Transmission Attenuation of 110kv Asymmetric Transmission Lines Based on Measured Data

PANG Songling¹, TAN Fali², ZHAO Hailong¹, ZHANG Meng², LIAO Jian² and PENG Yang²

¹Electric Power Research Institute, Hainan Power Grid Co., Ltd., Haikou, 570100
²Wuhan sunshine power Science &Technology Co., LTD, Wuhan, 430074, China

903805217@qq.com

Abstract: The characteristic of traveling wave transmission has great influence on the location precision of the fault point. In order to accurately evaluate the transmission and attenuation characteristic of actual traveling wave on transmission lines, a typical asymmetric arrangement 110kV transmission line is selected as the research object. First, the parameters of the transmission line are calculated, and the traveling wave decoupling algorithm is derived. Then, the traveling wave current collected by the distributed traveling wave monitoring system on the line is analyzed. The results show that for a short distance asymmetric 110kV line, it can be decoupled by the conventional decoupling balance line method, and the coupling component ratio is less than 2% after decoupling. With the increase of transmission distance, the attenuation degree of traveling wave increases. When the transmission distance is 60km, the attenuation of line mode is 21.2% and the zero mode attenuation is 50.4%.

1 Introduction
Traveling wave ranging technology has been widely applied to various voltage grade transmission lines[1]. Compared with the traditional impedance measurement technology, traveling wave ranging technology is not affected by the size of load, operation mode and the size of transition resistance[2]. It has shown remarkable advantages in positioning accuracy and application range[3].

Based on the application of centralized traveling wave distance measurement, a new traveling wave location technology called distributed traveling wave location technology has sprung up in recent years[4]. In this technology, traveling waves of the transmission line are collected distributed, which reduces the influence of the change of line parameters and transmission attenuation on the distance measurement, which can further improves the positioning accuracy[5].

The application of related research and practical engineering shows that there exists attenuation and dispersion effect in the traveling wave transmission, which brings great interference to the row wave head extraction and the calibration of wave speed, and it seriously affects the accuracy of the traveling wave positioning results. Therefore, the accurate estimation of the traveling wave transmission characteristics is conducive to reduce the positioning accuracy error and further excavate the traveling wave location.

In paper[6], dispersion effect of traveling wave transmission is first proposed, and the influence of many factors on traveling wave transmission is studied by simulation. In paper[7],traveling wave dispersion characteristics of the double circuit transmission line of the same tower are studied by simulation. Paper[8] and paper[9] studied the influence of frequency dependent characteristics of line
parameters on transmission of traveling wave in distribution network and half wavelength line.

At present, the existing research is generally based on theoretical analysis and simulation, and there is still lack of practical engineering verification. In this paper, a common asymmetrical 110kV line is taken as the research object. First, the line parameters and traveling wave decoupling are calculated and analyzed respectively. Then based on the measured traveling wave data samples from the distributed traveling wave monitoring system on the line, the characteristic of traveling wave transmission and attenuation is analyzed, and the application of the zero mode traveling wave in the 110kV fault diagnosis is also studied.

2 Three phase decoupling and transmission parameter calculation of 110kV asymmetric lines

Due to the coupling effect between parallel transmission lines, when traveling wave exists on a conductor, there will be coupling components on other conductors. In order to eliminate the influence of the coupling component on the calculation, the original A, B, C phase traveling wave should be decoupled into independent $\alpha$, $\beta$, 0 component, where $\alpha$, $\beta$ are line mode travelling wave and 0 mode component is zero mode travelling wave. Taking lossless transmission lines as an example, the following wave equations are satisfied.

\[
\begin{align*}
\frac{\partial^2 U}{\partial x^2} &= LC \frac{\partial^2 U}{\partial t^2} \\
\frac{\partial^2 I}{\partial x^2} &= CL \frac{\partial^2 I}{\partial t^2}
\end{align*}
\]  

(1)

In formula (1), $L$ and $C$ are inductance parameter matrix and capacitance parameter matrix respectively.

In order to decouple three-phase circuits, a suitable matrix $K$ must be found to make $LC$ and $CL$ diagonalization at the same time. For each element of such $K$ matrix, the following equation needs to be satisfied:

\[
\begin{align*}
k_{11} + k_{22} + k_{33} &= 0 \\
k_{12} + k_{22} + k_{32} &= 0 \\
k_{13} + k_{23} + k_{33} &= 0
\end{align*}
\]  

(2)

In formula(2), $k_{ij}$ is the $i$th row and $j$th column elements of the matrix $K$.

For common symmetric lines, it satisfies $LC=CL$, and we can simultaneously achieve the diagonalization of $LC$ and $CL$. Therefore, some specific methods can be used to realize three-phase line decoupling, such as Karenbauer transform and Clarke transform.

However, transmission distance of 110kV transmission lines is usually not more than 100km, the lines are not transposition, and the line parameters are no longer symmetrical, so they cannot be decoupled by the above methods. Decoupling method of such asymmetric line needs to be reanalyzed. The typical tower layout of the 110kV line studied in this paper is shown in Figure 1 below.

![Figure 1. Schematic layout of 110kV transmission line tower](image)

Due to the correlation between the transmission line parameters and the frequency, a typical 10 kHz is selected as the calculation frequency. The inductance and the capacitance matrix of the line in Figure 1 can be obtained by numerical calculation, which is as shown as below.
In formula (1), the unit of inductance is mH/km and the unit of capacitance is uF/km. Diagonalize matrix $LC$ and matrix $CL$ respectively, and we can obtain the voltage transformation matrix $M$ and the current transformation matrix $N$ respectively, which are as shown as follows:

$$
M = \begin{bmatrix}
-0.5941 & -0.7134 & -0.3027 \\
-0.5520 & 0.6758 & -0.5348 \\
-0.5851 & 0.1850 & 0.7889
\end{bmatrix}
$$

$$
N = \begin{bmatrix}
-0.6321 & -0.7484 & -0.2938 \\
-0.5068 & 0.6459 & -0.5282 \\
-0.5861 & 0.1507 & 0.7967
\end{bmatrix}
$$

It can be seen from formula (4) that the $M$ matrix and the $N$ matrix approximately satisfy the formula (4), therefore, non-transposition of 100kV short distance has little effect on phase to mode transformation. Since the waveforms measured by the distributed traveling wave monitoring system are all traveling wave current, the latter analysis is only for traveling wave current. Further, the traditional Karenbauer transform matrix $S$ and Clarke transform matrix $T$ are used to transform the current matrix $CL$ in turn. The results are as follows:

$$
S^{-1}CLS = \begin{bmatrix}
0.8457 & 0.0081 & 0.0019 \\
0.0142 & 0.5148 & -0.0084 \\
-0.0058 & -0.0030 & 0.5254
\end{bmatrix} \times 10^{-6}
$$

$$
T^{-1}CLT = \begin{bmatrix}
0.8457 & -0.0101 & -0.0023 \\
-0.0277 & 0.5191 & -0.0073 \\
-0.0112 & -0.0071 & 0.5212
\end{bmatrix} \times 10^{-6}
$$

Through formula (5), we can see that after the Karenbauer transformation and the Clarke transformation, the coupling current traveling wave is very low, and for the Karenbauer transformation, the ratio of the coupling component is only 2%, therefore, the Karenbauer transform can be considered to decouple the line in this paper.

Further, the transmission parameters of line mode traveling wave and zero mode traveling wave at different frequencies are calculated, which are as shown in Table 1 and Table 2.

| frequency /Hz | wave velocity /m·μs⁻¹ | wave impedance /Ω | attenuation coefficient /Np·m⁻² |
|---------------|------------------------|-------------------|-------------------------------|
| 50            | 293.2                  | 284.3             | 9.85×10⁻⁹                    |
| 10k           | 294.3                  | 283.9             | 5.22×10⁻⁷                    |
| 50k           | 295.8                  | 283.3             | 2.05×10⁻⁷                    |
| 100k          | 297.1                  | 282.6             | 7.76×10⁻⁷                    |
| 500k          | 298.2                  | 282.1             | 1.19×10⁻⁵                    |
Table 2. Transmission parameters of traveling wave of earth mode at different frequencies

| Frequency /Hz | Wave velocity /m·μs⁻¹ | Wave impedance /Ω | Attenuation coefficient /Np·m⁻¹ |
|--------------|------------------------|-------------------|-------------------------------|
| 50           | 215.1                  | 674.3             | 5.68×10⁷                      |
| 10k          | 276.9                  | 587.1             | 9.07×10⁶                      |
| 50k          | 285.6                  | 569.2             | 4.12×10⁻⁶                     |
| 100k         | 293.3                  | 553.5             | 3.34×10⁻⁵                     |
| 500k         | 295.9                  | 538.5             | 1.52×10⁻⁴                     |

Data of Table 1 and Table 2 show that the attenuation of traveling wave propagation is significantly increased with the increase of frequency. In addition, the attenuation constant of the zero mode traveling wave at the same frequency is 10 times more than the attenuation constant of the line mode. Therefore, as the frequency increases, the transmission distance is elongated, high frequency component of the zero mode wave speed is easily attenuated or even disappeared.

3 distributed traveling wave monitoring system

3.1 monitoring terminal layout

As shown in Figure 2 below, monitoring terminals are distributed installed on three-phase wires of #i, #j, #m, #n towers of an asymmetrical 110kV transmission line, with a total length of 90371m and no transposition of wires. M and N are substations at both ends of the line. \( l_1, l_2, l_3 \) are the distances between substations and monitoring terminals and between monitoring terminals and monitoring terminals, which are 15225m, 20239m, 20058m, 19762m and 14587m respectively.

![Figure 2. Layout of distributed traveling wave monitoring terminal](image)

When a transmission line fails or a circuit breaker acts in substation, it will generate traveling waves and propagate along the line throughout the power grid. For all the monitoring terminals in Figure 2, the substation M and N can be regarded as a natural travelling wave source. When the M or N produces traveling wave, all the monitoring terminals can simultaneously monitor the line traveling wave signal.

According to operating experience, traveling wave will be reflected when it meets the substation, resulting in failure to accurately extract the waveform of the original traveling wave. In order to avoid the effect of traveling wave reflection, the distance between monitoring terminals and substations should be large enough.

In Figure 2, #n tower is 14587m away from the N station, and the traveling wave speed is 293m/μs. Calculation result shows that when traveling wave main pulse duration is less than 99.6μs, reflected wave will not overlap with original traveling wave. The duration of most of the traveling wave pulses in the actual measurement is less than 100μs, therefore, the monitoring method in Figure 2 can avoid the influence of the reflected wave from the substation.

3.2 Principle of monitoring terminal

Monitoring terminals acquire energy through coupled CT, collects the line traveling wave in real time, and sends data to the data center remotely through the wireless 4G mode. In order to accurately monitor and restore the line traveling current, the terminal adopts a closed Rogowski coil as a sensor, adopts self-integral form, and its output is
\[ e(t) = -M \frac{di_1(t)}{dt} = L_0 \frac{di_2(t)}{dt} + (R_0 + r)i_2(t) \] (6)

Where \( i_1(t) \) is the current on the wire, \( M \) is the mutual inductance between the Rogowski coil and the wire, and \( L_0, R_0, C_0 \) and \( r \) are the sensor coil self-inductance, internal resistance, distributed capacitance, and integral resistance, respectively. \( i_2(t) \) is the current on the integrating resistor. Since \( R_0 + r \) is small for self-integration, when the waveform frequency is high, it satisfies \( wL_0 \gg R_0 + r \), then

\[ e(t) \approx \frac{Mr}{L_0} i_1(t) \] (7)

By collecting \( e(t) \), the traveling wave waveform of the transmission line can be accurately obtained.

### 4 Analysis and discussion of measured waveform

#### 4.1 Typical measured traveling wave of transmission line

Figure 3 and 4 are typical traveling wave waveforms monitored by distributed traveling wave monitoring system, in which Figure 3 is line mode traveling wave, and Figure 4 is zero mode traveling wave. Through traveling wave location analysis, the traveling wave is transmitted from the M substation to the transmission line, and then passes through \#i, \#j, \#m and \#n towers.

**Figure 3.** Traveling wave of air mode at different monitoring points

**Figure 4.** Traveling wave of earth mode at different monitoring points

As can be seen from Figure 3 and Figure 4, the amplitude of the line mode traveling wave attenuates with the increase of the propagation distance. The distance between \#i tower and \#j tower is 60059m, and when the traveling wave is transmitted from \#i to \#j, the amplitude is reduced by 21.2%. In addition, the characteristic of the line mode traveling wave of different measurement points is similar.

Compared with the line mode traveling wave, the amplitude of zero mode attenuates faster with the increase of propagation distance. After spreading 60059m, the amplitude of the zero mode traveling wave attenuates 50.4%. At the same time, the pulse width of the zero mode traveling wave increases significantly, and the rising and falling edges of the wave form become more slowly.

#### 4.2 Influence of propagation distance on attenuation characteristics of traveling wave

In this paper, the transmission characteristics of traveling waves are quantitatively analyzed by Discrete Fourier transform. It is assumed that the traveling wave sampling rate is \( f_s \), the length is \( N \), and the traveling wave waveform sequence is \( x[n] \), where \( n=0, 1...N-1 \). Discrete Fourier transform is performed on \( x[n] \), and then a complex sequence \( X[k] \) is obtained, where \( k=0, 1...N-1 \). According to the properties of the discrete Fourier transform, \( X[k] \) corresponds to the component of the original signal with a frequency of \( k \times f_s / N \) (\( 1 \leq k < N/2 \)), and the mode value is \( N/2 \) of the same frequency component of the original signal. Define as follows:
In formula (8), $P(i)$ is the power of components of the original traveling wave which frequency is $k*f/N$. According to the formula (8), the power spectrum of traveling wave is analyzed. Power spectrum of the line mode traveling wave of #n tower in Figure 3 and the zero mode traveling wave of #n tower in Figure 4 are shown as Figure 5 and Figure 6, respectively.

![Figure 5. Power spectrum traveling wave of air mode at #n](image1)

![Figure 6. Power spectrum traveling wave of air mode at #n](image2)

Since the proportion of the frequency components above 200 kHz in actual traveling wave is mostly less than 1%, Figure 5 and Figure 6 show the power spectrum distribution in the 0-200 kHz section. From Figure 5 and Figure 6, it can be seen that components above 40 kHz of the line mode traveling wave still exist after transmission at a distance of 60059m, while the components above 40 kHz in the zero mode traveling wave have almost disappeared.

The attenuation rate of traveling wave is defined as follows.

$$\eta = \frac{\sum_{n,m} P_0(i) - \sum_{n,m} P(i)}{\sum_{n,m} P(i)} \times 100\%$$ (9)

In formula (9), $\sum_{n,m} P_0(i)$ and $\sum_{n,m} P(i)$ represent the sum of power of components in frequency band $[m,n]$ of travelling wave at #i tower and #c tower, respectively, and c=j, m, n. Attenuation rate of different frequency line mode and zero mode traveling wave at different measuring points are shown in Table 3.

### Table 3. Attenuation of power spectrum in different frequency bands at different monitoring points

| travelling wave type    | frequency band /kHz | #j  | #m  | #n  |
|-------------------------|----------------------|-----|-----|-----|
| line mode travelling wave | 0–10                | 1.7 | 3.1 | 5.6 |
|                         | 10–20                | 3.9 | 6.6 | 9.2 |
|                         | 20–40                | 7.5 | 11.2| 17.4|
|                         | 40–80                | 9.3 | 13.8| 19.9|
|                         | 80–160               | 12.1| 15.6| 22.3|
|                         | 0–10                 | 3.1 | 5.7 | 8.6 |
|                         | 10–20                | 5.4 | 9.3 | 18.9|
| zero travelling wave    | 20–40                | 10.6| 17.7| 27.8|
|                         | 40–80                | 24.1| 39.3| 54.4|
|                         | 80–160               | 38.4| 54.9| 76.6|
Data in Table 3 shows that attenuation rate increases when transmission distance increases, besides, the higher the frequency, the higher the traveling wave attenuation rate. In addition, the attenuation rate of the zero-mode traveling wave in the same frequency band is higher than that of the linear mode traveling wave, which are consistent with the theoretical analysis.

5 Conclusion
1) Method of decoupling balanced lines can be used to decouple asymmetrically arranged 110 kV lines with short transmission distances, and the decoupled coupling components account for only about 2%.
2) As the transmission distance increases, both the line mode traveling wave and the zero mode traveling wave attenuate, and the higher the frequency, the greater the attenuation.

References
[1] Dong Xinzhou, Ge Yaozhong, Xu Bingyin, et al. Study of transmission line fault location based on travelling waves and GPS technique. Automation of Electric Power Systems, 1996, 20(12): 39-42.
[2] PENG Xiayang, MAO Xianying, LI Xin, et al. Errors analysis of overhead transmission line fault location based on distributed travelling wave. High Voltage Engineering, 2013, 39(11): 2706-2713.
[3] XU Min, CAI Ze-xiang, LIU Yong-hao, et al. A novel fault location method for HVDC transmission line based on the broadband travelling wave information. Transactions of China Electro technical Society, 2013, 28(1): 259-265.
[4] MA Dandan, WANG Xiaoru. Single terminal methods of traveling wave fault location based on wavelet modulus maxima. Power System Protection and Control, 2009, 37(3): 55-59.
[5] Shu Hongchun, Cao Pulin, Dong Jun. Traveling wave transmission research for overhead lines of UHV half wavelength AC transmission lines considering frequency characteristics. High Voltage Engineering, 2015, 41(3): 716-723.
[6] Chen Shilong, Zhang Jie, Bi Guihong, et al. A fault location method for UHVDC transmission lines based on high frequency attenuation characteristics. Power System Protection and Control, 2014, 42(10), 77-83.
[7] Deri A, Tevan G, Semlyen A, et al. The complex ground return lane a simplified model for homogeneous and multi-layer earth return. IEEE Transactions on Power Apparatus and Systems, 1981, 100(8): 3686-3693.
[8] Ding Hongfa, Duan Xianzhong. Unbalance issue caused by un-transposed transmission lines and its solution. Power System Technology, 2004, 28(19): 24-28.
[9] Feng Wanxing, Yan Biwu, Zhao Chun. Application of lightning transient full response monitoring system in DC transmission line fault diagnosis. Insulators and Surge Arresters, 2015(6): 142-147.