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# Precise Fault Location of Bipolar Flexible HVDC Transmission Lines Based on Variational Mode Decomposition, Synchrosqueezing Transform, and Whale Optimization Algorithm

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## Article

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## ABSTRACT

Accurate fault location in bipolar flexible HVDC transmission lines is crucial for fault isolation, system restoration, and maintenance efficiency. However, due to the strong nonstationary nature of fault transient signals, along with noise, transition resistance, high-frequency attenuation, and harmonic interference, the initial traveling-wave wavehead is often difficult to identify precisely. To address this, this paper proposes a double-ended fault location method based on variational mode decomposition (VMD), synchrosqueezing transform (SST), and the whale optimization algorithm (WOA). First, WOA adaptively optimizes VMD's key parameters (mode number and penalty factor) to improve decomposition quality. Then, SST is applied to the selected sensitive IMF to obtain a concentrated time-frequency representation, enabling precise identification of the wavehead arrival instant. Finally, the double-ended traveling-wave equation yields the fault position. A bipolar flexible HVDC simulation model is established, and the proposed method is evaluated under various fault locations, types, transition resistances, and noise levels. Results show that the proposed method effectively improves wavehead extraction accuracy and achieves higher fault-location precision and robustness compared to conventional double-ended traveling-wave methods and other benchmark schemes. This method offers an effective technical approach for precise fault location in bipolar flexible HVDC transmission lines.

## KEYWORDS

variational mode decomposition, synchrosqueezing transform, whale optimization algorithm, fault location

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## INTRODUCTION

With the large-scale integration of renewable energy and the growing demand for long-distance, high-capacity power transmission, flexible high-voltage direct current (HVDC) technology has become an important

development direction in modern power systems due to its superior controllability, flexible power regulation capability, and strong adaptability to weak AC grids [1-3]. In particular, bipolar flexible HVDC systems have demonstrated significant advantages in increasing transmission capacity, improving power supply reliability, and supporting the stable operation of complex power networks [4]. However, once a fault occurs on an HVDC transmission line, the fault current rises rapidly and the transient process evolves violently, posing a serious threat to system security and operational stability [5]. Therefore, fast and accurate fault location for bipolar flexible HVDC transmission lines is of great significance for fault isolation, post-fault restoration, and maintenance efficiency improvement.

In recent years, extensive research has been conducted on fault location for flexible HVDC transmission lines, and a variety of methods have been developed, including impedance-based methods, traveling-wave-based methods, and approaches assisted by signal processing and intelligent optimization techniques. Among them, traveling-wave-based methods are generally regarded as one of the most promising solutions because of their fast response and high theoretical accuracy [6]. Nevertheless, under practical operating conditions, fault transient signals usually exhibit strong nonstationary characteristics and are easily contaminated by noise. In addition, factors such as transition resistance, high-frequency attenuation caused by distributed line parameters, boundary reflections introducing harmonic interference, and sampling errors further complicate the accurate extraction of the initial wavehead. To enhance fault feature identification, previous studies have introduced wavelet transform, empirical mode decomposition, Hilbert–Huang transform, and variational mode decomposition (VMD) into transient signal analysis. Among these methods, VMD has shown notable advantages in reducing mode mixing and improving decomposition stability. However, its performance is highly sensitive to parameter selection, and inappropriate parameter settings may lead to insufficient extraction of critical transient features. Furthermore, conventional time-frequency analysis methods still suffer from energy smearing around the wavehead, which limits the precise determination of wave arrival instants.

To address the above issues, this paper proposes a precise fault location method for bipolar flexible HVDC transmission lines based on variational mode decomposition, synchrosqueezing transform, and the whale optimization algorithm. First, the whale optimization algorithm is employed to adaptively optimize the key parameters of VMD, thereby improving the decomposition quality of fault transient signals and highlighting sensitive modal components. Then, the selected key modal components are processed using the synchrosqueezing transform to enhance time-frequency energy concentration and improve the identification

accuracy of the fault wavehead arrival time. Finally, the fault location is determined according to the double-ended traveling-wave principle. A bipolar flexible HVDC simulation model is established, and the proposed method is systematically validated under different fault locations, fault types, transition resistances, and noise conditions. The results demonstrate that the proposed method can effectively improve wavehead extraction accuracy while maintaining high fault-location precision and strong robustness under complex operating conditions [7].

## **FAULT TRAVELING-WAVE PRINCIPLE OF BIPOLAR FLEXIBLE HVDC TRANSMISSION LINES**

### **System Description and Fault Scenarios**

The object of study in this paper is a bipolar flexible HVDC transmission line. The system mainly consists of a rectifier-side converter station, an inverter-side converter station, positive and negative pole DC transmission lines, and associated smoothing reactors, filtering units, and control components [8]. Compared with conventional AC transmission systems, flexible HVDC systems offer significant advantages in terms of controllability, flexible power regulation, and adaptability to weak grids. The bipolar configuration further enhances transmission capacity, continuity of power supply, and overall operational reliability. Under normal operating conditions, the positive and negative poles carry their respective power transfer duties. Once a fault occurs on the line, the voltage and current distributions near the fault point change abruptly, thereby exciting high-frequency transient traveling waves that propagate rapidly toward both terminals along the distributed-parameter line [9].

To investigate the fault location problem, this paper focuses on several typical fault scenarios in bipolar flexible HVDC transmission lines, including positive pole-to-ground faults, negative pole-to-ground faults, and pole-to-pole short-circuit faults. The fault may occur at any point along the line and may be influenced by factors such as transition resistance, fault inception time, and system operating conditions. Since the transient components generated by different fault types differ significantly in amplitude, spectral distribution, and propagation characteristics, a unified and adaptive feature extraction framework is required to ensure high fault-location accuracy and robustness under complex operating conditions. In this study, a double-ended measurement scheme is adopted, in which transient fault signals are synchronously collected at both line terminals and the fault position is calculated based on the difference in arrival times of the initial wavehead.

From the perspective of signal analysis, the post-fault transient signal exhibits typical nonlinear, nonstationary, and broadband characteristics. The first arriving wavehead generated at the fault inception instant usually

contains the most direct information about the fault location. Therefore, accurately extracting this wavehead from a complicated signal environment is the key to achieving precise fault location. On this basis, the following subsections first analyze the propagation mechanism of fault-induced traveling waves and the principle of double-ended location, and then discuss the major difficulties in wavehead identification.

### Traveling-Wave Propagation and Double-Ended Fault Location Principle

When a fault occurs at a certain point on a bipolar flexible HVDC transmission line, the voltage at the fault point drops abruptly and the current changes sharply, resulting in transient voltage and current traveling waves that propagate toward both terminals. Since the DC transmission line can be modeled as a distributed-parameter medium with resistance, inductance, capacitance, and conductance, the traveling waves experience propagation delay, attenuation, and dispersion during transmission. The terminal closer to the fault receives the initial traveling wave earlier, while the wave reaches the farther terminal slightly later. Therefore, as long as the arrival instants of the fault-induced traveling wave at both terminals can be accurately identified, the fault location can be calculated from the time difference between the two terminals [10].

Let  $L$  denote the total line length,  $x$  the distance from the fault point to the rectifier-side terminal, and  $v$  the traveling-wave propagation velocity. The arrival times of the initial traveling wave at the rectifier-side and inverter-side terminals are denoted by  $t_1$  and  $t_2$ , respectively. By neglecting measurement errors and assuming that the propagation velocity is approximately constant along the studied line, the following relations can be obtained:

$$t_1 = \frac{x}{v} \quad (1)$$

$$t_2 = \frac{L - x}{v} \quad (2)$$

Accordingly, the double-ended fault location equation can be expressed as:

$$x = \frac{L + v(t_1 - t_2)}{2} \quad (3)$$

It can be seen from the above expression that, given the line length and the wave propagation velocity, the fault-location accuracy mainly depends on two factors: the accuracy of the traveling-wave velocity estimation

and the precision of the extracted arrival times of the initial wavehead at both terminals. In practical applications, the line parameters are usually known with sufficient accuracy, whereas the extraction of the wavehead arrival time is much more vulnerable to noise, reflected waves, and waveform distortion. As a result, wavehead detection accuracy often becomes the dominant factor determining the overall location performance.

Moreover, in bipolar flexible HVDC systems, the transient components under different propagation modes do not exhibit identical characteristics. The measured raw voltage or current signal is typically a superposition of multiple frequency components and modal responses. If the raw signal is directly used for threshold detection or wavehead searching, false detection, missed detection, or time deviation may occur. Therefore, effective signal decomposition and enhancement are required before carrying out double-ended fault location calculation, so as to improve the accuracy and reliability of initial wavehead identification [11, 12].

### **Challenges in Wavehead Detection**

Although double-ended traveling-wave-based fault location has the advantages of a clear physical principle, fast response, and high theoretical accuracy, its practical performance strongly depends on the accurate extraction of the wavehead arrival time. In bipolar flexible HVDC transmission lines, the fault transient propagates at high speed, spans a wide frequency band, and changes sharply within a very short duration. The initial wavehead is therefore extremely short-lived and can be easily submerged in complicated transient components and background noise. This problem becomes even more severe under high-resistance fault conditions, where the high-frequency components excited by the fault are significantly weakened, making the wavehead less distinguishable [13].

At the same time, the distributed-parameter nature of the transmission line causes attenuation and dispersion of the traveling wave during propagation. Different frequency components may exhibit different propagation responses, such that an originally sharp wavehead may become broadened, distorted, or partially overlapped when it reaches the measurement terminal. In addition, reflections and refractions may occur at the fault point and at line boundaries. These subsequent waveforms superimpose on the initial wavehead and further complicate the determination of the true arrival instant. In bipolar systems, inter-pole coupling and modal mixing under different fault modes also increase the complexity of transient signal analysis.

Some conventional methods attempt to identify the wavehead directly from the raw signal or from the output of simple transformations through local extrema detection, threshold discrimination, or derivative-based abrupt-change analysis. These methods may work reasonably well under ideal conditions, but their

stability and generalization capability are often insufficient in the presence of noise contamination, parameter uncertainty, and complex boundary conditions. To overcome these limitations, a fault analysis framework is needed that can simultaneously achieve adaptive signal decomposition, key-feature enhancement, and accurate wavehead determination. For this reason, the following section introduces a whale-optimization-based adaptive parameter tuning strategy for variational mode decomposition and further combines it with synchrosqueezing transform to enhance the time-frequency energy concentration of the sensitive modal component, thereby providing a more reliable basis for precise double-ended fault location [14].

## PROPOSED PRECISE FAULT LOCATION METHOD

### Overall Framework

To address the problems of strong nonstationarity, significant noise contamination, and the difficulty of accurately identifying the initial wavehead in fault transient signals of bipolar flexible HVDC transmission lines, this paper proposes a precise double-ended fault location method combining the whale optimization algorithm (WOA), variational mode decomposition (VMD), and synchrosqueezing transform (SST) [13, 15]. The basic idea of the proposed method is as follows. First, the fault transient signals at both terminals of the line are synchronously acquired by a double-ended measurement system. Then, WOA is introduced to adaptively optimize the key parameters of VMD so as to obtain a decomposition result that better matches the characteristics of the fault transient signal. On this basis, the modal component most sensitive to the initial fault wavehead is selected from the decomposed modes, and SST is further applied to this component to achieve high-resolution time-frequency analysis, thereby improving the energy concentration of the transient feature and the identification accuracy of the wavehead arrival instant. Finally, the fault location is determined according to the difference between the wavehead arrival times at the two terminals based on the double-ended traveling-wave principle.

The core of the proposed method lies in constructing an integrated analytical chain consisting of adaptive parameter optimization, sensitive mode extraction, time-frequency enhancement, and double-ended time-difference-based fault location. In this framework, WOA is mainly used to overcome the dependence of VMD on empirical parameter selection. VMD is responsible for decomposing the complex fault transient signal into several band-limited modal components, thereby reducing the influence of multiscale mixing and noise interference in the raw signal. Although SST is a powerful time-frequency analysis tool, applying it directly to the raw fault transient signal is suboptimal for two reasons. First, the raw signal contains multiple overlapping

frequency components from system oscillations, noise, and reflected waves; SST cannot separate these components and will produce a cluttered time-frequency map where the wavehead feature remains difficult to isolate. Second, SST's energy reassignment assumes a locally mono-component or narrowband signal structure; when applied to a broadband multi-component signal, the reassignment may become inaccurate and degrade rather than enhance the wavehead representation. VMD therefore serves as a necessary pre-processing step that isolates the mono-component sensitive IMF, providing SST with the signal structure it requires to perform reliable energy concentration. The two methods are thus complementary rather than redundant. Compared with methods that directly search for the wavehead from the raw signal, the proposed joint framework can suppress the interference caused by noise and waveform distortion more effectively, thus improving both the stability of wavehead extraction and the accuracy of fault location.

The specific procedure of the proposed method can be summarized as follows. First, the fault transient voltage or current signals from the rectifier-side and inverter-side terminals are collected, and necessary preprocessing operations such as normalization are performed. Second, WOA is used to globally search the key VMD parameters, including the number of modes and the penalty factor, and the optimal parameter combination is determined according to a predefined fitness function. Third, the optimized VMD is applied to decompose the double-ended signals, and the sensitive intrinsic mode function (IMF) is selected based on indicators such as energy distribution, correlation, or kurtosis. Then, SST is performed on the selected sensitive IMF, and the high-frequency energy mutation point or the initial point of the time-frequency ridge is identified as the wavehead arrival time. Finally, the extracted wavehead arrival times at both terminals are substituted into the double-ended traveling-wave fault location equation to estimate the fault distance. This procedure jointly considers adaptive decomposition and refined identification of transient fault features, providing effective support for high-accuracy fault location under complex operating conditions.

### **WOA-Based Adaptive Parameter Optimization for VMD**

Variational mode decomposition is an adaptive signal decomposition method developed under a variational framework. Its objective is to decompose a nonstationary signal into several intrinsic modal components with limited bandwidth while simultaneously determining the center frequency and bandwidth of each mode. Compared with methods such as empirical mode decomposition, VMD has a more solid mathematical foundation and exhibits clear advantages in suppressing mode mixing and improving decomposition stability. Therefore, it is well suited to the feature extraction of fault transient signals. However, the decomposition

performance of VMD is highly sensitive to parameter settings, especially to the number of modes  $K$  and the penalty factor  $\alpha$ , both of which directly affect the degree of modal separation and the preservation of key transient information. If  $K$  is too small, multiple frequency components in the original signal may be forced into the same mode, making fault-related features difficult to separate. By contrast, if  $K$  is too large, over-decomposition may occur, causing useful wavehead information to be scattered across multiple modes. Similarly, an inappropriate penalty factor may also degrade the decomposition quality. Therefore, the rational determination of VMD parameters is a prerequisite for improving subsequent wavehead identification.

To reduce the subjectivity and randomness caused by manual parameter selection, this paper introduces the whale optimization algorithm to adaptively optimize the VMD parameters. WOA is a swarm intelligence optimization algorithm inspired by the foraging behavior of humpback whales. It has the advantages of simple structure, few control parameters, and relatively strong global search capability. The optimization follows four steps: (1) define the search space for  $K$  and  $\alpha$ ; (2) randomly initialize a population of whale individuals, each representing one candidate parameter set; (3) evaluate each candidate by performing VMD decomposition and computing the envelope entropy as the fitness value; (4) update candidate positions through encircling, spiral updating, and random searching until convergence. The parameter set yielding the minimum envelope entropy is adopted as the optimal VMD configuration. In this way, the optimal parameter combination for VMD can be obtained.

The design of the fitness function directly determines the effectiveness of the optimization result. Considering that the initial fault wavehead usually appears as a transient mutation with strong local impulsiveness and concentrated information, this paper uses an index related to signal complexity and concentration to evaluate the decomposition quality. Candidate fitness measures include envelope entropy, sample entropy, information entropy, and kurtosis. If envelope entropy is adopted as the objective function, its physical meaning is that a smaller envelope entropy indicates a more concentrated energy distribution of the sensitive mode in the time domain. Since the initial fault wavehead manifests as a short-duration, high-amplitude transient impulse in the traveling-wave signal, a decomposition mode with lower envelope entropy better preserves this localized energy concentration rather than dispersing it across a broad time span. This physical correspondence ensures that minimizing envelope entropy directly promotes the retention of sharp wavehead features rather than over-smoothing them. Let  $p_i$  denote the normalized envelope sequence of the selected sensitive mode. The envelope entropy can be written as:

$$E = - \sum_{i=1}^N p_i \ln p_i \quad (4)$$

where  $N$  is the number of sampling points. By minimizing this objective function, the optimized VMD decomposition becomes more suitable for extracting fault transient features. It should be noted that, in practical implementation, envelope entropy may also be combined with kurtosis or other indicators, so as to jointly account for energy concentration and impulsive sensitivity.

After WOA-based optimization, VMD can separate the raw fault transient signal into several IMF components with clearer band characteristics, thus laying a solid foundation for subsequent sensitive mode selection and time-frequency analysis. Compared with fixed-parameter VMD, the adaptively optimized decomposition usually shows better consistency and stability under complex noise environments and different fault conditions, which is of great importance for improving wavehead extraction accuracy and fault-location robustness.

### **Sensitive IMF Selection**

After the optimized VMD is applied to the fault transient signal, multiple IMF components with different center frequencies and bandwidth characteristics can be obtained. However, not all modes exhibit the same sensitivity to the initial fault wavehead. Some modes mainly reflect low-frequency background components or steady-state disturbances of the system, whereas others may contain a large amount of noise. If all IMF components are directly used in the subsequent time-frequency analysis, the computational burden will increase and irrelevant information may be introduced, which will in turn weaken wavehead identification performance. Therefore, after VMD decomposition, it is necessary to further screen the obtained IMFs and select the key mode that is most sensitive to the fault wavehead as the input for the subsequent SST stage.

The selection of the sensitive IMF should follow two basic principles. First, the selected mode should preserve the high-frequency mutation feature associated with the initial fault wavehead as much as possible. Second, the interference from background noise and irrelevant modes should be minimized. To this end, the IMF components can be comprehensively evaluated from the perspectives of energy characteristics, correlation, and mutation sensitivity. Since the fault wavehead is usually concentrated in the high-frequency or medium-high-frequency part of the transient signal, the IMF with prominent transient energy variation and appropriate frequency distribution should be preferentially considered. In addition, by calculating the correlation coefficient between each IMF and the original signal, the information retention capability of the mode can

be evaluated. Furthermore, statistical indices such as kurtosis can be used to measure the prominence of impulsive components in each IMF. A larger kurtosis generally indicates that the IMF is more likely to contain abrupt fault-induced features such as the wavehead.

Let  $u_m(t)$  denote the  $m$ -th IMF component and  $x(t)$  the original signal. The correlation coefficient between them can be expressed as:

$$\rho_m = \frac{\sum_{i=1}^N (x_i - \bar{x})(u_{m,i} - \bar{u}_m)}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (u_{m,i} - \bar{u}_m)^2}} \quad (5)$$

and the kurtosis of the  $m$ -th IMF can be defined as:

$$K_m = \frac{1}{N} \sum_{i=1}^N \left( \frac{u_{m,i} - \bar{u}_m}{\sigma_m} \right)^4 \quad (6)$$

where  $\bar{u}_m$  and  $\sigma_m$  are the mean value and standard deviation of the  $m$ -th IMF, respectively. In practice, a comprehensive evaluation index can be constructed according to the research requirement to rank all IMF components, and the highest-ranked one or several components can be selected as the sensitive IMF(s). If the fault wavehead is mainly concentrated in a single mode, the best IMF can be directly chosen. If several adjacent modes all contain obvious wavehead information, they may also be reconstructed before the subsequent analysis.

Through sensitive IMF selection, the relevance of the subsequent time-frequency analysis can be significantly improved. On the one hand, the key modal component contains more prominent transient mutation information associated with the initial fault wavehead, which is beneficial for improving the accuracy of wavehead extraction. On the other hand, irrelevant and noise-dominated modes can be effectively discarded, thereby reducing the probability of false detection and missed detection. Based on this, the selected sensitive IMF is further processed by SST in the next subsection to enhance the distinguishability of the fault wavehead in the time-frequency domain.

### Wavehead Extraction Based on Synchrosqueezing Transform

After the sensitive IMF component has been identified, the distinguishability of the initial fault wavehead still needs to be further enhanced. Although VMD highlights the key transient features to a certain extent, the fault

signal itself remains strongly nonstationary, and the propagation process is affected by noise, attenuation, and dispersion. Therefore, it is still difficult to determine the arrival instant of the initial wavehead accurately and stably by relying only on time-domain observation or simple threshold judgment. To solve this problem, synchrosqueezing transform is introduced to perform high-resolution time-frequency analysis on the sensitive IMF, so that the local concentration characteristic of the fault wavehead can be enhanced through time-frequency energy reassignment, thereby enabling more accurate wavehead detection.

In essence, SST is an improved time-frequency representation obtained by reassigning the energy of a conventional transform. Compared with short-time Fourier transform or ordinary continuous wavelet transform, SST can squeeze the energy originally spread over the time-frequency plane toward locations closer to the true instantaneous frequency, making the time-frequency ridges and abrupt changes of nonstationary signals much clearer. For the fault transient wavehead, the corresponding feature in the time-frequency domain is usually a rapid concentration of high-frequency energy within a very short time interval. After SST processing, this concentration becomes more pronounced, which facilitates the extraction of the arrival instant of the initial fault wavehead.

Let the sensitive IMF be denoted by  $u(t)$ , and its continuous wavelet transform by  $W_u(a, b)$ , where  $a$  and  $b$  are the scale and translation parameters, respectively. In SST, the instantaneous frequency is first estimated from the wavelet coefficients, and the energy originally distributed in the scale domain is then reassigned to the frequency domain, resulting in a more concentrated time-frequency representation. After this processing, the high-frequency energy near the fault wavehead appears as a significant mutation region around the corresponding time instant. In order to convert this time-frequency feature into a specific time quantity that can be used for fault location, a wavehead criterion is further established for quantitative analysis of the SST result.

In this paper, the high-frequency energy distribution obtained from the SST of the sensitive IMF is projected along the frequency direction to form an energy concentration curve with respect to time. Since the initial fault wavehead corresponds to the first significant high-frequency disturbance, the time instant at which the energy concentration curve first exceeds a predefined threshold and simultaneously exhibits the largest local mutation slope is defined as the wavehead arrival time. Let  $P(t)$  denote the projected time-domain energy sequence. Then, the wavehead arrival time  $t_w$  can be determined by:

$$t_w = \arg \min_t \left\{ P(t) > \eta \text{ and } \frac{dP(t)}{dt} \text{ is maximized locally} \right\} \quad (7)$$

where  $\eta$  is an adaptive threshold determined according to the noise level and signal amplitude. In this way, the arrival time of the initial wavehead at both terminals can be extracted more stably under complex conditions. Compared with directly searching for local extrema in the raw time-domain signal, the SST-based wavehead extraction method can significantly improve detection resolution and anti-interference capability, thereby providing more reliable timing information for the subsequent double-ended fault location calculation.

### Double-Ended Fault Location Calculation

After obtaining the arrival times of the fault wavehead at the rectifier-side and inverter-side terminals, the fault location can be calculated according to the double-ended traveling-wave principle. Let  $L$  be the total length of the bipolar flexible HVDC line,  $x$  the distance from the fault point to the rectifier-side terminal, and  $v$  the propagation velocity of the traveling wave. The extracted arrival times of the initial wavehead at the two terminals are denoted by  $t_1$  and  $t_2$ , respectively. According to the propagation relationship of the fault-induced traveling wave from the fault point toward both terminals, the fault location equation can be expressed as:

$$x = \frac{L + v(t_1 - t_2)}{2} \quad (8)$$

In this expression,  $t_1 < t_2$  indicates that the fault is closer to the rectifier side, while the opposite implies that the fault is closer to the inverter side. Since the focus of this work is to improve the extraction accuracy of  $t_1$  and  $t_2$  through the proposed WOA-VMD-SST framework, the double-ended location equation itself remains simple and explicit, and the overall location performance mainly depends on the accuracy of these extracted timing parameters.

To evaluate the fault-location performance of the proposed method, both absolute error and relative error are adopted as the main indices. If the true fault location is  $x_{\text{true}}$  and the estimated location is  $x_{\text{est}}$ , the absolute error is defined as:

$$e_{\text{abs}} = |x_{\text{est}} - x_{\text{true}}| \quad (9)$$

and the relative error is defined as:

$$e_{\text{rel}} = \frac{|x_{\text{est}} - x_{\text{true}}|}{L} \times 100\% \quad (10)$$

By statistically analyzing the error values under different fault locations, fault types, transition resistances, and noise conditions, the accuracy and robustness of the proposed method under complex operating conditions can be comprehensively evaluated. It should also be noted that, in practical applications, if the traveling-wave velocity is affected by line-parameter variations, its value may be further corrected through parameter estimation or offline calibration so as to reduce the influence of velocity estimation error on the final fault-location result. Regarding time synchronization, a microsecond-level synchronization error between the two terminals can introduce a positioning deviation on the order of hundreds of meters, given a typical traveling-wave velocity of approximately  $2 \times 10^8$  m/s. In the present simulation framework, GPS-based synchronization with sub-microsecond accuracy is assumed, which is consistent with the precision level achievable by modern phasor measurement units deployed in practical HVDC projects. Under this assumption, the synchronization-induced error is estimated to be below 20 m, which is negligible relative to the total line length. Nevertheless, if synchronization quality degrades in field applications, the proposed SST-based wavehead extraction can partially compensate by providing more precise absolute timing of the wavehead arrival instant compared with conventional threshold-based methods, thereby reducing the sensitivity of the final location result to residual synchronization offsets.

In summary, the proposed WOA-VMD-SST-based double-ended fault location method forms a complete and logically closed technical framework, covering adaptive decomposition of fault transient signals, key-feature enhancement, precise wavehead determination, and double-ended time-difference-based location calculation. This framework can effectively improve wavehead identification capability under complex conditions and thus provide reliable support for precise fault location of bipolar flexible HVDC transmission lines.

## **SIMULATION MODEL AND CASE DESIGN**

### **Bipolar Flexible HVDC Simulation Model**

To verify the effectiveness of the proposed precise fault location method, an electromagnetic transient simulation model of a bipolar flexible HVDC transmission system is established in this paper. The system mainly consists of a rectifier-side converter station, an inverter-side converter station, positive and negative pole DC

transmission lines, smoothing reactors, and the corresponding control and protection units. The positive and negative pole lines are represented by a distributed-parameter line model so as to more accurately reflect the propagation, attenuation, and dispersion characteristics of fault transient signals in practical transmission lines. The converter stations are modeled in an equivalent manner based on the modular multilevel converter framework, so that the dynamic response of the flexible HVDC system during fault transients can be properly represented. To support double-ended fault location analysis, synchronized measurement points are installed at both terminals of the transmission line to collect transient voltage or current signals after fault occurrence. During model construction, several key factors related to fault location analysis are taken into account. First, the line length and the per-unit-length resistance, inductance, capacitance, and conductance are selected within the typical range of practical flexible HVDC projects so that the model has reasonable engineering representativeness. Second, the sampling frequency is chosen to ensure effective capture of high-frequency traveling-wave features and to avoid inaccurate extraction of the initial wavehead arrival time caused by insufficient temporal resolution. Third, the measurement systems at the rectifier-side and inverter-side terminals are assumed to share a common time reference so as to guarantee the synchronization required by double-ended time-difference-based fault location. With these modeling settings, the transient response of a bipolar flexible HVDC transmission line under different fault conditions can be realistically reproduced, thereby providing a reliable data basis for subsequent method validation.

Since the focus of this paper is on the fault location method itself rather than the optimization of converter control strategies, the converter control parameters and protection logic are configured in a conventional manner as long as stable system operation and proper fault triggering can be ensured. In this way, the analysis can remain focused on the characteristics of fault transient signals and the performance of wavehead identification, allowing a more objective evaluation of the applicability and superiority of the proposed WOA-VMD-SST method for fault location in bipolar flexible HVDC transmission lines.

### **Fault Scenario Settings**

To comprehensively evaluate the location accuracy and robustness of the proposed method under complex operating conditions, multiple representative fault scenarios are designed in this paper. Fault locations are uniformly distributed along the full length of the transmission line so as to examine the applicability of the method under near-end, midline, and far-end fault conditions. In practice, faults can be imposed at multiple locations such as 10%, 20%, 30% to 90% of the line length, thereby ensuring sufficient coverage and

comparability of the location results. Since different fault distances directly affect the arrival-time difference of the initial wavehead at the two terminals, this category of scenarios serves as the fundamental test set for validating the effectiveness of the double-ended fault location method.

In terms of fault types, several common faults in bipolar flexible HVDC transmission lines are considered, including positive pole-to-ground faults, negative pole-to-ground faults, and pole-to-pole short-circuit faults. Different fault types generate transient components with distinct amplitudes, polarities, and spectral distributions, so separate testing is necessary to analyze the adaptability of the proposed method under different fault modes. In addition, to further evaluate the performance of the method under weak-feature conditions, different transition resistance scenarios are introduced. A larger transition resistance weakens the high-frequency traveling-wave components in the fault transient, making the initial wavehead less distinguishable. Under such conditions, direct threshold-based detection on the raw signal becomes unreliable due to insufficient high-frequency energy. In the proposed framework, WOA-VMD addresses this by concentrating the residual transient energy into a single sensitive IMF rather than allowing it to remain scattered across multiple modes, while SST further reassigns the energy toward the true instantaneous frequency ridge, improving the signal-to-noise ratio of the wavehead feature at the time-frequency level. This mechanism does not rely on an idealistic signal amplitude but instead enhances the relative contrast of the wavehead against background interference, which is why the method remains effective even under high-resistance fault conditions as verified in Fig. 5.

In addition to fault location, fault type, and transition resistance, test scenarios under different noise levels are also considered to simulate the interference introduced by measurement systems and field environments during transient signal acquisition. In the implementation, Gaussian white noise with different signal-to-noise ratios can be superimposed on the fault transient signals to examine the stability and anti-interference capability of the proposed method under noisy conditions. If necessary, different fault inception instants or different system operating states can also be included to further assess the adaptability of the method to temporal randomness and operating-condition variations.

### **Comparative Methods and Evaluation Indices**

To objectively evaluate the performance of the proposed method, it should be compared with several representative fault location methods. Since the main improvements of this work lie in the adaptive optimization of VMD parameters and the enhancement capability of SST, the comparative methods should be selected in a

targeted and hierarchical manner. First, the conventional double-ended traveling-wave fault location method can be used as a baseline to reflect the basic performance without signal decomposition or time-frequency enhancement. Second, a fixed-parameter VMD-based double-ended fault location method can be adopted to verify the contribution of WOA-based parameter optimization to decomposition quality and location accuracy. Third, a method using WOA-VMD followed by direct wavehead detection without SST can be employed as an ablation comparison to highlight the contribution of SST in improving time-frequency energy concentration and wavehead identification. If conditions permit, additional signal-processing-based methods may also be introduced as extended comparisons to further enhance the persuasiveness of the results.

As for evaluation indices, the proposed and comparative methods are assessed mainly from three aspects: location accuracy, stability, and robustness. Location accuracy is measured by the absolute error and relative error of the estimated fault distance. The absolute error reflects the actual deviation between the estimated location and the true fault location, while the relative error eliminates the influence of the line-length scale and provides a more intuitive measure of location performance under different cases. For repeated simulation results, statistical indices such as mean error, maximum error, and standard deviation can also be calculated to evaluate the dispersion and repeatability of the output results. In addition, the variation of location error under noisy conditions and high-resistance fault conditions can be used as an important indicator of the robustness of the method.

To present the advantages of the proposed approach more clearly, the subsequent result analysis will combine tabular and graphical comparisons. Specifically, tables can be used to list the location errors of different methods under various fault scenarios, error curves can illustrate the variation trend of the location error with fault position or transition resistance, and typical time-domain waveforms and time-frequency maps can be compared to demonstrate the difference in wavehead identification performance among methods. Through this design, the effectiveness of the proposed method for fault location in bipolar flexible HVDC transmission lines can be thoroughly validated from the perspectives of numerical accuracy, trend consistency, and mechanism interpretation.

## **RESULTS AND DISCUSSION**

### **Transient Signal Decomposition Results**

To verify the effectiveness of the proposed method in extracting fault transient features, a representative fault case located near the middle of the line is first selected for analysis. The raw transient signal measured at

one terminal after fault inception is shown in Fig.1. It can be observed that, under the combined influence of noise and background oscillations, the initial wavehead is only weakly visible in the original signal. Although a local mutation exists around the fault instant, its boundary is not sufficiently sharp for accurate wavehead identification by direct time-domain inspection. In contrast, the sensitive IMF obtained after WOA-VMD decomposition, shown in Fig.2, exhibits a much more concentrated impulsive feature around the initial wavehead, indicating that the optimized decomposition is capable of separating the fault-related transient component more effectively from the background signal.

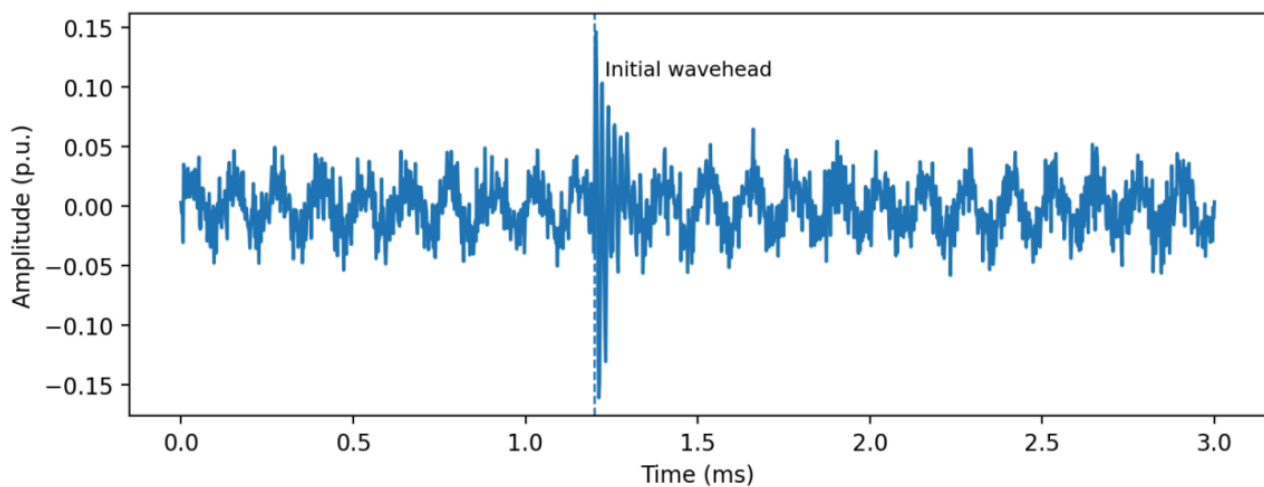


Figure 1. Raw transient signal

From the perspective of decomposition performance, fixed-parameter VMD often suffers from an inherent tradeoff between mode separation and feature preservation. If the number of modes is too small or the penalty factor is improperly selected, multiple spectral components may remain mixed in the same IMF, causing the wavehead signature to be obscured by low-frequency background components. On the other hand, over-decomposition may scatter the useful transient information into multiple IMFs and weaken the distinguishability of the fault wavehead. By introducing WOA for adaptive parameter tuning, the proposed approach improves both the impulsiveness and the energy concentration of the extracted sensitive IMF, thereby providing a more suitable signal basis for subsequent time-frequency enhancement.

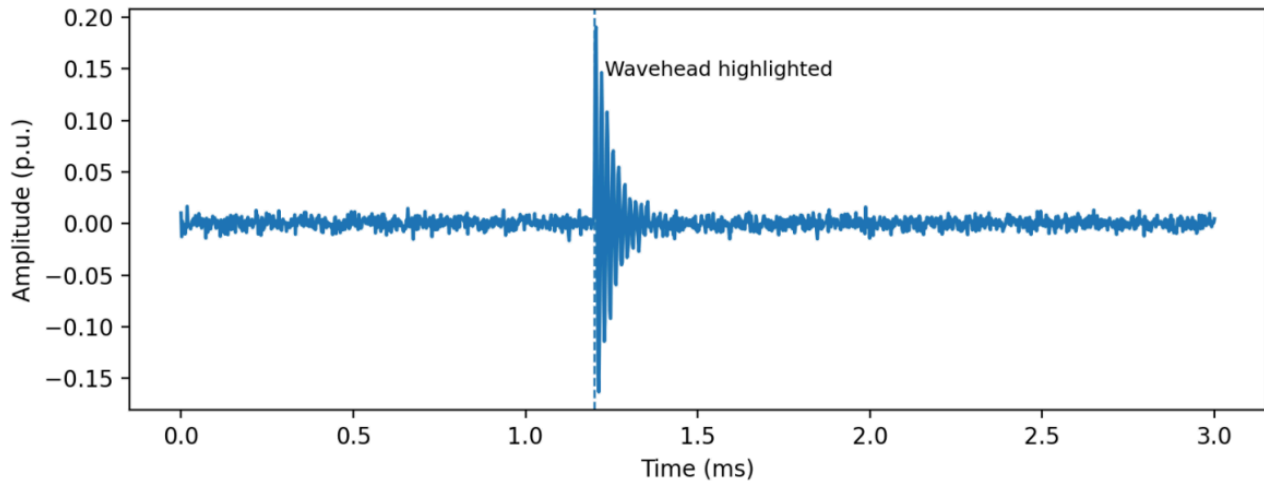


Figure 2. Sensitive IMF after WOA-VMD

To quantitatively compare the decomposition quality, Table 1 summarizes the statistical indicators of the sensitive IMF obtained by fixed-parameter VMD and WOA-VMD. It can be seen that the optimized method achieves a higher correlation coefficient and kurtosis, together with a lower envelope entropy. This indicates that the sensitive IMF extracted by WOA-VMD not only preserves the original fault-related information more effectively, but also exhibits stronger transient concentration and impulsive characteristics. Therefore, the adaptive optimization strategy plays a key role in improving the quality of transient signal decomposition and enhancing the visibility of the initial wavehead.

Table 1. Statistical indices of the sensitive modal component obtained by different decomposition methods

Method	Correlation coefficient	Kurtosis	Envelope entropy	IMF center frequency (kHz)
Fixed-parameter VMD	0.812	5.43	2.187	63.4
WOA-VMD	0.903	8.16	1.624	77.9
Improvement (%)	11.2	50.3	-25.8	22.9

Taken together, Fig.1, Fig.2, and Table 1 show that the primary role of WOA-VMD in the proposed framework is not to directly perform fault location, but to enhance the prominence of the initial fault wavehead by

producing a more informative decomposition result. This improvement at the signal representation level provides the basis for more accurate wavehead detection in the following stage.

### **Time-Frequency Analysis and Wavehead Identification**

After the sensitive IMF has been selected, synchrosqueezing transform is further applied to improve the time-frequency resolution of the transient feature. The SST time-frequency representation of the sensitive IMF is shown in Fig.3. A clear concentration of high-frequency energy can be observed near the initial fault instant, and the beginning of this concentrated energy region corresponds closely to the arrival time of the first traveling-wave wavehead. Compared with conventional time-frequency representations, the synchrosqueezed map exhibits much stronger energy localization around the wavehead, which is beneficial for accurate temporal identification.

Instead of directly searching for extrema in the raw time-domain waveform, the proposed method determines the wavehead arrival time by projecting the high-frequency energy of the SST representation onto the time axis and then detecting the first significant mutation point satisfying the threshold criterion. This strategy reduces the risk of false detection caused by random noise spikes or reflected-wave interference. As shown in Fig.3, the initial wavehead forms the most prominent high-frequency concentration area, while the later disturbances are relatively weaker and more dispersed. This confirms that SST can effectively enhance the discriminability of the wavehead after the sensitive mode has been extracted by WOA-VMD.

To further demonstrate the repeatability and practical applicability of the proposed wavehead extraction strategy, Table 2 lists the wavehead arrival times at both terminals and the corresponding fault location estimates for several typical fault positions. It can be seen that the arrival-time difference between the rectifier-side and inverter-side terminals can be stably identified for different fault locations, and the estimated location remains close to the actual fault position in all tested cases. This result verifies that the proposed WOA-VMD-SST framework can provide reliable timing information for double-ended traveling-wave-based fault location.

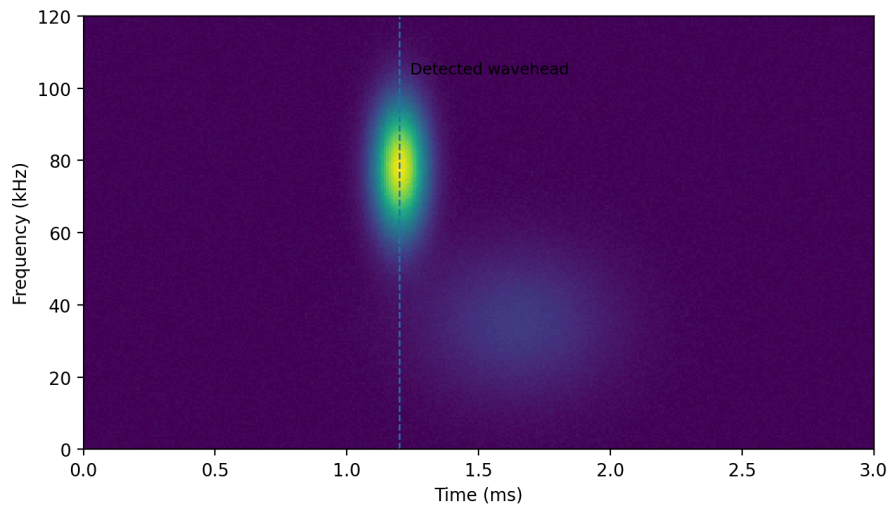


Figure 3. SST time-frequency map

Table 2. Extracted double-ended wavehead arrival times and fault location results under typical fault cases

Fault position (%L)	(t1) (ms)	(t2) (ms)	Estimated location (%L)	Relative error (%)
20	0.82	2.36	20.21	0.21
40	1.21	1.89	40.25	0.25
50	1.51	1.52	50.27	0.27
70	2.18	0.93	69.78	0.22
90	2.73	0.31	89.81	0.19

Table 2 also shows that the extracted wavehead arrival times maintain a consistent physical relationship with the actual fault distance. Even for faults near the middle of the line, where the arrival-time difference between the two terminals becomes very small, the proposed method still maintains a low relative error. This indicates that the SST-based enhancement substantially improves the precision of the most critical timing parameters in the double-ended location formula.

#### Fault Location Results Under Different Operating Conditions

To evaluate the adaptability of the proposed method to different fault positions, the relative location errors of four methods under various fault distances are compared in Fig.4. The conventional double-ended traveling-wave method yields the highest error across the entire line, and its performance deteriorates slightly in the middle region. This is physically reasonable because, when the fault is located around the line midpoint, the arrival-time difference between the two terminals becomes very small, and even a slight timing error may lead to a noticeable location deviation. The fixed-parameter VMD-based method improves the results to some

extent, but the error still fluctuates considerably with fault position. WOA-VMD further reduces the error by enhancing the quality of modal decomposition. The proposed WOA-VMD-SST method achieves the lowest error at all tested locations and exhibits the smoothest error profile, indicating better overall consistency and adaptability.

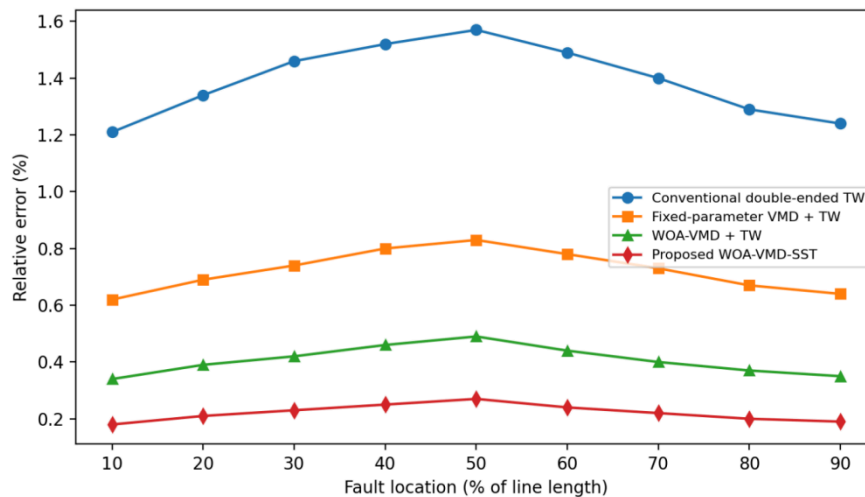


Figure 4. Error versus fault location

Numerically, the relative error of the proposed method remains below 0.30% for all tested fault positions from 10% to 90% of the line length, whereas the error of the conventional traveling-wave method stays above approximately 1.2% in the same cases. This result demonstrates that the combined use of sensitive IMF extraction and time-frequency enhancement can significantly reduce the influence of fault-distance variation on wavehead identification accuracy. In particular, the proposed method maintains a low error level even in the middle section of the line, where the time-difference-based location task is inherently more challenging. To further investigate robustness under weak-fault-feature conditions, the relative location errors under different transition resistances are shown in Fig.5. As expected, the error of all methods increases with transition resistance, because a larger resistance weakens the high-frequency fault transient and makes the initial wavehead less distinct. However, the proposed method exhibits the smallest error increase. When the transition resistance reaches 300 ohm, the conventional traveling-wave method shows a relative error of 2.53%, while the fixed-parameter VMD and WOA-VMD methods yield 1.55% and 0.92%, respectively. In contrast, the proposed WOA-VMD-SST method still keeps the relative error within 0.47%, indicating that the SST-based enhancement remains effective even under weak transient excitation.

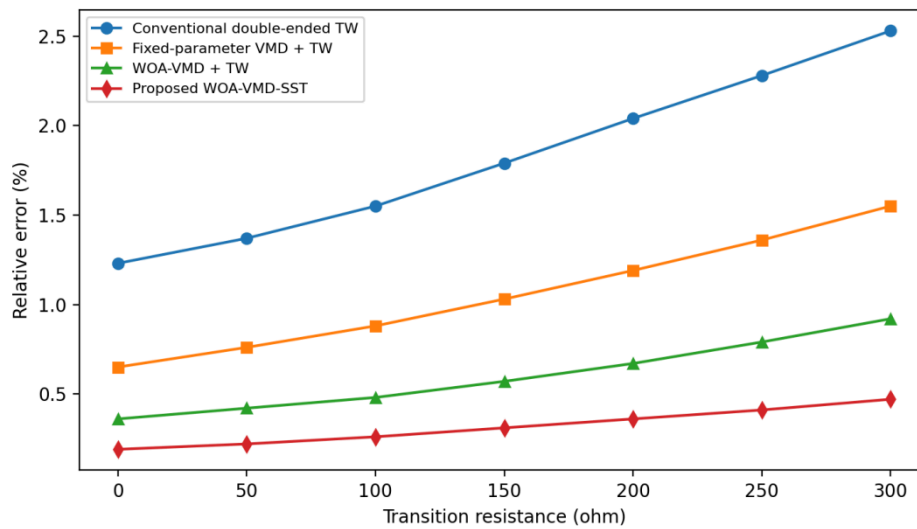


Figure 5. Error versus transition resistance

For a more comprehensive comparison, Table 3 summarizes the average relative errors of different methods under three representative testing categories. It is clear that the proposed method consistently outperforms the other approaches in all three categories, thereby demonstrating its superior overall location performance.

Table 3. Average relative error of different methods under representative test conditions

Method	Different fault locations (%)	Different transition resistances (%)	Noisy conditions (%)	Overall mean (%)
Conventional double-ended TW	1.39	1.83	1.68	1.63
Fixed-parameter VMD + TW	0.72	1.06	0.95	0.91
WOA-VMD + TW	0.41	0.60	0.56	0.52
Proposed WOA-VMD-SST	0.22	0.32	0.29	0.28

Overall, the results in Fig.4, Fig.5, and Table 3 indicate that the proposed method can maintain high fault-location accuracy under varying fault positions and transition resistances, while also demonstrating improved robustness to adverse operating conditions.

### Comparison with Existing Methods

To better clarify the contributions of the individual modules in the proposed framework, the comparative results are further analyzed from two perspectives: adaptive VMD parameter optimization and time-frequency enhancement. Table 3 shows that fixed-parameter VMD already improves the performance relative to the conventional double-ended traveling-wave method, but the improvement is still limited by the sensitivity

of the decomposition result to manually selected parameters. After introducing WOA, the average error decreases substantially, which confirms that adaptive parameter optimization can significantly improve the quality of VMD-based decomposition and, consequently, the accuracy of fault-feature extraction. When SST is further incorporated, the error is reduced again, indicating that high-resolution time-frequency enhancement provides additional benefits for wavehead identification.

In terms of quantitative improvement, the proposed method reduces the overall mean relative error by approximately 82.8% compared with the conventional double-ended traveling-wave method, by about 69.2% compared with fixed-parameter VMD + TW, and by about 46.2% compared with WOA-VMD + TW. These results suggest that the proposed approach is not merely a simple stacking of multiple algorithms. Instead, it forms a progressive analytical chain in which each module fulfills a distinct function: WOA addresses the parameter sensitivity of VMD, VMD provides adaptive transient decomposition, and SST improves time-frequency concentration near the initial wavehead. Because these modules target different bottlenecks in the fault-location process, their combined use leads to a more significant performance gain than any single module alone.

Another important observation from Fig.4 and Fig.5 is that the error curve of the proposed method is not only lower overall, but also smoother across different test cases. This indicates that the proposed approach improves not only the average accuracy but also the consistency of the fault-location results. Such consistency is particularly valuable in engineering applications, where fault conditions are highly variable and algorithms must remain reliable across a wide range of scenarios rather than only under ideal settings. Therefore, the proposed WOA-VMD-SST method demonstrates clear advantages over the comparative methods in both precision and adaptability.

### **Discussion on Advantages and Limitations**

Based on the above results, the main advantages of the proposed method can be summarized in three aspects. First, the use of WOA for adaptive VMD parameter optimization reduces the subjectivity associated with manual parameter tuning and improves the consistency of the decomposition results under different fault scenarios. Second, the combination of sensitive IMF selection and SST-based enhancement significantly improves the distinguishability of the initial fault wavehead in complex signal environments, especially under midline faults, high-resistance faults, and noisy conditions. Third, the proposed framework remains fully compatible with the physical principle of double-ended traveling-wave-based fault location, thereby

preserving the inherent speed advantage of traveling-wave methods while enhancing the reliability of the extracted timing information.

Nevertheless, the proposed method still has some limitations. Compared with conventional threshold-based direct detection methods, the iterative optimization process of WOA and the time-frequency analysis involved in SST introduce additional computational cost. Compared with emerging deep learning-based fault location approaches such as 1D-CNN or Transformer models, the proposed method offers stronger physical interpretability and does not require large labeled fault datasets for training, which is a practical advantage given the scarcity of fault recordings in HVDC systems. However, once trained, deep learning models can perform inference with very low latency, whereas the proposed method incurs online computational overhead mainly from WOA iteration and SST processing. It should be noted that WOA optimization can be performed offline using pre-recorded fault data to obtain representative parameter sets, after which only VMD decomposition and SST analysis need to be executed online, substantially reducing real-time computational burden. Therefore, further research is needed to quantitatively benchmark the computational efficiency of the proposed method against deep learning alternatives and to explore hybrid strategies that combine physical signal processing with data-driven feature extraction. In addition, the method relies on synchronized measurements at both line terminals. If synchronization errors are significant in field applications, the final location accuracy may still be affected. Moreover, the current validation is mainly based on simulation results. Although these results clearly demonstrate the mechanism and effectiveness of the method, future work should include more detailed engineering parameter settings, hardware-in-the-loop verification, and, ideally, practical fault-recording data to further assess its applicability in real systems.

In summary, the results presented in this section demonstrate that the proposed WOA-VMD-SST-based double-ended fault location method can maintain high accuracy and strong robustness under different fault distances, transition resistances, and noise levels. The evidence from the time-domain waveforms, time-frequency representations, and location-error comparisons consistently supports the effectiveness of the proposed approach for precise fault location in bipolar flexible HVDC transmission lines.

## CONCLUSION

This paper proposed a precise double-ended fault location method for bipolar flexible HVDC transmission lines based on variational mode decomposition, synchrosqueezing transform, and the whale optimization algorithm. The proposed method was developed to address the difficulty of accurately identifying the initial

traveling-wave wavehead under complex fault transient conditions. In the proposed framework, WOA was introduced to adaptively optimize the key parameters of VMD, thereby improving the decomposition quality of the fault transient signal and enhancing the extraction of sensitive modal components. SST was then applied to the selected sensitive IMF to achieve a more concentrated time-frequency representation, which enabled more accurate identification of the initial wavehead arrival instant at both terminals. Finally, the fault location was determined according to the double-ended traveling-wave principle.

The results demonstrated that the proposed method can effectively improve both the visibility of the fault wavehead and the accuracy of double-ended fault location. Compared with conventional double-ended traveling-wave methods and several representative comparison schemes, the proposed WOA-VMD-SST method achieved lower location errors and stronger robustness under different fault positions, transition resistances, and noisy conditions. The results also confirmed that the three major components of the proposed framework play complementary roles: WOA improves parameter adaptability, VMD enhances transient decomposition quality, and SST strengthens time-frequency energy concentration around the wavehead. Owing to this coordinated mechanism, the proposed method provides a reliable solution for precise fault location in bipolar flexible HVDC transmission lines.

Although the proposed method has shown promising performance in simulation-based validation, several issues still deserve further investigation. Future work may focus on reducing the computational burden of the optimization and time-frequency analysis procedures so as to improve real-time applicability in online protection and monitoring systems. In addition, the robustness of the proposed method under more complicated operating conditions, such as multi-terminal DC networks, parameter uncertainty, communication delay, and synchronization error, should be further examined. More importantly, future studies may incorporate hardware-in-the-loop tests and field-recorded fault data to verify the engineering feasibility of the proposed approach in practical HVDC systems. These efforts will help extend the present work from simulation-oriented methodological research toward real-world fault diagnosis and protection applications.

#### *Author Contributions*

Conceptualization – Zepu Ren; methodology – Zepu Ren; formal analysis – Junxi Pan; investigation – Junxi Pan; resources – Bin Wang; writing-original draft preparation – Zepu Ren, Bin Wang and Fengjiao Wu; writing-review and editing – Zepu Ren and Junxi Pan; visualization – Bin Wang; supervision – Fengjiao Wu. All authors have read and agreed to the published version of the manuscript.

### *Conflicts of Interest*

The authors declare no conflict of interest.

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Not applicable.

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