A novel single-ended fault location method for long-distance HVDC transmission lines based on cross-correlation analysis

Lei Shi¹, Ningming Guo² ⁴, Jincheng Qi³, Ruopeng Liu¹ and Chunxiang Mao¹

1 State Grid NingXia Power Maintenance Company, Yinchuan city, NingXia Autonomous Region, China
2 C-EPRI Electrical Power Engineering Co., Ltd, ChangPing district, BeiJing city, China
3 Xi'an Jiaotong University, BeiLin District, Xi'an, Shuanxi, China
4 North China Electric Power University, ChangPing District, BeiJing city, China
E-mail: guoningming@sgepri.sgcc.com.cn

Abstract. The transmission line, as the faultiest device in power system, cross many complex areas which will cause worse work condition. This is, both the rate of faulty and the difficulty of the manual fault location are raised. While accurate fault location method could reduce the workload and outage cost, increase the speed of repairing and improve both the reliability and economics of power system. Therefore, it is essential for HVDC systems which have much longer transmission lines. The existing fault location device of HVDC transmission lines are based on the principle of transient travelling-wave. However, due to the interference caused by on-off of power electronic devices and signal resonances, the single-ended travelling-wave method can not be applied in HVDC. The characteristics of clutter interferences of HVDC system and the coupling between double pole lines are analyzed in paper. A novel single-ended travelling-wave fault location method for HVDC transmission lines based on the correlation between two pole lines is proposed. The signal of the non-fault pole line is applied as reference signal; the method suppresses interference through the cross-correlation calculation between the fault and the no-fault pole line. So the reflected wave is enhanced and the identification reliability of the reflected wave is improved. The validity of the method is verified by simulation and on-site data analysis.

1. Introduction
For HVDC transmission lines which length is long, accurate fault location is of great significance for post-processing of HVDC line failures [1]. At present, the two-ended travelling-wave fault location is mainstream fault location method in the HVDC transmission projects. From the operational experience, the accuracy of two-ended travelling wave method has satisfied the on-site requirement, but it needs both ended data, and the fault location may fail if one side device is abnormal. However, the length of HVDC transmission line is long in general, the abnormality probability of one side device is relatively higher suffered from severe signal attenuation. In the backup measures research of the two-ended travelling-wave method, due to the influences of the signal transformer, the line parameters, and other factors the methods based on the principle of frequency-domain analysis or voltage distribution analysis cannot replace the travelling wave method.
In AC transmission system, single-ended travelling-wave fault location method can locate faults based on one side data. It has been widely used as the backup method in fault analysis. But the research on single-ended fault location of HVDC line is relatively few. In [2], the identification of reflected wave
based on waveform correlation analysis is proposed. A method using auxiliary time window to solve the problem of reflected wave identification is presented in [3]. [4] proposes improving the identification method of reflected wave through neural network technology; and the paper [5] proposes the method of single-ended fault location of HVDC line. Overall, the existing research focuses on the waveform and polarity analysis of reflected wave and similarity comparison [6,7], the influence of system clutter interference and signal resonance is seldom considered. However, the background noise caused by the on-off of power electronic equipment in HVDC system is much stronger than that of the AC system, which makes the identification of reflected waves more difficult. In this paper, a single-ended travelling-wave fault location method for HVDC transmission based on cross-correlation analysis of bipolar signal is proposed. The signal of non-fault pole line is used as reference quantity. The influence of interference and resonance are suppressed through the cross-correlation calculation of the two poles, so the identification success rate of reflected wave is improved. It ensures the reliability of single-ended fault location.

2. Principle and Influencing Factors of Single-ended Travelling-Wave Method for DC Lines

2.1. Principle of Single-ended Travelling-Wave Location

\[
d_1 = (t_1 - t_0) \times v / 2 \tag{1}
\]

\[
d_1 = L - (t_2 - t_0) \times v / 2 \tag{2}
\]

The basic principle of single-ended travelling-wave fault location for the transmission line is shown in formula 1 [8–10]. The location is completed by using the arrival time difference between initial travelling wave and the reflected wave of the fault point, or the reflected wave of the opposite side. Among them, \(d_1\) is the distance between the fault point and the measuring device, \(t_0\) is the arrival time of the initial travelling wave, \(t_1\) is the arrival time of the fault point reflected wave, \(t_2\) is the arrival time of the reflected wave at the opposite end of the line, \(L\) is the full length of the line, and \(v\) is the propagation speed of the travelling wave. The main difficulties of single-ended travelling wave fault location of HVDC lines as following:

The reflected wave is relatively weaker. Because the length of HVDC line is generally long, the transient travelling wave attenuates seriously in the process of long-distance propagation. The background noise is serious. The noise intensity of HVDC system is obviously higher than that of AC system due to the system clutter interference caused by the on-off of power electronic equipment. When the background noise and reflected wave are superimposed, the identification of reflected wave is greatly affected.

2.2. Characteristics of Background Noise in HVDC System

For HVDC transmission projects, the influence background noise includes:

System clutter interference

The clutter interference in HVDC system includes: 1) the interferences caused by the on-off process of converter valves; (2) the interferences caused by load fluctuation, LLC-HVDC is equivalent to current source, and the load fluctuation can lead to voltage fluctuation, which is more obvious in the inverter side. In addition, the smoothing reactor will shield the interferences from the converter side in theory, but the [11,12] shows that the shielding effect of the separately installed smoothing reactor is relatively reduced. The interference from the AC side can still enter the line.

![Graphs a and b showing amplitude versus sampling point](image)
Figure 1. Typical interference signal in HVDC

Figure 1. is the typical HVDC system interference which is collected in field. As is shown in figure 1(a), the influence of the interferences caused by the on-off process of power electronic equipment is more serious. Its frequency-band is wider, and its high frequency component exceeds 10 kHz, which crosses the frequency-band commonly used in fault location. Thus, these interferences cannot be removed thoroughly by using the traditional frequency-band filtering. But these interferences have one characteristic that it is mainly related to the working-condition of the convert valves. As is shown in figure 2, the interference signals of two poles is not synchronous, and their frequency-spectrum also have some differences.

Figure 2. Frequency spectrum and waveform of interference signal in HVDC

Figure 3. Equivalent circuit of the faulty HVDC line

The equivalent circuit of the faulty HVDC lines is shown in figure 3; the transient travelling-wave will reflect between the converter station and the fault point after failure, it produces a series of resonance signals in the process. At the same time, the inductance/capacitance of the transmission line and reactor/coupling capacitor at the convert station will produce a specific frequency resonance signal, especially when the fault point is close to the converter station. The above resonance signal is another important factor for identification of reflected wave. But the resonance signals of the non-fault pole line is quite different from that of the fault pole because there is no fault point in circuit.

Overall, the on-off process of power electronic equipment and signal resonance cause a lot of clutter interferences in HVDC transmission project. The frequency-band of these interferences and the fault signals is overlap. So, the weaker reflected wave may be affected by the noise in the pass-band even after filtering, and the filter process may reduce the signal characteristics in part. Therefore, the existing fault location methods based on frequency-band filtering is affected in HVDC projects.

3. Signal coupling process of two pole lines

3.1. Signal Coupling Process

When HVDC transmission lines failure, it can be considered as a transient voltage/current source is superimposed on the fault point. Because there is mutual inductance and coupling capacitance between positive and negative pole lines, the transient voltage will be emerged on the non-fault pole line.
As shown in figure 4, the coupling process between the two pole lines includes: electromagnetic coupling and electrostatic coupling. The coupling quantity is shown in equation 3/4 [13~16].

\[
\begin{align*} 
- \frac{d}{dx} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} &= \begin{bmatrix} R_1 & L_{11} \\ R_2 & L_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} + \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Z_s & Z_m \\ Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \\
- \frac{d}{dx} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} &= \begin{bmatrix} G_1 & C_{11} \\ G_2 & C_{22} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} + \begin{bmatrix} C_{11} + C_{21} \\ -C_{21} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} Y_s & Y_m \\ Y_m & Y_s \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} 
\end{align*}
\]

(3)

(4)

Since the direction of the electrostatic coupling and electromagnetic coupling is opposite. Formulas 3 and 4 can be simplified as follows:

\[
\begin{bmatrix} Z_s Y_s + Z_m Y_m \\ Z_s Y_s + Z_m Y_m \end{bmatrix} = \begin{bmatrix} Z_s Y_s + Z_m Y_m \\ Z_s Y_s + Z_m Y_m \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix}
\]

(5)

Among them, Zs is self-impedance and Zm is mutual impedance. Both of them are frequency-dependent, so it means that the coupling signal on two pole lines is frequency-dependent too.

3.2. Characteristics of Bipolar Coupled Signals

Based on the parameters of 800 kV Yunnan-Guangzhou HVDC transmission project, the EMTDC simulation model is established in figure 5. The coupling process between positive and negative poles is analyzed by injecting fixed frequency signals. If the signal which frequency is 5kHz is injected, the transient voltage waveforms on the two pole lines are shown in figure 6. It demonstrates that the waveform of the coupling signal in is basically the same as that of the original signal, but amplitude and phase is different.
Figure 5. EMTDC simulation model

Figure 6. Transient voltage waveform of two pole lines

Note: The unit of ordinate is V, the unit of abscissa is S, the larger amplitude is the injected signal.

Figure 7 The character of coupling signal in two pole lines

Note: The unit of ordinate in figure7(a) is kHz, The unit of ordinate in figure7(b) is rad. The coupling coefficient and phase-shift of the signal in two pole lines is shown in figure 6/7, which is calculated through sweeping frequency. The higher the frequency is, the stronger the signal on the non-fault pole line is. In signal phase aspect, there is a phase-shift (it can be considered as time-delay) between the two-pole signals, but it is relatively stable as a whole.

4. Single-terminal fault location method for HVDC transmission based on cross-correlation analysis

4.1. Basic Principles

From the analysis of section 1 and section 2, it can be concluded that the interference signals of the two pole lines are different in time and frequency domain, while the coupling signals of the two pole lines are highly similar. Therefore, using non-fault pole transient voltage as reference signal and enhancing the common part of signal in two pole lines through cross-correlation calculation can reduce the influence of interference and resonance signal in theory. Assuming that the fault pole signal is $x(t)$, the non-fault pole signal $y(t)$ is used as the reference quantity, and the principle of cross-correlation calculation is shown in figure 8. There are two key-points in calculation.
There is a time-delay between the signal of the non-fault pole line and the original signal of the fault pole. Therefore, the time-delay correction should be carried out in the cross-correlation calculation. Although the coupling coefficient is positive correlated with frequency, and the higher components is suit for fault location in theory. However, in actual fault analysis, because the frequency component of the signal is uncertain and related to the fault point and the fault condition, multi-scale analysis should be adopted.

Take the artificial short-circuit test of the 1100kV Changji-Guquan UHV transmission project as example, the cross-correlation calculation process is analyzed in paper. The current of neutral point that flows through coupling capacitor is shown in figure 9 (a)/(b). It is difficult to figure out the reflected wave from background noise if only filtering is performed. Figure 9(c)/(d) is the transient voltage after the waveform restoration based on time-domain integral calculation, the low-frequency signal has been restored in part. Figure10 (a)/ (b) are the frequency-spectrum of the fault pole and the non-fault pole signal which are extracted through the Morlet wavelet transformer. It can be found that the similarity parts of the two poles signal after cross-correlation operation are enhanced in figure10(c). The waveform of the main analysis scale after cross-correlation calculation is shown in figure11; the identification difficulty of reflected wave is significantly reduced.
4.2. Algorithmic Flow
The flow chart of single-ended fault location method for HVDC transmission line based on cross-correlation analysis is as follows:

(1) Time-domain integration: Generally, the existing fault location device collects the neutral point current of the coupling capacitor, which corresponds to the difference value of voltage. The voltage difference restrains the lower frequency components and the signal waveform is changed. Therefore, the transient voltage is restored by the time-domain integral calculation as follows:

\[ u(t) = u(t_0) + \int_{t_0}^{t} \left( \frac{1}{C} \right) i(t) dt \]  

In the above formula, C is the capacitance value of the coupling capacitor and the neutral point current sampling signal is \( i(t) \).

(2) Time-shift compensation and correlation calculation: the arrival time of non-fault pole and fault pole can be figured out by the modulus maximum method based on wavelet transform [8]. Assuming that arrival time is \( t_1 \) and \( t_2 \), then the time-shift of the two pole lines is \( \Delta t = t_2 - t_1 \). The wavelet cross-correlation of \( x(t) \) and \( y(t) \) at given scales and time-shift \( \Delta t \) is defined as:

\[ WC_{XY}(a,t) = E \left[ W_{XX}(a,t) W_{YY}(a,t + \Delta t) \right] \]  

In formula 7, \( W_{xx}(a,t) \) corresponding to the wavelet transform detail coefficient of the fault pole signal \( x(t) \), and \( W_{yy}(a,t+\Delta t) \) corresponding to the non-fault pole signal \( y(t) \), \( a \) is the wavelet transform scale, and using the forward shift of the non-fault pole wavelet coefficients \( \Delta t \) to compensate the time delay. So, the wavelet correlation sequence of the two poles signal can be obtained.

(3) Identification of reflected wave: the catadioptric characteristics of the two polar lines are consistent, the reflected of the fault point is positive, and the reflected wave from the opposite end of the HVDC line is negative. But compared with the fault pole line, the reflected wave of the non-fault
pole line has two characteristics: 1) the reflected wave of the opposite end is relatively high; 2) the reflected wave for the fault point is only generated by the coupling between the two poles, thus, the amplitude is lower. The above characters can be used as another auxiliary criterion for the identification of the reflected wave.

(4) Single-ended fault location: After the identification of reflected wave, the traditional single-ended travelling wave can be used to complete the final fault location.

In actual fault analysis, compared to the two-ended travelling wave method. For the reason that it is not affected by the timing error, and the distance and velocity errors are relatively small, the accuracy of single-terminal travelling wave method is superior to the two-ended travelling-wave method.

5. Simulation and verification of actual fault data

5.1. Simulation Verification

Based on the section 3.2 model, the proposed method is verified through EMTDC simulation. In the calculation, different fault location points are set: the head of the line, the end of the line and the 3/4 position of the line. Metallic and high-resistance grounding faults are simulated respectively. The fault transition resistance is 1 ohm for metal grounding fault and 150 ohm for high resistance fault. Under typical fault conditions, the waveform of non-fault pole and fault pole line are collected by 2.8nF coupling capacitor. In the simulation, Gauss noise is added which to simulate the actual noise interference. After simulation, the current of neutral point that flows through coupling capacitor is shown in figure 12 and the signal after cross-correlation calculation is shown in figure 13. After cross-correlation calculation, the interference is suppressed and the identification difficulty of reflected wave is reduced.

Fig 12. Simulated neutral point current of two pole lines

Fig 13. Transient voltage after cross-correlation calculation

Under different fault conditions, the simulation results are shown in the table 1. In case that the identifying the reflected wave is precise; the single-ended travelling wave method has higher accuracy. Even in the case of 150 ohm fault transition resistance, its errors are basically within 500 m.
Table 1. Simulation result

| Fault distance | Fault transition resistance=1Ω | Fault transition resistance=150Ω |
|---------------|-------------------------------|----------------------------------|
|               | Fault location(km)  | Error(km)  | Fault location(km)  | Error(km)  |
| 10km          | 10.098             | 0.098      | 10.19              | 0.19       |
| 1350km        | 1350.22            | 0.22       | 1350.33            | 0.33       |
| 1020km        | 1020.36            | 0.36       | 1020.47            | 0.47       |

5.2. Verification of Actual Fault Data

The following is the analysis of the artificial short circuit test data, the test data is collected during the test of 800 kV QiShan-ShaoXing HVDC transmission project in May, 2017. The total length of the HVDC transmission line is 1095.6 km. The artificial short circuit test point is 13.8 km away from the Qilian converter station. The test is nearly a metal-grounding fault. The sampling frequency of the equipment is 1.25 MHz. Figure 14(a) is the neutral point current waveform of the non-fault pole line, figure 14(b) is the waveform of the fault pole line. The amplitude of the non-fault pole line is about 90% of the fault pole line; figure 14(c)/(d) is the transient voltage waveform after integral transformation.

![Figure 14](image)

As shown in figure 15(a)/(b), the wavelet coefficients are obtained by decomposing the positive and negative pole signals through wavelet transform. After the time-delay compensation of the non-fault pole and the fault pole line, the cross-correlation sequence is calculated as shown in the figure 15(c). The interference is effectively suppressed after the cross-correlation calculation.
After recognizing the reflected wave, the traditional single-ended fault location method can be adopted to complete the location calculation. As shown in figure 15, there are 119 sampling points between the reflected wave of the fault point and the initial travelling-wave, corresponding time difference is 95.2us. Assuming that the velocity of travelling wave is 296.2m/us, the distance between the fault point and the converter station is 14.099km. The error is about 300 meters. In this test, because the fault point is close to the converter station, the accuracy of single-ended fault location is even higher than the traditional two-ended travelling wave method.

6. Conclusion

In HVDC, the existing single-ended travelling-wave method based on the identification of waveform similarity is influenced by interference caused by the power electric equipment. The success rate of reflected wave identification is relatively low, the reliability of fault location is affected greatly. To solve the above problems, the following research work has been carried out:

1. In HVDC, the interference caused by power electric equipment and signal resonances have wide frequency band, they are main influence factors for the single-ended fault location. However, the interference of the two pole lines is basically independent, and there are differences in frequency band and time domain. Thus, it is feasible to suppress interference by cross-correlation analysis.

2. The signal coupling process of the non-fault pole and the fault pole in HVDC system is analyzed in paper. The EMTDC simulation reveals that the coupling coefficient of the two poles is positive correlated with frequency, and there is a time-shift in the coupling signal of two poles.

3. A novel single-ended travelling-wave fault location method for HVDC lines is proposed in paper. Using the signal of non-fault pole lines as reference quantity, it suppresses interference by cross-correlation calculation of two polar signals and improves the reliability of reflected wave identification. The validity of the method is verified by simulation and on-site data analysis in paper.

7. References

[1] M. Ando, E.O. Shweitzer, R.A. Baker, Development and field-data evaluation of single-end fault locator for two-terminal HVDC transmission lines. Part I: data collection system and field data, IEEE Trans. Power App. Syst. PAS-104 (12)(1985) pp3524–3530.
[2] Hanif Livani, Cansin Yaman Evrenosoglu etc, *A single-ended fault location method for segmented HVDC transmission line* [J]. Electric Power Systems Research, 2014, 107 pp190–198.

[3] Mohammad Farshad, Javad Sadeh, *A Novel Fault-Location Method for HVDC Transmission Lines Based on Similarity Measure of Voltage Signals* [J]. IEEE transactions on power delivery, 2013, vol28 (4) pp123-132.

[4] J. Sadeh, H. Afradi, *A new and accurate fault location algorithm for combined transmission lines using adaptive network-based fuzzy inference system* [J], Electrical power System. 2009, vol79 (11) pp1538–1545.

[5] I. Niazy, J. Sadeh, *A new single ended fault location algorithm for combined transmission line considering fault clearing transients without using line parameters* [J], Electrical power System, 2013, vol44 (1) pp616–623.

[6] SHU Hong-chun, WU Qian-jin, ZHANG Guang-bin, et al. *Single terminal travelling wave fault location method based on ANN*[J]. Proceedings of the CSEE, 2011, 31(4) pp85-92.

[7] R. Salat, S. Osowski, *Accurate fault location in the power transmission line using support vector machine approach*, IEEE Trans. Power Syst. 29 (2) (2004) pp979–986.

[8] QIN Jian, GE Wei-chun, QIU Jin-hui, et al. *Study on single terminal method and double terminal method of travelling wave fault location in transmission line*[J]. Automation of Electric Power Systems, 2006, 30(6) pp92-95.

[9] O.M.K.K. Nanayakkara, A.D. Rajapakse, R. Wachal, *Fault location in extra long HVDC transmission lines using continuous wavelet transform*, in: International Conference on Power Systems Transients, Delft, The Netherlands, 2011, pp14–17.

[10] WANG Kui-xin, ZHU Cheng, SUN Jia-jia, et al. *Research of combined travelling wave fault location method on transmission lines*[J]. Power System Protection and Control, 2012, 40(15) pp82-86.

[11] Mo Fu-jiang, Chen Yun-ping, Ruan Jiang-jun, *Analysis of coupling mechanism and calculation of lightning induced over-voltage for overhead transmission lines*[J], Power Systems Technology, 2005, 29(6) pp72-96.

[12] Sun Ban-xin *Configuration scheme of smoothing reactor in UHVDC system* [J], Electrical engineering technology, 2009, 13(5) pp2-7.

[13] Xiao Yao, Deng Jun, Xia Gu lin, *A New Method for Measuring Distribution Parameters of HVDC Transmission Lines*[J]. Proceedings of the CSEE, 2015, 35(20) pp5375-5382.

[14] Wang De-ling, Lv Peng-fei, Ruan Si-Ye etc *Mutual inductance effect of UHVDC bipolar transmission lines and Its Countermeasures*[J]. Proceedings of the CSEE, 2015, 35(18) pp4210-4216.

[15] Zhang Fu-xuan, Zhou qiang etc, *Mutual Inductance Effect and Control Strategy Improvement of UHVDC Bipolar Lines*[J], Power Systems Technology, 2017, 41(11) pp3547-3542.

[16] Chu xu, Wang Liang, Wang Hua-wei, *Effect of inter-pole coupling on HVDC transmission line and fault pole selection scheme*[J], Power Systems Technology, 2017, 37(4) pp140-145.