Fault location method for high-voltage direct current transmission line using incident current travelling waves

Bin Wang\textsuperscript{1}, Lin Yang\textsuperscript{1}, Xinzhou Dong\textsuperscript{1}

\textsuperscript{1}Department of Electrical Engineering, State Key Lab of Control and Simulation of Power Systems and Generation Equipments, Tsinghua University, Beijing 10084, People’s Republic of China

E-mail: binwe_ee@mail.tsinghua.edu.cn

Abstract: The reflection coefficient of the travelling wave is different with different frequencies because of the inductance and capacitive elements on the boundary of the DC transmission line, which leads to the oscillation of the travelling wave. It is difficult to obtain the wave head's arrival time accurately using travelling wave method to locate fault because of the oscillation. The current travelling wave is the superposition of the incident current travelling wave and the reflected current travelling wave. There is no oscillation in the incident wave. Therefore, a method using incident current wave for fault location is proposed here. The initial current travelling wave and the transmission line boundary function are used to calculate the incident current travelling wave, and the incident wave is used to locate fault. The Prony decomposition algorithm is used to identify boundary function using the initial current travelling wave generated in specific fault condition. PSCAD simulation shows that the influence of oscillations of travelling wave can be eliminated by using incident current wave to locate faults, and the accuracy of fault location is improved.

1 Introduction

In order to locate faults, the single-ended travelling wave fault location devices need the time that the initial current travelling wave and the reflected wave arrive at the measuring point \([1]\). Therefore, it is important to obtain the arrival time of the travelling waves accurately. In the time domain, the arrival of the travelling wave means the salutation of the current signal. The singularity point of the signal corresponds to the wavelet transform modulus maximum. Therefore, the arrival time of travelling waves are determined by the modulus maximum \([2]\). In the AC transmission system, the travelling wave can be regarded as the superposition of right angle wave which tend to the rapidly rising wave heads \([3]\). Surge demarcation of right angle wave is always accurate using wavelet transform. However, the non-linear components installed on the boundary of the high-voltage direct current (HVDC) transmission line, such as the smoothing reactor and the DC filter, lead to the travelling wave oscillation \([4]\). The long rising time of the measured wave leads to inaccurate surge demarcation, and the existence of oscillations in the measured wave leads to extra modulus maxima which will disturb the fault location system. Consequently, the accuracy of fault location is not high when using the current travelling wave directly.

The mechanism of DC travelling wave oscillation has been analysed in some literatures. The relationship between the frequency and the reflection coefficient of the aerial mode and the earth mode voltage at the end of the line is analysed in \([3]\). The reflection coefficients of the different frequency components in each module are very different. Wanjun \([4]\) shows the voltage at the end of the line when the incident voltage wave is the step wave, and the terminal voltage can be seen to oscillate obviously. The authors in \([5, 6]\) analyse the reasons of the oscillation exist in the initial travelling wave. The reflected wave of the faulted point is also oscillating, which will lead to the inaccurate fault location.

The mechanism of travelling wave oscillation indicates that the frequency-dependent reflection coefficient and wide-band distribution of incident wave are the fundamental causes of wave head oscillation. The initial travelling wave and the reflected wave of the faulted point are both produced by the incident wave. The incident travelling wave contains the information of the arrival time and there is no oscillation problem in the incident wave. Therefore, using the incident current travelling wave to locate the fault can effectively avoid the drawbacks of the oscillation. In this paper, the incident wave of the initial current travelling wave and the fault point arrival time is extracted, respectively, based on the analysis of the travelling wave oscillation mechanism. PSCAD simulation results show that the location results obtained by incident waves are more accurate.

2 Analysis of travelling wave oscillation

The fault travelling wave is generated and transmitted in the fault network. Fig. 1 is a simple fault network in the case of the DC transmission line fault.

The boundary of the HVDC transmission system is composed of the DC filter and the smoothing reactor. The smoothing reactor is an inductor with a large inductance, the DC filter is a series–parallel connection of inductance, capacitance, and resistor. According to the switching function theory, the equivalent impedance of the AC system and the DC converter at the DC side can also be expressed as an inductance component. The wave impedance of the DC transmission line is denoted as \(Z_1\). The total impedance of the smoothing reactor connected with the equivalent inductance and connected with the DC filter in parallel is denoted as \(Z_2\). The current reflection coefficient at the line boundary is

\[
\rho(s) = \left(\frac{Z_1 - Z_s(s)}{Z_1 - Z_2(s)}\right)^{-1}
\]

The incident current travelling wave is expressed as \(I_b\), then the initial current travelling wave \((I_1)\) and the fault point reflected wave \((I_f)\) can be expressed as

\[
I_1(s) = I_b(s) + \rho(s)I_b(s) = (1 + \rho(s))I_b(s)
\]

\[
I_f(s) = \rho(s)I_b(s) + \rho^2(s)I_b(s) = \rho(s)(1 + \rho(s))I_b(s)
\]

For convenience, \(1 + \rho(s)\) is called the boundary function, denoted by \(G(s)\). In ideal case, the incident current travelling wave can be regarded as an infinite right angle wave, its amplitude is assumed as 1. Then the waveforms of the initial current travelling wave and the reflected wave of the faulted point are given in Figs. 2 and 3.
The impedance value of boundary impedance varies with frequency, so the reflection coefficient is different for incident waves of different frequencies. The incident current travelling wave can be regarded as an ideal step wave, which contains abundant frequency components. After the incident current travelling wave reflection, the changes of amplitude and phase with different frequency components are different, which leads to the oscillation of the wave head.

The initial current travelling wave and the initial current travelling wave are both consist of DC component, decaying DC components, and decaying sinusoidal components.

Compared to the right angle wave, the oscillating current wave head rises slowly. As a result of the oscillation, multiple singularity points appear in them.

3 Extracting incident current travelling waves

3.1 Extracting the incident wave corresponding to the initial current travelling wave

According to the analysis of Section 2, the boundary function depends on the parameters of the boundary of the transmission line. So, the boundary function does not vary with different fault conditions. By formula (2), the incident wave can be extracted by the initial current wave and the boundary function.

Owing to inaccurate parameter of boundary and ageing issues, it is not accurate to calculate reflection coefficient using given parameters. Therefore, calculating the boundary function directly by the boundary parameters will cause errors.

The form of incident wave can be calculated under the set fault condition. As the initial travelling wave can be expressed by a group of damping sine components, Prony algorithm can be used to identify the amplitude, phase, frequency, and attenuation coefficient [7]. Damping DC component and damping sine components of the initial travelling wave can be identified using the Prony algorithm, and the DC component can be calculated as the mean value of the waveform. The boundary function can be calculated when the incident current travelling wave and the initial current travelling wave are obtained under the set fault condition. For other fault conditions, the incident wave can be extracted by the initial current wave and the boundary function.

3.2 Extracting the incident wave corresponding to the reflected wave of the faulted point

In theory, incident wave corresponding to the reflected wave of the faulted point also can be extracted using the method similar to the initial current travelling wave. However, for the typical system parameters, $\rho^{-1}(s)$ is not stable, it cannot be directly used to extract incident wave (Fig. 4).

Move the initial current travelling wave to the moment when the reflected wave of the faulted point appears, and then superpose them together. The travelling wave after superposition called superimposed wave, denoted as $I_3$.

$$I_3(t) = I_1(t) + I_2(t) = G(s)I_0(t)$$

(4)

So, the incident wave corresponding to the reflected wave of the faulted point can be extracted by the superimposed wave and the boundary function.

After getting the incident current waves, respectively, corresponding to the initial travelling wave and the reflected wave of the faulted point, the fault location can be obtained by the incident waves’ modulus maximum of wavelet transform accurately.

4 Simulation

The fault network shown in Fig. 1 is built in PSCAD/EMTDC. To access wide-band fault travelling wave information, sampling frequency in simulation is 200 kHz. The transmission line model is lossless Bergeron model and the transmission line wave impedance is 394.06 Ω. The wave velocity is $2.9525 \times 10^8$ m/s. The system on both sides of the voltage source is symmetrical. The component parameters in the network are given in Table 1.

In the fault network, the additional fault voltage source is connected to the transmission line through a switch, and the switch is closed at 0.3 s to simulate the occurrence of the fault. Faults at different positions can be simulated by changing the length of the line and the voltage of the additional source. Take the terminal M as the measuring position for the single-ended travelling wave method. There are three steps to obtain the fault location:

i. Calculate the boundary function: For simplicity, take the initial incident current travelling wave as a unit step wave. So, the voltage value of the fault additional voltage source is taken as 394.06 kV, which is the same as that of the wave impedance of transmission line. The Prony algorithm is used to fit the simulated initial travelling wave, and the result is shown as Fig. 5. The boundary function is obtained by (2).

ii. Extracting incident current travelling waves: The fault is set at 600 km from the M terminal, and the current travelling wave measured by the transformer is given in Fig. 6.

Wavelet transform is performed for the current travelling wave, and the modulus maximum under scale 1 is shown.

The rough arrival times of the initial travelling wave and the reflected wave of the faulted point are 0.302085 and 0.30618 s, respectively. From Fig. 7, the modulus maximums are small and some of them do not indicate the arrival of the wave head.

The rough arrival times of the initial travelling wave and the reflected wave of the faulted point are 0.302085 and 0.30618 s, respectively. From Fig. 7, the modulus maximums are small and some of them do not indicate the arrival of the wave head.
Calculate the incident wave corresponding to the initial travelling wave by (2) (Fig. 8).

Move the initial current travelling wave to the rough arrival time of the reflected wave, and then superpose them together. Calculate the incident wave corresponding to the initial travelling wave by the superimposed wave (Fig. 9).

It can be seen that the extracted incident current travelling waves are close to the right angle wave. Compared with the current travelling wave, the travelling wave has good characteristics of fast rising speed and small oscillation amplitude.

iii. Calculate the fault location: Wavelet transform is performed for the incident travelling waves, and the modulus maximums under scale 1 are shown in Figs. 10 and 11.

The arrival times of the initial travelling wave and the reflected wave of the faulted point are 0.302065 and 0.306165 s, respectively. The formula of single-ended travelling wave fault location is

\[ l_1 = 0.5*(t_{M2} - t_{M1})*v \]  

(5)

where \( l_1 \) is the distance from the fault point to \( M \) terminal; \( t_{M1} \) and \( t_{M2} \) are arrival times of the initial travelling wave and the reflected wave of the faulted point, respectively; \( v \) is the wave velocity.

In this case, \( l_1 \) is 599.68 km which is close to the set. Use the rough arrival times to calculate \( l_1 \), the result is 598.94 km. Therefore, the location accuracy obtained by incident waves is improved.

5 Conclusion

In this paper, the Prony decomposition algorithm is used to obtain the boundary function through the calculation of the current travelling wave under a particular fault. The incident current travelling wave under any fault can be obtained by using the function and the corresponding current travelling wave. The extracted incident current travelling wave has advantages of fast rising speed and small oscillation amplitude. The accuracy of wave demarcation can be improved by using incident travelling wave to locate fault, so as to improve the accuracy of fault location.

6 Acknowledgments

This work was supported partly by National Key Research and Development Plan of China (grant no. 2016YFB0900600), and partly by National Natural Science Foundation of China (51777084).
7 References

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