POWER CABLE FAULT LOCATION TECHNIQUE BASED ON PARAMETER OPTIMIZED VARIATIONAL MODAL DECOMPOSITION

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ABSTRACT

With the complexity of power systems and the increase of loads, power cable faults occur frequently, affecting the safety of power supply. A parameter optimization-based variational modal decomposition (VMD) technique combined with wavelet transform is used. Through in-depth analysis of cable fault signals, this study first applies VMD to decompose the signals, and then further analyzes the processed signals in combination with wavelet transform. The experimental results show that the method achieves a significant reduction in the average localization error in the simulated fault test, with an average error of less than 1%, which improves the localization accuracy by about 30% compared with the traditional method. In the processing of complex fault signals, the present method shows better adaptability and robustness. Overall, this study not only improves the accuracy of fault localization, but also provides a new technical path for the diagnosis and maintenance of power system faults.

KEYWORDS

Power cable fault location, variational modal decomposition, parameter optimization, wavelet transform

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1. INTRODUCTION

Cables are widely used in power distribution networks and play a significant role in power supply reliability. Although the power supply reliability of power cables is higher than that of overhead lines, they are generally buried directly underground and the line structure is more complex, so it is not easy to locate the fault location and troubleshoot the fault in time when a fault occurs [1-3]. Therefore, fast and accurate localization of distribution network cable faults is very important for fault removal, reducing fault outage time and improving power supply reliability [4-5].

In recent years with the increasing service life of cables, the incidence of cable faults has begun to rise gradually, and the problem of detecting and diagnosing cable faults has gradually attracted people's attention [6-8]. Cable fault refers to a series of faults occurring in cables, including but not limited to insulation aging, insulation breakdown, joint failure, conductor breakage, etc. The occurrence of these faults will seriously affect the stable operation of the power system, and may even cause safety accidents. Therefore, the detection and diagnosis techniques of cable faults are of great significance in ensuring the stable operation of power systems and extending the service life of cables [9].

Different techniques have different advantages and disadvantages, and in the actual signal cable fault screening and localization, the applicability of different techniques, the reliability is different. Literature [10] introduces a method based on transient current measurement of cable shield grounding, which can identify the fault identification and localization of underground cables and hybrid lines, based on which a new transient grounding fault detection and localization algorithm is proposed, the new algorithm has the ability of autonomous learning, compared with the traditional method can be identified under the conditions of transient grounding faults on the distribution feeder branch, and the feasibility of the algorithm is examined through the test. Literature [11] aims to realize the precise location of cable faults, and proposes two hybrid schemes, MT-CT-DFT scheme and ANN-WT, and detects and compares the two schemes through multi-fault type tests, and finds that the ANN-WT method is more accurate and shows low sensitivity to parameter changes. Literature [12] describes the evaluation of a fault localization technique based on the FasTR method in an airborne portable system, and the results show that the system can achieve on-line detection of transient faults in complex networks and ensure the accuracy of the detection. Literature [13] describes Megger's new EZ-THUMP 3 cable fault location system, which works by combining TDR measurements with a surge generator to identify high resistances and thus locate faults. It can help users to locate faults easily, quickly and accurately. Literature [14] designed a hybrid fault location method for overhead lines containing underground cables, which was proved to be superior to other traditional methods by simulation techniques, showing high accuracy in both fault location and identification functions. Literature [15] discusses Megger's new SMART THUMP ST25-30 portable cable tester, which is based on automated test sequencing technology and provides fault identification and location, as well as interpretation and analysis of the test results for non-specialized users to obtain

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reliable fault location results in a safe and fast manner. Literature [16] on the iterative method and non-iterative method of localization function of the simulation test method for comparison, the results show that the positioning accuracy of the PD by the algorithm error, iteration algorithm, the number of iterations and iteration of the initial value of the impact of the algorithm. Literature [17] describes a strategy to reduce the occurrence of CCFS currents in cables by using current limiting reactors to shield the cables and then connect them to the electrodes of the primary substation, which can effectively reduce the thermal burning of insulation due to CCF in cables. Literature [18] studied cable joint breakdown faults, and through the analysis of fault waveforms, simulation model calculations and discussion of finite element methods, it was pointed out that moisture in the internal joints of cables causes transient ground faults, damages the grounding wire, and reduces the sensitivity of the protective device. Literature [19] proposes a Bayesian function based signal type identification method to identify the signal. A scheme to discriminate pole-to-pole and pole-to-ground short circuits in VSC cables is also proposed, and the reliability and innovation of the described method is confirmed by the study of real cases. Literature [20] points out that in cable-related construction, cross-connection errors often occur resulting in no effective limitation of the induced voltage in the metal shield, resulting in cable accidents, in order to solve this status quo, the cross-grounding faults in the metal shield of the 5kv single-core power cables are investigated, and at the same time remedial suggestions and measures are given for the cross-grounding faults.

In this paper, we analyze the characteristics of cable faults and select a suitable signal processing method. Then, VMD is used for the initial processing of the cable fault signal, followed by the application of wavelet transform for further analysis and noise reduction. On this basis, the key parameters of VMD and wavelet transform are adjusted using parameter optimization methods to adapt to different fault signal characteristics. The effectiveness of the proposed method is evaluated through comparative analysis and compared with traditional methods to verify its superiority.

2. POWER CABLE FAULT RELATED ANALYSIS

Power cables with its small footprint, high reliability, easy maintenance and other unique advantages in the distribution network is increasingly widely used, and along with the social and economic take-off, national consumption level, the reliability and security of the distribution network operation of high-level quality requirements. Under the threat of extreme weather, line aging, natural disasters, external damage, man-made theft of cables and other factors, it is very easy to cause cable operation faults, resulting in the entire power line blackout accidents, power transmission interruptions directly lead to the production of life safety hazards and economic property losses. This chapter mainly discusses the relevant basic knowledge of power cable faults, in order to realize the precise positioning of power cable faults to provide support.

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2.1. POWER CABLE FAILURE RELATED CAUSES

2.1.1. CAUSES OF POWER CABLE FAILURES

City cables are generally buried in the ground and the pipeline by the cable length of the impact of the existence of two cables with joints, cable storage is not good there are old and new cables and cables in the laying of grafting whether in strict accordance with the requirements of these are for the occurrence of faults buried hidden dangers. In addition, the actual operation of many other reasons for failure, power cable line failure causes are mainly the following:

1. External damage. Cables are mostly laid in the ground, the rise of central China in recent years, infrastructure construction increased, urbanization accelerated, rural decentralized building into a centralized, mechanical damage caused by a lot of cable failures.

2. Cable joint failure. Cables and cables are connected by the joints, in the cable joints are prone to failure, the joints have become the entire cable part of the most "fragile" place.

3. Chemical corrosion. For the existence of acid and alkali soil laying cable will inevitably be eroded by acid and alkali, often resulting in damage to the external protective layer.

4. External environment. Whether the heat source around the cable exceeds the standard needs to be taken into account, overheating will cause damage to the insulation of the cable, reduce the insulation strength of the cable caused by insulation breakdown resulting in power outages.

5. Cable long-term overload operation. Due to the cable's own design defects, three-phase load imbalance, etc., so that the cable in the unprotected environment for a long time overloading operation will lead to the cable with the operation of the time to lengthen the temperature is too high, too high a temperature will make the "fragile" joints part of the first damage.

6. The lack of technology. Cable body in the manufacturing process is not in strict accordance with the design requirements of the environment and technology, materials, such as failure to lead to normal aging or in the normal energized lead to breakdown and so on.

2.1.2. CHARACTERISTICS OF POWER CABLE FAULTS

When power cables have various types of faults, the consequences of which can lead to regional local power outages, or paralyze the entire power supply system, thus seriously affecting the productivity of enterprises. In order to quickly determine the type of cable faults and maintenance strategies, first of all need to classify the power

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cable faults, and then according to the classification results to choose the appropriate protection measures, in order to quickly restore power supply, minimize the loss of enterprises. The classification method of cable faults can be classified according to different criteria, and its specific classification is shown in Figure 1, which mainly includes three categories of series faults, parallel faults and compound faults.

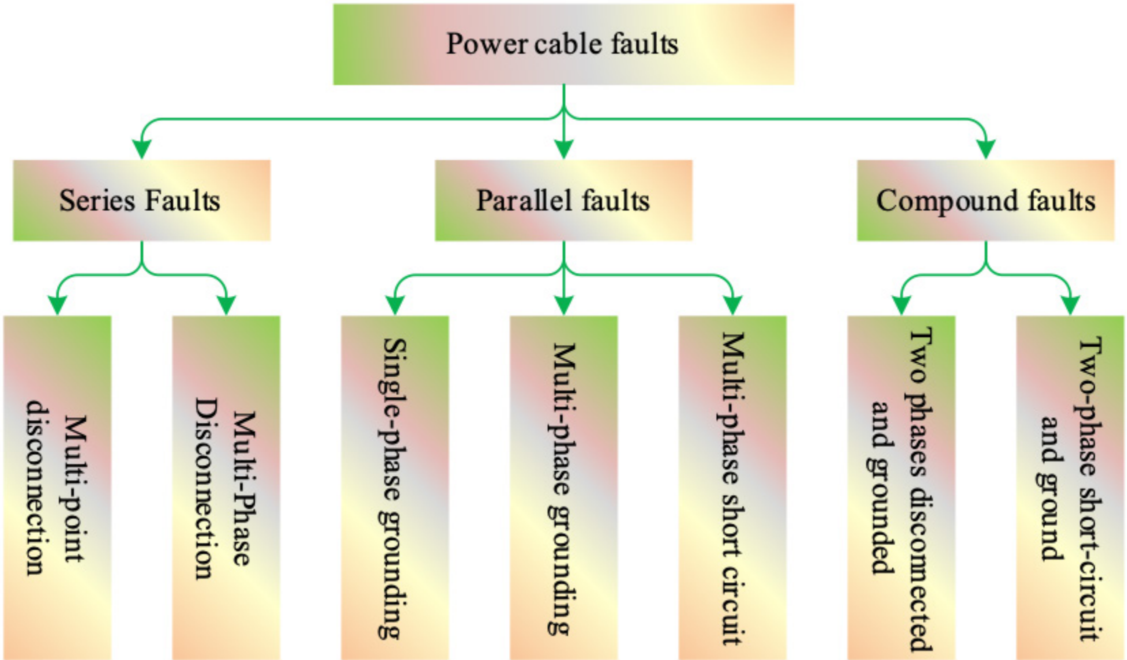

Figure 1 Power cable fault classification chart

Series fault refers to the internal conductor of the cable at a place where a break or short circuit occurs, resulting in a cable blackout accident, parallel fault is due to the loss of insulation medium between the core wires inside the cable and lead to parallelism between the core wires, resulting in faults, composite faults refers to the simultaneous existence of the above two types of faults in the cable.

2.2. POWER CABLE FAULT DETECTION PROCESS

2.2.1. FAULT DETECTION OF POWER CABLES

Power cable fault diagnosis process shown in Figure 2, the specific principle is that the cable core conductor resistance and core distance into a proportional relationship, as long as the calculation of the beginning of the fault phase of the cable to the fault point of the core conductor resistance and the fault phase of the proportionality coefficient of the conductor resistance, then in the case of the full length of the cable known to be able to calculate the distance from the beginning of the point of failure, to complete the diagnosis of the cable fault and localization.

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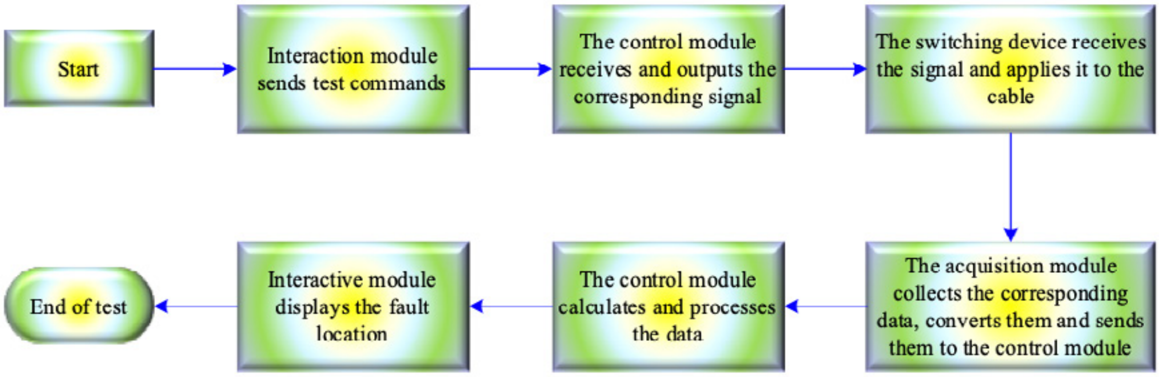

Figure 2 Fault diagnosis process of power cable

The above method is currently a relatively simple and fast way to diagnose and locate power cable faults, can effectively, accurately, quickly, conveniently and safely determine the cable fault category and locate the fault point, is to protect the normal operation of the power system is the key. Reasonable analysis of the causes of power cable faults to help solve the source of cable faults, and for the development of scientific cable fault detection technology to provide a basis.

2.2.2. EQUIVALENT MODELING OF POWER CABLES

Power cable is a power transmission line, when the power cable is considered a long line, it is no longer a simple conductor - insulation - to ground circuit, but many more equivalent resistance, conductance, inductance, capacitance composed of these parameters are uniformly distributed along the entire cable line, so called distribution parameters. Figure 3 for the cable equivalent long line distribution parameter circuit. Figure $R_0(\Omega/m)$ for the cable line unit length of the resistance, $G_0(S/m)$ for the cable line unit length of the conductance, $L_0(H/m)$ for the cable line unit length of the inductance, $C_0(F/m)$ for the cable line unit length of the capacitance.

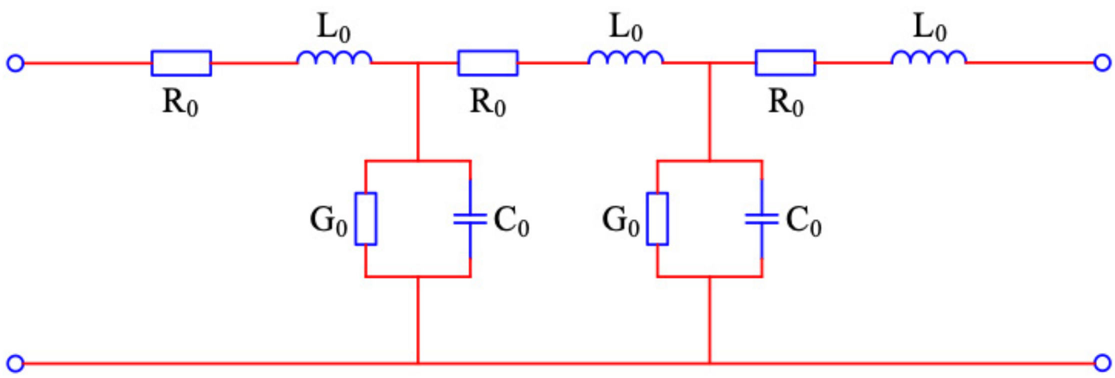

Figure 3 Equivalent long line distribution parameter circuit of cable

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Signal current after resistance and inductance, through the unit length of the cable line, are generated voltage drop and through the conductance, capacitance, etc., split the flow, and in the middle of the flow back. Cable transmission of high-frequency waves, it will lose a considerable amount of energy into the attenuation, at this time, conductivity, resistance and other losses can be ignored, and such a circuit is known as lossless circuit.

2.3. POWER CABLE FAULT TRAVELING WAVE PROCESS

2.3.1. TRAVELING WAVE VELOCITY OF POWER CABLE

Power cable traveling wave speed is expressed in the traveling wave propagation process fast and slow physical quantities, when the traveling wave propagation in the cable line, from a point in the cable propagation to another point needs to go through a certain amount of time, the traveling wave propagation distance and propagation time ratio is known as the wave speed.

For the purpose of calculating the wave velocity *v*, assume that the current wave acting on the wire is an oblique angle current wave. Suppose that the initial condition is zero, and that an oblique wave current of value $i = \alpha t$ (α in units of $A/s, t$ in units of *s*) is applied to the wire at point *A* at $t = 0$. Suppose that the wave moves along the wire with some known wave speed *v* and after an elapsed time *t*, the wave reaches point *B* and the potential at point *B* is zero. Then the voltage drop across the inductor *LOx* point *A* to point *B* is the potential $\boldsymbol{u}_A$ at point *A*. And since $x = vt$ and therefore $L_0x = L_0vt$, the following relation for u_A can be written:

$$u_A = L_0 vt \frac{di}{dt} = L_0 vt\alpha \qquad (1)$$

Assuming that the charge per unit length of wire at point *A* is *q*, according to the definition of capacitance, it can be seen that the charge *qdx* stored on the capacitance C_0dx of the d_x section at point *A* and the potential u_A at point A can be expressed as $C_0dx = u_Aqdx$, i.e., the potential u_A at point *A* can be expressed in terms of capacitance:

$$u_A = \frac{qdx}{C_0dx} = \frac{q}{C_0} \qquad (2)$$

According to the definition of current, the current *i* at point *A* is the number of charges passing per unit time is:

$$i = \frac{qdx}{dt} = q\frac{dx}{dt} = qv \qquad (3)$$

Thus, the charge per unit length *q* can be expressed as:

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$$q = \frac{i}{v} \tag{4}$$

Bringing Eq. (4) into Eq. (2) and replacing *i* with *at* yields the relation for u_A as:

$$u_A = \frac{i}{vC_0} = \frac{\alpha t}{vC_0} \tag{5}$$

Up to this point, two expressions (1) and (5) for u_A are obtained and this two equations should be equal, i.e.:

$$L_0 vt\alpha = \frac{\alpha t}{vC_0} \tag{6}$$

Organizing the above equation, the expression for the wave velocity *v* is obtained as:

$$v = \pm \frac{1}{\sqrt{L_0 C_0}} \tag{7}$$

Substituting $L_0 = \frac{\mu_0 \mu_r}{2\pi} \ln \frac{2h}{r}$ and $C_0 = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln \frac{2h}{r}}$ into equation (7) we get:

$$v = \pm \sqrt{\frac{1}{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} \tag{8}$$

Since ε_0 and μ_0 are both constants, it can be seen according to Eq. (8) that the wave velocity *v* of the cable line is only related to the relative permittivity $\mathscr{E}$ of the medium around the cable core and the relative permeability coefficient μ_r of the medium around the cable core such as insulation and shielding, while factors such as the material of the conductor core and the cross-sectional area do not affect the wave velocity of the cable line.

2.3.2. CALCULATE REFLECTED AND REFRACTED WAVES

Reflected and refracted waves are important concepts in the calculation of traveling waves. When a voltage is applied to a power cable, a current is generated on the cable, then if a sudden change occurs in the power a A, then refracted and reflected waves will be generated at A now. The refraction and reflection of traveling waves is shown in Figure 4, according to the relationship between circuit current and voltage, then there is:

$$\left.\begin{aligned} u_{r2} &= u_{r1} + u_{f1} \\ i_{r2} &= i_{r1} + i_{f1} \end{aligned}\right\} \tag{9}$$

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$$\left.\begin{aligned} u_{r1} &= i_{r1}Z_1 \\ u_{r2} &= i_{r2}Z_2 \\ u_{f1} &= -i_{f1}Z_1 \end{aligned}\right\} \tag{10}$$

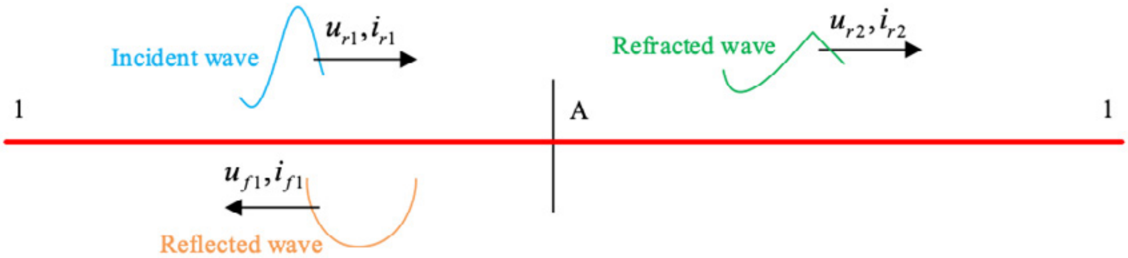

Figure 4 Refraction and reflection of the traveling waves

from Eq. (9) and Eq. (10):

$$\left.\begin{aligned} u_{r2} &= \frac{2Z_2}{Z_2+Z_1}u_{r1} = \gamma_u u_{r1} \\ u_{f1} &= \frac{Z_2-Z_1}{Z_1+Z_2}u_{r1} = \rho_u u_{r1} \end{aligned}\right\} \tag{11}$$

Where γ_u is the voltage refraction coefficient, $\gamma_u = \frac{2Z_2}{Z_2+Z_1}$, ρ_u is the voltage reflection coefficient, $\rho_u = \frac{2Z_2}{Z_2+Z_1}$. .

From Eq. (11) and Eq. (10), it can be solved as follows.

$$i_{f1} = -\rho_u i_{r1} \tag{12}$$

$$\rho_i = -\rho_u \tag{13}$$

Where,ρ_i is the current emission coefficient.

3. POWER CABLE FAULT LOCATION DIAGNOSIS

The development of urbanization needs to build more power cables as a support, urban power transmission needs to use advanced scientific power transmission methods, to provide great convenience and safety for people's electricity. nowadays, the city mainly uses underground cables for power transmission, this way not only can ensure the stable transmission of electricity, but also can reduce the probability of power cable line faults. however, underground cable power transmission can also have faults and need to be repaired. this chapter mainly explores the optimization based on the skyhawk algorithm variable modal decomposition combined with wavelet transform in power cable fault location related technology, in order to realize the power cable faults. This chapter mainly explores the optimized variational modal

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decomposition based on the eagle algorithm combined with the wavelet transform in the power cable fault localization technology, to provide technical support for the realization of the accurate positioning of power cable faults.

3.1. PARAMETER OPTIMIZED VARIATIONAL MODAL DECOMPOSITION

3.1.1. VARIATIONAL MODAL DECOMPOSITION (VMD)

Variational modal decomposition (VMD) algorithm is a non-recursive decomposition of a set of signals into *K* quasi-orthogonal and specific sparsity intrinsic modal functions (IMFs) to achieve effective separation of signals. The VMD algorithm is based on the concepts of Wiener filtering, the Hilbert transform, and frequency mixing, etc., and the overall idea is to construct a variational problem. The constraints on the variational components need to be satisfied that all the sums of the components are consistent with the original signal, and the constraints on the variational model are as follows.

$$\begin{cases} \min_{\{u_k\}w_k}\left\{ \sum_{k=1}^{K} \| \partial_t\left[\left(\delta(t)+\frac{j}{\pi t}\right)*u_k(t)\right]e^{-jw_k t} \|_2^2 \right\} \\ \text{s.t. } \sum_k u_k = f(t) \end{cases} \tag{14}$$

Where, $\{u_k\}$ is the *K* eigenmode components obtained after VMD decomposition, $\{u_1, u_2, \cdots, u_k\}$, $\{w_k\}$, are the center frequencies of each of the *K* eigenmode components, $\{w_1, w_2, \cdots, w_k\}$, $f(t)$ are the original signals, ∂ is the sign of gradient computation, $\delta(t)$ is the Dirac Lay function,* is the sign of convolution operation, and s.t. is the constraint term.

In order to solve the variational constrained problem and complete the transformation from constrained to unconstrained problem, the Lagrange operator and the quadratic penalty factor α are introduced, and the transformations result in the augmented and generalized Lagrange formulas, namely:

$$L\left(\{u_k\},\{w_k\},\lambda\right) = \alpha \sum_{k=1}^{K} \| \partial_t\left[\left(\delta(t)+\frac{j}{\pi t}\right)*u_k(t)\right]e^{-jw_k t} \|_2^2 + \| f(t) - \sum_{k=1}^{K} u_k(t) \|_2^2 + \left\langle \lambda(t), f(t) - \sum_{k=1}^{K} u_k(t) \right\rangle \tag{15}$$

In the formula, the value of α affects the denoising effect of the algorithm, and the appropriate value of α can reduce the noise interference.

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Finally, the alternating direction multiplier algorithm is used to iteratively update $\{u_k\}$, $\{w_k\}$, and λ until the termination condition is satisfied, and the final K IMF components and the corresponding center frequencies are output.

From the above formula, it can be seen that the values of parameters *K* and α will have an important impact on the decomposition results of the algorithm. If the *K* value is too small, it will lead to insufficient decomposition, if it is too large, it will be prone to problems such as false components and frequency overlap, if the α value is too small, the signal denoising will not be thorough enough, and if it is too large, the active components will be removed by mistake. Empirical selection of the above parameter values does not ensure that they are optimal.

To address this problem, this paper introduces the Skyhawk optimization algorithm to improve the VMD and get the optimal parameter combination $[K, \alpha]$. In this process, the envelope entropy reflects the sparsity of the signal, the more noise there is in the signal, the less effective components there are, which is manifested by the larger envelope entropy value; on the contrary, the more the signal contains effective components, the smaller the envelope entropy value is, i.e., when the value of envelope entropy is the smallest, the signal contains the largest number of effective components, and at this time, the corresponding parameter is the optimal. Therefore, the author adopts the minimum value of the envelope directrix as the fitness function of the Skyhawk optimizer to evaluate the decomposition effect of the parameter combination. The mathematical formula for the envelope entropy E_p is as follows.

$$E_p = -\sum_{q=1}^{m} p_q \lg p_q \tag{16}$$

$$p_q = a(q) / \sum_{q=1}^{m} a(q) \tag{17}$$

$$a(q) = \sqrt{[x(q)]^2 + \{H[x(q)]\}^2} \tag{18}$$

Where, m is the number of sampling points, P_q is the normalized form of *a(q)*, *a(q)* is the envelope signal after Hilbert transform.

3.1.2. AOA LGORITHMIC OPTIMIZATION OF VMD PARAMETERS

The VMD is continuously updated in the frequency domain and transformed to the time domain by Fourier inverse transform, and the final results will be different when different decomposition layers K and quadratic penalties are inputted, so finding the optimal combinations of decomposition layers K and quadratic penalties is the key to the VMD. In this paper, we propose to optimize the parameters of the VMD based on the AO algorithm, and the optimized parameters can be obtained quickly and accurately. The AO algorithm is a new population-based optimization method, which

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mainly simulates the natural behavior of the eagle in the process of capturing prey, so as to achieve the purpose of optimization, with strong optimization ability and fast convergence speed, etc. Therefore, the AO algorithm is used to optimize the VMD.

Therefore, the AO algorithm is used for iterative optimization of the number of decompositions and the penalty factor in the VMD, and the optimization dimension is set to 5, the optimization interval is set to [5,12], and the optimization interval is set to [0,20,000].The loss function of the VMD is used as the fitness function for the optimization of the AO algorithm, and the calculation formula is as follows: the VMD loss function is used as the fitness function for the optimization of the AO algorithm, and the calculation formula is as follows: the VMD loss function is used as the adaptation function for the optimization of the AO algorithm.

$$L_{\text{loss}} = \frac{\sum_{t=1}^{T} \left| f(t) - f'(t) \right|}{T} \tag{19}$$

Where $f(t)$ is the original input signal, $f'(t)$ is the decomposed signal and T is the time length.

The original signal is decomposed into K modal components by VMD, if the modal components contain less noise components, the feature information related to the original signal will be more obvious, and the envelope entropy will be smaller, and the AO algorithm is used to seek the minimum envelope entropy, so that the IMF obtained by this way can maximize the retention of the characteristics of the fault signal of the power cable.

3.2. AO-VMD-CWT FAULT LOCALIZATION MODEL

3.2.1. CONTINUOUS WAVELET TRANSFORM (CWT)

The translation factor and scale factor in the wavelet time-frequency transform define the position and shape of the time-frequency window, which makes the wavelet transform adaptive and multi-resolution, and is widely used in the field of signal processing. The continuous wavelet transform (CWT) adopts a time-frequency window that can be adaptively adjusted with the frequency, which overcomes the limitation that the size of the window of the short-time Fourier transform (STFT) can't be adjusted with the frequency or the time, which is difficult to accurately respond to the relationship between the frequency and the time, and is more suitable for dealing with the transient and sudden change of the signals.

For the function $\varphi(t) \in L^2(R)$, if it satisfies $\int_{-\infty}^{\infty} \varphi(t)dt = 0$, then $\varphi(t)$ can be written as the mother wavelet. By performing a series of scale translation transformations on the mother wavelet $\varphi(t)$ a series of consecutive wavelet functions can be obtained, which are called analytic wavelets. The transformation formula is:

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$$\varphi_{u,v}(t) = \frac{1}{\sqrt{v}}\varphi\left(\frac{t-u}{v}\right), v > 0, u \in R \tag{20}$$

In the formula, *u* is the translation factor, *v* is the scale factor, also known as the expansion factor, when $v > 1$, stretching along the horizontal direction, when $v < 1$, compression along the horizontal direction, in order to keep the energy constant after the expansion transformation need to multiply the scale factor $1/\sqrt{v}$ in front of the front, i.e., $\| \varphi_{u,v}(t) \| = \| \varphi(t) \|$, *u* is the translation parameter, which can be taken as an arbitrary real number, *u* and *v* are continuous variables, so it is known as the continuous wavelet. Wavelet transform.

The continuous wavelet transform of the signal $x(t) \in L^2(R)$ is expressed by the following equation:

$$\mathrm{CWTx}(u,v) = \int_{-\infty}^{\infty} x(t)\varphi_{u,v}^{*}(t)dt = \frac{1}{\sqrt{v}}\int_{-\infty}^{\infty} x(t)\varphi^{*}\left(\frac{t-u}{v}\right)dt \tag{21}$$

Where $\varphi^{*}(t)$ is the complex function of the function $\varphi(t)$. The inverse transformation is given by:

$$x(t) = \frac{1}{C_{\varphi}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \varphi_{u,v}(t)CWT(u,v)\frac{dudv}{v^2} \tag{22}$$

Formula, $C_{\varphi} = 2\pi\int_{-\infty}^{\infty}\frac{|\hat{\varphi}(\omega)|}{|\omega|}d\omega$..

The mother wavelet function needs to satisfy the following conditions to ensure that the wavelet transform can accurately construct the original signal with corresponding inverse transform.

1. First of all, the value of the mother wavelet function outside the window function is zero.

2. It needs to be satisfied: $\int_{-\infty}^{\infty}\frac{|\hat{\varphi}(\omega)|}{|\omega|}d\omega < +\infty$。

3. The mother wavelet function satisfies $\hat{\phi}(\omega)\Big|_{\omega=0} = 0$。

3.2.2. AO-VMD-CWT SIGNAL NOISE REDUCTION

The search strategy of AO algorithm adopts repeated trajectories to explore the approximate optimal solution or the reasonable location of the optimal solution, which has high convergence, robustness and strong optimization ability. Therefore, this paper introduces the AO algorithm to search for the optimization of decomposition number and penalty factor in the VMD, and uses the minimum envelope entropy as the fitness function to transform the iterative optimization process into the process of AO algorithm to seek for the minimum envelope entropy. The specific optimization process is as follows The specific optimization process is as follows

Step1 Initialize the population, set the number of iterations of AO algorithm, the population size, the number of variables and the upper and lower limits of the problem to be solved.

Step2 Decompose the input signal by VMD.

Step3 Calculate the minimum value of the envelope entropy of each modal component as the fitness function and substitute it into the optimization algorithm.

Step4 Update the position of the population and the global optimal solution, and stop the iteration when the optimization algorithm meets the iteration termination condition.

On this theoretical basis, this paper proposes a parameter optimization VMD-CWT based power cable fault signal noise reduction method, the method is shown in Fig. 5. the specific process is as follows.

1. The AO algorithm optimizes the VMD, and the signal decomposition is performed using the VMD to obtain *K* IMF components.
2. According to the cliff-correlation coefficient, the IMF components are divided into pure components and noise components.
3. Perform wavelet threshold noise reduction on the noise component to remove the noise component in the signal.
4. The pure component and the wavelet threshold noise reduction processed noise-containing component were reconstructed to obtain the joint noise reduction signal.

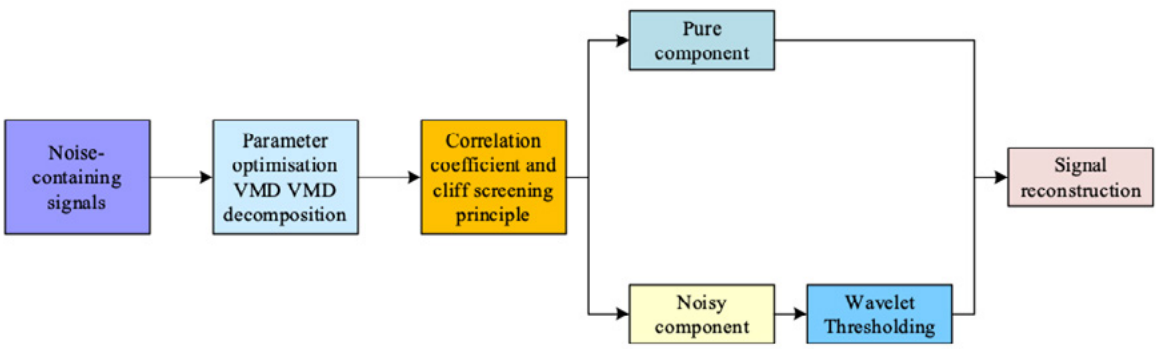

Figure 5 Signal denoising method for parameter optimization of AO-VMD-CWT

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In this paper, we choose to use continuous wavelet transform to decompose the data after parameter-optimized VMD decomposition at multiple scales as a method to construct time-frequency maps, and to generate two-dimensional wavelet time-frequency domain maps so that we can take into account the ability of local information in the time-frequency domain at the same time.

4. POWER CABLE FAULT LOCATION SIMULATION

Power cable lines have unique advantages over overhead lines, including small footprint, high power supply reliability, low voltage drop, low fault rate and lightning protection, etc. In recent years, with the construction and development of the city and the increase in the use of power cables, their faults have received more and more attention, so how to quickly locate the faults of the cable is critical to reduce the outage time. This chapter mainly focuses on the effectiveness of the parameter optimization VMD-CWT fault location method given in the previous section to carry out the simulation analysis of the data, so as to help the accurate positioning of power cable faults, in order to enhance the safety of electricity, reduce the economic losses caused by power outages to provide protection.

In the cable fault location algorithm research, need to verify the feasibility of the algorithm through the test, the field test is not only very high cost and not safe enough, the general use of computer simulation methods to replace the real operating environment of the power system. this paper will use ATPDraw for cable fault model drawing, and then use EMTP to transient analysis of cable faults, the results obtained from analysis. The results of the analysis will be imported into MATLAB for data processing and display. using ATPDraw for modeling simulation, simulation simplification principle shown in Figure 6.

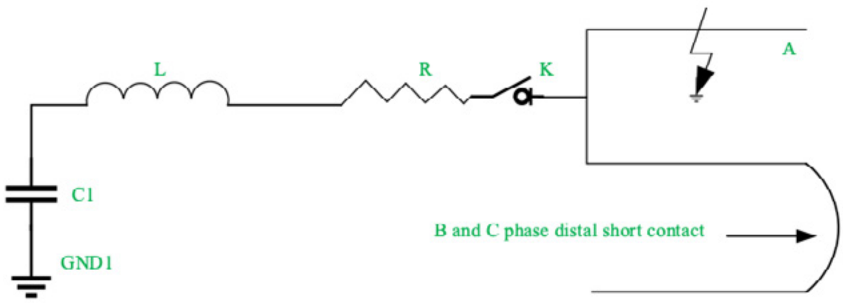

Figure 6 Simulation schematics

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4.1. SIGNAL NOISE REDUCTION AND FAULT LOCALIZATION SIMULATION

4.1.1. AO-VMD-CWT SIGNAL NOISE REDUCTION

In order to analyze the effectiveness of the AO-VMD-CWT method proposed in this paper in the power cable fault signal noise reduction, this paper designed the corresponding power cable fault simulation model based on ATPDraw, and designed the corresponding noise-containing power cable fault signal. After the noise-containing signal is decomposed and denoised by using the AO-VMD method, the signal is decomposed by six modal components, and the denoised signal is obtained by analyzing the modal components obtained through the correlation coefficient as shown in Fig. 7. The correlation coefficient analyzes the modal components of the decomposition, and the denoised signal is shown in Fig. 7.

As can be seen from the figure, after the VMD decomposition denoising, the effect of signal noise reduction is achieved to a certain extent, using the formula given in the previous section, the signal-to-noise ratio of the original noise signal can be calculated as 20.47 dB, while the signal-to-noise ratio of the noise-reduced signal after the VMD denoising is 53.38 dB, which is 1.61 times more than that of the original noise signal, which indicates that the AO This shows that the AO-VMD-CWT method given in this paper can effectively realize the noise reduction of power cable fault signals, obtain a more accurate power cable fault localization effect, and reduce the localization error caused by the fault signal noise.

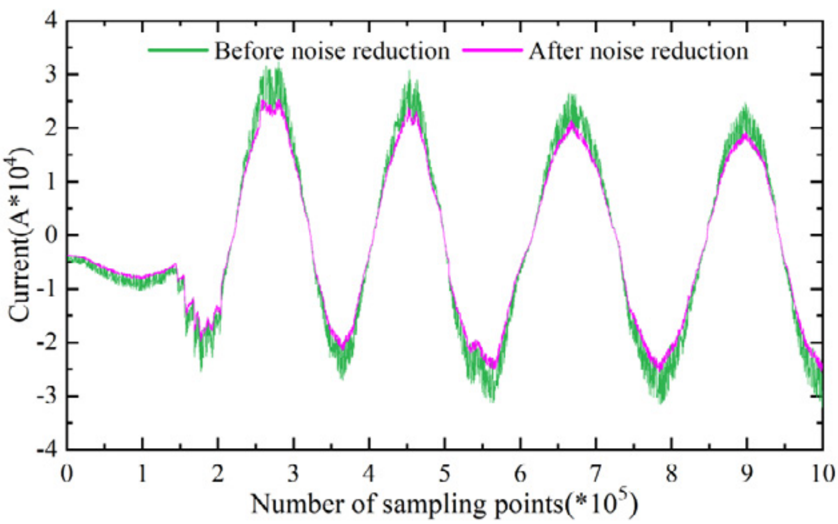

Figure 7 Noise reduction waveform of the AO-VMD-CWT signal

In order to further illustrate the noise reduction effect of this paper's method, the noise reduction waveforms of this paper's method, the CWT method and the VMD method are compared, and the signal-to-noise ratios of the noise reduction are also compared. Figure 8 shows the noise reduction waveforms of the power cable fault signals obtained by different noise reduction methods.

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From the noise reduction waveforms of power cable fault signals in the figure, it can be clearly seen that the method of this paper is better than a single wavelet transform method and the noise reduction waveform obtained by the variational modal decomposition method, which can better reflect the fault situation of power cables. Using the signal-to-noise ratio solution method given in the previous section to solve the signal-to-noise ratios of the three kinds of noise reduction waveforms, it can be clearly defined that the signal-to-noise ratios of the wavelet transform and variational modal decomposition method are respectively 24.65 dB and 28.19 dB, and the signal-to-noise ratio of the wavelet transform method is 24.65 dB and 28.19 dB, respectively. The signal-to-noise ratio of the wavelet transform and the variational modal decomposition method is 24.65dB and 28.19dB respectively, which is 53.82% and 47.19% lower than that of this paper's method, and the parameter optimization VMD algorithm combined with the continuous wavelet transform can obtain better noise reduction waveforms of power cable fault signals, with a larger improvement in the signal-to-noise ratio, which can provide accurate signal waveforms for power cable fault localization and can effectively avoid the loss of some useful signals when the VMD algorithm is used for noise reduction. It can also effectively avoid the loss of some useful signals when the VMD algorithm is used for noise reduction.

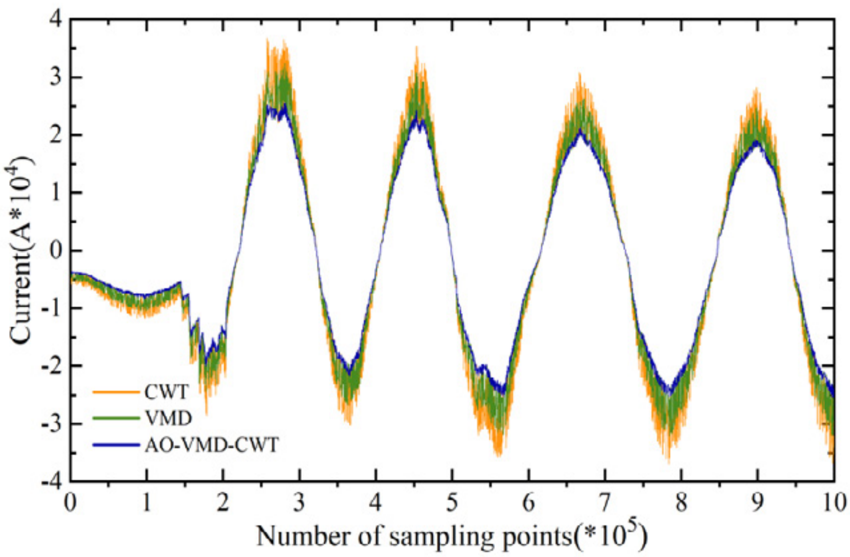

Figure 8 Comparison of Three Noise Reduction Waveforms

4.1.2. SIMULATION OF POWER CABLE FAULT DISTANCE

In order to assess the feasibility of the proposed fault location method, combined with the previous power cable fault simulation model, assuming that the cable length is 5km, the fault is set on phase A, and the voltage-controlled switch is used to simulate the fault click-through, and the fault distances are set to be 50, 100, 500, 1000, 2000, 3000, 4000 and 5000 m. The normal phases, phase B and phase C are shorted at the far end, and the travelling wave is traveling. The high voltage signal generator model is used to send out the coupled current output signal to analyze the correlation between the fault signal and the non-fault signal output signal before the

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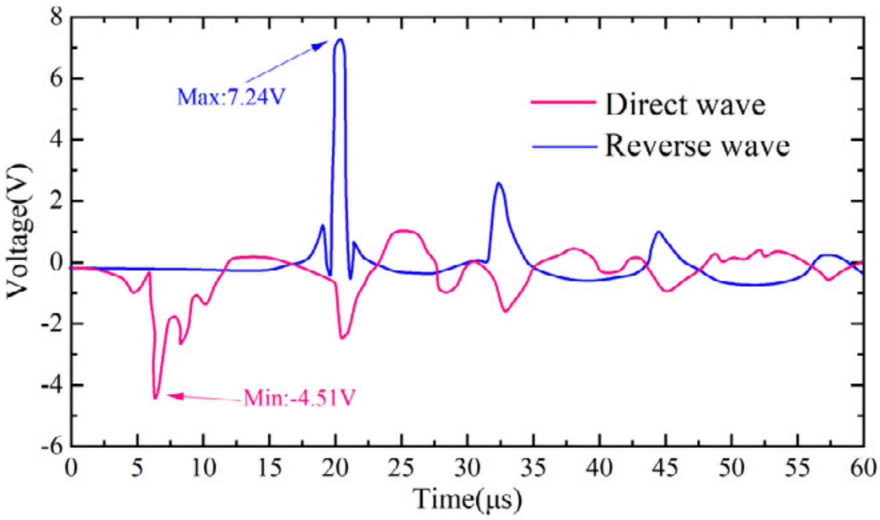
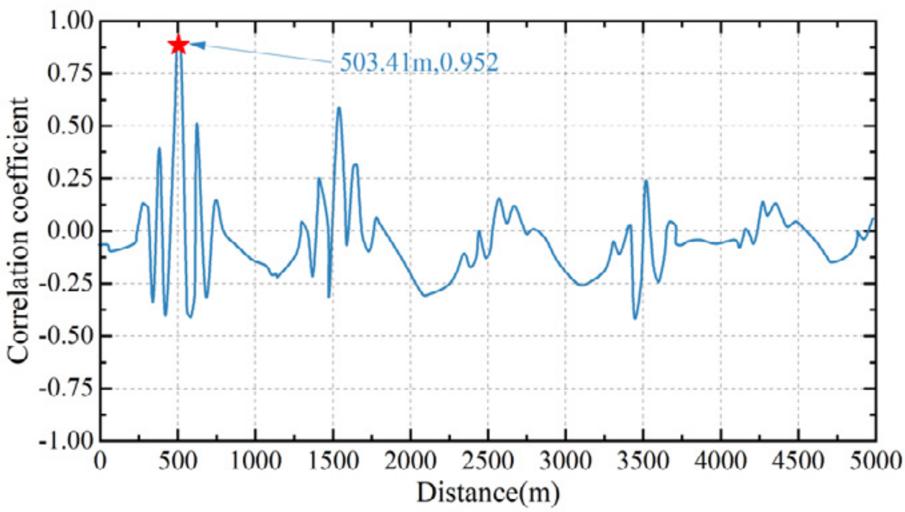
fault clicks through, and the fault phase and the non-fault phase current are used for the construction of the forward and reverse voltage traveling wave, and the resulting direction of the traveling wave wave is shown in Fig. 9, of which Fig. 9(a) and (b) are the forward and reverse voltage traveling wave and the correlation coefficient curve, respectively.

Combined with the forward and reverse voltage traveling wave and correlation coefficient curves, when the coupled current output signal reverse traveling wave transmission in the 21.48μs period to reach the voltage maximum value of 7.24V, and at this time the fault ranging is shown as 503.41 meters, the correlation coefficient of the maximum of 0.952. Combined with this paper to set up the fault point, the fault point of the difference between the 500 meters and the fault point of 3.41 meters, the relative error of 0.682%. 0.682%.



(a) Forward and backward direction voltage traveling wave(L=500)



(b) Correlation coefficient curve(L=500)

Figure 9 Direction traveling waveform

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According to the above method, the simulation results of all fault distances are solved, and the relative errors of different fault distances are shown in Table 1. From the simulation results, except for the fault location distance of 50 meters and 100 meters which is more than 1.00%, the relative errors of other fault location of power cables within 5 kilometers are maintained in the range of 0.45%~0.70%, and the average value of the relative errors is about 0.849%. The above results verify the feasibility of this paper's method in power cable fault localization, and provide technical support for the realization of timely repair of power cable faults.

Table 1 Simulation ranging results

Fault distance	Simulation result	Absolute error	Fractional error
50m	50.69m	0.69m	1.38%
100m	101.75m	1.75m	1.75%
500m	503.41m	3.41m	682 %
1000m	1006.96m	6.96m	696 %
2000m	2009.38m	9.38m	469 %
3000m	3015.82m	15.82m	527 %
4000m	4026.54m	26.54m	664 %
5000m	4031.27m	31.27m	625 %

4.2. POWER CABLE FAULT LOCATION PERFORMANCE COMPARISON

4.2.1. COMPARISON OF DOUBLE-ENDED TRAVELING WAVE RANGING METHODS

In order to verify the performance of this paper's algorithm for power cable fault location, we choose to compare it with the classical double-ended traveling wave ranging (DRW) method, using the power cable fault simulation model given in the previous section to send out 500 coupled current signals, and comparing the average positioning results of the two methods on 500 samples of data with the average absolute positioning error as an evaluation index. The average localization results of different algorithms are shown in Table 2, which are obtained by choosing four types of faults, namely, single-phase grounded short circuit, two-phase short circuit, two-phase grounded short circuit, and three-phase short circuit, and taking 10km, 50km, 80km, and 100km as the fault distance.

From the average positioning results of different algorithms, the traditional double-ended traveling wave ranging method has low accuracy, mainly due to the

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propagation speed of traveling waves in power cables affected by the fault distance, fault type, etc., with uncertainty, the average positioning error is more than 0.51km, and the average absolute positioning error is more than 0.5%. The localization accuracy of the AO-VMD-CWT algorithm proposed in this paper is significantly higher than that of the double-ended traveling wave method, and the average absolute localization errors for fault distances of 10km, 50km, 80km, and 100km are less than 1.315%, 0.278%, 0.163%, and 0.151%, respectively, for different fault types.

Among the single-phase grounded short-circuit fault types, this paper's algorithm has the highest localization accuracy, and the average absolute localization errors for fault distances of 10km, 50km, 80km, and 100km are 1.151%, 0.273%, 0.152%, and 0.108%, respectively. This is due to the fact that the proposed AO-VMD-CWT algorithm utilizes the AO-VMD algorithm in combination with continuous wavelet transform to reconstruct the original power cable fault signals. This is because the proposed AO-VMD-CWT algorithm utilizes the AO-VMD algorithm combined with the continuous wavelet transform to reconstruct the original power cable fault signals, which can accurately predict the fault distance of the input fault traveling wave signals by retaining most of the fault features and at the same time proposing some of the useless signals.

Table 2 Average localization results for the different algorithms

Fault type	Fault distance	Average positioning results		Average absolute localization error	
		DRW	This article	DRW	This article
Phase earth fault	10km	10.56	10.13	5.136 %	1.151 %
	50km	50.63	50.12	1.247 %	273 %
	80km	80.85	80.09	955 %	152 %
	100km	100.91	100.11	613 %	108 %
Line to line fault	10km	10.86	10.15	8.276 %	1.315 %
	50km	50.48	50.17	1.061 %	278 %
	80km	80.61	80.16	792 %	102 %
	100km	100.57	100.14	513 %	111 %
Two-phase short circuit ground	10km	10.62	10.09	4.356 %	1.124 %
	50km	50.55	50.13	815 %	273 %
	80km	80.67	80.15	679 %	163 %
	100km	100.79	100.16	736 %	151 %
Three-phase short-circuit	10km	10.58	10.14	4.521 %	1.221 %
	50km	50.52	50.12	1.248 %	216 %
	80km	80.69	80.16	822 %	153 %
	100km	100.38	100.13	1.613 %	132 %

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4.2.2. COMPARE TO OTHER NETWORK MODELS

In order to verify the superiority of the AO-VMD-CWT method proposed in this paper in the power cable fault localization algorithm, it is chosen to be compared with BiLSTM and cable fault ranging based on the combination of EMD and wavelet transform (EMD+CWT), and the three algorithms fault localization results are visualized as shown in Fig. 10, and the experimental results data statistics are shown in Table 3.

Combined with Figure 10, Table 2 and Table 3, it can be seen that the localization error of EMD+CWT method is generally maintained within 0.04km, which is mainly due to the use of EMD decomposition and wavelet transform to remove some of the redundant signals and extract the useful information in the dominant component of the noise, so that the filtered signals in the calculation of the reflected waveform transmission time to improve the accuracy of the filter. The localization error of the BiLSTM algorithm is within 0.065 km, which shows the advantage of BiLSTM in the training of time series samples, while the algorithm in this paper combines the advantages of the wavelet transform, firstly preprocessed by the wavelet transform, and then combined with the cross-extraction of travelling signal features by the AO-VMD method, and the localization error is maintained within 0.02 km, which is significantly better than that of the other two methods. The localization error is generally maintained within 0.02km, and the localization accuracy is obviously better than the other two methods.

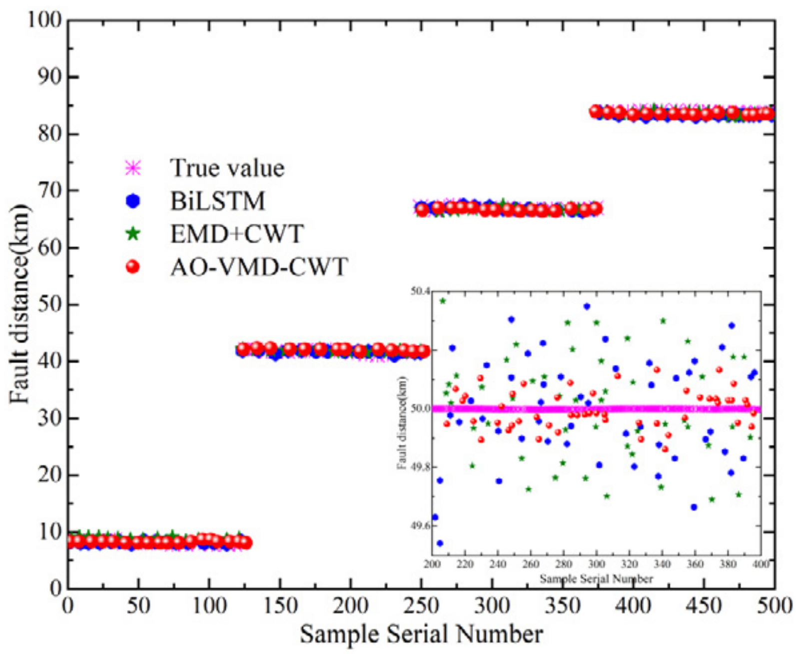

Figure 10 Visualization of fault location results by three algorithms

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Table 3 Average positioning result of power cable faults

Fault type	Fault distance	Average positioning results		Average absolute localization error	
		BiLSTM	EMD+CWT	BiLSTM	EMD+CWT
Phase earth fault	10km	10.28	10.32	2.415 %	2.435 %
	50km	50.26	50.24	463 %	396 %
	80km	80.23	80.39	265 %	247 %
	100km	100.49	100.45	354 %	313 %
Line to line fault	10km	10.51	10.21	4.912 %	3.248 %
	50km	50.63	50.28	556 %	665 %
	80km	80.41	80.24	232 %	263 %
	100km	100.36	100.27	357 %	304 %
Two-phase short circuit ground	10km	10.12	10.26	1.468 %	1.927 %
	50km	50.22	50.18	593 %	515 %
	80km	80.35	80.27	382 %	326 %
	100km	100.36	100.29	304 %	281 %
Three-phase short-circuit	10km	10.21	10.26	2.718 %	2.569 %
	50km	50.24	50.27	415 %	384 %
	80km	80.19	80.18	226 %	261 %
	100km	100.46	100.34	463 %	357 %

5. CONCLUSION

In this study, a power cable fault location technique based on parameter-optimized variational modal decomposition is successfully proposed and validated. The experimental results demonstrate that by combining the variational modal decomposition and wavelet transform, the proposed technique makes significant progress in enhancing the identification and processing efficiency of cable fault signals. Specifically, in the simulated fault test, the average localization error of the proposed method is reduced to less than 1%, which improves the accuracy by about 30% compared with the traditional fault localization methods. Especially in the processing of complex fault signals, the proposed method shows better adaptability and robustness.

By optimizing the processing of parameters of cable fault signals, this study significantly improves the accuracy of fault location. In the tests, the technique demonstrated good processing capability for different types of cable fault signals, especially in the face of non-standard or complex fault signals, and was able to identify and accurately locate the fault point. For example, the relative error of fault localization is maintained between 0.5% and 1% when testing a cable of up to 5 km in length, which demonstrates the efficiency and reliability of the technique in practical

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applications. The application of parameter-optimized variational modal decomposition based on parameter optimization in power cable fault localization proposed in this study not only improves the accuracy of fault localization, but also provides a new technical path for fault diagnosis and maintenance of power systems.

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