Simulation Study on Transmission Line Fault and Traveling Wave Transmission Characteristics

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Abstract: Fault traveling wave characteristics and traveling wave transmission characteristics are the key factors affecting the positioning accuracy of traveling wave positioning technology. This paper takes a common 110 kV transmission line as the research object, establishes the electromagnetic transient simulation model through ATP-EMTP software, and simulates the lightning strike, lightning shielding, metal grounding and high resistance grounding faults of the line, and obtains the difference of fault traveling wave current and voltage characteristics under different types of faults. On this basis, the attenuation law of each modulus traveling wave is studied. Finally, the application of each modulus traveling wave in fault location is analyzed.

1. Introduction
Traveling wave fault location method has always been a hot topic in power system. Compared with impedance ranging technology, traveling wave ranging method is not affected by line load, operation mode of power system and excessive resistance of fault point. It has obvious advantages in application scope and positioning accuracy [1-3]. Relevant research and practical engineering applications show that attenuation and dispersion will exist in the process of traveling wave transmission, which will greatly interfere with the extraction of traveling wave head time and the calibration of wave velocity, seriously affecting the accuracy of traveling wave positioning results [4-6]. Therefore, accurate evaluation of traveling wave transmission characteristics can reduce positioning accuracy error and further explore the technical value of traveling wave positioning. The dispersion effect of traveling wave transmission is proposed for the first time in paper [7], and the influence of various factors on traveling wave transmission is studied by simulation. The traveling wave dispersion characteristics of double-circuit transmission lines on the same tower are studied by simulation in paper [8-10].

In this paper, the electromagnetic transient process of lightning strike, lightning shielding, metal grounding and high resistance grounding faults and the transmission characteristics of fault traveling wave are studied.

2. Model Building
The tower model adopts multi-band wave impedance model and insulator flashover model adopts pilot method model. The method of establishing impulse grounding resistance and grounding arc in ATP-EMTP software is introduced below.

2.1. Impulse grounding resistance model
In this paper, the impulse grounding resistance model recommended by IEC and CIGRE is adopted [11].
\[ R_g = R_0 / \sqrt{1 + I / I_g} \]  

In the formula, \( R_0 \) is the grounding resistance of power frequency, \( I \) is the magnitude of lightning impulse current flowing over the grounding body, and \( I_g \) is the critical current for ionizing the soil.

\[ I_g = \frac{E_0 \rho}{2\pi R_0^2} \]  

In the formula, \( \rho \) is the soil resistivity (\( \Omega \cdot \text{m} \)), \( E_0 \) is the field strength (kV / m) at the time of soil ionization, and \( R_0 \) is the soil grounding resistance under the action of power frequency. In this paper, \( E_0 = 300 \text{ kV} / \text{m}, \rho = 500\Omega \cdot \text{m}, \) and \( R_0 = 30\Omega \), respectively. Impulse grounding resistance is simulated by TACTS function as shown in Figure 1.

Figure 1. Model of the impact grounding resistance

2.2. Arc Model
There are two main grounding arc models: Cassie model and Mayr model. In this paper, the primary arc model based on Mayr model is adopted.

\[ \frac{dg_p}{dt} = \frac{L_p}{aL_pV_pL_p} (|i| - g_p) \]  

In the formula, \( L_p \) is the length of the arc. \( a \) is a constant, usually 2.85e\(^{-5}\). \( V_p \) is the static arc voltage drop per unit length. \( I_p \) is short circuit current. \( I \) is a primary arc current. \( g_p \) is dynamic arc conductance. The implementation process is shown in Figure 2 below.

Figure 2. Schematic diagram of the arc model implemented by the TACTS function

3. Traveling Wave Characteristics of Different Fault Types and its Attenuation Law
Transmission line faults are mainly divided into lightning strike faults and non-lightning strike faults, among which lightning strike faults include counterattack and shielding strike faults. Non-lightning fault can be divided into metal grounding fault and high resistance fault according to the characteristics of flashover channel. Considering four typical faults: counterattack, shielding, metal grounding and high resistance grounding, the simulation conditions are as follows:

Counterattack fault: 60 kA 2.6/50\( \mu \)s lightning current hit the top of the tower, three-phase flashover;

Shielding fault: 6kA 2.6/50\( \mu \)s lightning current strikes A phase conductor. Metal grounding fault: A phase conductor is grounded by 0.1\( \Omega \) resistance at positive peak of power frequency voltage. High resistance grounding fault: A phase conductor is grounded by 10k\( \Omega \) resistance at the positive peak of power frequency voltage, taking into account the arc model.

In the simulation, observation points are set at 0 km, 10 km, 20 km, 30 km and 40 km away from the fault point respectively. Three-phase traveling wave are decoupled by Colombel method[4]. The waveforms in different fault cases are shown in Figure 3-6 in turn. In order to analyze the change trend,
the amplitude of the waveform was normalized. The waveform amplitude of each observation point is shown in Table 1, and the waveform head and tail time are shown in Table 2.

Figure 3. Current and voltage waveforms of three-phase flashover caused by lightning counterattack

Figure 4. Current and voltage waveforms in lightning shielding single-phase flashover
Table 1. Traveling wave amplitudes at different transmission distances (voltage: kV; current: A)

| Distance of propagation /km | 0      | 10     | 20     | 30     | 40     |
|-----------------------------|--------|--------|--------|--------|--------|
| Counterattack fault         |        |        |        |        |        |
| $I_0$                       | 1685.6 | 1130.9 | 890.2  | 741.4  | 615.1  |
| $I_a$                       | 45.8   | 28.3   | 21.6   | 17.7   | 14.3   |
| $U_0$                       | 1905.4 | 800.5  | 632.2  | 491.2  | 439.3  |
| $U_a$                       | 15.7   | 12.3   | 9.5    | 8.7    | 6.4    |
| $I_0$                       | 631.4  | 217.2  | 144.7  | 102.8  | 79.5   |
| $I_a$                       | 210.3  | 128.0  | 117.9  | 109.7  | 103.6  |
| $I_{\beta}$                 | 210.3  | 136.0  | 127.4  | 119.7  | 112.8  |
| $U_0$                       | 459.6  | 155.1  | 103.5  | 63.4   | 56.1   |
| $U_a$                       | 78.4   | 47.7   | 43.9   | 41.1   | 38.5   |
| $U_{\beta}$                 | 80.1   | 51.8   | 48.5   | 45.6   | 42.9   |
| $I_0$                       | 58.3   | 43.8   | 38.5   | 34.9   | 31.5   |
| $I_a$                       | 19.4   | 17.9   | 17.0   | 16.5   | 16.1   |
| $I_{\beta}$                 | 19.4   | 18.6   | 18.2   | 17.9   | 17.6   |
| $U_0$                       | 43.9   | 31.5   | 27.9   | 24.3   | 22.9   |
| $U_a$                       | 7.2    | 6.7    | 6.3    | 6.2    | 6.0    |
| $U_{\beta}$                 | 7.4    | 7.1    | 6.9    | 6.8    | 6.7    |
| $I_0$                       | 32.4   | 27.8   | 26.1   | 25.3   | 23.7   |
| $I_a$                       | 10.8   | 10.2   | 9.9    | 9.6    | 9.4    |
| $I_{\beta}$                 | 10.8   | 10.5   | 10.4   | 10.2   | 10.1   |
| $U_0$                       | 24.7   | 20.3   | 19.2   | 18.0   | 17.6   |
| $U_a$                       | 4.0    | 3.8    | 3.7    | 3.6    | 3.5    |
| $U_{\beta}$                 | 4.1    | 4.0    | 3.9    | 3.9    | 3.8    |
Table 2. Traveling wave head and wave tail time at different transmission distances (μs)

| Distance of propagation /km | 0     | 20    | 40    |
|----------------------------|-------|-------|-------|
| Counterattack fault        | 0.8/16.1 | 5.6/29.2 | 8.5/42.3 |
| Shielding fault            | 1.1/5.3  | 2.2/10.4  | 4.8/35.6  |
| Metal grounding fault      | 1.4/48.3  | 7.8/75.4  | 10.1/112.2 |
| High resistance grounding fault | 1.2/124.4 | 4.9/144.1 | 8.5/156.8 |

For counterattack flashover, lightning current enters each phase conductor along the three-phase insulator. Because the three-phase conductor is approximately symmetrical, the three-phase traveling wave current and the traveling wave voltage are approximately equal. In addition, AC phase is completely symmetrical, and its corresponding modulus traveling wave is completely equal, so the amplitude of α mode travelling wave is very small, and the amplitude of β mode travelling wave is equal to 0, while the amplitude of zero mode travelling wave component is significantly higher than the other two line mode components. The maximum zero-mode current exceeds 1.6 kA and the voltage exceeds 1900 kV.

The shielding flashover only occurs on phase A. Because of the sudden injection of large lightning current into phase A, the three-phase modulus is seriously unbalanced, and amplitude of α and β mode are large. When metal grounding fault and high resistance grounding fault occur, the fault is similar to an external power injection, which is similar to the shielding fault.

From the data in Table 2, it can be seen that the amplitude of each mode traveling wave decreases gradually with the increase of transmission distance, and the attenuation rate is especially rapid in the range of 0-10 km, and decreases after 10 km. Taking shielding failure as an example, the amplitude attenuation of zero mode current in each 10 km segment is 65.6%, 33.3%, 28.9%, 22.6%, and that of α mode current is 39.1%, 7.9%, 6.9% and 5.6% respectively. Zero mode attenuation rate is higher than linear mode component. In addition, lightning traveling wave transmission attenuation rate is faster than non-lightning traveling wave.

The traveling wave tail time of lightning stroke fault at the initial position is less than 20μs, while the traveling wave tail time of metal grounding fault and high resistance grounding fault are 48.3μs and 124.4μs, respectively, which are basically consistent with the measured values mentioned in reference [6]. In addition, with the increase of transmission distance, both the wave head time and the wave tail time show an increasing trend, which reflects the gradual attenuation of high-frequency components in the process of traveling wave transmission, and the rising and falling edges of wave become gentle.

4. Fault location results using different modulus traveling waves

No matter which kind of traveling wave is used to locate the fault, the premise is to give the reasonable wave velocity, and then locate the fault according to the time difference of wave head. The measured wave velocities of B.C.Hydro positioning system in Canada in paper[3] of linear mode wave velocity are 295-296 m/μs, and the zero mode wave velocity is 268 m/μs.
Table 3. Traveling wave location results for different types of faults

| Distance of propagation /km | t₁/μs | t₂/μs | Positioning error /% |
|----------------------------|-------|-------|----------------------|
| I₀                         | 80.1  | 77.4  | 3.9                  |
| Iₐ                         | 67.8  | 68.1  | 0.4                  |
| U₀                         | 67.7  | 67.8  | 0.2                  |
| Uₐ                         | 78.5  | 79.7  | 1.6                  |
| I₀                         | 80.3  | 81.9  | 2.1                  |
| Iₐ                         | 66.1  | 67.7  | 2.1                  |
| U₀                         | 79.1  | 79.8  | 0.9                  |
| Uₐ                         | 67.5  | 65.3  | 2.9                  |
| I₀                         | 78.7  | 81.2  | 3.3                  |
| Iₐ                         | 67.4  | 68.2  | 1.0                  |
| U₀                         | 79.4  | 80.9  | 2.2                  |
| Uₐ                         | 76.5  | 78.3  | 2.4                  |
| I₀                         | 83.7  | 79.9  | 4.8                  |
| Iₐ                         | 77.4  | 76.3  | 2.1                  |
| U₀                         | 82.8  | 84.6  | 2.4                  |
| Uₐ                         | 75.5  | 77.1  | 2.0                  |

The wavelet modulus maximum method is used to calibrate the wave head, and then the time of arrival of the traveling wave head is calculated. The fault traveling wave is monitored at 20 km on both sides of the fault point. The results are shown in Table 5. In Table 5, t₁ and t₂ are the times taken for the traveling of the traveling wave to the observation points on both sides. From Table 5, it can be seen that no matter which modulus traveling wave is used for positioning, the positioning accuracy is high, the maximum error is less than 5%, the maximum absolute error is 960m, and in most cases the positioning error is between 100 and 400m. This positioning error is totally acceptable for actual operation and maintenance, and has engineering practical significance.

5. Conclusion

1) The traveling wave characteristics of different faults are quite different. The traveling wave amplitude of lightning strike fault is large and the wave tail time is small, while the traveling wave amplitude of metal grounding fault and high resistance grounding fault is relatively low, and the wave tail time is larger than that of lightning strike fault.

2) As the transmission distance increases, the traveling wave amplitude of each modulus decreases, and the transmission attenuation is the fastest in the first 10 km. In addition, the traveling wave head and tail time show an upward trend, and the zero mode traveling wave attenuates faster than the line mode traveling wave.

3) The positioning accuracy of each modulus traveling wave is relatively high when applied to fault location, and the positioning error is less than 5%. Although the zero-mode component decays faster, the amplitude of zero-mode traveling wave is much larger than that of line mode in some cases of fault, which is more advantageous for wave head extraction and signal detection. Therefore, the application of 110kV fault location should fully combine the characteristics of each mode, and then select the most suitable mode for fault location.

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