FINITE ELEMENT ANALYSIS OF POWER CABLE CONNECTION LINE FAULTS UNDER THE TIME-DOMAIN REFLECTION METHOD

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ABSTRACT

In this paper, finite element analysis of power cable connection line faults based on the time-domain reflection (TDR) method is designed to improve the accuracy and efficiency of fault detection. In terms of methodology, a distributed parameter model is used to describe the cable, and based on the fluctuation equation and characteristic impedance theory, the impedance characteristics under different fault types are analyzed. In terms of results, the effectiveness of the method is verified by mathematical modeling and simulation of single-phase ground faults and disconnection faults through the Simulink platform in MATLAB. The simulation results show that in terms of fault localization accuracy, our method controls the error within 0.07m, which is significantly improved compared with the traditional method. In addition, the fault detection under different noise signals is analyzed, which further establishes the accuracy of the TDR method in judging different fault types. The TDR-based power cable fault detection method proposed in this study not only improves the accuracy of fault localization, but also provides a reliable theoretical basis for the identification of different types of faults, which contributes to the stable operation and maintenance of power systems.

KEYWORDS

Time domain reflectometry (TDR), power cable faults, fluctuation equations, impedance characterization

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1. INTRODUCTION

Power cable is an important channel for the transmission of information and power in the power system, the cable line in the service process will often be subject to external and internal factors such as damage, such as man-made barbaric construction, animal bites, high temperature, corrosive gases, liquids, etc., as well as with the increase in the service time resulting in the aging of the insulation layer of the surface of the cable and other situations, the above phenomena will be on the transmission of power and even the entire power grid system security power supply caused by the important impact [1-3]. All these phenomena will have an important impact on power transmission and even the safety of the entire power grid system [1-3]. All-weather monitoring of cables in the core areas or key transmission channels can greatly improve the safety of the power grid system and reduce the major economic losses and safety accidents caused by cable failures [4-5].

With the increasing proportion of high-voltage power cables in transmission and distribution lines, the safety, stability and reliability of their operation have received widespread attention [6-8]. At present, high-voltage power cables usually use a single-core structure, this structure of the cable failure, because of its insulation thickness, the use of metal sheath cross-interconnection wiring mode and the use of cable T-joints and many other factors, resulting in high-voltage single-core cables than the 10kV three-core cable fault localization is more difficult [9-10].

Cable is an important material and equipment for power system to transmit information and electric energy. With the rapid development of cities and the increasing scale of industrial electricity consumption, the safety and reliability of cables, as an important carrier of information and energy, have been increasingly emphasized. Literature [11] proposed a novel shape memory alloy (SMA) cable constrained high damping rubber (SMA-HDR) bearing. It can effectively simplify bridge design and mitigate cable failures due to potential damage to cables from strong NF earthquakes. Literature [12] studied the submarine cable detection method in shallow areas (sea area within 200 meters), and pointed out that Brillouin RF can be used to detect submarine cables, and the method has no negative impact on cables. Some discussions on the development and trend of submarine cable detection technology were also carried out. Literature [13] designed a metal device around the feeder line, aiming to reduce and minimize the ground fault current generated in the event of a ground fault in a substation powered by a cable line. The reliability of this metal device was confirmed by simulation tests. Literature [14] envisions a new type of zero sequence current filter and ground fault protection relay based on the principle of cable shielding against ground currents. Numerical tests using PowerFactory simulation software corroborate the high sensitivity and low number of false trips of this device. Literature [15] conceived a coordinated protection system designed to ensure stable operation of the power system even when high temperature superconducting cables are used, and the feasibility and superiority of the scheme were corroborated by simulation verification using the PSCAD/EMTDC program. Literature [16] designed a modified K-means algorithm for feeder selection for full

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cable network grounding faults to increase the accuracy of feeder selection for full cable network grounding under various fault conditions. A full cable network model with five feeders is used for testing and it is proved that this method has high feeder selection accuracy. Literature [17] discusses the function of distributed temperature sensor, which is a spatially continuous temperature sensor that measures the temperature along the cable through a sensing fiber pair. Based on simulation tests and formula calculations, it is feasible to detect and locate power cable heating faults using this tool. Literature [18] presents a fast method for detecting and handling faults inside and on the DC side of a full-bridge bipolar MMC-HVDC line. Electromagnetic transient simulations corroborate that the above method can exert a positive influence on transient voltages and current stresses, among others. Literature [19] conceived a new method for cross-linked polyethylene cable insulation fault detection based on fiber optic temperature sensors. The distributed fiber optic temperature measurement technique was operated for insulation degradation test of XLPE pairs of cables, and it was pointed out that the above method can accurately locate the insulation faults. Literature [20] proposed a method based on input impedance spectrum to solve the problem of strong coupling between conductors of 10kv three-core armored cables, where defects and fault types are difficult to identify. After PSCAD circuit simulation tests, the results show that the proposed method can effectively identify faults and local defects in three-core cables. Literature [21] proposes an original algorithm based on known arc combustion theory to simulate the maximum overvoltage value during arc combustion. The effect of arc suppression coils on the nature and magnitude of transient overvoltages and arc excitation overvoltages due to cable insulation breakdown is investigated. According to the simulation tests on the operation simulation of different power grids, it is found that the proposed model can clarify the minimum insulation margin and overvoltage protection trigger threshold of power grid equipment to ensure the reliable operation of the power grid.

The research idea of this paper is firstly based on the time-domain reflection (TDR) method, which utilizes the distribution parameter model to characterize the cable connection line. The impedance characteristics under different fault types are analyzed by constructing fluctuation equations and characteristic impedance theory. Subsequently, the Simulink platform in MATLAB is used to conduct simulation experiments, including the mathematical modeling of single-phase ground faults and disconnection faults. The effectiveness of the theoretical method is verified by observing the simulation results. At the same time, the changes in impedance characteristics of different types of faults are explored, as well as the influence of noise signals on fault detection. Finally, through data analysis and theoretical comparison, conclusions are drawn to demonstrate the advantages of this research method in improving the accuracy and efficiency of fault detection.

2. METHODS

2.1. FAULT LOCALIZATION TECHNIQUE BASED ON TIME-DOMAIN REFLECTION METHOD

Power cable connection line belongs to a kind of transmission line, in the ideal case, the cable connection line can be regarded as a uniform transmission line, so it is feasible to use distribution parameters to describe the cable model. Its equivalent distribution parameter model in R, L, C, G represent the distribution resistance, inductance, capacitance and conductance per unit length of the transmission line, respectively.

Its fluctuation equation can be obtained based on the above parameters, which are obtained:

$$\begin{cases} -\frac{\partial u}{\partial x} = Ri + L\frac{\partial i}{\partial t} = (R + j\omega L)i \\ -\frac{\partial i}{\partial x} = Gu + C\frac{\partial u}{\partial t} = (G + j\omega C)u \end{cases} \quad (1)$$

The characteristic impedance Z_0 is the ratio of the incident wave voltage u to the incident wave current i, which can be obtained as:

$$Z_0 = \frac{u}{i} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (2)$$

Among them, the capacitance C and inductance L are related to the dielectric constant of the cable, the cross-sectional area of the material core, etc., which indicates that the wave impedance is different for different kinds of cables.For the transmission line with small losses, the characteristic impedance Z_0 can be simplified to $Z_0 = \sqrt{L/C}$ because of $\omega L \gg > R, \omega C \gg > G$,.The reflection coefficient can be expressed as follows.

$$\rho = \frac{Z_\mathrm{L} - Z_0}{Z_\mathrm{L} + Z_0} \quad (3)$$

Where, Z_L is the load at the fault point.According to the time interval between the injection pulse time and the pulse reflection time, the location of the fault point is calculated as:

$$L = \frac{1}{2}v_\rho\left(t_1 - t_2\right) \quad (4)$$

Where, v_p for the pulse propagation speed in the cable medium, and the dielectric constant of the medium related to t_1, t_2, respectively, for the pulse sent to the moment

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and the pulse returned to the launch point of the moment. in the frequency is very high, the cable in the electromagnetic wave propagation speed tends to a constant constant.

According to the theory based on time-domain reflection method, we can obtain the basic characteristics of the impedance of the cable connection line fault as follows.

When the cable is normal, the load impedance and characteristic impedance is matched, that is, $Z_L - Z_0$, then according to the formula (3) reflection coefficient $\rho = 0$ no reflection echo. at this time the whole section of the cable impedance uniformity without mutation points, the impedance waveform curve is specifically expressed as a straight line section of basically unchanged amplitude.

When the cable connection line breakage fault occurs, there is $Z_L = \infty$, then the reflection coefficient $\rho = 1$, the incident wave and the reflection wave has the same polarity, the incident and reflected voltage waveform shown in Figure 1. at this time, the cable impedance in the breakage point of a sudden change in the impedance waveform curve is specifically expressed by the normal impedance waveform, a sudden increase in the amplitude of a certain location, and tends to be close to positive infinity. the distance between the point of the mutation and the normal impedance waveform starting point. The distance between the mutation point and the starting point of the normal impedance waveform, i.e., the incident/reflected pulse time difference, and the location of the actual cable connection line short-circuit fault point to meet the formula

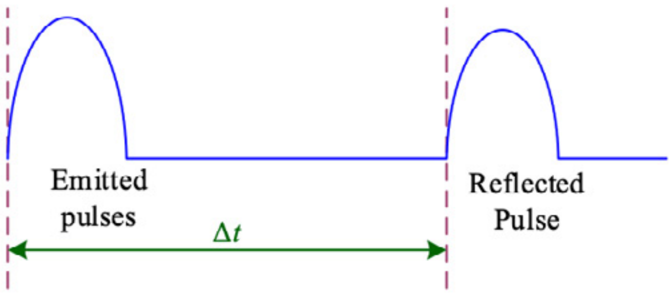

Figure 1. Schematic diagram of incident and reffected waves, when the cable open circuit occurs

When the cable short-circuit fault, there is $Z_L = 0$, then the reflection coefficient $\rho = -1$. incident and reflected waves of opposite polarity, the incident and reflected voltage waveforms shown in Figure 2. at this time, the cable impedance in the short-circuit point of a sudden change in the impedance waveform curve is specifically manifested by the normal impedance waveform suddenly in a position of amplitude changes to 0. The mutation point and the normal impedance waveform starting point of the distance between the distance between that is, the incident/reflected pulse time difference with the actual cable short-circuit fault point location to meet the equation (4).

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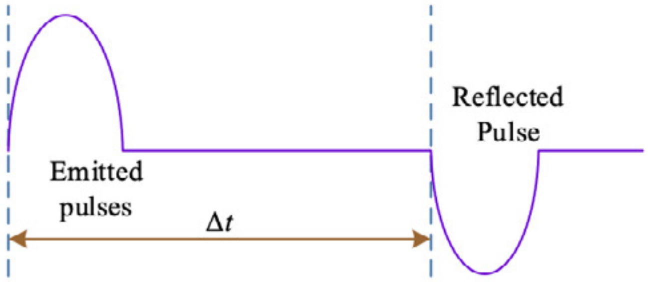

Figure 2. Schematic diagram of incident and reffected waves, when the cable short circuit occurs

Cable connection lines occur insulation skin folding, wear and shielding damage, furthermore, taking into account the on-board cables are usually bundled through the power center connector connection, where each cable is usually connected through the contact coupling, the introduction of the connection point will inevitably have an impact on the test line impedance. this time, there are $Z_L \neq 0, -1 < \rho < -1$, equivalent to the fault / anomaly for the inductor, capacitor, resistance, series or parallel connection. At this time, the cable impedance will also undergo a sudden change, but these states of the electric pulse signal can continue to propagate along the cable, only part of the signal in the fault/anomaly at the point of reflection, so the cable impedance after a sudden change can still be restored to a smooth state. the impedance waveform curve is specifically manifested as a section of the amplitude of a stable straight line in a certain position amplitude suddenly changed, and then return to normal, amplitude re The distance between the sudden change point and the normal impedance waveform start point, i.e., the incident/reflected pulse time difference, and the actual cable connection line fault/anomaly location also meets the formula (4).

According to the above analysis, it can be seen that when the cable connection line short-circuit and disconnection faults occur, the reflected waveform and cable fault impedance characteristics are obvious, and the impedance test can be used to directly determine the type of fault, while for other types of faults or anomalies, although it can be obtained from the characteristics of the change, but for the judgment of the type of faults or anomalies, the need for more in-depth theoretical support.

2.2. HIGH-PRECISION SINGLE CABLE FAULT DIAGNOSIS METHOD

The following analysis of the influencing factors of the positioning accuracy, from the TDR cable connection line fault location principle considerations, according to the law of linear superposition of error transfer, can be measured cable fault length *l* of the error can be expressed as follows.

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$$\Delta l = \frac{1}{2}(t\Delta v + v\Delta t) \tag{5}$$

v is the propagation speed of the TDR detection signal in the cable, t is the time interval between the peak of the incident wave and the peak of the reflected wave, Δv is the wave speed error, and Δt is the time interval measurement error.

The main reason for the existence of the error is mainly due to the measurement error of the wave speed, as well as the time interval measurement error. positioning accuracy is the largest positioning error, so in order to improve the positioning accuracy, the following by reducing the wave speed error and time measurement error to improve fault location accuracy.

2.2.1. REDUCED TIME MEASUREMENT ERROR

When analyzing the time measurement error of TDR peak point acquisition, when the sampling rate f is certain, the sampling time T is determined, and the waveform is finally recorded as a discrete point. Due to the principle of TDR fault detection, it is necessary to collect the incident and reflected peak points.When the peak points are collected by the direct counting method as shown in Fig. 3, the actual collection point may not be the real peak point, so that there exists a time measurement error, and the maximum time measurement error meets the formula.

$$\left|\Delta t'\right| \leq \frac{T}{2} \tag{6}$$

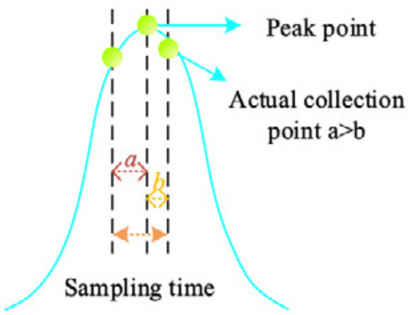

Figure 3. Schematic diagram of peak extraction by TDR through sampling

Since the system needs to collect the correlated incident wavehead and the correlated reflected wavehead, there are two samples, so the measurement error of the whole system satisfies the following equation.

$$\Delta \mathrm{t} = \left|2\Delta t'\right| \leq T = \frac{1}{f} \tag{7}$$

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At present, the sampling rate of the prototype of the localizer is *500MHz*, and if it is assumed that there is no error in the propagation speed of the detected signals calculated by the theory before, it can be calculated that the positioning error is.

$$-0.207m \leq \Delta l = \frac{1}{2} v \Delta t \leq 0.207m \tag{8}$$

It can be seen that in the center frequency of *60.5MHz*, the signal propagation speed is *500MHz*, in the sampling rate of $2.15 * 10^8 \mathrm{m/s}$, the positioning error is within $\pm 0.215\mathrm{m}$, if you want to continue to reduce the positioning error, you need to improve the hardware sampling rate, but due to the increase in the hardware sampling rate caused by the substantial increase in the cost of the hardware, so taking into account the savings in hardware costs, through the peak extraction algorithm is studied to reduce the time measurement error and reduce the fault location error. Therefore, in consideration of saving hardware cost, the peak point extraction algorithm is used to reduce the time measurement error and fault localization error.

For the cable fault diagnosis signal obtained by the relevant operation in this paper, the signal sequence is expressed as follows:

$$\left(x_1, y_1\right), \left(x_2, y_2\right), \ldots, \left(x_i, y_i\right), \ldots, \left(x_N, y_N\right) \tag{9}$$

Where N is the length of the signal sequence, x_i is the time coordinate of the i th data point, and y_i is the amplitude of the i th data point.The principle of this fitting problem is that for a given signal sequence$\left(x_i, y_i\right)$, Φ is the class of functions consisting of polynomials of all times not exceeding $m(m \leq N)$, and $P_m(x) = \sum_{k=0}^{m} a_k x^k \in \Phi$ is found such that:

$$I = \sum_{i=1}^{N} \left[P_m(x_i) - y_i\right]^2 = \sum_{i=1}^{N} \left(\sum_{i=1}^{m} a_k x^k - y_i \right)^2 \tag{10}$$

The $P_m(x)$ that satisfies the minimum value of I in Eq. (10) is called the least squares fitting polynomial.

The TDR signal waveform can be fitted by a quadratic polynomial, and since the delay time needs to be obtained by analyzing the incident and reflected waveforms together, it is necessary to do two quadratic polynomial fits to the incident and reflected waveforms in the TDR signal. From this, we set the quadratic curve equation to be.

$$p(x) = a_0 + a_1 x + a_2 x^2(\qquad 11)$$

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2.2.2. REDUCED CALIBRATION SPEED ERROR

In practice, when fault localization is carried out by TDR on a certain cable connection, it is necessary to calibrate the speed, and the steps of calibration are as follows.

1) First take a section of cable of known length *l*.

2) The calibration method is not known in the case of signal propagation speed, the first given a signal propagation speed.

3) According to the signal transmission time is the same as the establishment of the equation, the solution to obtain the true signal propagation speed, the formula is.

$$\frac{l}{v} = \frac{l'}{v'} \tag{12}$$

Where l is the real cable length, l' is the measured cable length, v is the real signal propagation speed, v' is the given signal propagation speed.

According to Equation (12), the calibrated signal propagation speed can be calculated as.

$$v_{\text{Calibration}} = l * \frac{v'}{l'} \quad (13)$$

However, in practice, due to errors in time measurements, it is necessary to add the time , so that the actual relationship is:

$$\frac{l}{v} = \frac{l'}{v'} + \Delta t \tag{14}$$

The exact true speed, then, is.

$$v = \frac{l}{\frac{l'}{v'} + \Delta t} \tag{15}$$

Therefore, the velocity error can be calculated according to Eq. (14) and Eq. (15), obtaining.

$$\Delta v = v_{\text{Calibration}} - v = l * \frac{v'}{l'} - \frac{l}{\frac{l'}{v'} + \Delta t} \tag{16}$$

Set $\frac{l'}{v'} = t$. Then the velocity error equation can be expressed as.

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$$\Delta v = \frac{l}{t} - \frac{l}{t+\Delta t} = \frac{l * \Delta t}{t^*(t+\Delta t)} = \frac{l}{t+\Delta t} * \frac{\Delta t}{t} = v^* \frac{\Delta t}{t} \quad (17)$$

Since the time measurement error Δt satisfies Eq.

$$0 \leq |\Delta t| \leq \frac{1}{f} \quad (18)$$

Therefore the range of speed measurement error is.

$$0 \leq |\Delta v| \leq \frac{v}{tf} \quad (19)$$

According to the above formula, the following conclusions can be drawn, because f is the real speed for a certain value, for the device sampling frequency, ignoring its error, is also a constant value. *t* is related to the length of the calibration cable, it can be seen that when the longer the length of the calibration, the smaller the range of speed measurement error. by increasing the length of the calibration cable, the calibration error can be confined to a smaller range to reduce the positioning error.

3. RESULTS AND DISCUSSION

3.1. POWER CABLE CONNECTION LINE FAULT SIMULATION

In this paper, the Simulink simulation platform in MATLAB is used for mathematical modeling of single-phase ground fault and single-phase disconnection fault of power cables respectively, and TDR is applied to analyze and process the reflected signals of the fault point to realize fault ranging of cables, and the feasibility and accuracy of the TDR on-line detection method and the localization algorithm designed in this paper are further verified by observing the detection effect under different signal-to-noise ratios. Accuracy of the TDR on-line detection method and the localization algorithm designed in this paper.

Due to the complexity of the power system line connection, so in the cable fault modeling process, to simplify the processing. according to the cable fault type, in Simulink to find the corresponding module for the connection, when the cable ground fault occurs, the specific simulation circuit model as shown in Figure 4, which includes the ranging signal generator module, power supply module, as well as the signal transmission and fault module, etc. where R indicates the beginning of the matching resistance, resistance value of 50Ω, C_1 for the 3.5 *nF* insulating capacitance. set the length of the first cable for 100m, the second cable section length of 500m, the total length of the line is 600m. in the two sections of the cable to join between the three-phase fault generator, this time, the cable fault occurs at the location of 100m. the three-phase power supply module in the figure for the ideal power supply system, the beginning of the phase is 0 degrees, the operating frequency is 0 degrees, the

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operating frequency is 0 degrees, the operating frequency is 0 degrees. The three-phase power supply module in the figure is an ideal power system, the starting phase is 0 degrees, the operating frequency is 20Hz, taking into account the voltage amplitude in the experimental environment has nothing to do with the detection method, low-voltage value is more conducive to the graphical observation, so set the operating voltage of 220V.

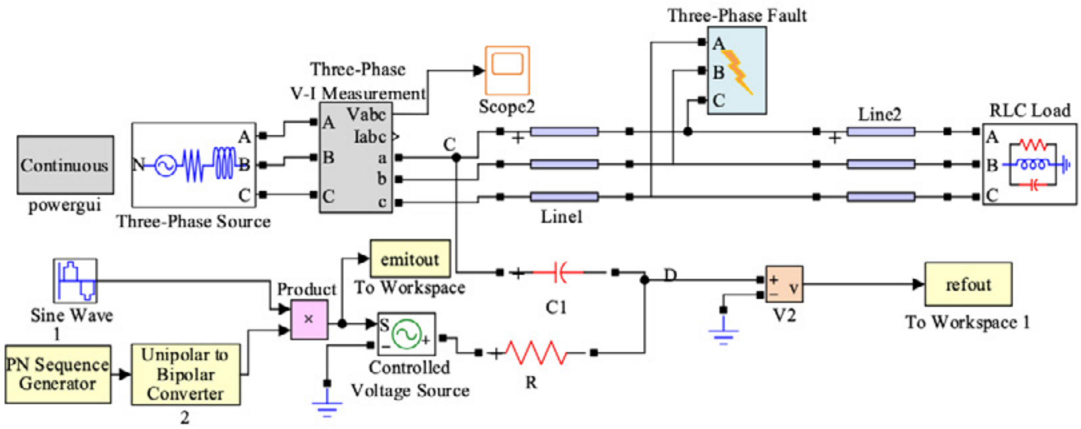

Figure 4. Cable grounding fault circuit model

Characteristic parameters of cable connection line include positive sequence and zero sequence two parts, cable characteristic parameter settings as shown in Table 1, which are set for the unit resistance, reactance and capacitive reactance of the two sections of the cable. positive sequence and zero sequence unit length reactance (Ω/km) are 0.2016 and 0.3774, respectively. through the three-phase fault generator to simulate single-phase low-resistance ground faults in cables, just select the phase A faults in the Fault Generator Parameter Dialog, and set the grounding resistance. The grounding resistance $R_g = 10\Omega$ is set.

Table 1. Cable feature parameter Settings

Parameter type	Positive sequence	Zero sequence
Reactance per unit length (Ω/km)	0.2016	0.3774
Reactance per unit length (H/km)	0.2085×10^{-2}	1.2131×10^{-2}
Unit length tolerance (F/km)	0.112×10^{-5}	0.212×10^{-5}

In order to further verify that the TDR method can complete the detection of intermittent cable link faults, the fault duration is set to 0.05s. For the test signals, the frequency of the local cosine carrier signal is $f = 10\mathrm{MHz}$, the corresponding duration of the *m* sequence is $2 \times 10^{-5}s$, and the period of the sequence is 128. The starting time of the simulation is 5s, respectively, through the To Workspace module, the reference signal and the fault signal are outputted to the MATLAB workspace, and analyzed by the signal processing module. in the process of the simulation, the fault location can be changed by setting the length of the first section of the cable, and at the same time, the total length of the cable can be adjusted. in accordance with the above requirements to complete the parameter settings of the modules, the test signals are made of m-sequence and cosine signals in accordance with the 1:1 BPSK modulation, and their waveforms are shown in Fig. 5.

The upper and lower parts of the figure are the waveforms of the m sequence and the TDR test signal, respectively. it can be seen that in the same $2 \times 10^{-5} s$ time, the m sequence completed 15 reflections, while the TDR test signal reflection amplitude and number of times than the sequence. The test signal generated by the above is injected into the cable to be tested through the detection point (D), the test signal and the normal operation of the cable in the AC signal superposition of the AC signal. because of the amplitude of the test signal is very small compared to the effective signal transmission, almost does not have any impact on the normal operation of the signal transmission, so it is possible to use the TDR to achieve the on-line detection of cable faults.

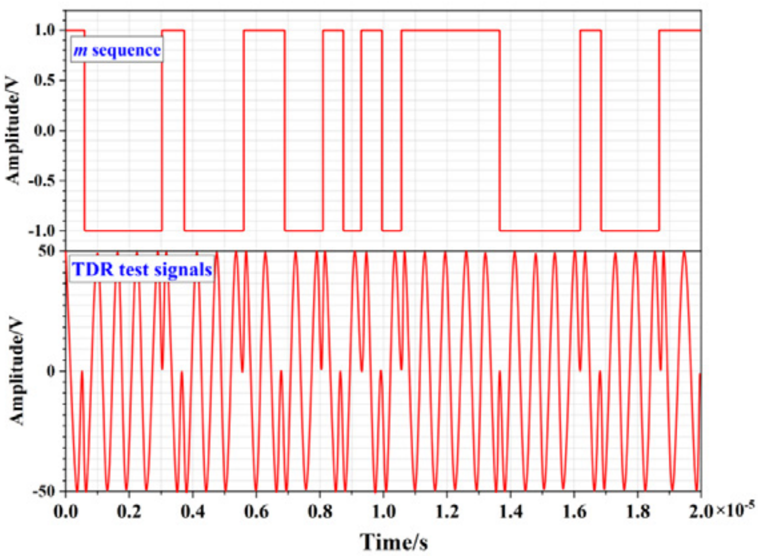

Figure 5. The sequence and corresponding TDR test signals

When the test signal in the cable transmission process encounters 100m at the single-phase ground fault point, will be reflected back, the reflection coefficient and the impedance value of the fault point of the size of the impedance value is related to the ground short-circuit fault, the value of the coefficient of -1, the reflected signal and the test signal is reversed. D point of the original signal collected by the high-pass filtering, to get the ideal zero-noise environment under the fault signal shown in Fig. 6. it can be seen that the fault signal in the cable transmission process amplitude frequency attenuation, from -50~50 (V) amplitude frequency attenuation of -9.63~9.85 (V). It can be seen that the fault signal in the cable transmission process has amplitude and frequency attenuation, compared with the test signal has a time delay, the time delay is about 0.2×10^{5}. The amount of time delay is related to the location of the fault point and the propagation speed of traveling wave in the cable.

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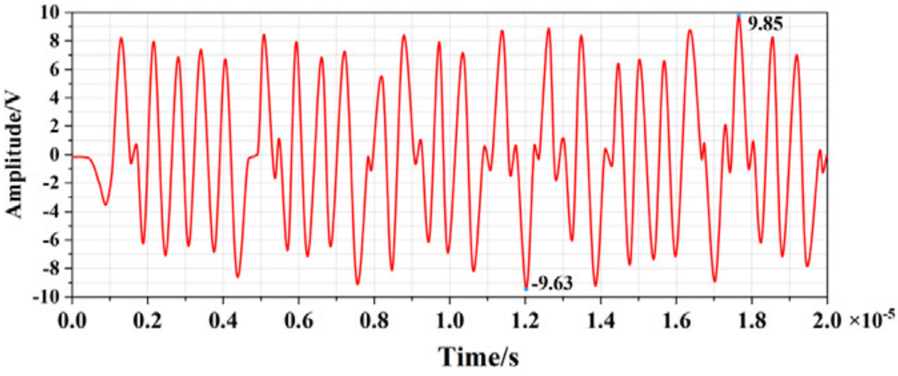

Figure 6. Reflected signal at the fault point under ideal conditions

Application of 2.2 chapter described in the high-precision single cable fault diagnosis method for isolation of fault signals and point C incident signal processing, the output of the system as shown in Figure 7. in order to facilitate the observation of the results of the figure has been transformed through the corresponding formula of the transverse coordinate by the sampling point into the amount of time, the transformation of the signal with the sampling frequency of the f related to the peak detection, you can get the relevant waveform peak point, the value of -0.1447, the corresponding horizontal coordinate is 1.8199×10^{-5}, that is, the delay time of the reflected signal is 1.8199×10^{-5}s. From the characteristic parameters of the power cable. The velocity value of the traveling wave in the cable is estimated $v = 1/\sqrt{LC} = 1.6350 \times 10^{8}$m/s as by the characteristic parameter *L* and *C* of the power cable, and according to the formula of the cable fault ranging, it can be seen that the location of the cable fault is about 99.93m away from the detecting point D, which has an error of 100m from the actual fault. The error is only 0.07 m. Since the correlation peak is negative, the type of cable fault can be judged accordingly. in the case of high signal-to-noise ratio, the correlation peak is more obvious, which indicates that the TDR method can achieve better fault localization with high-precision single cable fault diagnosis algorithm.

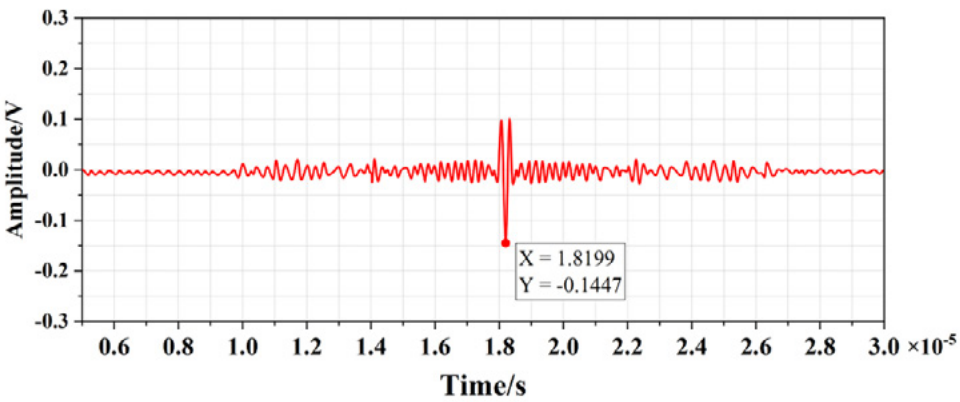

Figure 7. Waveform related to cable grounding faults at a high SNR

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3.2. SIMULATION RESULTS ANALYSIS

The noise signals with different center wavelengths of TDR are used to detect the faults of different branches at the same time, and the simulation results are shown in Fig. 8, in which Fig. 8(a) shows the experimental results of detecting the faults of 63.60 m with the noise signals with the center wavelength of 1472.47 nm. The correlation peak in the 0 position is used as the reference peak of the measurement, and indicates the zero point of the measurement. The distance of the second highest correlation peak relative to the reference peak indicates the location of the break fault, and it is accurately located at 63.60 m. In addition, the two small peaks on the right side are caused by the reflected harmonics of the second (2nd refl) and the third (3nd refl) of the break fault.Fig. 8(b) sets up a short-circuit fault in the cable to be measured at 63.60 m, and the noise signal with the center wavelength of 1473.22 nm is used as the detected signal of the branch. It can be seen that there is a correlation peak at 63.60m, and it is negative (-158.45), indicating that a short-circuit fault has occurred there.

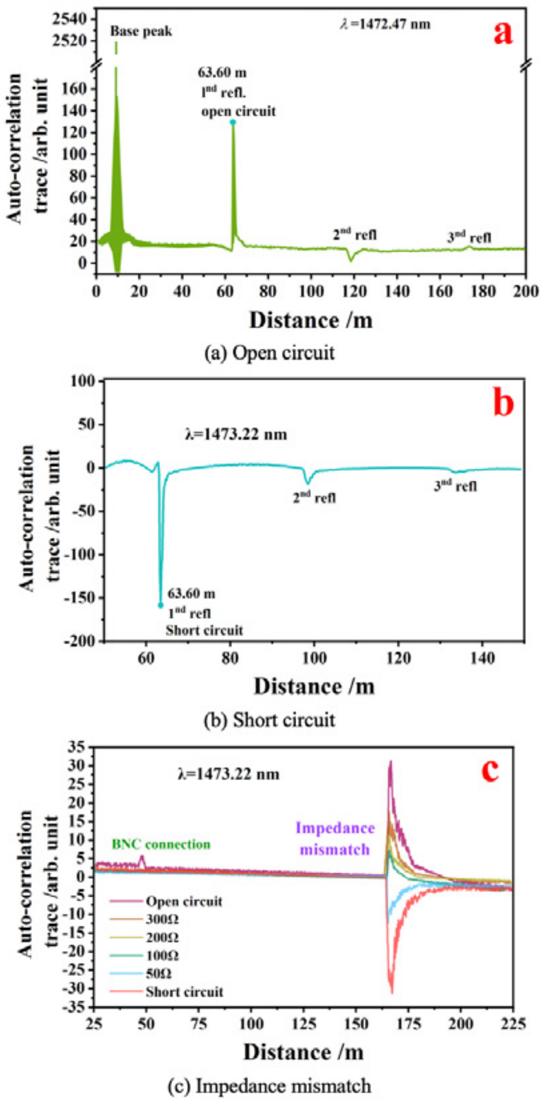

Figure 8. Detection results of cable faults on different cable branches

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Fig. 8(c) shows the results of impedance mismatch fault detection using a noise signal with a center wavelength of 1474.75 nm. The impedance mismatch fault on the cable to be tested consists of a coaxial cable connector (BNC) connection point and an impedance tunable termination load, and the impedance values of the termination load are set to be 300, 200, 150, 50, and 0 Ω (short-circuit), respectively. Since the correlation peak in the disconnected state indicates total reflection, normalizing the peak there, the correlation peaks of the rest of the curve at the impedance mismatch indicate the actual reflection coefficients, which are 0.534, 0.338, 0.212, and -0.357, respectively, and therefore, according to the curves, the impedances at the impedance mismatches are 173±8, 157±6, 83±11, and 27±3 Ω. Similarly, the reflection coefficients and impedance values of the BNC connections are measured as Similarly, the reflection coefficient and impedance value of the BNC connection point can be measured as 0.0022 and 59±4Ω, respectively.

In the simulation experiment, the relative error is used to measure the measurement accuracy, and the relative error E_r is expressed as follows.

$$E_r = \frac{|x-a|}{a} \times 100\%$$

Where, *x* represents the actual measurement value of the length of power cable, represents the standard length of cable, which is agreed to be the nominal value of the cable under test. different lengths of cable were measured several times, and the polynomial fitting of the relative error results of different lengths were obtained, as shown in Fig. 9. it can be seen that in the measurement range of 100m, the relative error is around 1%, with the increase of the length of measurement, the relative error gradually increases, and in the measurement range of 700m, the relative error is controlled within the range of 3.73%. It can be seen that in the measurement range of 100 m, the relative error is around 1%, and with the increase of the measurement length, the relative error increases gradually, and in the measurement range of 700 m, the relative error is controlled in the range of 3.73%, which proves that the TDR method can be used for the online detection of cable faults, and it has high efficiency and low error.

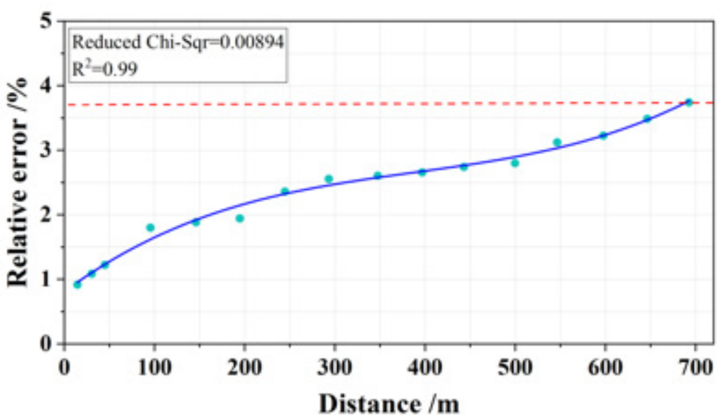

Figure 9 Relative error changes with measurement distance

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4. CONCLUSION

In this study, we have achieved remarkable research results for the finite element analysis of power cable connection line faults by the time-domain reflection (TDR) method. Through simulation experiments, we found that the TDR method can effectively reflect the change of cable impedance in the case of single-phase ground faults and disconnected faults, so as to accurately locate the fault location. The simulation results show that the error of fault localization is controlled within 0.07m, which is much better than the traditional method.

In addition, this study also explores the fault detection effect under different noise signals, and finds that the TDR method is still effective in identifying and localizing faults even under different signal-to-noise ratio environments. For example, the location of the break fault detected under the noise signal with a center wavelength of 1472.47 nm is accurate to 63.60 m, which proves the stability and reliability of the method under different conditions.

The analyzed data show that the relative error is controlled within 1% in a measurement range of 100m, while in a longer measurement range (e.g. 700m), the error is still controlled within 3.73%. This result not only confirms the high efficiency of the TDR method for cable fault detection, but also demonstrates its feasibility for long distance detection.

The finite element analysis method of TDR based on power cable connection line faults proposed in this study proves its effectiveness both theoretically and practically. The method not only improves the accuracy and efficiency of fault localization, but also provides strong technical support for the safe operation of power systems. This result has important guiding significance for fault detection and prevention in the power industry, as well as for future cable design and maintenance.

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