A Novel Traveling Wave Fault Location Method Based on ICEEMDAN-NTEO for Distribution Network

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Abstract

The traditional traveling wave fault location method is easily disturbed by load-side noise, which leads to low accuracy of traveling wave head identification and further leads to large location errors. This study aims to propose a new traveling wave fault location method based on ICEEMDAN-NTEO for distribution networks. By analyzing the frequency characteristics in the faulty traveling wave signal, the ICEEMDAN method is used to decompose the faulty signal and effectively filter out the noise components in the signal. The NTEO method is then used to calculate the energy values of the obtained modal components, enhancing the transient characteristics of the traveling wave. This method solves the problems of decomposition scale or modal aliasing that exist in traditional location methods and has higher anti-noise characteristics. Based on the accurate identification of the traveling wave head, this method further improves the accuracy of the traveling wave location in the distribution network.

Keywords: ICEEMDAN, NTEO, traveling wave (TW), distribution network (DN), fault location (FL)

1. Introduction

The structural environment of distribution lines is characterized by significant challenges, which frequently result in faults. Reliable, accurate, and fast line fault location plays an important role in improving the accuracy of fault detection and maintaining the reliable operation of the power grid [1]. Accurate fault location in distribution networks is often affected by noise interference, which leads to low accuracy in identifying traveling wave heads. Distribution networks in mountainous areas have the characteristics of long distribution lines, weak signals, and easy interference. Traditional location and ranging methods cannot meet the needs of the development of new distribution networks.

The traveling wave location method has high theoretical accuracy and is unaffected by the system operation mode, transition resistance, and CT saturation. However, the calibration time of the traveling wave head significantly affects the accuracy of location [2]. To realize the comprehensive development of a distribution automation system and accelerate the construction of smart power grids, it is crucial to determine fault location quickly after the fault occurs and study the stable and reliable fault location. The existing traveling wave location methods have weak anti-interference ability and are significantly affected by noise interference from power electronic devices, resulting in insufficient location accuracy. Therefore, a traveling wave location method that can accurately identify the wave head in complex noise environments is urgently needed.

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As an effective method to deal with nonlinear and non-stationary signals, the improved complete ensemble empirical mode decomposition with adaptive noise (ICEEMDAN) can improve the quality of signal decomposition results by introducing more accurate noise control methods. Combined with the novel Teager energy operator (NTEO), it is suitable for the online detection and processing of traveling wave signals. The anti-noise capability can be enhanced by improving the sensitivity of signal frequency, which is conducive to improving the accuracy and reliability of fault location.

Fault location methods based on the traveling wave principle [3] include the time domain method and frequency domain method. Because of their advantages, such as simple principle, little influence from operation mode, and DG access, these methods have been widely popularized and developed rapidly. From the perspective of a time domain, it can be divided into single-ended location and double-ended location methods [4]. The single-ended location method locates the fault by collecting the initial traveling wave of the fault and the time of arrival of the reflected traveling wave head to that side at the detection end [5]. This approach requires less equipment installation, has lower-ranging costs, and covers a larger coverage area. The double-ended location method relies on the time of the initial traveling wave of the fault arriving at different detection ends to locate the fault [6]. However, real-time data of the double-ended detection data may not be synchronized under different circumstances. The accuracy of the fault location method based on the traveling wave principle depends on the accuracy of the time when the fault traveling wave head arrives at the detection terminal. Therefore, the accurate identification of the traveling wave head is the key point for improving the accuracy of the traveling wave location.

For the calibration of the traveling wave head, many scholars have identified the wave head by proposing the derivative method, the mutual correlation function method [7], the waveform curve fitting method, and the optimized configuration of the fault location device. However, these methods face serious noise, such as interference in long transmission lines, serious aliasing between wave head and interference signal, and too many uncertain operating factors for fault location devices in the field. As a result, the wave head calibration accuracy needs to be further improved. Zeng et al. [8] construct a location matrix by collecting the first traveling wave head data and realize fault location during the change of matrix elements.

At present, the main methods used are the Wavelet transform [9-11] and the Hilbert-Huang transform [12], which can reduce the influence of interference signals to a certain extent. However, due to the wavelet transform method theoretically having many wavelet basis functions and decomposition scales, it is difficult to have a good adaptive ability. The Hilbert-Huang transform (HHT) [13-14] is mainly a combination of the empirical mode decomposition (EMD) and the Hilbert transform, which mainly relies on the signal changes to decompose the high-frequency components and has a better effect in analyzing the mutated signals and non-smooth signals [15]. It has better results in analyzing mutating signals and non-stationary signals. However, the EMD decomposition algorithm has over-envelope and under-envelope problems in theory, and the decomposed modal components will have serious endpoint effects and aliasing phenomena, which makes it difficult to calibrate the traveling wave head signal.

The Teager energy operator (TEO) is a nonlinear operator commonly used in determining traveling wave signals in power systems. It amplifies the instantaneous energy change characteristics of the traveling wave head. Han et al. [16] propose a location method that combines EMD and TEO to identify the wave head more accurately [17]. However, the end effect and aliasing phenomena existing in the EMD algorithm have not been effectively solved. Ye et al. [18] propose a traveling wave fault ranging method based on CEEMD and improved energy operator (Novel Teager Energy Operator, NTEO) [19], which improves the performance effect of anti-noise by enhancing the detection ability and response speed to the fault signal frequency.

In this paper, a traveling wave detection method based on ICEEMDAN-NTEO is used to locate different fault points of distribution network grounding faults in a double-ended traveling wave location model. The method improves the operation of adding white noise sequences to the source signal in the CEEMD method while enhancing its anti-noise performance. By selecting the *k*th component of the *i*th set of white noise, ICEEMDAN reduces more pseudo-modalities compared to the above empirical modal decomposition methods. Additionally, it effectively filters out similar noise and signal scales, achieving fault location more quickly and accurately.

2. Fault Transient Traveling Wave Signal Analysis of Distribution Network

It is very important to measure and utilize transient signals accurately. This chapter introduces the principle of traveling wave locating and the method of transforming the three-phase voltage signal. The intelligent measurement unit monitors the fault transient signal in the distribution network line in real time, and the fault distance can be measured by the single-ended and double-ended traveling wave location methods. The fault transient signal is decoupled by Karenbauer phase mode transformation and then further analyzed by the separated line-mode component.

2.1. Accurate measurement of traveling wave signals

According to the principle of traveling wave generation, it is known that when a fault occurs on a power system line, a traveling wave signal is generated at the fault point and transmitted to each end of the line. The traveling wave head refers to the sudden change in the transient traveling wave voltage/current signal detected when the traveling wave signal reaches the intelligent column switch. The focus of traveling wave location technology is to determine the arrival time of the traveling wave head. The traditional traveling wave location of the transmission network usually collects the fault transient signal in the substation at both ends of the line. On the other hand, due to the wide coverage area of the distribution network, the complexity of the line branches, and other factors, the fault signal is weak, and the signal has been greatly attenuated when it reaches the end of the substation. There are problems such as failure not starting, inaccurate judgment, and low ranging accuracy.

With the development of the power system, the protection and control technology of the distribution network has been continuously improved, and a large number of intelligent column switches and new monitoring sensors have been installed in the distribution network, the double-ended traveling wave location method requires the installation of traveling wave detection devices at both ends of the line or at intervals, which is more costly but has high location accuracy and reliability, and is an ideal solution for fault location in new power systems.

In this paper, fault transient signals are monitored in real time for fault location using intelligent measurement units distributed in the distribution network. The signal detected by each node is deeply analyzed to determine the arrival time of the traveling wave head. As an example, consider a 10 kV distribution network in a region, as shown in Fig. 1, where *S1-S6* are intelligent measurement units [20-21]. When a fault occurs at point *f*, the signal propagates continuously along the fault point to both sides of the line. The intelligent measurement unit measures the fault transient signal in real time and analyzes the signal processing, calibrates the nanosecond synchronous time scale, and realizes the high-precision measurement of the fault transient traveling wave signals. The two waveforms shown in the figure are the waveforms of the intelligent switch S2 and S3 receiving the traveling wave signal of the fault transient voltage.

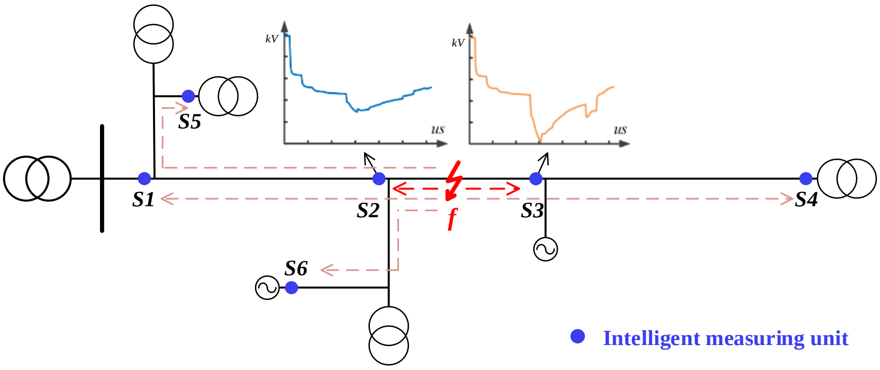


Fig. 1 Distribution network traveling wave signal measurement diagram

2.2. Accurate fault location method

At the moment when the line fails, it can be equivalent to superimposing a power source at the position of the fault point and the time before the fault. The superimposed voltage source generates an initial traveling wave signal that propagates at the speed of light to both sides of the line. Reflection and refraction phenomena occur at the location of wave impedance discontinuity until the signal is completely attenuated, as illustrated in Fig. 2. After the signal mutation, the traveling wave signal undergoes a dispersion phenomenon in the transmission process, dispersing the energy of the transient signal, resulting in the arrival moment of the traveling wave head being difficult to determine. t_P and t_Q represent the time when the first traveling wave head arrives at both ends of the line, and t_{fP1} and t_{fQ1} represent the time when the reflected traveling wave at point f first arrives at both ends of the line.

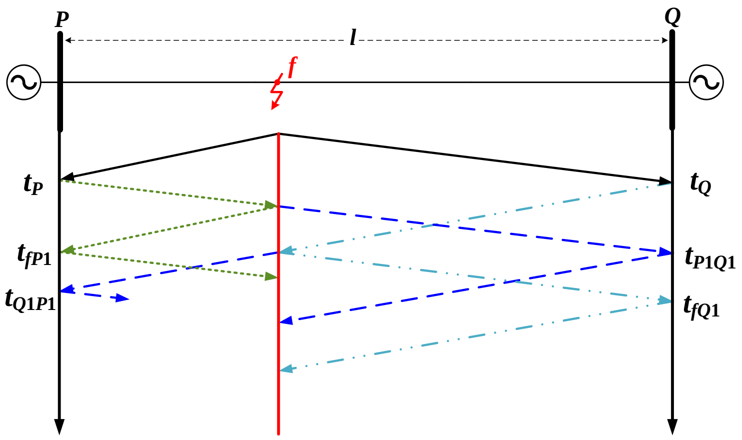


Fig. 2 Propagation law of traveling wave reflection

The single-ended traveling wave location method requires determining the time of the first traveling wave arriving at the detection end after the fault, the time of the reflected traveling wave arriving at the detection end, and the line wave speed.

$$d = \frac{1}{2} \cdot v\left(t_{fP1} - t_P\right) \tag{1}$$

The double-ended traveling wave location method utilizes the timing of the first traveling wave head measured by the detection device for location.

$$d = \frac{1}{2} \cdot \left[l + v\left(t_P - t_Q\right)\right] \tag{2}$$

After calibrating the arrival moment of the traveling wave head, the distance from the fault point to the detection end can be calculated by (1) and (2). However, both have certain shortcomings, due to the wide coverage area of the distribution network topology and complex line branches, there will be more noise interference effects of new energy equipment in the actual situation. Consequently, it is difficult for the single-ended method to accurately identify the arrival time of the reflection row wave. The double-ended method will be affected by the fact that the clocks of different traveling wave detection devices cannot be accurately synchronized. The location of the fault point in the line changes, and the arrival time of the reflected traveling wave head at both ends will also change. Relying on the acquisition of transient signal arrival time sequence makes it difficult to accurately identify the source of the signal. When the distance between point *f* and P terminal is greater than the distance between point *f* and Q terminal, the second moment of the transient traveling wave signal detected at P terminal may not be the first reflected traveling wave from point *f* but may be the reflected wave from Q terminal. So, the accurate calibration of the traveling wave head affects the accuracy of fault location to a great extent.

2.3. Fault traveling wave modulus analysis

There exists electromagnetic coupling between the three-phase traveling wave signals, to analyze each phase component clearly, the most commonly used Karenbauer phase mode transformation is selected in this paper to decouple the transient signal obtained at the detection end. The three-phase component is converted into more independent zero-mode and line-mode components to simplify the solution process. The zero-mode component flows between the three-phase conductor and the earth, and the wire-mode component takes the wire as the loop. The wave speed of the line-mode component is relatively large, close to the speed of light, and the wave impedance is smaller than that of the zero-mode component. Additionally, the wave speed is not easily affected by external factors during the propagation process. The parameters of the line-mode loop of the power line are the same as those of the positive sequence loop in the symmetric component method. The parameters of a zero-mode loop are the same as those of a zero-sequence loop, and the line-mode components are usually analyzed separately.
where x_0 is the zero-mode component of voltage or electric popular wave, and x_1 and x_2 are the line-mode components.

$$\begin{cases} x_0 = (x_a + x_b + x_c)/3 \\ x_\alpha = (x_a - x_b)/3 \\ x_\beta = (x_a - x_c)/3 \end{cases} \tag{3}$$

According to Kirchhoff's current law, accurate equations for calculating the zero-mode component and line-mode component can be obtained:

$$\begin{cases} U_0 = \dfrac{Z_0}{Z_0 + 2Z_1 + 6R} U \\ U_\alpha = U_\beta = \dfrac{Z_1}{Z_0 + 2Z_1 + 6R} U \end{cases} \tag{4}$$

The initial traveling wave under a single-phase grounding fault in a small-current grounding system generates both zero-mode and line-mode components, whereas, in a phase-to-phase short-circuit fault, it contains only line-mode components. In complex network topology, with the increase of transmission distance, the traveling wave modulus will gradually decrease and accelerate. Due to the serious dispersion of the zero-mode component, the line-mode component is subsequently selected for analysis in this paper.

3. Traveling Wave Head Identification Based on ICEEMDAN-NTEO

According to the principle of traveling wave location, whether the arrival time of the traveling wave head can be accurately calibrated greatly affects the accuracy of fault location. To identify traveling wave heads accurately, the ICEEMDAN method is used to decompose transient signals effectively and improve the quality of signal decomposition results. Combined with the NTEO algorithm, the instantaneous energy of the signal is extracted reliably.

3.1. Principles of the ICEEMDAN method

ICEEMDAN [22] is a further optimization based on the CEEMD and CEEMDAN decomposition methods. Compared with CEEMDAN, which directly adds white noise in the decomposition process, ICEEMDAN selects the *k*th IMF (intrinsic mode function) component of white noise under modal decomposition, such a process means that the noise component of the signal as well as the similar modal component of the aliasing are effectively filtered out. The specific steps of the algorithm are as follows:

(1) The *k*th IMF component obtained by EMD decomposition of Gaussian white noise is added to the original signal $x(t)$ to obtain a new set of signal sequences $x'(t)$.

$$x'(t) = x(t) + \mu_0 E_1\left(w^{(i)}\right) \tag{5}$$

(2) The first set of residual components R_1 is obtained:

$$R_1 = S\left(x'(t)\right) = \frac{1}{N}\sum^{N} K\left[x'(t)\right] \tag{6}$$

where $S\left(x'(t)\right)$ is the local mean value taken for the signal, and $K\left[x'(t)\right]$ denotes the new signal sequence $x'(t)$ minus the first modal component IMF_1 obtained by EMD decomposition. Thus, it can be seen that the first modal component IMF_1 of the original signal $x(t)$ is:

$$IMF_1 = x(t) - R_1 \tag{7}$$

(3) Continue to add Gaussian white noise to obtain the second set of residual components R_2:

$$R_2 = S\left[R_1 + \mu_1 E_2\left(w^{(i)}\right)\right] \tag{8}$$

The second modal component is:

$$IMF_2 = R_1 - R_2 \tag{9}$$

(4) Iterative extrapolation is performed in this order to compute the *k*th residual component and the *k*th modal component:

$$R_k = S\left[R_{k-1} + \mu_{k-1} E_k\left(w^{(i)}\right)\right] \tag{10}$$

$$IMF_k = R_{k-1} - R_k \tag{11}$$

(5) All residual components and modal components are obtained until the end of the decomposition step is reached.

The flowchart of the ICEEMDAN algorithm is shown in Fig. 3.

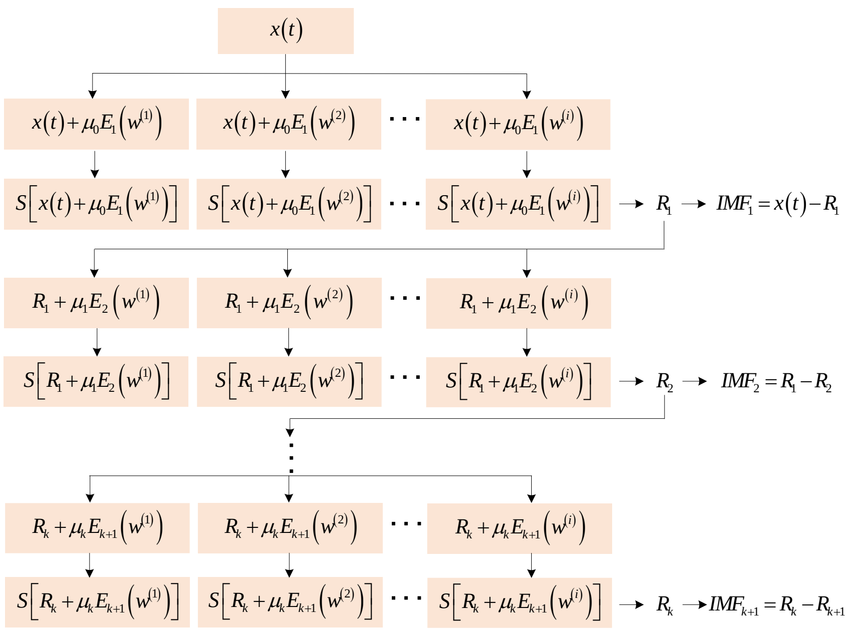


Fig. 3 ICEEMDAN algorithm flowchart

3.2. *Teager energy operator*

As a nonlinear operator, the Teager energy operator is simple, time-efficient, and can reliably extract the instantaneous energy of a signal in a variety of situations. TEO operation has been widely used in power quality detection, while wavelet transform has high sensitivity in coping with fault signal singularities, but its operation is more complex. Liu et al. [13] combine wavelet transform with Teager energy operator to detect complex disturbance signals of power systems. In the simulation process, it is concluded that the Teager energy operator has a fast response speed and accurately identifies power disturbance signals. Subasi et al. [17] combine the Hilbert transform and the Teager energy operator to analyze the amplitude envelope to detect the disturbed signal, which can highlight the signal processing capability of TEO operations. The Teager energy operator of the signal in continuous time is defined as:

$$\psi\left[\lambda(t)\right]=\lambda'(t)\cdot\lambda'(t)-\lambda(t)\cdot\lambda''(t) \tag{12}$$

where $\lambda'(t)$ and $\lambda''(t)$ are the first and second derivatives of the continuous time signal $\lambda(t)$.

However, since the commonly used in practical applications are generally discrete-time signals, the discrete Teager energy operator is defined as:

$$\psi\left[\lambda(n)\right]=\lambda(n)\cdot\lambda(n)-\lambda(n+1)\cdot\lambda(n-1) \tag{13}$$

The difference operation is carried out on the first modal component to enhance the instantaneous energy change characteristics of the signal, and the signal IMF_1 of the first modal component is selected from each frequency modal component, discrete Teager energy operator is used to calibrate the fault traveling wave head of the sampled signal:

$$\psi\left[IMF_1(t)\right]=IMF_1(t)IMF_1(t)-IMF_1(t+1)IMF_1(t-1) \tag{14}$$

The signal amplitude and frequency obtained by TEO operation at different sampling times can be calculated:

$$\begin{cases} V(t)=\dfrac{2\psi\left[IMF_1(t)\right]}{\sqrt{\psi\left[IMF_1(t+1)-IMF_1(t-1)\right]}} \\ f(t)=\dfrac{1}{2}arc\cos\left[1-\dfrac{\psi\left[IMF_1(t+1)-IMF_1(t-1)\right]}{2\psi\left[IMF_1(t)\right]}\right] \end{cases} \tag{15}$$

where $V(t)$ is the signal amplitude and $f(t)$ is the signal frequency.

Define a discrete signal of the form $\lambda(t)=A\cos(\omega t+\varphi)$, angular frequency $\omega=2\pi f_0 / f_m$, where f_0 is the fundamental frequency, and f_m is the sampling frequency, so it follows:

$$A^2\sin^2\omega=\lambda^2(t)-\lambda(t+1)\cdot\lambda(t-1) \tag{16}$$

When $\omega<\pi/2$, that is $f_0<f_m/4$, Eq. (16) has a unique solution. Additionally, when $\omega<\pi/4$, that is $f_0<f_m/8$, the equation can be approximately considered valid. That is, when the sampling frequency is greater than eight times the fundamental frequency of the signal, there is a simple way to measure the energy of the signal, which is expressed in the form:

$$\psi\left[\lambda(t)\right]=\lambda^2(t)-\lambda(t+1)\cdot\lambda(t-1)\approx A^2\omega^2 \tag{17}$$

where $\psi\left[\lambda(t)\right]$ denotes this energy operator and $\lambda(t)$ is the signal to be analyzed.

Eq. (17) shows that the Teager energy operator can analyze the instantaneous energy of the signal at three adjacent time points in the discrete time signal.

3.3. Novel Teager energy operator

The traditional TEO operation uses three adjacent sampling points of the signal to estimate the instantaneous energy of the signal. However, due to the insufficient anti-noise ability of TEO operation, the energy of the noise will affect the results of the energy operator operation to a certain extent, affecting the accuracy of the detection results. A novel Teager energy operator, NTEO, is proposed in this section, which refers to the instantaneous energy obtained by extracting the transient energy of the transient signal through the novel Teager energy operator method. A parameter *i* [6] is introduced into the NTEO algorithm. As a result, it is innovatively proposed that different from the traditional TEO operation to select three adjacent sampling points, the NTEO algorithm selects three points that are *i* sampling points away from each other for calculation and then obtains a new calculation equation:

$$\psi\left[IMF_1(t)\right] = IMF_1(t)\,IMF_1(t) - IMF_1(t+i)\,IMF_1(t-i) \tag{18}$$

The amplitude and frequency of its signal are shown as follows:

$$\begin{cases} V'(t) = \dfrac{2\psi\left[IMF_1(t)\right]}{\sqrt{\psi\left[IMF_1(t+i) - IMF_1(t-i)\right]}} \\ f'(t) = \dfrac{1}{2} arc\cos\left[1 - \dfrac{\psi\left[IMF_1(t+i) - IMF_1(t-i)\right]}{2\psi\left[IMF_1(t)\right]}\right] \end{cases} \tag{19}$$

where $V'(t)$ is the signal amplitude and $f'(t)$ is the signal frequency.

The upper limit of *i* can be calculated from the constraint conditions $i < f_s/8f_0$, which facilitates the choice of the value of *i* at the moment of signal detection.

Similarly, the NTEO algorithm is not computationally intensive, and the energy of the discrete signal can be calculated by selecting the values of one of the sampling points and two adjacent points that are *i* sampling points away. NTEO can quickly track changes in signals and respond quickly. If the energy value calculated by NTEO is larger, the amplitude or frequency of a given signal will change faster.

4. Simulation Analysis

Under the premise that the clock synchronization error of double-ended sensor data acquisition is not large, the double-ended traveling wave method can ensure the high efficiency and reliability of location. This method is widely used at present. In this section, the multi-branch line model is used for simulation analysis. The location results of the ICEEMDAN-NTEO method before and after adding noise are verified. The location errors of the proposed method and the wavelet transform method under the influence of high and low noise are compared.

4.1. ICEEMDAN-NTEO traveling wave fault location method

The process of ICEEMDAN-NTEO's traveling wave fault location method is as follows:

(1) Measuring of three-phase voltage traveling wave data U_a, U_b, U_c after fault occurrence.

(2) The traveling wave line-mode component of the voltage is obtained by Karenbauer phase mode transformation.

$$\begin{bmatrix} U_0 \\ U_\alpha \\ U_\beta \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (20)$$

where U_0 is the zero-mode component of the voltage traveling wave, and U_α and U_β are the line-mode components of the voltage traveling wave.

(3) ICEEMDAN decomposition is performed on the voltage traveling wave line-mode components to extract several *IMF* components.

(4) Calculate the NTEO energy value of the *IMF* component. The moment of highest amplitude in the NTEO energy spectrum is the moment of arrival of the traveling wave head.

(5) Multiple measuring devices communicate to obtain the earliest two times.

(6) The distance from the fault point to the endpoint is measured by Eq. (2). If the positioning result is within the interval, then the result is the location of the fault point.

The flowchart of ICEEMDAN-NTEO's traveling wave fault location is shown as follows:

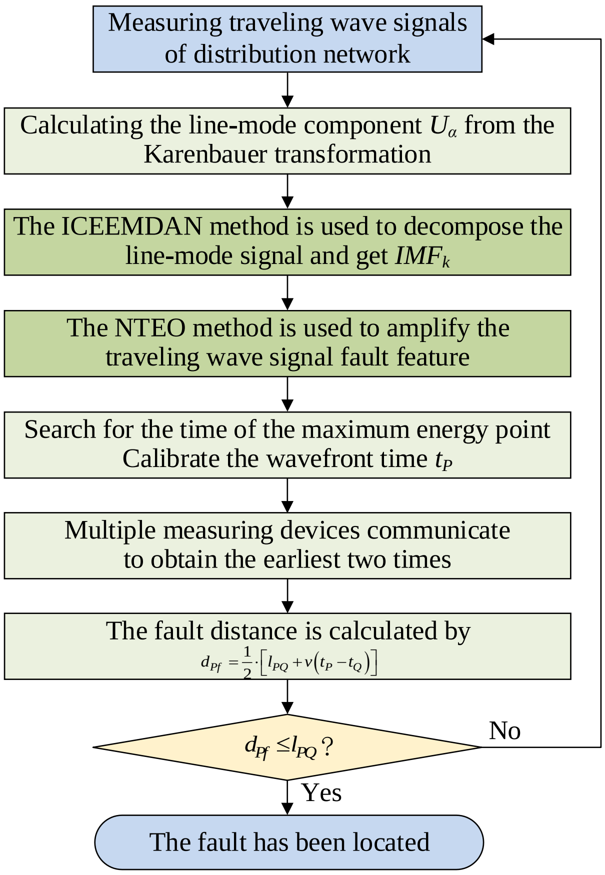


Fig. 4 ICEEMDAN-NTEO traveling wave fault location flowchart

4.2. Simulation model building

The double-ended traveling wave method is widely used nowadays, as it can ensure the efficiency and reliability of location under the premise that the clock synchronization error of double-ended sensing data acquisition is not large. Therefore, the method of double-ended traveling wave fault location mainly focuses on the measurement of double-ended traveling wave fault signal. It is necessary to calibrate the traveling wave head accurately to improve the location accuracy of the line. In this paper, a multi-branch line model is used for simulation analysis, which is modeled and analyzed by PSCAD. Frequency-Dependent (Phase) Model Options are used in the transmission line model, which is suitable for the transient and harmonic conditions of the line. The line wave speed is determined to be 2.9×10^8 m/s, and the A-phase ground fault occurred at 0.040 s.

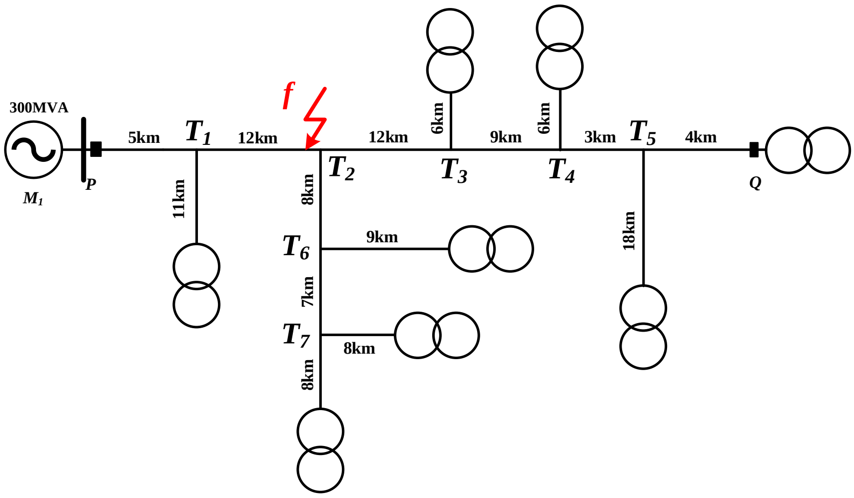
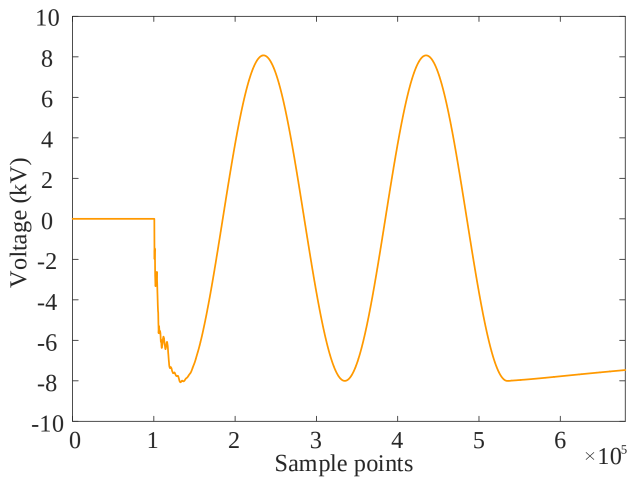
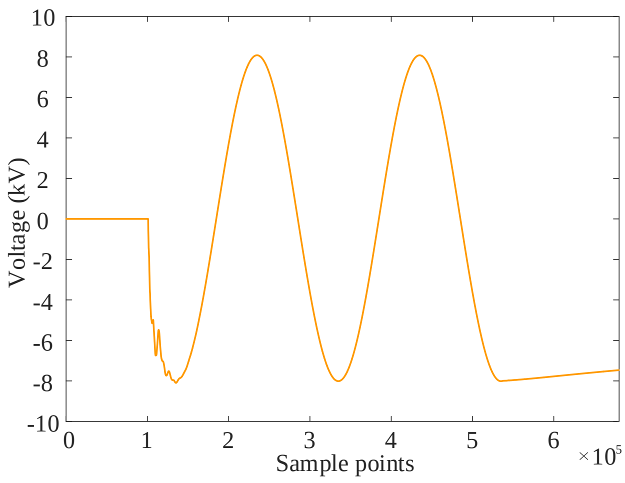


Fig. 5 Typical 10kV distribution network

In the multi-branch line, as shown in Fig. 5, the total length of the PQ line is 45 km, d_{Pf} = 17 km, d_{Qf} = 28 km. Extract the voltage traveling wave signals from the traveling wave detection devices at the P and Q terminals. The sampling rate in the simulation program is consistent with that of the actual intelligent measurement unit, which is set to 10 MHz. The alpha line-mode component of the voltage traveling waves is obtained from Eq. (20), and the corresponding waveform is shown in Fig. 6.



(a) P terminal

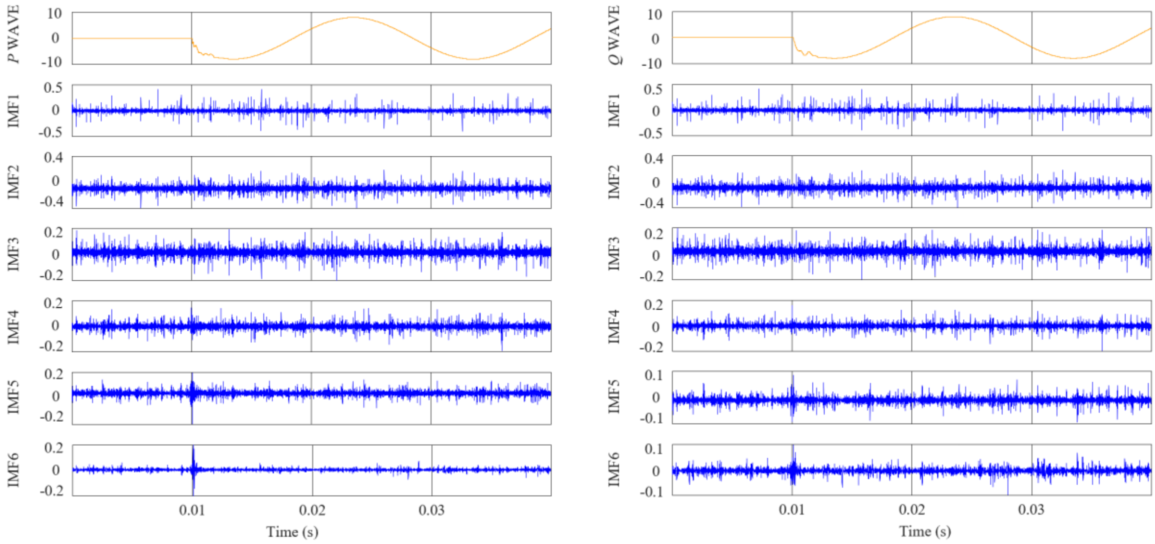


(b) Q terminal

Fig. 6 Voltage traveling wave alpha line-mode component

4.3. ICEEMDAN decomposition

Without adding noise to the original signals, the voltage traveling wave signal at both ends of the line is decomposed by ICEEMDAN, which can reflect the mutation characteristics of the traveling wave signal so that the subsequent NTEO can accurately calibrate the wave head. It uses an adaptive algorithm to filter out the noise, reducing the modal aliasing phenomenon in the decomposition process. The decomposition of the voltage traveling wave signals at the P and Q terminals by the ICEEMDAN method is shown in Fig. 7.

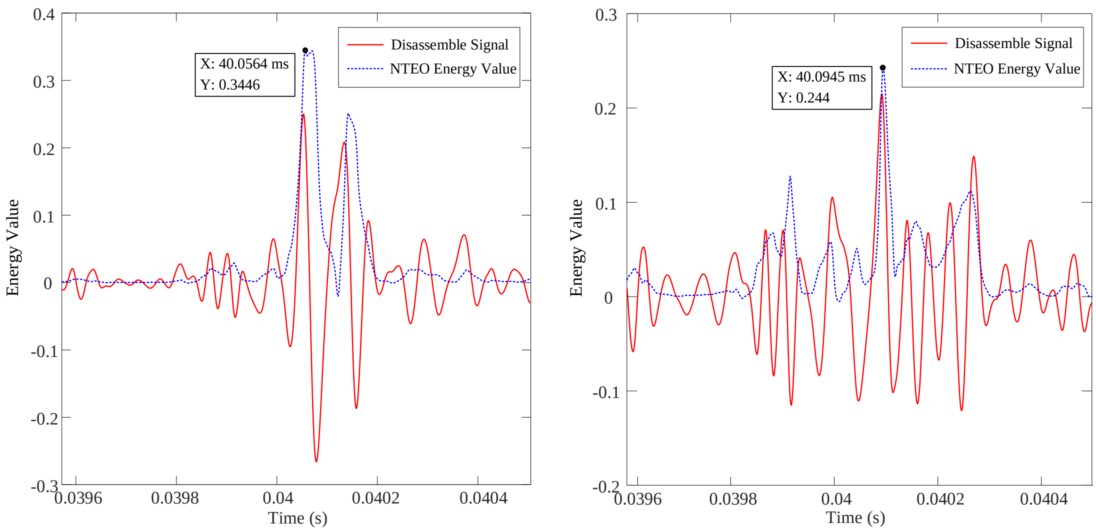


(a) P terminal signal decomposition result (b) Q terminal signal decomposition result

Fig. 7 ICEEMDAN decomposed voltage traveling wave signals

4.4. *NTEO fault feature extraction*

After ICEEMDAN decomposition, the IMF_6 component of the traveling wave signal is collected, and the NTEO energy value of the IMF_6 component is calculated. The time of the maximum point of the NTEO energy value is calibrated as the traveling wave head time, as shown in Fig. 8. Sampling frequency f_s = 10 MHz, the resolution of the NTEO is usually chosen to be 5 when the minimum constraints $i < f_s/8f_0$.

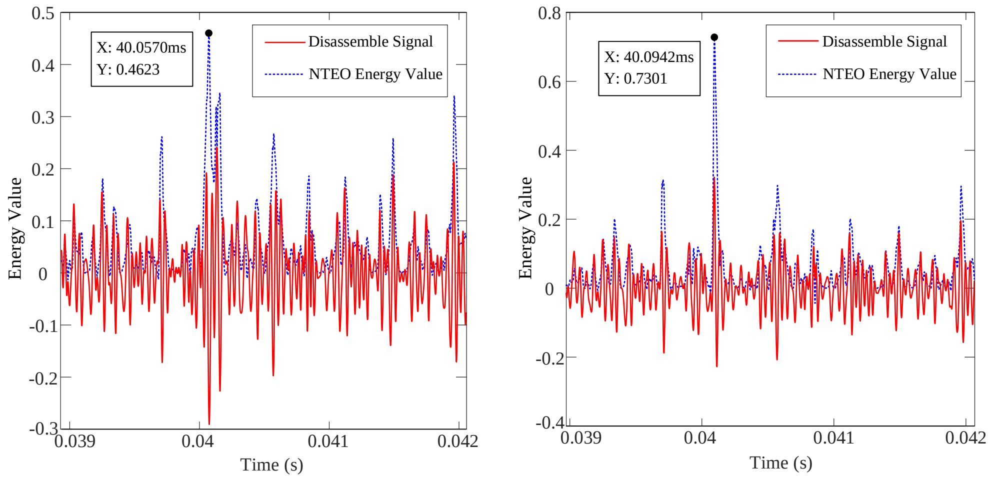


(a) P-terminal (b) Q-terminal

Fig. 8 NTEO traveling wave head feature enhancement effect

According to Fig. 8, the calibration time of the traveling wave head detected by the ICEEMDAN-NTEO method is t_P = 40.0564 ms, t_Q = 40.0945 ms. The fault location is calculated according to Eq. (2), and compared with the fault location set by simulation, the error is -25 m, which has a high location accuracy.

To verify the practicability of the location method, the method of adding zero mean white noise is used to simulate the actual power grid. White noise up to 8 dB is added to the P and Q terminal voltage traveling wave sampling signal, and then the ICEEMDAN-NTEO fault location is performed on it. After decomposition, the NTEO algorithm is performed on its IMF_6 component to verify the advantages of the proposed method, and the instantaneous energy spectrum is obtained, as shown in Fig. 9.



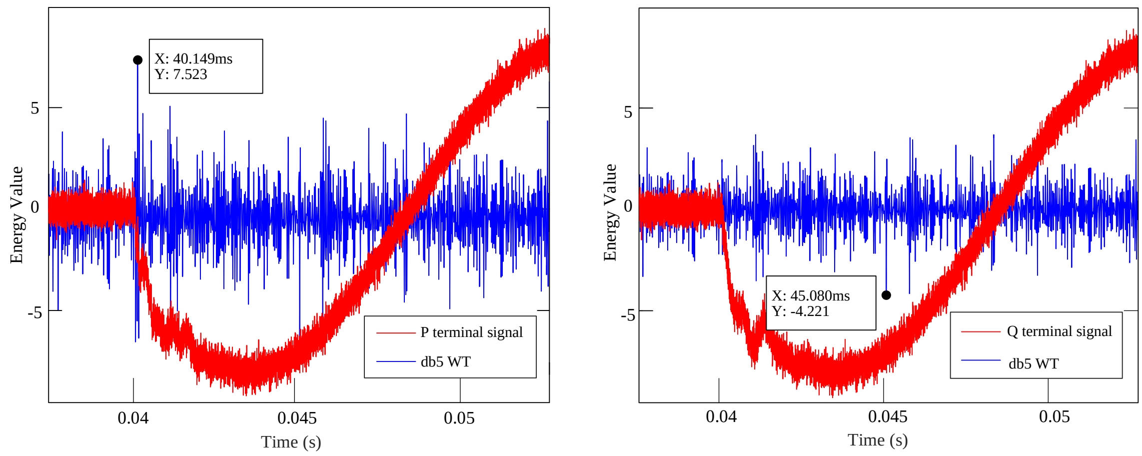
(a) P-terminal (b) Q-terminal

Fig. 9 ICEEMDAN-NTEO processing results after adding noise

As shown in Figure 9, the method can still accurately identify the faulty traveling wave head in the case of strong noise interference, and the calibration time is t_P = 40.0570 ms, t_Q = 40.0942 ms. The fault location error is +106 m. Therefore, ICEEMDAN-NTEO is considered to have a stronger anti-noise ability and can be adapted to the complex interference situations of new power systems.

4.5. Comparison and verification with existing positioning method

In this section, the ICEEMDAN-NTEO method is compared with the traditional wavelet transform (WT) analysis location method to verify its location accuracy. db5 is selected as its wavelet basis function for the traditional wavelet transform method. The wavelet decomposition head calibration in the case of 8 dB noise is shown. The results of the db5 wavelet transform of the voltage traveling wave at the P and Q terminal are shown in Fig. 10.



(a) P-terminal (b) Q-terminal

Fig. 10 The result of traditional db5 wavelet transform

Fig. 10 clearly shows that under the same noise interference, the maximum value of wavelet mode cannot accurately calibrate the traveling wave head, and the fault location error is large. Compared with Fig. 9, it is found that the ICEEMDAN-NTEO method possesses more excellent location results in complex noise environments. In this paper, the influence of the traditional wavelet transform method and ICEEMDAN-NTEO method on fault location at different fault distances and adding different noise signals is compared. When the fault point is 8, 17, and 40 km away from the P end, noise signals of 30 dB, 10 dB, and 8 dB are added, respectively. By varying the SNR of the noise signal and fault location distance, the control variables are simulated several times. Table 1 shows the location errors of the two methods in different cases.

Table 1 Error comparison of two fault location methods under the influence of high and low noise

Fault location method	Fault distance (km)	Additional noise signal (dB)	Location result (km)	Location error (m)
Wavelet transform	8	30	8.041	+41
	8	10	7.686	-314
	8	8	6.621	-1379
	17	30	16.954	-46
	17	10	17.185	+185
	17	8	14.751	-2249
	40	30	39.944	-56
	40	10	39.770	-230
	40	8	37.474	-2526
ICEEMDAN-NTEO	8	30	8.021	+21
	8	10	7.951	-49
	8	8	7.858	-142
	17	30	16.970	-30
	17	10	16.947	-53
	17	8	17.106	+106
	40	30	39.978	-22
	40	10	39.960	-40
	40	8	40.174	+174

Comparing the location errors of the two methods of wavelet transform and ICEEMDAN-NTEO at different fault distances and different SNR. The larger the SNR of the traditional wavelet transform method is at the same fault distance, the larger its location error is under noise interference, making it inapplicable to the actual grid environment. By comparison, the absolute error of the ICEEMDAN-NTEO method can be controlled within 20-30 m under different fault distances and 30 dB noise. Under different fault distances and 10 dB noise, the absolute error of this method can be controlled within 40-60 m. Under different fault distances and 8 dB noise, the absolute error of this method can be controlled within 100-200 m. Under the same fault distance and the same SNR environment, the ICEEMDAN-NTEO method is much better than the traditional wavelet transform method in terms of location effectiveness.

Moreover, the wavelet transform method has multiple choices in selecting the wavelet basis function, which makes it difficult to ensure fault location accuracy in different situations. Additionally, the arrival time of the calibrated traveling wave head is difficult to identify accurately. The ICEEMDAN-NTEO fault location method proposed in this paper is capable of controlling the location error within 200 m under different SNR conditions, and it can realize accurate fault location in solving the deficiencies of the traditional wavelet transform method.

5. Conclusion

To address the problem that the existing traveling wave positioning methods cannot accurately calibrate the traveling wave head and the positioning error is large. In this paper, a new traveling wave localization method based on ICEEMDAN-NTEO is proposed. This method is more accurate in calibrating the arrival time of the traveling wave head and can realize fault location with less error. Through theoretical analysis and simulation verification, the conclusions are as follows.

(1) In this paper, the ICEEMDAN method is used to decompose the measured signals, filter the noise, and select the effective traveling wave sign. The NTEO method is then used to enhance the decomposed signal, highlight the abrupt characteristics of the traveling wave, and determine the time of the traveling wave head. Combining the two methods can effectively separate the fault signal from the measured signals. In addition to ensuring positioning accuracy, the anti-noise

performance under high noise background is enhanced.

(2) The results show that under the same fault distance and the same SNR environment, the ICEEMDAN-NTEO method has a much better positioning effect than the traditional wavelet transform method. The proposed method is accurate in positioning and less affected by high noise. It can better adapt to the complex distribution network environment. which has good practical application value in engineering.

(3) This method requires the installation of traveling wave detection devices at the end of each line, which can lead to increased costs. In the future, further research is needed to reduce the number of traveling wave detection devices without affecting the positioning effect. This will improve the applicability of the proposed method in the distribution network.

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Conflicts of Interest

The authors declare no conflict of interest.

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