Fault Location Technology of Transmission Line based on Asynchronous Phasor Measurement from PMUs

Che Xiaotao¹, Jian Hangli²* , Sun Qian², Shang Dong¹, Huangfu Wujun¹, Yang Shihui¹, Liu Weimin¹, Li Yalin¹, Shang De¹, Li Jiang²*

¹ State Grid Luoyang Electric Power Supply Company, Luoyang, Henan, 471000, China
² School of Electrical Engineering, Northeast Electric Power University, Jilin City, Jilin Province, 132012, China

Corresponding author’s e-mail: 2202000261@neepu.edu.cn

Abstract: With the continuous expansion of the scale of the modern power system, when the fault occurs at transmission networks, it will have a serious impact on the economy and people's life. In this paper, a fault location method based on synchronous phasor measurement from the phasor measurement unit (PMU) is proposed in transmission networks. Firstly, the real-time synchronous voltage and current phasors of the transmission lines are measured by the PMU at two buses. Then, the characteristic impedance and propagation coefficient of the line is calculated according to the measurement phasors, and the fault point voltage is listed at both ends of the line. Finally, the fault distance is obtained by solving the complex equation under fault condition at both ends to realize the fault location of transmission networks without branches. Compared with the single-terminal fault location method, the proposed method can eliminate the errors caused by various factors, such as the uneven distribution of capacitance and the uncertain transition resistance. At the same time, this paper uses PSACD software to build a model to verify the effectiveness and superiority of the method.

1. Introduction

Nowadays, the interconnected grids have increased the complexity and scale of the grid structure. Because when a local power grid fails, it will cause a relevant effect on interconnected grids [1]. And when a serious fault occurs, it will cause the grid to stop or even collapse [2]. Therefore, fault location is an important link to ensure the safe and stable operation of the power grid [3].

The phasor measurement unit (PMU) is an essential device for analyzing the dynamic characteristic of the power grid. Phasor measurement needs the relative timestamp of the phasor angle at a specific time. To realize synchronous phasor measurement [4], it is necessary to assume a reference system and take GPS as the authoritative time source to complete the timestamp acquisition. However, asynchronous measurement difference has become an inevitable effect factor in fault location because of communication delay, missing data, network blocking, and so on. At present, the methods of fault location include mainly the traveling wave-based method [5] and impedance-based method [6].

The traveling wave transmission theory was first proposed in the 1950s. With the rapid development of computer technology and traveling wave transmission theory, traveling wave-based fault location is widely used in transmission networks. The traveling wave-based fault location
method mainly uses transient current, voltage traveling wave, or temporary signal of circuit breaker reclosing to implement fault location. It can be divided into six kinds of ranging methods: A, B, C, D, E, F [7]. The traveling wave-based method is not affected by the model of the system and the change of the transition resistance, which has the advantages of high accuracy and strong applicability [8]. There are also the high-cost problem and the invalid short-line network, which is too short to detect the fault by using the traveling wave signal.

The basic principle of the impedance-based fault location method is to calculate the line impedance by using measured voltage and current phasors, whose impedance is proportional to fault distance [9]. Furthermore, the impedance-based method can be divided into a single end distance measurement method and a double end distance measurement method [10]. The single-ended method only needs to collect the voltage and current signals at one end, which is easy. However, it is greatly affected by the operation mode, system parameters, transition resistance, and other factors [11]. The two-terminal methods are developed based on the single-terminal method. There are measurement devices at both ends, which can collect information at the same time. The asynchronous measurement problem is inevitable because of the communication delay. Thus, the standard fault location method in a large-scale power grid system is the double terminal fault location method [12]. However, the impedance-based method needs to measure voltage and current phasor without additional devices for the current measurement. In contrast, the traveling wave-based method has to install a traveling wave device with a higher sampling frequency. Thus, the hardware cost is higher [13-15].

In this paper, an asynchronous measurement-based fault location algorithm is proposed, which is compared with the synchronous measurement-based location algorithm. In Section 2, the on-line estimation method of line parameters is introduced. In Sections 3 and 4, the PMU synchronous and asynchronous measurement-based fault location algorithm is explained. In Section 5, the simulation experiment and comparative analysis of the two algorithms are carried out, and the feasibility of the proposed method is verified.

2. Transmission lines model with distributed parameter
Transmission line parameters are usually shown by using π type lumped model. However, line parameters may be affected by various external factors, such as environment, climate, geology, etc. [16,17]. If the fault location still uses fixed parameters, the accuracy of fault location will be significantly affected [18, 19]. The synchronous measurement data provides a feasible condition for obtaining the real-time parameters of transmission lines [20]. The model of the transmission line under the fault is shown in Figure 1.

![Figure 1](image)

**Figure 1.** The transmission line under the fault

In Figure 1, l is the line length, x is the distance from the fault point to the G end, and l-x is the distance from the fault point to the H end.

In [21], the lumped parameter model of the transmission line is adopted, and the influence of distributed capacitance is ignored. Generally, the proposed method in [21] can only be used in the case of a short transmission line, but the error is large for the long-distance high-voltage transmission lines with distributed parameters. If the distributed parameters are not considered, the fault location accuracy will be affected. Thus, this paper adopts the distributed parameter model shown in Figure 2 [22].
In Figure 2, the voltage and current phasor at the G terminal can be expressed by using the voltage and current phasors at the H terminal. Taking the above model as an example, hyperbolic trigonometric equations, as shown in (1) and (2) are listed.

\[ \hat{U}_g = \hat{U}_h \cosh \gamma l - \hat{I}_h Z_c \sinh \gamma \]  
\[ \hat{I}_g = \hat{U}_h \sinh \gamma l/Z_c - \hat{I}_h \cosh \gamma l \]  

Where \( \hat{I}_g \) and \( \hat{U}_g \) are current and voltage phasors from PMU at G terminal before fault respectively; \( \hat{I}_h \) and \( \hat{U}_h \) are current and voltage phasors at H terminal from PMU before fault respectively; \( l \) is the length of the line, \( \gamma \) is the transmission coefficient of the transmission line, \( Z_c \) is the characteristic impedance, \( \cosh \) and \( \sinh \) are hyperbolic cosines and hyperbolic sine functions respectively.

By solving equations (1) and (2), we can get the following results:

\[ Z = \frac{1}{\gamma} \frac{\hat{U}_g \hat{I}_G - \hat{U}_H \hat{I}_H}{\hat{U}_H \hat{I}_G - \hat{U}_G \hat{I}_H} \]  
\[ Y = \frac{\gamma Z_c}{Y} \]  

According to the system definition, \( \gamma = \sqrt{Z Y} \) and \( Z_c = \sqrt{Z Y} \) are substituted into the above formula to obtain the distribution impedance \( Z \) and admittance \( Y \) as follows:

\[ Z = \gamma Z_c \]  
\[ Y = \gamma Z_c \]  

It can be seen from (5) and (6) that the parameters of the line can be obtained on-line according to the real-time synchronous data from PMU. In the above formulas, each voltage and current can be expressed by sequence component or mode component by symmetrical component method, and the obtained line parameters also correspond to their sequence component or mode component parameters.

3. Fault location algorithm

The measurement data of PMU has a unified timestamp from GPS satellites for the whole network [23]. Also, the fault location results obtained by synchronous measurement data under the same timestamp have good adaptability under various operation modes [24]. Therefore, fault location based on PMU dual terminal synchronous data can significantly improve the location accuracy.

In Figure 1, \( Z_c = \sqrt{R^2 + jQ} \) and \( \gamma = \sqrt{(R + jQ)(G + jC)} \) represents the characteristic impedance and propagation coefficient of the line in the two-terminal power supply system respectively. R, G, L, and C are the resistance, conductivity, inductance, and capacitance per unit length of the transmission line in Figure 2 respectively.
When the fault occurs at Point F, the two end phasors of fault point can be obtained by the PMUs at G end and H end respectively:

\[ U_F = U_G \cosh \gamma x - i_G Z_c \sinh \gamma x \]  
(7)

\[ \dot{U}_F = \dot{U}_H \cosh \gamma (l-x) - i_H Z_c \sinh \gamma (l-x) \]  
(8)

Since the voltage at the fault point cannot be changed suddenly, the calculated voltage phasors from the two-terminal measurements are equal. The complex equation is as follows:

\[ U_G \cosh \gamma x - i_G Z_c \sinh \gamma x = \dot{U}_H \cosh \gamma (l-x) - i_H Z_c \sinh \gamma (l-x) \]  
(9)

Where \( \cosh(\gamma x) = \frac{e^{\gamma x} + e^{-\gamma x}}{2} \), \( \sinh(\gamma x) = \frac{e^{\gamma x} - e^{-\gamma x}}{2} \), \( x = \alpha + j\beta \). These three formulas can be simplified into the formula (10)

\[ e^{2\gamma x} = \frac{2(\alpha + j\beta)x}{U_G - i_G Z_c - (U_H + i_H Z_c)e^{-\gamma l}} = A + jB \]  
(10)

Where \( \alpha \) is a real number, \( A \) is the whole part of the complex number obtained, and \( B \) is the imaginary part of the complex number. Similarly,

\[ e^{2\alpha x} = \frac{U_H - i_H Z_c e^{\gamma l} - U_G - i_G Z_c}{U_G - i_G Z_c - (U_H + i_H Z_c)e^{-\gamma l}} = \sqrt{A^2 + B^2} \]  
(11)

The fault distance is obtained:

\[ x = \frac{0.25 \ln(\alpha^2 + B^2)}{\alpha} \]  
(12)

By using the imaginary part \( B \), another expression can be obtained:

\[ x = \frac{1}{2\beta} \arctan \left( \frac{B}{A} \right) \]  
(13)

In the high voltage alternative current (HVAC) transmission line model, the imaginary part \( \beta \) of \( \gamma \) is much larger than the real part \( \alpha \), that is, \( \beta \gg \alpha \). Thus, the stability and accuracy of formula (13) are better than that of formula (12), and this paper uses the formula (13) to implement the fault location.

From the above, it can be seen that the fault location algorithm based on the distributed parameter model eliminates the errors from the unevenly distributed capacitance and the transition resistance.

4. Fault location under asynchronous measurement

The fault location accuracy under asynchronous PMU data is analyzed in this section. The phasor angle difference is set as \( \delta \) between the two end phasors with PMU, which is caused by communication delay, missing data, network blocking, data fusion, and so on [25, 26].

In Figure. 1, the complex equations can be written by setting the phase angle difference, and the influence of line parameter error is taken into account in (14) an (15).

\[ U_G e^{j\delta} = U_H \cosh(1+\alpha) \gamma l - i_H Z_c \sinh(1+\alpha) \gamma l \]  
(14)

\[ i_G e^{j\delta} = i_H \sinh(1+\alpha) \gamma l / Z_c - i_H \cosh(1+\alpha) \gamma l \]  
(15)

Where, \( i_G \) and \( U_G \) are current and voltage phasors before fault at G-terminal respectively; \( i_H \) and \( U_H \) are current and voltage phasors before fault at H-terminal respectively; \( l \) is the length of the
line, \( \gamma \) is the transmission coefficient of the transmission line, \( Z_c \) is the characteristic impedance, \( \cosh \) and \( \sinh \) are hyperbolic cosines and hyperbolic sine functions respectively.

The above parameters are known variables, and the unknown parameters are error reduction coefficient \( \alpha \) and phasor angle difference \( \delta \). The error reduction coefficient can be obtained by solving equations (15) and (16) simultaneously:

\[
\alpha = \frac{1}{\gamma} \arctan \left( \frac{I_H \overline{U} + iG \overline{U}_H}{Z_c + iH \overline{I}_G Z_c} \right) - 1
\]

Substituting the \( \alpha \) obtained from equation (16) into (14), the unsynchronized angle at both ends can be obtained as follows:

\[
\delta = \arg \left( \frac{\cosh(\gamma l + \alpha) - \cosh(\gamma l)}{\frac{\cosh(\gamma l - \alpha) \sinh(\gamma l + \alpha)}{U_G}} \right)
\]

When the fault occurs at point F, the data of G end and H end can be written into equation:

\[
\begin{align*}
U_F &= U_G e^{i\delta} \cosh(\gamma x) - i_G e^{i\delta} Z_c \sinh(\gamma x) \\
U_F &= U_H \cosh(\gamma (l-x)) - i_H Z_c \sinh(\gamma (l-x))
\end{align*}
\]

According to the simultaneous equations (18) and (19), the following results can be obtained:

\[
\begin{align*}
\frac{U_G \cosh(\gamma x) - i_G Z_c \sinh(\gamma x)}{e^{i\delta} = U_H \cosh(\gamma (l-x)) - i_H Z_c \sinh(\gamma (l-x))}
\end{align*}
\]

Substitute \( \cosh(\gamma x) = e^{2x} + e^{-\gamma x} \) and \( \sinh(\gamma x) = e^{2x} - e^{-\gamma x} \) into the above formula (20):

\[
e^{2(\gamma x)} = e^{2(m+jn)x} = e^{2(m+jn)x} = \frac{(U_H - i_H Z_c)e^{(1+\alpha)\gamma l}(U_G + i_G Z_c)e^{i\delta}}{(U_G - i_G Z_c)e^{i\delta}(U_H + i_H Z_c)e^{(1+\alpha)\gamma l}} = A + jB
\]

In the above formula (21), \( A \) and \( B \) are the real and imaginary parts of the simplified complex number. It can be obtained from the fact that the phase angles of complex numbers at both ends are equal \( 2nx = \arctan \left( \frac{B}{A} \right) \). Then, the fault distance can be obtained

\[
x = \frac{1}{2n} \arctan \left( \frac{B}{A} \right)
\]

The asynchronous phase angle difference \( \delta \) and error \( \alpha \) at two terminals are calculated according to (16) and (17) under the normal operation condition. The measurement data from PMU are substituted into equations (21) and (22) to calculate the distance \( x \). The relation between \( \delta \) and \( \alpha \) is shown in Figure 3. According to the image, as the length of the line is longer, the different angles of the two ends become larger, and the angle of the two ends asynchrony reaches the maximum when it is close to 3000km.
5. Case study

5.1 Parameters

To verify the effectiveness of the proposed on-line estimation algorithm, PSCAD is used to simulate the 500 kV transmission line model with total length \( l = 300 \text{km} \) in Figure 4. The parameters are as follows: the rated frequency 50 Hz, the positive sequence impedance \( Z_{G1} = 9.19 + j52.10 \Omega \), the zero-sequence impedance \( Z_{G0} = 6.69 + j37.92 \Omega \), the positive sequence impedance at H terminal bus \( Z_{H1} = 8.19 + j42.11 \Omega \), and zero sequence impedance at H terminal bus \( Z_{H0} = 6.52 + j34.16 \Omega \). The distribution parameters are: \( Z_{L} = 0.035 + j0.43 \Omega / \text{km} \), \( Z_{Z} = 0.30 + j1.15 \Omega / \text{km} \), \( Y_{1} = (0.1 + j2.73) \times 10^{-6} \text{S/km} \), \( Y_{0} = (0.1 + j1.95) \times 10^{-6} \text{S/km} \).

The fundamental component is extracted from the measurement phasors and substituted into equations (3), (4), and (13) to realize fault location. The calculated line parameters by formula (3) and (4) are: transmission coefficient \( \gamma = 0.0000658 + j0.00106 \) and \( Z_c = 394.89 - j8.89 \). To analyze the influence of line parameters on fault location accuracy, the given parameter error 1\% is used in this section. The output ranging results are shown in Tables 1 and 2. To discuss the accuracy of fault location under different parameters, the fault location error is defined as follows:

\[
E\% = \frac{\text{Positioning results} - \text{Actual fault distance}}{\text{Total length of line}} \times 100\%
\]  

(23)

5.2 Comparative analysis

The simulation model of the 500kV power supply system in Figure 4 is a built-in simulation software PSCAD. In Figure 4, the total line length is 300km, the transition resistance is 50 \( \Omega \), and the fault occurs at \( t = 0.35s \). The voltage phase angle difference between the two ends of the power supply is 20\(^\circ\) for the phasors from PMU.

The two fault location algorithms are simulated under synchronous and asynchronous measurement data with the transition resistance 50 \( \Omega \), whose results and error under different fault types and fault locations are shown in Tables 1 and 2. From the Table 1 and 2, it can be seen that the location accuracy in the middle area is better than that in the front area by using the double terminal synchronous fault location method or the dual terminal asynchronous fault location method. When the fault occurs in the front area of the line, the double terminal synchronous fault location method is better than the two-terminal asynchronous fault location method. When the fault occurs in the middle area of the line, the fault location accuracy of the two terminal synchronous fault location method is better than the two-terminal asynchronous fault location method in most cases. When three-phase short-circuit fault occurs, the algorithm has the highest accuracy and the smallest error. Furthermore, the measurement error of the single-phase grounding fault is relatively more extensive, but it can still meet the accuracy requirements.
Tab.1 Distance measurement results and errors

| Fault Type                  | Fault Location /km | Asynchronous Ranging Results/km | Error/% | Synchronous Ranging Results/km | Error/% |
|-----------------------------|--------------------|---------------------------------|---------|--------------------------------|---------|
| Single line-to-ground fault |                    |                                 |         |                                |         |
| 10                          | 15.48              | 1.83                            | 11.74   | 0.58                           |
| 30                          | 31.77              | 0.59                            | 31.35   | 0.45                           |
| 270                         | 271.46             | 0.54                            | 268.95  | 0.35                           |
| 290                         | 285.82             | 1.39                            | 288.38  | 0.54                           |
| 10                          | 15.43              | 1.81                            | 11.32   | 0.44                           |
| 30                          | 31.11              | 0.37                            | 30.55   | 0.18                           |
| 270                         | 270.42             | 0.14                            | 269.81  | 0.06                           |
| 290                         | 285.54             | 1.49                            | 291.23  | 0.41                           |
| 10                          | 14.85              | 1.62                            | 11.86   | 0.62                           |
| Interphase fault            |                    |                                 |         |                                |         |
| 30                          | 30.72              | 0.24                            | 29.61   | 0.13                           |
| 270                         | 270.45             | 0.15                            | 270.51  | 0.17                           |
| 290                         | 285.63             | 1.46                            | 288.95  | 0.35                           |
| 10                          | 15.02              | 1.67                            | 10.96   | 0.32                           |
| Two-phase ground short circuit |                |                                 |         |                                |         |
| 30                          | 30.78              | 0.26                            | 30.25   | 0.08                           |
| 270                         | 270.63             | 0.21                            | 269.69  | 0.10                           |
| 290                         | 285.16             | 1.61                            | 290.84  | 0.28                           |
| Three-phase short circuit   |                    |                                 |         |                                |         |
| 10                          | 14.85              | 1.62                            | 11.86   | 0.62                           |

The faults under different sections are simulated, and the simulation results are shown in Table 3.

Tab.2 Distance measurement results and errors in the central region

| Fault Type                  | Fault Location /km | Asynchronous Ranging Results/km | Error/% | Synchronous Ranging Results/km | Error/% |
|-----------------------------|--------------------|---------------------------------|---------|--------------------------------|---------|
| Single line-to-ground fault |                    |                                 |         |                                |         |
| 100                         | 101.29             | 0.43                            | 100.37  | 0.21                           |
| 150                         | 150.69             | 0.23                            | 149.97  | 0.01                           |
| 200                         | 200.75             | 0.25                            | 199.64  | 0.12                           |
| 250                         | 249.01             | 0.33                            | 248.98  | 0.34                           |
| 100                         | 101.14             | 0.38                            | 100.03  | 0.17                           |
| 150                         | 150.54             | 0.18                            | 149.96  | 0.01                           |
| Interphase fault            |                    |                                 |         |                                |         |
| 100                         | 101.23             | 0.41                            | 99.64   | 0.12                           |
| 200                         | 200.75             | 0.29                            | 199.85  | 0.05                           |
| 250                         | 250.93             | 0.31                            | 249.43  | 0.19                           |
| Two-phase ground short circuit |                |                                 |         |                                |         |
| 150                         | 150.21             | 0.23                            | 149.88  | 0.04                           |
| 200                         | 200.69             | 0.18                            | 199.85  | 0.05                           |
| 250                         | 250.75             | 0.25                            | 249.58  | 0.14                           |
| 100                         | 100.54             | 0.18                            | 100.24  | 0.08                           |
| 150                         | 149.58             | 0.14                            | 149.94  | 0.02                           |
| Three-phase short circuit   |                    |                                 |         |                                |         |
| 200                         | 200.48             | 0.16                            | 199.79  | 0.07                           |
| 250                         | 249.37             | 0.21                            | 249.70  | 0.10                           |

Tab.3 Error comparison under synchronous and asynchronous measurement at G

| Fault Type                  | Fault Location /km | Asynchronous Ranging Results/km | Error/% | Synchronous Ranging Results/km | Error/% |
|-----------------------------|--------------------|---------------------------------|---------|--------------------------------|---------|
| Single line-to-ground fault |                    |                                 |         |                                |         |
| 20                          | 21.38              | 0.46                            | 19.64   | 0.12                           |
| Interphase fault            |                    |                                 |         |                                |         |
| 25                          | 25.55              | 0.18                            | 24.55   | 0.15                           |
| Two phase ground short circuit |                |                                 |         |                                |         |
| 180                         | 179.85             | 0.05                            | 179.97  | 0.01                           |
| Three phase short circuit   |                    |                                 |         |                                |         |
| 135                         | 134.88             | 0.04                            | 134.97  | 0.01                           |

To compare the errors under synchronous and asynchronous measurement data, the error comparison is drawn in Figure 5. In Figure 5, the fault location accuracy under asynchronous measurement has been improved, but the error is larger than that under synchronous measurement, which is not affected by fault location, transition resistance, and other factors. It is proved that the
dual terminal synchronous fault location algorithm can significantly improve the fault location accuracy.

![Figure 5. Error comparison under different faults](image)

6. Conclusion
This paper proposes a fault location algorithm based on the distributed parameter model for PMU with dual terminal asynchronous phasor data. It eliminates various factors' effects on fault location accuracy. The comparative analysis of the simulation results shows that the dual terminal fault location algorithms under synchronous measurement from PMU has good adaptability to various fault situations and is not affected by the transition resistance, fault location, system operation mode, and other factors. In the future, it has excellent numerical stability and can improve the reliability for fault identification.

ACKNOWLEDGMENTS
This research is supported by *Synchronous Phasor Measurement and Fault Location Technology based on NB-IoT in Distribution Networks*, 2020 Scientific Development Plan of State Grid Henan Province Electric Power Company, No. 5217A020000Y

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