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Study on cable fault location based on fast identification of starting point of reflection wave

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Abstract: Traveling wave reflection method is widely used in cable length measurement and fault location. How to effectively remove noise interference and accurately identify the starting point of pulse reflection is the key problem to be solved by this method. In this paper, two new methods, the improved weighted coefficient method based on the wavelet theory and the curve fitting method, are proposed for different identification accuracy and velocity by analyzing the measured reflected wave signal. The improved weighted coefficient method was used to process the traditional denoising threshold with the same value of $\pm thr$, and then the calculated weighted threshold was used to reduce the noise of the measured signal, so as to highlight and identify the starting point of reflection pulse. The curve fitting method is adopted to compare the reflected wave anomaly with the threshold value of the corresponding length cable. If the threshold value is exceeded, the fault reflection can be judged as fault reflection. Then the quadratic function fitting is carried out here, and the starting point of the reflected pulse is directly determined by using the intersection point of the quadratic curve and the reference voltage. The experimental and simulation results show that the improved weighted coefficient method solves the problems of unsmoothness of denoising and discontinuity of derivative of denoising function, improves the accuracy of identifying the starting point of reflection wave, provides a new algorithm for improving the measurement accuracy. The curve fitting method has high speed, low demand for hardware, and the error can be controlled within 10ns, which is more suitable for low-cost equipment based on Microcontrollers.

Keywords: Detection of defects; Pattern recognition, cluster finding, calibration and fitting methods

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1 Introduction

In the process of power production and operation, the accurate measurement of cable length and fault location is of great significance to cable production, power construction, fault detection and fault diagnosis [1–3].

Traveling wave method is based on the theory of wave impedance and widely used in cable fault detection [4–7]. When the cable fails, due to mismatching of line impedance, the pulse voltage transmitted at the first end of the line will generate reflection waves at the fault point or connection. At the same time, the reflection time at the first end can be detected to have a linear relationship with the length of the line fault point [6]. The distance from the fault point can be determined according to the time difference between the incident pulse and the reflected pulse and the propagation speed of the incident pulse in the cable [7–9]. In the case of uniform insulation medium, the traveling wave method is independent of the structure of cable circuit, and the measuring results of traveling wave method are not affected by high-resistance faults when high-resistance faults occur [10].

Fast and accurate determination of the starting point of reflected wave signal is the key to traveling wave method [11]. High frequency noise is the main factor affecting the accurate identification of the starting point of reflection wave by traveling wave method [12]. Many experts have studied how to effectively eliminate the effect of high frequency noise. Pourahmadi-nakhli put forward the wavelet method to process the reflected wave signal, which decomposes the signal in multiple layers, filters the high-frequency coefficients of each layer, and rebuilds the processed signal to achieve the purpose of denoising [13]. The signal after denoising by wavelet method has the ability to characterize signal mutation, which is widely used in fault detection and fault identification [14]. In the wavelet method proposed by Chanda et al., the processed signal lost its original smoothness due to the discontinuity of the selected threshold function [15]. Therefore, many experts have improved it and put forward the corresponding improved algorithm for fault location. Livani et al. proposed a fault location method for hybrid transmission lines based on machine learning and wavelet transform [16]. Aritra Dasgupta proposed a transmission line location based on wavelet entropy and neural network. Vahidi proposed a wavelet method, using correlation coefficients to distinguish between internal faults and surge current [17]. However, in the above literature, the signal is not denoised according to the characteristics of high-frequency noise in the actual measurement, and the derivative of the threshold function is discontinuous, which makes the signal waveform after processing deviate from the original signal to a certain extent, affecting the accuracy of starting point identification. The improved weighted coefficient method is an improvement of the traditional wavelet method. For the normal distribution of noise signal, the non-important coefficients within $3\sigma<thr$ are selectively filtered, and the threshold function is weighted. The improved threshold function and derivative are continuous. The experimental results show that the improved weighted coefficient method overcomes the disadvantages of traditional denoising, and the processed reflection wave is smoother and the deviation from the original signal is reduced.

The improved weighted coefficient method can effectively reduce the influence of high frequency noise on the initial point identification of reflection wave and improve the accuracy of the initial point identification. But it is not suitable for cheap devices, such as microcontrollers, due to its large amount of calculations. In order to solve this problem, a curve fitting method is proposed in this paper. In the curve fitting method, according to the attenuation law of the reflected signal in the cable, the threshold of the corresponding length is set, and compared with the threshold at the abnormal place of the cable, the excess is judged as the line fault point, and the quadratic function fitting is carried out at the fault point. The intersection of the fitting curve and the reference voltage is used as the starting point of the reflected wave. The experimental results show that the curve fitting method can quickly determine the starting point of the reflected wave.

2 Theoretical analysis of improved weighted coefficient method and curve fitting method

2.1 Theoretical model of improved weighting coefficient method

2.1.1 Wavelet denoising model

The reflected signal f(n) polluted by noise signal is s(n), and the denoising model can be expressed as:

$$s(n) = f(n) + \sigma e(n) \tag{2.1}$$

In the formula, $e(n)$ is the noise signal and σ is the noise intensity [18].

2.1.2 Process of wavelet denoising

According to the mathematical model of formula (2.1), wavelet denoising is to suppress noise signal *e(n)* and highlight original signal *f(n)*. Therefore, the process of denoising is shown in figure 1:

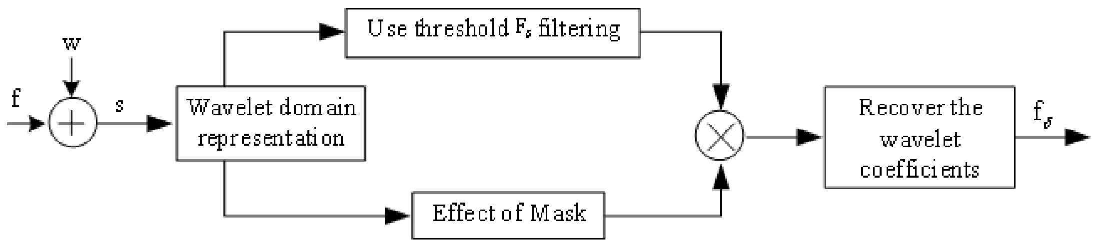

Figure 1. Wavelet denoising process.

In the figure 1, f is the reflected signal, w is the noise signal, and s is the signal after noise pollution. As can be seen from the figure, the denoising process can be divided into the following four steps:

(1) Reflection signal and noise signal of s signal after wavelet decomposition are respectively saved in the partition coefficient.

(2) Threshold filtering process is to compare the coefficients of each layer with the threshold value, and to retain the signals beyond the threshold value and filter the signals below the threshold value.

(3) The Mask is a generalization of the threshold operator. The threshold operator is realized by introducing the system modulus value.

(4) Wavelet reconstruction, restore the signal f_δ.

2.1.3 Soft threshold denoising theory

Soft threshold denoising is based on discrete orthogonal wavelet transform, and the finite length signal after noise pollution can be expressed as:

$$s_i = f_i + e_i\,, \qquad i = 1, 2, \ldots, n \tag{2.2}$$

s is the signal containing noise, f is the original signal [19], the vector symbol s ,f are used to represent $\{si\}$ and $\{fi\}$, W is the discrete wavelet operator, s and f are the discrete orthogonal wavelet transform of $\{si\}$ and $\{fi\}$ respectively:

$$S = Ws, \qquad F = Ws \tag{2.3}$$

Where, F represents the estimation of F in S, then the denoising method can be realized by the following three steps:

(1) Calculate the orthogonal transformation *S*=*Ws*.

(2) Apply threshold value method to denoising. MATLAB wavelet toolbox provides a variety of wavelet denoising functions, the application of the most is the hard threshold and soft threshold denoising. Among them:

$$\overset{\wedge}{d_j(k)} = \begin{cases} d_j(k), & \left|d_j(k)\right| \geq thr \\ 0, & \left|d_j(k)\right| \leq thr \end{cases} \tag{2.4}$$

Threshold function of soft threshold:

$$\overset{\wedge}{d_j(k)} = \begin{cases} sgn(d_j(k))(d_j(k) - thr), & \left|d_j(k)\right| \geq thr \\ 0, & \left|d_j(k)\right| \leq thr \end{cases} \tag{2.5}$$

Where, *thr* is the threshold value.

(3) Calculate $\hat{f} = w^{-1}s$, $\hat{f}$ is the original signal of recovery.

2.1.4 Improved weighted coefficient method and determination of threshold value

Traditional wavelet denoising is divided into hard threshold method and soft threshold method. The hard threshold method is to set the wavelet coefficients below the threshold value of each subspace to zero, and the wavelet coefficients above the threshold value remain unchanged. Therefore, the threshold function is discontinuous at -*thr* and +*thr*, and the denoised signal may oscillate, losing the smoothness of the original signal. He soft threshold method is to shrink the wavelet coefficient to zero according to a fixed quantity, and then reduce the noise by the new wavelet coefficient, and reconstruct the signal after noise reduction. Soft threshold denoising is better than hard threshold denoising, preserving the smoothness of the original signal, but the derivative of soft threshold denoising is discontinuous, which has a certain deviation from the original signal.

To solve this problem, an improved weighted coefficient method is proposed. Since the measured noise signal is generated randomly, the noise coefficient distribution after decomposition conforms to the normal distribution rule. According to the 3σ principle of normal distribution, 99.74% of the noise signal in the (u-3σ, u+3σ) interval is divided into two parts in the wavelet decomposition. The main noise signal in the (u-3σ, u+3σ) interval is the non-important factor. The signal outside the (u-3σ, u+3σ) interval contains the reflected wave signal and is the important factor. Therefore, the transformation domain is divided into two parts. DJ (k) is used to represent the threshold value of s(n) containing noise signal. In order to retain the reflection signal with important coefficients, the normal distribution denoising threshold is selected as follows:

(1) Important parameters
$\left|d_j(k)\right| \geq 3\sigma \geq thr$, $\left|d_j(k)\right| i \geq 3\sigma i \geq thr^2$, so $thr \geq \frac{thr^2}{\left|d_j(k)\right|}$, so select $\frac{thr^2}{\left|d_j(k)\right|}$ as the threshold.

(2) Set the non-important coefficient at 0

Since the non-important coefficient is set to 0, the smoothness of the reflected signal after denoising is reduced. In order to retain the smoothness of the original signal, the soft threshold and

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the above threshold are weighted by formula (2.6) to obtain the new threshold $d_{j1}(k)$.

$$d_{j1}(k) = \begin{cases} (1-u) \cdot d_j(k) + u \cdot sgn(d_j(k))(d_j(k) - thr), & \left|d_j(k)\right| \geq thr \\ 0, & \left|d_j(k)\right| \leq thr \end{cases} \tag{2.6}$$

Where, u is the improved weighting coefficient, and the calculation factor of u is:

$$u = \frac{thr}{\left|d_j(k)\right| \cdot a^{\sqrt{\frac{\left|d_j(k)-thr\right|}{\left|d_j(k)+thr\right|}}}} \tag{2.7}$$

Calculation formula (2.7), $0 \leq u \leq 1$, and the new threshold $d_{j1}(k)$ between soft threshold and the threshold of normal distribution, when$|d_j(k)|=thr$ u=0, when $|d_j(k)| \to thr$, u=1, and with u (k) decreases with the increasing of $|d_j(k)|$, when $|d_j(k)| \to \infty$, $u \to 0$. The derivative of u and u is continuous in the entire denoising interval, which solves the disadvantages of the denoising of hard threshold and soft threshold. The value of the unknown factor a in u affects the denoising effect.

2.2 Curve fitting method and calculation process

The denoising effect of wavelet method is obvious and the identification precision is improved. In order to solve the problem of large amount of calculation, curve fitting method is proposed to determine the starting point of reflection wave quickly. In this paper, the established simulation model is used to set fault points at different lengths, and the reflected amplitude is fitted. The simulation results show that with the increase of the length of the cable, the amplitude of the reflected wave attenuates exponentially. According to the attenuation law, the fitting threshold on the corresponding length is calculated, and the three-fourths fitting threshold is selected as the threshold to judge the fault point. Compared with the threshold value of corresponding length at the abnormal part of the cable, the fault point will be determined if the threshold value is exceeded.

The measured results contain noise, but the amplitude of noise is far less than the threshold value. In the actual measurement process, the short-time pulse signal after input pulse signal has the same propagation characteristics as the pulse signal, but the transmitted wave generated by the pulse signal, with small amplitude and short time, will be generated after the pulse signal and will not affect the judgment of the starting point of the reflected wave. Therefore, the selection of three-fourths fitting threshold as the threshold of fault point judgment can eliminate the influence of noise and short-term pulsating signals on the judgment of fault point.

Three points are needed for the quadratic function fitting, and the selection of different three points has a great influence on the shape of the fitting curve. In this paper, the maximum value of reflected wave, threshold value and half threshold value are selected as the three points of the fitting curve on the basis of multiple experiments to achieve the best fitting effect. The intersection of the fitting curve and the reference voltage serves as the starting point of the reflection wave.

3 Establishment of simulation model and comparison with measured data for verification

3.1 Establishment of cable fault MATLAB simulation model

In order to better analyze and verify the two methods proposed in this paper. MATLAB is used to establish the cable fault simulation model, and the open circuit and short circuit fault simulation is carried out. The model is shown in figure 2.

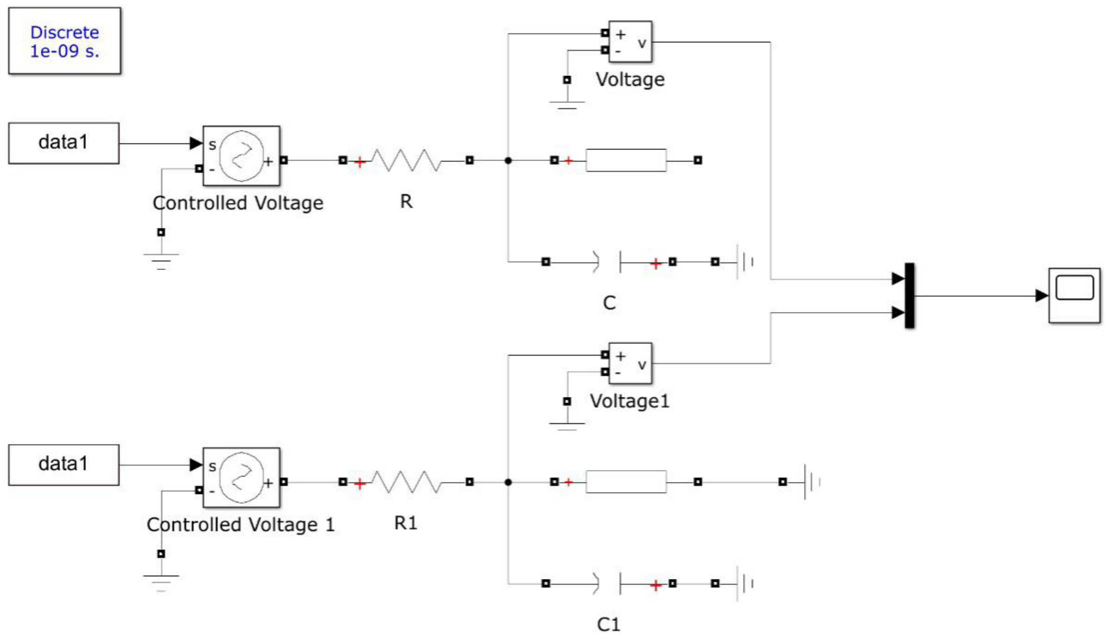

Figure 2. Simulation model of traveling wave.

Since the cable with concentrated parameters can only reflect the overall performance of the cable and cannot truly reflect the actual propagation effect of pulse signal in the cable, the selected cable model in the simulation adopts distributed parameters. The input pulse signal adopted is the same as the pulse source used in the experiment, with a pulse width of 100ns and an amplitude of 12v. The two lines in the model have the same parameters, which are used to simulate open circuit and short circuit faults respectively, and the incident pulse and reflected pulse voltage signals are measured at the cable head. The parameters of the simulation line model are shown in table 1.

Table 1. Line simulation parameters.

R	10Ω/km
L	2.37e-3H/km
C	8.32e-9F/km

3.2 Comparison between simulation and measured data

In this paper, the open circuit and short circuit faults of the 76m cable are first measured experimentally, and the measured waveforms are shown in figure 3 and figure 4 respectively.

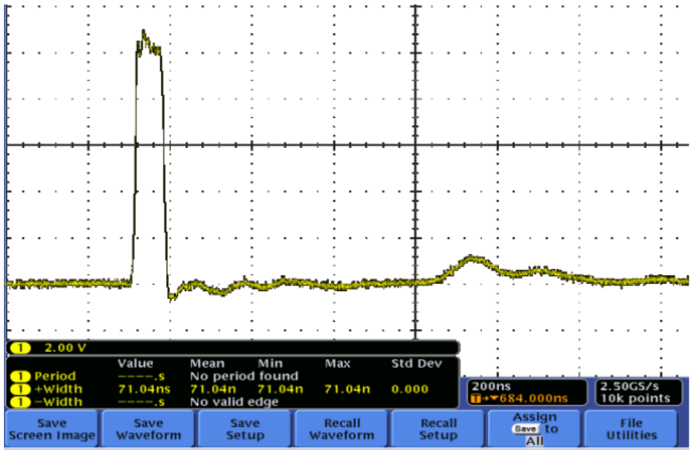

Figure 3. The measured of 76 m cable (open circuit fault).

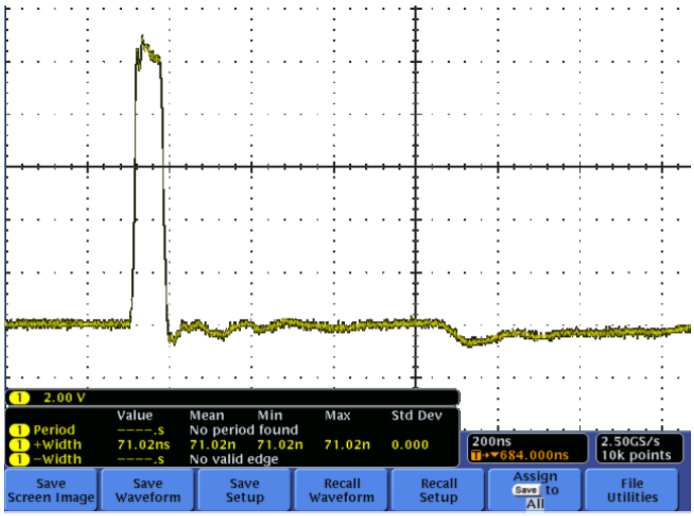

Figure 4. The measured of 76 m cable(short circuit fault).

In order to carry on the subsequent denoising and the convenience carries on the comparison analysis with the simulation waveform. The data measured by the open circuit and short circuit fault experimental oscilloscope are imported into the MATLAB workspace by using the load function, and the corresponding graphics are drawn, as shown in figure 5.

In order to make the simulation correspond to the actual experiment, the measured pulse signal in the actual experiment is used as the pulse source in the simulation experiment, and From Workspace is used to read it from the workspace. The pulse width is 100ns.

The established cable fault simulation model is used to carry out open circuit and short circuit fault simulation for 76m cable respectively. The voltage waveform measured at the head of the cable is shown in figure 6.

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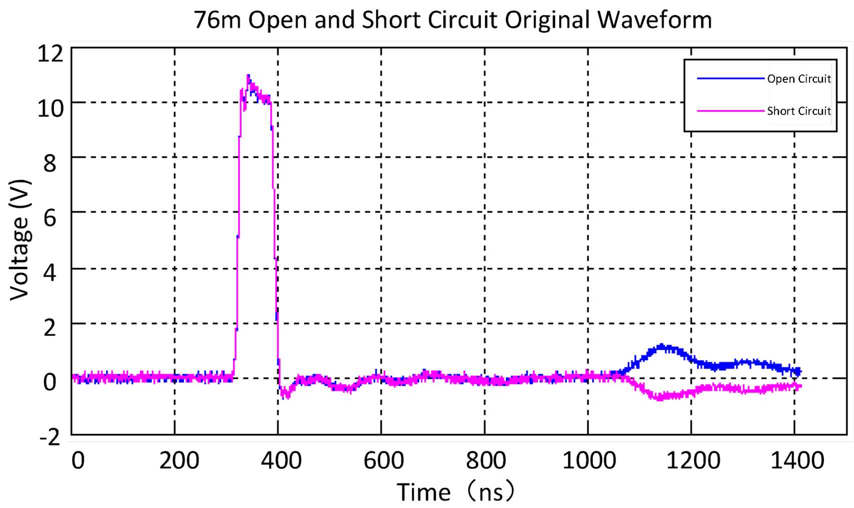

Figure 5. The measurement of 76m cable.

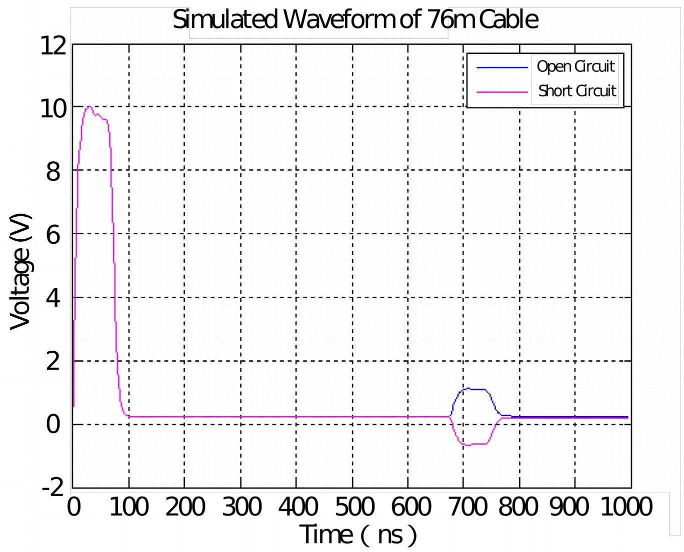

Figure 6. The simulation of 76m cable measurement.

By comparing figure 5 and figure 6, it can be found that the measured waveform, due to noise interference, produces a lot of burrs in the whole traveling wave process, while the simulation experiment is carried out in an ideal environment, and the waveform is smooth. The comparison shows that the reflection waveform at the fault point is positive voltage in the case of open-circuit fault of the cable, and negative voltage in the case of short-circuit fault, and the amplitude is similar and the reflection time is the same, which well reflects the propagation rule of pulse signal in the fault of the cable. The measured waveform has the same reflection rule as the simulated waveform, which proves the correctness of the simulation model.

The comparison shows that there are three small fluctuations in figure 5 after the pulse. This is because the electronic device cannot be shut off immediately after the pulse is sent out, resulting in a short-term pulsation signal.

Also found in the process of actual measurement cable bending and pulse transmission circuit grounding method will influence on the measuring signal, measure actual experiment using polyethylene cable, cable on the electrical parameters show resistance capacity, in extreme cases measurement cable rolls, part of the pulse signal will be under the action of distributed capacitance directly from the head to the end of the cable, it is difficult to accurately identify the starting point of the reflection wave, greatly affect the measurement result.

4 Simulation and field measurement analysis of the two methods

4.1 Improved weighted coefficient method for simulation analysis

In order to verify the superiority of the algorithm proposed in this paper, traditional wavelet method, normal method and improved weighted coefficient method were used to de-noise the original fault waveform respectively, and the local waveform at the fault reflection wave was amplified. The results are shown in figure 7, figure 8, figure 9 and figure 10.

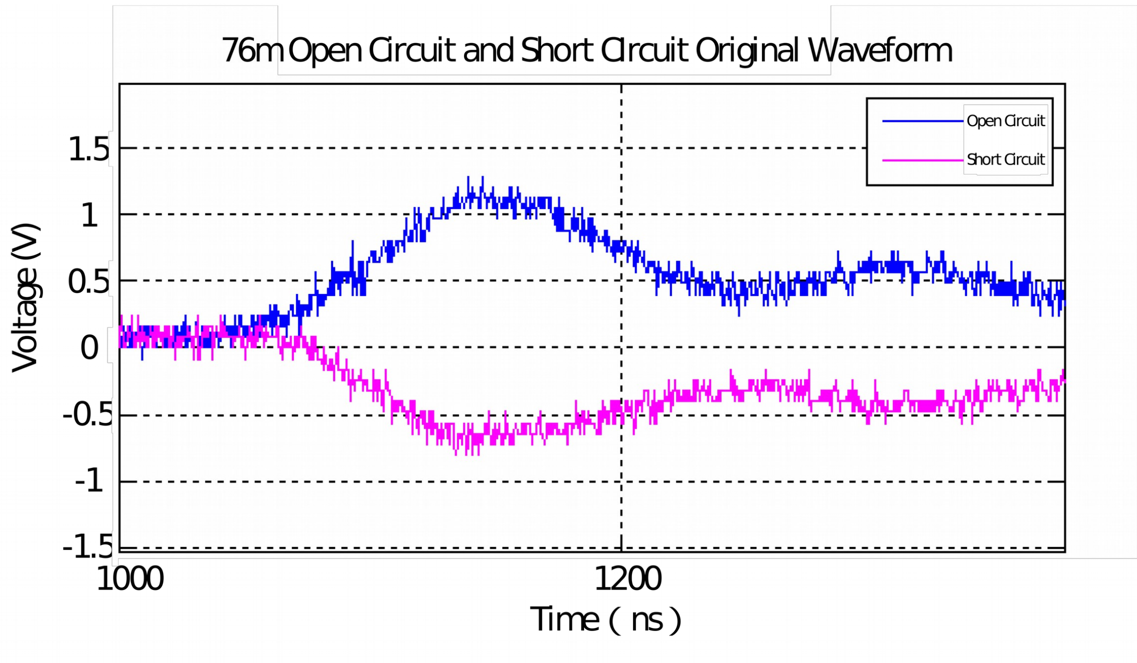

Figure 7. Original waveform.

Figure 8 and figure 9 are respectively compared with figure 7. It is found that due to the discontinuous threshold function, the waveform after denoising is not smooth, the adjacent sampling points have the jumping property, low signal-to-noise ratio and deviation from the original signal, and the original signal cannot be recovered well, which has an impact on the accurate identification of the starting point. Normal distribution denoising selectively inhibits the normal distribution of noise

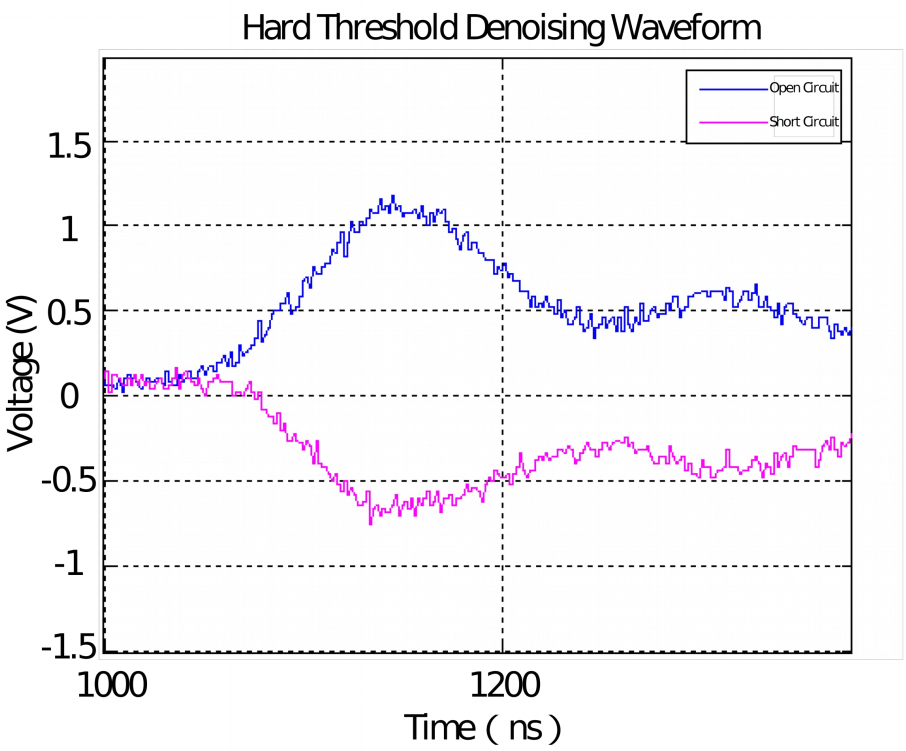

Figure 8. Hard threshold denoising.

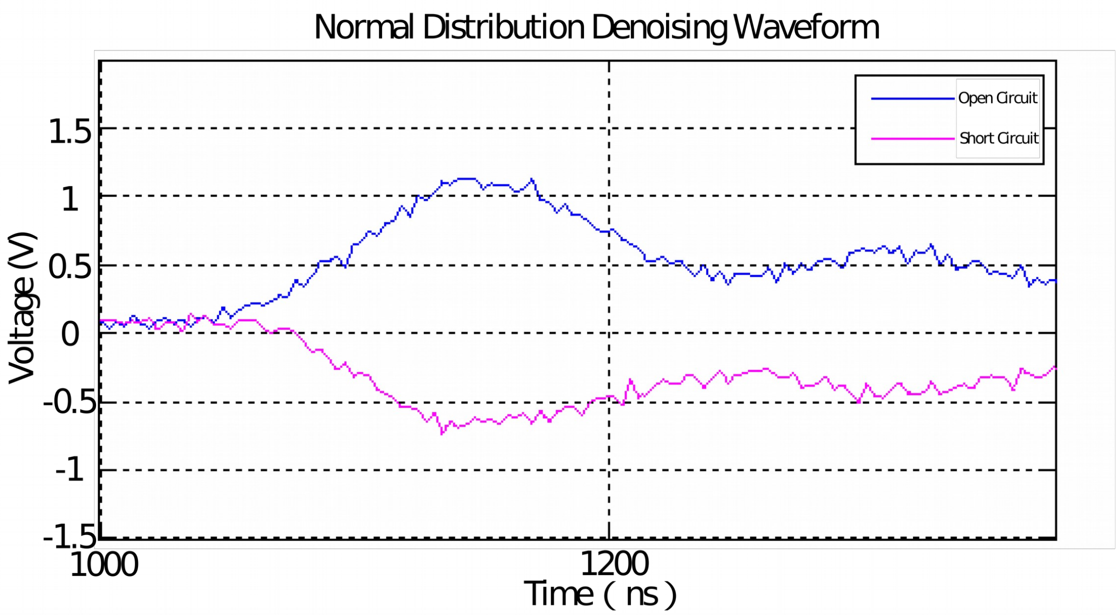

Figure 9. Normal Distribution Denoising.

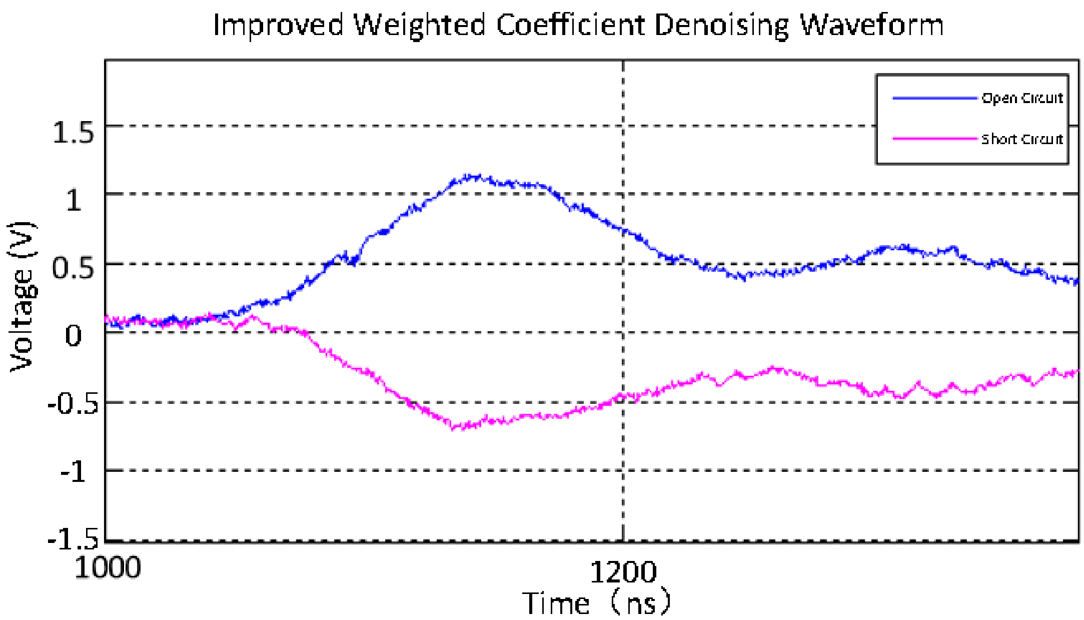

Figure 10. Improved weighted coefficient denoising waveform.

signal, and the waveform after denoising overcomes the problem of discontinuous noise reduction of hard threshold denoising function, improves the signal-to-noise ratio and has the improvement effect.

By comparing figure 9 and figure 10, it is found that the improved weighted coefficient method eliminates the jump between adjacent sampling points and further improves the signal-to-noise ratio. The processed reflection is smoother and can improve the identification accuracy of the initial point of reflection.

Similar to the weighted coefficient method, the selection of a in the improved weighted coefficient method affects the denoising effect, and the larger the value of a is, the denoising effect is close to the normal distribution denoising effect, and the smaller the value of a is, the closer the denoising effect is to the soft threshold method. When a=e, the denoising effect is the best. This conclusion is proved by many experiments in this paper, so this value is used in the improved weighted coefficient method.

4.2 Simulation analysis of curve fitting method

4.2.1 Attenuation law of reflection pulse

In this paper, the established model is used to set fault points at different lengths of cables, and the amplitude of reflected waves is fitted by a function. The experimental results are shown in figure 11.

As can be seen from the figure 11, the reflection amplitude of 76m cable measured and simulated results are both 1.1v, which proves that the simulation model is correct.The reflection amplitude value in the fitting simulation model is used to obtain the fitting threshold expression:

$$U = 1.732e^{-0.000777t} \tag{4.1}$$

Where, U is the fitting threshold of reflection wave, and t is the time of reflection wave.

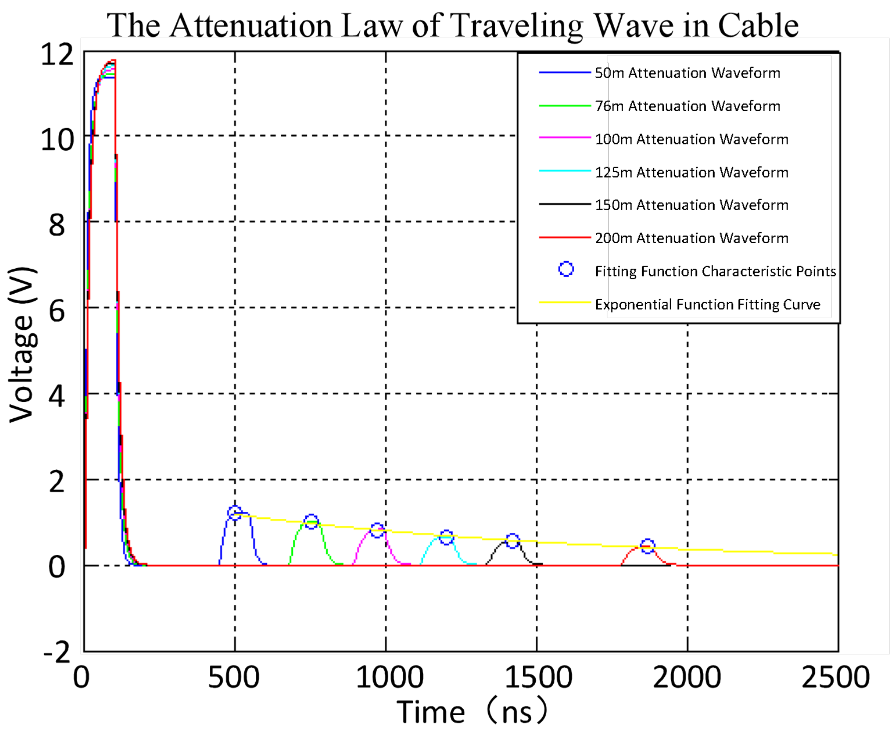

Figure 11. The attenuation law of traveling wave in cable.

The fitting threshold shows that the amplitude of reflection decreases exponentially with the increase of cable length. Where, the value of t is related to the type and length of cable. In this paper, 76m polyethylene cable is used in the experiment, and the expression of t and cable length is obtained according to the measured results:

$$t = 8.95l \tag{4.2}$$

Where, l is the length of the cable, and the unit is m

4.2.2 Curve fitting processing of reflected pulse

The curve fitting method was used to carry out quadratic function fitting for the reflected wave, and the fitting results were shown in figure 12. In the figure 12, the short-circuit fitting USES the three points mentioned in the paper as the fitting points of the quadratic function, and the open-circuit fitting USES the threshold, one-third of the threshold and the maximum three-point fitting. It can be seen from the short-circuit and open-circuit fitting curves that the fitting effect of the first half of the fitting curve is better than that of the actual reflection curve, while the second half cannot be fitted completely because the pulse signal is distorted in transmission.

Through the above figure, it is found that the fitting effect of the short-circuit fitting curve on the whole reflected wave is better than that of the open-circuit fitting curve, open the fitting curve in the second half of the reflection wave had a great deviation, but the two groups of fitting curve in judging the same as the basic starting point, rarely affect the starting point of judgment, short circuit and open circuit fitting errors are within 10 ns.

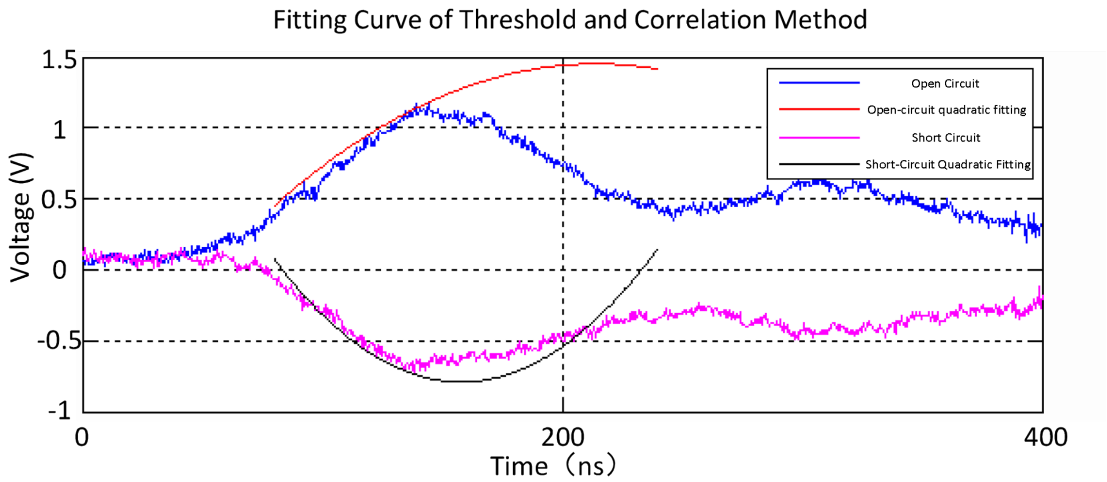

Figure 12. The curve fitting of the starting point.

4.3 Performance comparison and analysis of the two methods

In this paper, the actual measurement and simulation analysis of open circuit and short circuit faults are carried out for three types of cable lengths of 62 meters, 76 meters and 138 meters respectively, and the measured waveforms are processed respectively by the improved weighted coefficient method and curve fitting method proposed in this paper, so as to determine the starting point of reflection waves. The experimental results are shown in table .2.

Table 2. Error comparison between the two methods.

The length of the cable (m)	The fault types	Transmission time (ns)	Improved weighting coefficient method (ns)	Error %	Fitting curve method (ns)	Error %
62	Open circuit	555	559	0.72	561	1.08
	Short circuit	555	557	0.36	559	0.72
76	Open circuit	680	680	0	683	0.44
	Short circuit	680	680	0	680	0
138	Open circuit	1235	1241	0.41	1242	0.56
	Short circuit	1235	1240	0.40	1243	0.65

As can be seen from table 2, by comparing the transmission time, the judgment of the starting point of the reflected wave signal after the improved weighted coefficient method is more accurate, and the error can be controlled in a very small range. The curve fitting method has a slightly larger

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error than the improved weighted coefficient method, but it can quickly determine the starting point of the reflection wave due to its small amount of calculation and fast calculation speed, and the measurement error is within 10ns.

5 Conclusion

In this paper, the improved weighted coefficient method and curve fitting method are proposed to overcome the shortcomings of traditional wavelet method. The cable fault model based on MATLAB is established, and the correctness of the two methods proposed in this paper is verified by comparing the measured and simulated data.

The improved weighted coefficient method solves the problem that the hard threshold denoising is discontinuous at *-thr* and *+thr*, and the denoising signal may vibrate and lose the smoothness of the original signal. The problem of discontinuous derivative of soft threshold denoising and deviation from original signal is solved. At the same time, according to the normal distribution law of noise, the improved weighted coefficient method has selected to suppress the non-important coefficients, and the waveform processed by the improved weighted coefficient is smoother, which reduces the deviation from the original signal, has a high signal-to-noise ratio, and improves the accuracy of the identification of the starting point of reflection wave.

The curve fitting method is simple, has low requirements for equipment software and hardware, greatly improves the speed of starting point identification, and the measurement error is within 10ns, which is more suitable for low-cost detection equipment based on MCU.

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