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A Wavefront Identification Method Based on Similarity Calculation for Fault Location of DC Transmission Line

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Keywords: DC Transmission; Fault Location; Wavelet Basis; Wavefront Recognition; Traveling Wave Method

Abstract: With the rapid development of direct current (DC) transmission projects in China, the scale of cross-area transmission lines is expanding continuously, the length of lines is increasing, and the operation environment is complex, which puts forward higher requirements for fault location technology. In the existing ranging methods based on double-ended traveling wave theory, the accuracy of wavefront identification directly determines the accuracy of fault location, and the difficulty of wavelet basis selection is a key factor affecting the effect of wavefront identification. To solve this problem, a DC transmission line fault location method based on accurate wavelet basis selection is proposed in this paper. By constructing the wavefront similarity criterion, the optimal basis function is adaptively selected from the candidate wavelet bases, and the high-precision recognition of the wavefront time is realized by combining the wavelet transform and the modulus maximum method. Simulation and experimental results show that the proposed method can significantly reduce the wavefront time recognition error and ranging error, and has the engineering advantages of small amount of calculation and strong portability.

1. Introduction

With the rapid development of China's economy and the continuous growth of energy demand, the imbalance between energy distribution and load center has become more and more prominent. DC transmission has become a key technical means to realize the energy strategic layout of "power transmission from west to east, power supply from north to south" due to its significant advantages of long transmission distance, large transmission capacity and small energy loss. HVDC projects generally span long distances, often cross multiple provinces, and traverse complex terrain, frequently passing through harsh environments such as heavy icing areas and uninhabited regions. Compared with AC transmission projects, fault location and line inspection operation and maintenance are longer distance, more difficult and more costly. Due to the long transmission distance, the fault rate of these lines is relatively high, accounting for about 50% of the total DC system faults. The fault location is not accurate, which affects the efficiency of fault detection and maintenance. This extending of the power outage time reduces the reliability of power supply and increases the operation and maintenance cost. Therefore, fast and accurate fault location is of key significance to the security and stability of power grid and reliable power supply.

2. Research status

At present, the traveling wave ranging method based on double ends is commonly used in engineering. By collecting traveling wave signals synchronously at both ends of the line and using the time difference between the two ends of the traveling wave to calculate the location of the fault point, this method has the advantages of high ranging accuracy, strong adaptability, and can adapt to the needs of long distance and large voltage level line rapid location. However, in practical engineering applications, double-end traveling wave ranging method is still facing some challenges, such as wave first time accurate identification difficulty[1], high precision synchronization problems of double end data and circuit parameters and the influence of environmental factors on the ranging accuracy, etc.

At present, the traveling wave ranging method based on double end is common used in engineering. This method acquires traveling wave signals synchronously at both ends of the line and uses the arrival time of the traveling wave at each end to calculate the fault location. It features high ranging precision, strong adaptability, and suitability for rapid positioning requirements of long-distance, high-voltage-grade lines. However, in practical engineering applications, the double-end traveling wave ranging method still faces some challenges, such as the difficulty in accurately identifying the wavefront arrival time, the high-precision synchronization issue of double-end data and the impact of circuit parameters and environmental factors on the ranging accuracy.

Despite the fact that current fault location methods based on wavelet transform have made certain progress in theoretical research and practical application, there are still some shortcomings. Among them, the difficulty in selecting an appropriate wavelet basis is a key factor that impacts the effect of wavefront recognition and the precision of fault location. There are various types of wavelet bases, such as Haar, Daubechies, Coiflet, and Symlets. Each type possesses distinct time-frequency characteristics and waveform features. However, there is a lack of clear logical and mathematical rules to guide the selection of an appropriate wavelet basis from numerous options and its rapid, accurate matching with fault wavefront features. Currently, the commonly used exhaustive search method exhibits large computational complexity and low efficiency.

Furthermore, existing studies mostly rely on empirical selection of fixed wavelet bases. Due to the interference of noise, the variation of circuit parameters, and the influence of environmental factors, the accuracy of wavefront recognition still cannot meet the requirements of high-precision fault location. Even a minor error in wavefront positioning may lead to a significant distance deviation, which affects the efficiency and accuracy of fault troubleshooting and maintenance work. Therefore, without relying on complex tests and empirical assumptions, establishing an adaptive wavefront recognition method with low computational complexity and engineering feasibility is the key to improving the accuracy of fault wavefront identification and realizing method adaptability.

3. Principle of double-ended traveling wave ranging

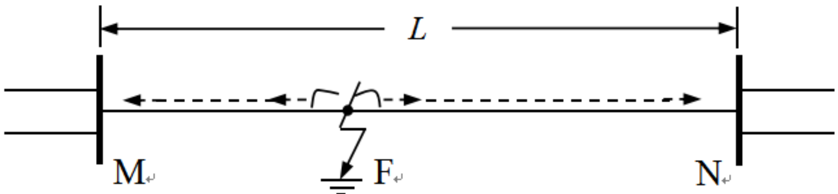


Fig.1 Propagation route of fault transient traveling wave and principle of double-end ranging

The double-ended traveling wave ranging method realizes fault location based on the propagation characteristics of traveling waves in transmission lines. When a fault occurs on the DC transmission line, the fault point will excite voltage waves and current waves, which propagate towards both ends at a speed close to the speed of light[2]. By synchronously collecting traveling wave signals at both ends of the line (designated as End M and End N), the position of the fault point can be calculated by comparing the time difference between the wavefronts arriving at each end (FIG.1).

Set a line fault waves came to the same propagation velocity v to M and N end bus (form the first line reverse waves) on either side of the absolute time respectively, and there are the following: T_M T_N

$$\begin{cases} \frac{L_{MF}}{v} - \frac{L_{NF}}{v} = T_M - T_N \\ L_{MF} + L_{NF} = L \end{cases}$$

Where: L_{MF} and L_{NF} are the distances from the buses at terminals M and N to the fault point, respectively; L is the length of line MN. The distance between M terminal and N terminal bus and the fault point can be obtained by solving the above equations.

$$L_{MF} = \frac{L + v(T_M - T_N)}{2}$$

Traveling wave ranging method is a commonly used fault location method for DC transmission lines. It has the advantages of high ranging accuracy, strong adaptability and suitability for long-distance lines, and can meet the rapid location requirements of long-distance and high-voltage-level lines. However, in practical engineering applications, the precision of the traveling wave ranging method depends on the propagation characteristics of traveling waves and the accurate identification of the first wavefront arrival time.

For example, it is difficult to calibrate the wavefront after the fault traveling wave passes through the high resistance ground in station ranging. For A-type single-ended ranging, it is difficult to identify and distinguish the reflected waves between the opposite end and the fault point. Affected by the propagation distance and line parameters, the non-constant wave speed of the fault traveling wave will lead to ranging error. The variation in line length, which is affected by environmental factors such as transmission-line temperature and icing, also leads to distance-measurement error. A dead time exists between the two trigger events of the traveling-wave device, which can cause the fault-traveling-wave signals to be missed. Lightning strikes produce electric waves on the line, which will cause the traveling wave ranging device to misoperate. Once there is a small error in the wavefront positioning ,it may lead to a ranging deviation of 100 meters or even larger.

At present, the ranging method of double-ended traveling wave is often corrected by short-circuit test or empirical value in engineering. Short circuit test checking principle is in the known position man-made fault, by comparing the measurement results and the true location, to adjust device parameters. It has limitations, such as short circuit test need power outage or special conditions, implementation cost is high. It can only be done in the construction/commissioning phase, and it is difficult to carry out frequently during operation. For ultra-long distance DC lines, the number of tests is limited, and the correction effect is also limited. The problem of insufficient recognition of wavefront accuracy cannot be solved fundamentally.

Based on the line operation experience, typical parameters or historical data, the empirical value method directly takes the fixed wave speed value or offset as the correction coefficient. This method is convenient and fast, and it does not need power failure or special test. However, the empirical value depends on past conditions, and when the environment changes (such as temperature, humidity, or the way the grid operates), the original empirical value may become invalid, resulting in increasing ranging errors.

In summary, the existing correction methods have obvious limitations: the former has high engineering cost, and the latter has insufficient reliability. Without relying on complex tests and empirical assumptions, establishing an adaptive wavefront identification mechanism with low computational complexity and engineering feasibility has become a key breakthrough to improve the ranging accuracy.

4. Wavefront identification for fault ranging

When a fault occurs in a DC transmission line, the wavefront often shows a step/sharp pulse mutation of voltage and current (local discontinuity or high-order derivative discontinuity), which belongs to the singular point. Such signal features are highly localized in the time domain, and contain abundant high-frequency components[3]. Wavelet transform has unique time-frequency characteristics. It can analyze the signal locally in both time-frequency domain and frequency domain, which overcomes the limitation that Fourier transform can only provide global frequency information of the signal. Wavelet transform, as a kind of effective information analysis tools, can highlight the fault in time and frequency domain two wave characteristics[2].

$$W_f(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} f(t)\,\psi^*\left(\frac{t-b}{a}\right)dt$$

Where ψ(t) is the mother wavelet, a is the scaling factor, and b is the translation factor. The transform is essentially a time-frequency local correlation analysis of the signal.

In practice, in order to facilitate computer processing, usually for discretization of continuous Wavelet Transform, Discrete Wavelet Transform (Discrete 'Wavelet Transform, DWT). The commonly used discretization method is the binary discretization of the scale factor and the translation factor[4].

$$W_f(m,n)=\frac{1}{\sqrt{2^m}}\int_{-\infty}^{\infty} f(t)\,\psi^*(2^{-m}t-n)\,dt$$

The discrete wavelet transform decomposes the signal into approximate components and detail components of different scales. The signal is analyzed by a series of low-pass filters and high-pass filters, and the signal is decomposed and reconstructed.

In essence, the fault wavefront is the singular point of the fault signal, and its derivative has discontinuous characteristics at this point. The wavelet transform has good sensitivity to signal singularities. When a singular point exists at $t=t_0$, the modulus maxima of Wf (a,b) will appear at the corresponding position $b=t_0$. If to is a singular point of the signal (such as a fault wavefront), the wavelet coefficients show modulus maxima near to at small scales:

$$|Wf(a,b)| \text{ reaches its maximum at } b\approx t_0$$

These maxima are aligned along $b=t_0$ at multiple scales a, and the wavefront time can be determined by tracking the modulus maxima.

By scaling and shifting the mother wavelet, the wavelet transform essentially completes the local correlation operation between the signal and the "detection template". In the small scale, the transform has good time resolution, which can acutely capture the instantaneous high-frequency mutation of the wavefront. In the large scale, it has a good frequency resolution, which is helpful to suppress the power frequency component and the slowly changing background signal.

In theory, the singularities of the signal generate the maximum amplitude of the wavelet coefficients at multiple small scales, forming a consistent maximum chain along the scale direction.

By tracking this chain of modulus maxima, the wavefront time can be robustly located in the presence of noise. Therefore, the wavelet transform can effectively highlight the characteristics of the fault wavefront in both time domain and frequency domain, and provide a reliable basis for the subsequent traveling wave ranging.

However, the wavelet coefficients essentially reflect the degree of similarity between the shape of the mother wavelet and the local signal. If the shape of the mother wavelet does not match the actual wavefront characteristics, the wavefront mutation cannot be fully amplified, which is easy to lead to recognition errors. It can be seen that the precise selection of wavelet basis is the key factor in ensuring the accuracy of wavefront recognition.

There are many kinds of wavelet bases (such as Harr, Coiflet, Symlets, sym3, coif5, etc.), and their effects on wave-front amplification and mutation description vary markedly. Such an exhaustive search requires a large amount of computation, and there is a lack of clear logical and mathematical principles to guide how to quickly and accurately select a suitable wavelet basis..

To solve this problem, this paper proposes a DC transmission line fault location method based on accurate selection of wavelet basis. By constructing a wavefront similarity criterion, the method adaptively selects the optimal wavelet basis, which fundamentally improves the accuracy of wavefront identification, and then improves the overall level of fault location.

5. Wavefront identification method based on similarity calculation

In order to select the wavelet basis accurately, this study constructs the wavefront similarity criterion based on the similarity calculation method. The core idea of the criterion is to select the optimal wavelet basis by quantitatively comparing the similarity between the wavelet basis and the fault waveform. The key feature of the fault waveform is the abrupt change of the wavefront, so 50 samples preceding and 50 samples following the wave-front(100 samples in total) are extracted from the fault signal to form a characteristic waveform vector. When the fault location and wave-front shape are similar to those of a given wavelet basis, the wavelet transform accentuates the amplitude-mutation features of the wavefront, thereby improving the accuracy of wavefront identification.[3].

(1) Construct a set of candidate wavelet bases. These include various common families of wavelet bases such as Harr, Daubechies, Coiflets, Symlets, etc.

(2) Acquire the fault waveform and compute the similarity between each candidate wavelet basis and the fault waveform. Based on the similarity values, wavelet bases whose shapes are poorly matched to the fault waveform are promptly discarded. The similarity calculation formula is as follows, where M_F is the fault waveform and M_W is the currently selected wavelet basis.

$$S_{FW}=\frac{|\sum_{n=1}^{N}[M_F(t_n)\cdot M_W(t_n)]|}{\sqrt{\sum_{n=1}^{N}[M_F(t_n)]^2}\cdot\sqrt{\sum_{n=1}^{N}[M_W(t_n)]^2}}$$

(3) The wavelet basis that has the highest similarity to the fault waveform is selected, and the wavelet transform is applied to the double-ended traveling-wave fault signal. Using the selected wavelet basis, the modulus maxima are extracted to accurately calibrate the time of the wavefront, in order to obtain the arrival times of the traveling wave at both ends.

$$WT_x(a,\tau)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty}f(t)\psi^*(\frac{t-\tau}{a})dt$$

(4) Distance calculation for a double-end traveling wave fault: based on the accurately determined wavefront time, the fault distance D is calculated according to the principle of double-

end traveling wave.

$$D = \frac{L + v(T_M - T_N)}{2}$$

Accurate selection of wavelet basis constitutes a breakthrough, which can significantly improve the quality of wavefront identification and systematically reduce the ranging error. It also provides the engineering advantages of small amount of calculation, easy program migration, and suitable for different voltage levels and line lengths.

6. Simulation experiment and results

The ±800kV DC transmission system was modeled using EMTDC/PSCAD. The structure of UHVDC is generally consistent with that of HVDC transmission systems. The most important equipment is the converter of AC and DC conversion. In addition, the system includes other key components such as converter transformers, filter reactors, filters and reactive-power compensation devices. It incorporates 6-pulse converter models, in which AM and GM interfaces are used to output the delayed trigger Angle α and extinguition-arc Angle γ, providing convenient real-time monitoring of system changes (FIG.2). A inputs the control result of the control system on the delay trigger Angle α, and KB inputs the lock signal output of the control system. Two 6-pulse converters are connected in series to form a 12-pulse converter, which becomes a converter valve group, and two 12-pulse converters form a pole. Consequently, the bipolar rated voltage of the UHVDC system is ±800kV, and the rated voltage of each converter-valve group should be ±400kV.

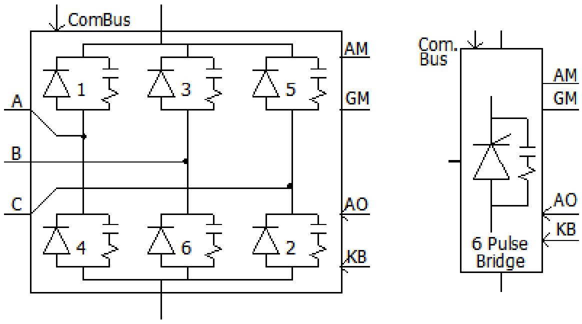
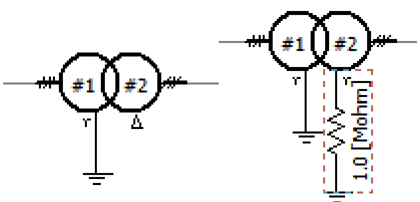


Fig.2 Pulse converter model

The converter transformer is one of the most important pieces of equipment in the UHVDC transmission system, working together with the 12-pulse converter bridge to achieve AC/DC conversion. In this model, two sets of three-phase double-winding converter transformers are connected to the 12-pulse bridge, and one of the valve-side windings is star-connected, while the other is delta-connected, so that a commutation voltage with phase difference of 30 ° is produced on the valve side of the two 6-pulse converter transformers, thereby forming a 12-pulse converter structure (FIG. 3).



(a) Yd structure (b) YY structure

Fig. 3 Structure of pulse wave converter

The simulation platform is applied to generate the following fault waveform. The total length of the line is 1700km, the fault occurrence time is 0.3s, and the actual fault distance is 1000 km from the rectifier side. The sampling frequency[4] is 1MHz, and the wave speed is selected.2.98×10^8m/s

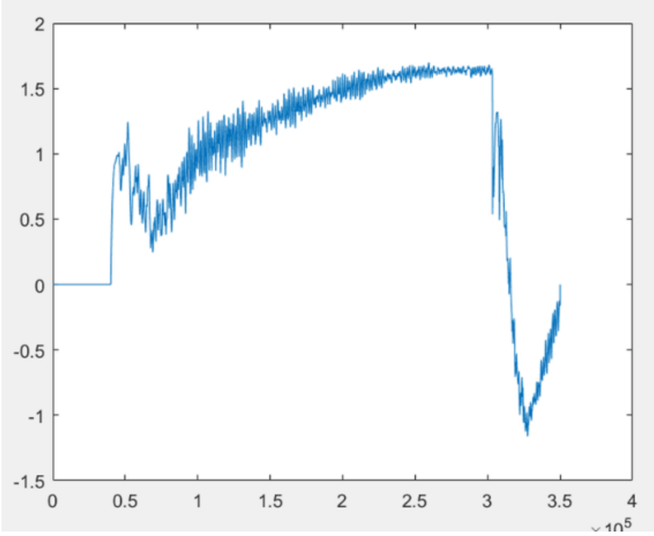


Fig. 4 Fault wave graph

Calculate the similarity between each candidate wavelet basis and the fault wave separately (FIG. 4). The order of similarity for the three optimal wavelet bases is Db2 > Coif4 > Sym5. The similarity between the wavelet basis Db2 and the fault waveform is the highest. Furthermore, the wavefront time recognition error and the fault distance error(relative to the true fault distance) are calculated for different wavelet bases.

Wavelet basis	Db2	Coif4	Sym5
Fault distance (meters)	192	341	3917

The optimized traveling wave ranging wavefront identification method can reduce the ranging error from 5μs commonly used in engineering to within 1-2 μs, and the corresponding wavefront positioning distance error from 1000m to 150-300 m.

7. Conclusion

Aiming at the core bottleneck of insufficient wavefront identification accuracy in fault location of DC transmission lines, a wavefront identification method based on similarity calculation for traveling wave location of DC transmission lines is proposed and verified. This method takes the local similarity of the wavefront as the criterion, adaptively selects the optimal wavelet basis, combines wavelet transform and modulus maximum extraction, and realizes the high-precision recognition of the wavefront time. The proposed method effectively reduces the wavefront recognition error and ranging error, and the overall ranging accuracy is improved to approximately three times that of the average level. At the same time, this method has the engineering advantages of small calculation, strong portability and wide adaptability. It can shorten the fault search time, reduce power outage loss, and significantly enhance the security and reliability of power grid in practical applications.

Acknowledgments

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