference [5] proposes a real-time expert detection system to detect faults in faulty cables. It greatly improves the system response and positioning speed, reduces the troubleshooting workload of maintenance personnel, and ensures the reliability of power supply. The literature [6] used sequence time domain reflectometry (STDR) and spread spectrum time domain reflectometry (SSTDR) to detect impedance mismatch points in early telephone twisted-pair lines. The results show that the method has good noise immunity and localization accuracy, and the SSTDR method was used in the literature [7] to solve the arc fault problem in photovoltaic systems. The extended spectrum test signal does not generate spectral overlap with the working signal in the power cable to be tested in the distribution network studied in this paper, and online detection can be implemented. The test signal not only has a very obvious autocorrelation peak, which is easy to detect, but also does not cause any interference to other signals after injecting into the cable to be tested, which can greatly reduce the detection error.

Therefore, this paper uses the extended spectrum time-domain reflection method for non-destructive fault detection in distribution networks, analyzes the basic transmission line model and the related fault location methods to establish the single-phase ground fault and single-phase disconnection fault models of distribution networks, and finally verifies the feasibility and accuracy of the method through simulation.

2. Transmission line basic model and positioning method analysis

2.1. Transmission line basic model

Ideally, the power cable in the distribution network can be regarded as uniform, and the electrical parameters G_0 , L_0 , C_0 , R_0 per unit length are used to describe the electrical properties of the cable, and it is known from the theory of distribution parameters that the entire uniform cable can be equated to many very small wire elements cascaded, as shown in Figure 1.

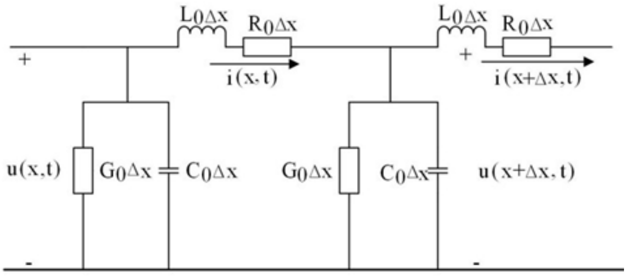


Figure 1: Unit length transmission line equivalent circuit

The voltage u and current i at each point along the line in Figure 1 are related to both time t and spatial position x . Assume the distance from a point on the cable to the beginning of the cable is x , and take $\Delta x \to 0$. According to Kirchhoff's law, the telegraph equation can be obtained as

$$\begin{cases} -\dfrac{\partial}{\partial \mathrm{x}} u(x,t) = R_0 i(x,t) + \mathrm{L}_0 \dfrac{\partial}{\partial t} i(x,t) \\ -\dfrac{\partial}{\partial \mathrm{x}} i(x,t) = G_0 u(x,t) + C_0 \dfrac{\partial}{\partial t} u(x,t) \end{cases} \tag{1}$$

From the voltage and current at the beginning or the voltage and current at the end, equation (1) can be solved to obtain the reflection coefficient of the test signal at the cable point x as

$$\rho = \frac{Z_x - Z_0}{Z_x + Z_0} \tag{2}$$

Where Z_x is the equivalent impedance at point x of the cable; Z_0 is the characteristic impedance of the cable, which is expressed as follows.

$$Z_0 = \sqrt{\frac{R_0 + jwL_0}{G_0 + jwC_0}} \tag{3}$$

As can be seen from equation (2), the reflection coefficient ρ at the fault point is related to the equivalent impedance and characteristic impedance at point x , and is a complex number. This equation reflects the difference between the injected test signal and the reflected signal, mainly in magnitude and phase, when the injected test signal meets the fault point of the faulty cable, it will be reflected due to impedance mismatch. The different types of faults accordingly affect the amplitude and phase of the test signal and the reflected signal, such as short-circuit case $Z_x = 0$, the test signal at the fault point of total reflection, when $\rho = -1$, that is, the two signals have the same amplitude and the opposite direction, the broken circuit case $Z_x = \infty$, the test signal at the fault point of total reflection, when ρ =1, that is, the two signals have the same amplitude and direction. When the transmission line occurs intermittent fault, partial reflection occurs at the fault point, ρ between -1 ~ 1, it can be seen that the test signal at the cable fault point generated by the reflected signal and its encountered impedance changes have a great relationship, not only can affect the amplitude of the reflected signal, but also affect the phase of the reflected signal, while, in turn, can be based on the collected reflected signal amplitude and phase to determine the fault encountered The impedance change at the point of encounter can be determined based on the amplitude and phase of the collected reflected signal, thus identifying the type of fault. The following is a summary of the results.

2.2. Analysis of SSTDR positioning methods

The main idea of the SSTDR fault detection method is to modulate the high frequency m sequence with a sine wave according to the period 1:1 by binary phase shift keying (BPSK) to form a test signal and then inject it into the cable under test [8], because there is a difference between the input and output impedance at the fault point of the faulty cable, when the test signal meets the fault point of the cable, it will reflect and form a reflected signal. Then the time domain correlation operation is performed on the two signals to obtain the delay time of the signal, so as to obtain the fault location of the cable, and at the same time, the type of cable fault can be judged according to the polarity of the peak point of the correlation function. The delayed test signal and the reflected signal are fed into the correlator, and the output is:

$$\begin{aligned} R_{st} &= \int_T S(\tau)\mathrm{r}(\mathrm{t}-\tau)\,\mathrm{d}\,\tau \\ &= \int_T S(\tau)\sum a_k(\mathrm{t}-\tau-\mathrm{T}_k)\,\mathrm{d}\,\tau + \int_T S(\tau)n(\mathrm{t}-\tau)\,\mathrm{d}\,\tau \end{aligned} \tag{4}$$

Where $S(t)$ is the incident signal; $r(t)=\sum a_k S(t-T_k)+n(t)$ is the received reflected signal, T_k (k=1,2,3...) is the delay time of the reflected signal, a_k is the attenuation coefficient, and $n(t)$ is the noise signal.

$$E\{R_{sn}(t)\} = E\{\int_T S(\tau)n(t-\tau)d\tau\} = 0 \tag{5}$$

According to equation (5), the expected value of the interrelation $R_{sr}(t)$ between the test signal and the reflected signal is

$$\begin{aligned} E\{R_{sr}(t)\} &= E\left\{\int_T S(\tau)\sum a_k S(\mathrm{t}-\tau-\mathrm{T}_k)\,\mathrm{d}\,\tau + \int_T S(\tau)\,\mathrm{n}(\mathrm{t}-\tau)d\tau\right\} \\ &= \int_T S(\tau)\sum a_k S(\mathrm{t}-\tau-\mathrm{T}_k)\,\mathrm{d}\,\tau \end{aligned} \tag{6}$$

From equation (6), it is known that the output is independent of the noise and is only related to the correlation value of the test signal and the reflected signal. At this time, the peak detection of the data after the correlation operation can get the location and type of cable fault.

The SSTDR method mainly uses the similarity between the detection signal and the reflected signal for fault location, which belongs to the single-end detection method. Since the PN sequence has good autocorrelation characteristics, the output peak of equation (6) corresponds to the location of the fault point of the cable, and the coordinates corresponding to the peak point are the delay amount of the reflected signal [9], and the location of the actual fault point can be derived from the following equation by the principle of the time-domain emission method.

$$d_{is} = \frac{v_0\tau}{2} \tag{7}$$

Where v_0 is the propagation speed of the test signal in the cable, is the time delay value of the fault signal, because the test signal in the process of propagation will have a round-trip process, so multiplied by a factor of 1/2.

When the detection signal is a high frequency signal or the transmission line loss is low, the wave speed is derived as follows.

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{L_0C_0}} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_r\mu_0\varepsilon_0\varepsilon_r}} \tag{8}$$

Where μ_r, ε_r refers to the relative permeability and relative permittivity of the surrounding medium at high frequencies; μ_0, ε_0 refers to the vacuum permeability and vacuum permittivity. Substituting $\mu_0 = = 4\pi\times10^{-7}$ and $\varepsilon_0 = 1/(36\pi\times10^9)$ into equation (8), the wave speed is obtained as:

$$\mathrm{v} \approx \frac{c}{\sqrt{u_r \varepsilon_r}} \tag{9}$$

Where c is the speed of light, $c = 3\times10^8 m/s$; from equation (9), it can be seen that the propagation speed of traveling waves in the cable depends on the relative permittivity and relative permeability of the cable insulation medium, and the cable conductor material, shape, length, for the same insulation medium of the cable, the signal propagation speed in its interior is the same. Table 1 shows the reference values of traveling wave propagation speed for some common cable materials.

Table 1: Calculated parameters of wave speed in cables with different insulation media

Wire and cable insulation media	μ_r	ε_r	V/(m*us^{-1})
Air Insulation	1	1.0	294
Butyl rubber	1	2.5	188
Cross-linked polyethylene	1	2.4	194
Polymers	1	2.6~3.3	166~186

3. Simulation study of single-phase fault detection and location in distribution network

3.1. Simulation Modeling and Verification

This paper is based on the location principle of SSTDR method to locate single-phase cable faults in distribution network online. In order to model the single-phase ground fault and single-phase disconnection fault of the distribution network cable, Simulink simulation environment is chosen to model the fault type and finally complete the online fault location of the cable to be tested based on the localization principle of SSTDR method with the built fault cable model. The influence of fault distance, ground resistance and signal-to-noise ratio on the detection effect of this method is considered to demonstrate the accuracy and adaptability of this method for fault location. In order to obtain a single-phase cable fault model that approximates the actual distribution network, a simulation system is constructed, which consists of nine important functional modules: power module, cable line module, fault module, detection signal generation module, modulation module, signal transmission module, signal acquisition module, signal processing module, and display module.

The test signal of SSTDR is a PN code modulated by binary phase shift keying with a sinusoidal waveform at period 1:1 to extend the frequency band of the PN code and thus reduce the overlap with the original signal in the cable, which is a Gaussian noise-like code with obvious peak characteristics and good anti-interference properties. The modulation of the incident signal is shown in Figure 2, and the amplitude of the test signal is 1V.

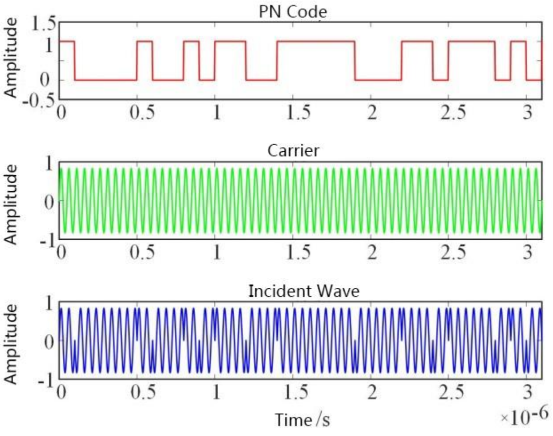


Figure 2: Schematic diagram of incident signal modulation

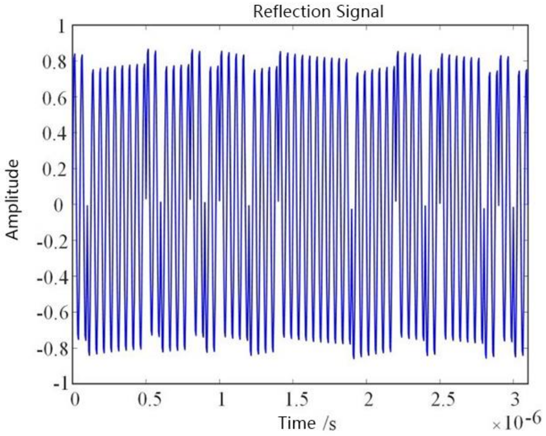
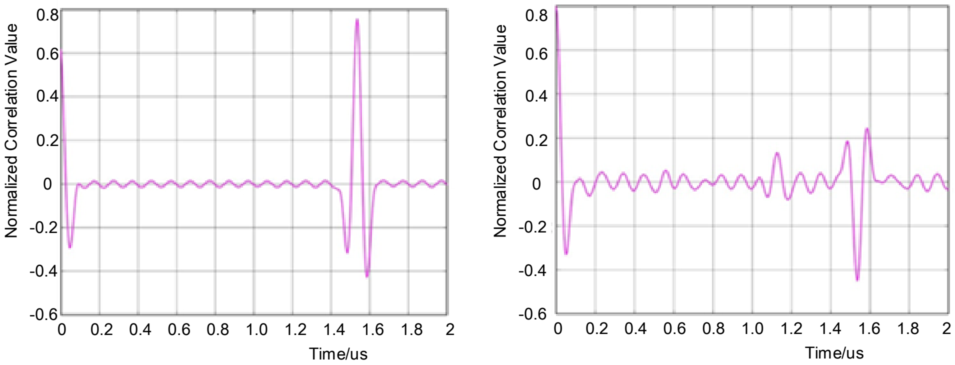


Figure 3: Schematic diagram of reflected signal

The above modulated test signal is injected into the cable to be tested. By comparing the amplitude of the injected test signal with other signals of the cable in normal operation, it is found that the amplitude of the injected test signal is so small that it does not cause any interference to other signals in the cable, thus realizing the online detection of the faulty cable. Figure 3 shows the reflected waveform of the test signal encountering the fault point. From the figure, it can be seen that the reflected signal not only becomes smaller in amplitude during transmission due to losses, but also has a time delay.

Figure 4 shows the autocorrelation value waveform obtained after correlation operation between the test signal and the reflected signal.



(a) *(b)*

Figure 4: Single-phase fault-related waveforms

The type of fault can be determined by the direction of the autocorrelation signal wave head in Figure 4. A wave head upward at the horizontal coordinate 1.535 appears in Figure 4(a), indicating that the test signal encountered a single-phase disconnection fault at this point and reflected, and a wave head downward at the horizontal coordinate 1.535 in Figure 4(b), indicating that the test signal encountered a single-phase ground short circuit fault at this point and reflected. Reflection.

3.2. Single-phase fault simulation results and analysis

The simulation platform is built in Simulink software, and the single-phase ground short circuit fault and single-phase break fault models are added to the distribution network cable model. The total length of the cable is set to 4 km, and the characteristic parameters of the cable include positive sequence and zero sequence, which are solved by Ansoft finite element simulation software as shown in Table 2.

Table 2: Cable distribution parameters

Sequence	Unit length inductance /(H*km^{-1})	Unit length capacitance /(F*km^{-1})	Unit length resistance /(Ω*km^{-1})
Preface	0.232×10^{-3}	0.16×10^{-6}	0.193
zero order	1.1275×10^{-3}	0.19×10^{-6}	0.3856

The mathematical model of Bergeron based on the traveling wave method was set up in Matlab simulation software using the characteristic parameters obtained in Table 2 [10] to construct an approximate model of the actual distribution network cables.

In order to study the effect of different fault locations on the detection accuracy of single-phase ground fault and single-phase break fault, the fault location is changed by changing the cable length, and the fault location is set at 1 km, 1.5 km, 2 km, 2.5 km and 3 km of the cable to verify whether the method can achieve the theoretically expected location accuracy, and the simulation waveforms are shown in Fig. 5 and Fig. 6.

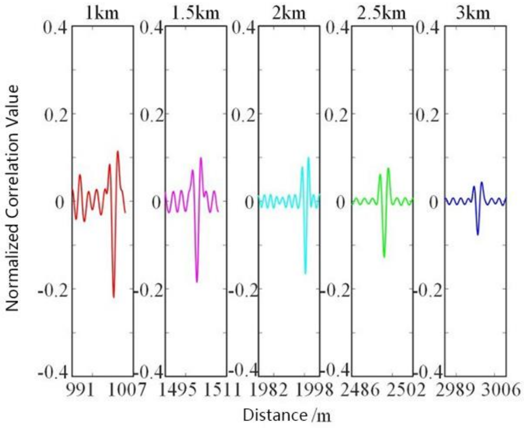


Figure 5: Single-phase ground fault simulation waveform

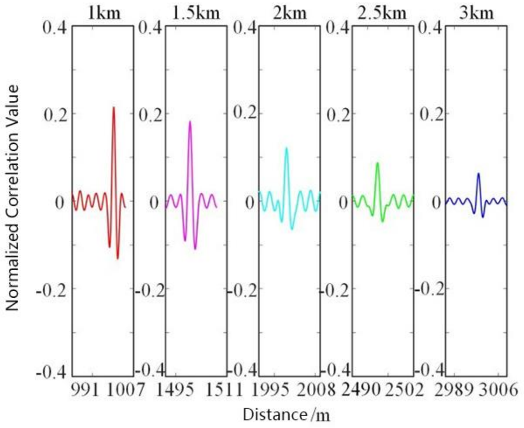


Figure 6: Simulation waveform of single-phase disconnection fault

Figure 5 shows the results of the online fault location for single-phase ground fault in distribution cables using this method. Similarly, Fig. 6 shows the specific simulation results when single-phase break faults occur in multiple distribution cables, and it can be seen that the single-phase break faults occur in different locations, which has little impact on the fault location accuracy. Also, from Figs. 5 and 6, it can be seen that the different locations of faults have almost no effect on the determination of fault types. The localization results of single-phase faults in distribution network cables are shown in Table 3.

Table 3: The localization results of single-phase faults in distribution network cables

Fault Type	Distance /km	Type	Detection distance/km	Correct Rate/%	error
Single-phase grounding	1	Single-phase grounding	0.999	100	1
	1.5	Single-phase grounding	1.499	100	1
	2	Single-phase grounding	1.999	100	1
	2.5	Single-phase grounding	2.499	100	1
	3	Single-phase grounding	2.998	100	2
Single-phase short circuit	1	Single-phase disconnection	0.999	100	1
	1.5	Single-phase grounding	1.499	100	1
	2	Single-phase grounding	1.999	100	1
	2.5	Single-phase grounding	2.499	100	1
	3	Single-phase grounding	2.998	100	2

From Figure 5 and 6, we can see that the test signal is reflected at the fault point and the reflected signal is attenuated during transmission due to the transmission loss of the cable. At the same time, the other interference signals collected by the signal receiving device will also be attenuated in the same proportion, so for different fault distances, the reflected signal peaks are still sharp and the positioning accuracy is still very good.

4. Conclusion

In this article, the SSTDR method based on the uniform transmission line model is used to solve the problem of locating single-phase ground fault and single-phase break fault in distribution networks. Then, the reliability of the method is analyzed for different fault distance, ground resistance, noise ratio, etc. Finally, the simulation signal processing is performed.

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