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Fault location method for transmission grids based on time difference of arrival of wide area travelling wave

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Abstract: In allusion to fault location failure on wide area travelling-wave-based fault location methods caused by the indeterminate shortest transmission path of initial travelling wave and the inaccurate travelling wave velocity, this study proposed a novel fault location method for complex transmission grids based on the time difference of arrival of wide area travelling wave. Firstly, the shortest transmission path in the loop network is determined online by using the time difference of arrival of the initial travelling wave measured at both ends of the fault line. Then, the travelling wave velocity and accurate fault distance are calculated by fusing arrival time of wide area initial travelling waves via the least-square estimation. The phase current travelling wave is used for the proposed method, and the S transform is used for detecting the arrival time of phase current travelling wave at the Nyquist frequency. The proposed method avoids the phase-mode transformation and the matching between the actual fault condition and the pre-determined shortest transmission path. The proposed method can also exactly calculate the fault distance without obtaining the travelling wave velocity. The performance of the proposed method is verified by the power systems computer aided design/electro magnetic transients in DC system (PSCAD/EMTDC) simulation results.

1 Introduction

With the development of the global energy Internet, the smart grid and the ultra-high voltage grid have become the future development mode of transmission grids, under these circumstances, the demand for safe and reliable operation of transmission grids is increasing. The fast, accurate and automatic fault location technology is the key to repair the fault line timely and reduce the outage time. It is the basis for ensuring the safe and reliable operation of the transmission grids; meanwhile, it is the technical problem to be solved urgently in power system [1, 2].

Techniques used in locating the fault on transmission line can be broadly classified into two categories: (i) impedance-based method [3–5]; and (ii) travelling-wave-based method [6–11]. Comparing with impedance-based method, travelling-wave-based method is immune to fault condition (fault type, fault resistance, fault-inception angle, and system parameters) and have high accuracy of fault location. Therefore, studies on travelling-wave-based method are increasing rapidly.

Travelling-wave-based method locates the fault by exploiting the correlation among the arrival time of travelling wave, the travelling wave velocity and the fault distance; and the aerial-mode component of travelling wave obtained by the phase-mode transformation is generally used for the travelling-wave-based methods, because its propagation velocity is relatively stable. According to the type of available measurements, the conventional travelling-wave-based method can be classified into single-ended algorithm [6–8] and double-ended algorithm [9–11]. However, the conventional travelling-wave-based method only target on single transmission line throughout the whole transmission grids, and is confronted location failure risk when one locating device invalidates, startup fails, or an error arrival time of the travelling wave is recorded. Therefore, the reliability and precision of the fault location can hardly be guaranteed.

At present, in parallel with the development of the wide-area synchronised measurements, travelling-wave-based methods are not limited using local measurements but data acquisition over the whole network. In an effort to accurately locate faults based on the wide area travelling wave, the authors of [12–14] have already proposed the fault location methods based on wide area travelling wave for transmission grids. In fact, it is shown that the wide area travelling-wave-based fault location method is an extended double-ended travelling wave fault location principle which is fusing the redundant measurement information of wide area travelling wave, and can overcome the above defects of the conventional travelling-wave-based method. However, when applied to the complex transmission grids, the wide area travelling-based method may fail to locate the fault correctly. Indeed, the main drawbacks of wide area travelling-wave-based method for transmission grids depends on the following two facts: (i) the shortest transmission path of initial travelling wave in the loop network cannot be determined uniquely; and (ii) the travelling wave velocity in wide area transmission grids cannot be accurately calculated.

The existing research on determination method for the shortest transmission path mainly uses the path searching algorithms in the computer field, such as the Floyd algorithm [15] and the Dijkstra algorithm [16]. In addition, the determination method based on the network topology structure and travelling wave measurement information is proposed in [17, 18]. The methods above are essentially offline determination methods. These methods require that the shortest transmission path matched with the pre-set fault condition is pre-determined. Then, the fault condition judgement (i.e. judging the actual fault belongs to which kind of the pre-set faults) based on the protection action information [15, 16] or travelling wave measurement information [17, 18] is performed to match the actual fault condition and the pre-determined shortest transmission path. As these methods require pre-processing of the whole power network data for each pre-set fault condition, these methods have the disadvantages of the huge calculation amount and the complicated implementation procedure. More important, the calculation result in [15, 16] may not contain the fault line, which may seriously reduce the accuracy of fault location. In fact, the online measurement information, such as arrival time of travelling wave, contains abundant fault information, which can be used for determining the shortest transmission path. However, there is no report on the online-information-based determination method at present.

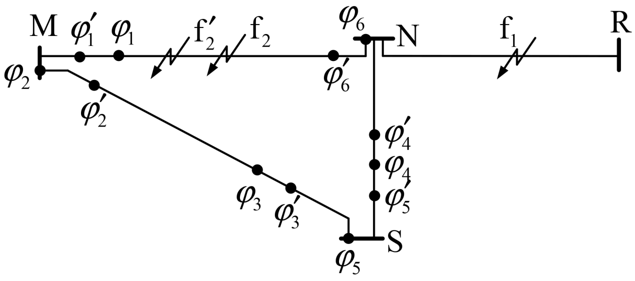

Fig. 1 *Diagram of typical loop network structure*

Since the accuracy of fault location is directly affected by the calculation accuracy of the travelling wave velocity, the accurate calculation method for the travelling wave velocity has received widely attention. The existing calculation method for the travelling wave velocity mainly contains the theoretical calculation method [19] and the online calculation method [20]. The theoretical method requires the line parameters at the non-power frequency. As the line parameters at the non-power frequency can hardly be obtained, the theoretical method is difficult to apply. When an external fault or disturbance occurs, the online method calculates the travelling wave velocity on the non-fault line by using the correlation between the arrival time of the initial travelling wave and the length of the line; however, its calculation accuracy is significantly affected by the detection error of the arrival time. It is should be pointed out that the travelling wave velocity is generally considered to be known in the existing travelling-wave-based fault location methods, so that it is essential to calculate the travelling wave velocity before calculating the fault distance. In fact, because the redundant data is used for wide area travelling-wave-based method for fault location, the dimension of the fault location equation is increased. Accordingly, we can adopt a novel idea to implement wide area travelling-wave-based fault location: the travelling wave velocity as well as the fault distance are regarded as the unknown parameters, and are solved simultaneously. Since this novel idea avoids calculating travelling wave velocity in advance, the influence of the calculation accuracy of the travelling wave velocity on the accuracy of fault location can be eliminated.

In this paper, a novel fault location method for complex transmission grids based on the time difference of arrival of wide area travelling wave is proposed. Firstly, the shortest transmission path of initial travelling wave in the loop network is determined online by comparing the reference time difference of arrival of the initial travelling wave with the measured time difference of arrival. Then, based on the redundant time difference of arrival of the initial travelling wave, the travelling wave velocity and the fault distance are calculated accurately by using the least-square estimation. Meanwhile, the phase current travelling wave is used for the proposed method, and the S transform is used for detecting the arrival time of phase current travelling wave at the Nyquist frequency. The proposed method avoids the phase-mode transformation as well as the matching between the actual fault condition and the pre-determined shortest transmission path. In addition, the proposed method can accurately calculate the fault distance without obtaining the travelling wave velocity in advance, so that the fault location precision is immune to the calculation error of the travelling wave velocity. PSCAD/EMTDC simulation results show that the precision, reliability, tolerant ability and adaptability of the proposed method can be guaranteed.

2 Analysis of the shortest transmission path

The fault location method based on the wide area travelling wave can be understood as an extended double-ended travelling wave fault location method. The double-ended method is shown as

$$d_{\rm M} = \frac{(t_{\rm M} - t_{\rm N})v + l_{\rm MN}}{2} \tag{1}$$

where the $d_{\rm M}$ is the distance from the fault point to the measuring point M, $l_{\rm MN}$ is the length of the shortest transmission path between M and N, $t_{\rm M}$ and $t_{\rm N}$ are, respectively, the arrival time of initial travelling wave to busbar M and N. It should be notice that the shortest transmission path must include the fault line, otherwise the fault distance cannot be calculated correctly. It should be notice that the shortest transmission path must include the fault line.

According to (1), double-ended method needs to determine the shortest transmission path between the two measuring points. Correspondingly, the fault location method based on the wide area travelling wave needs to determine the shortest transmission path in the wide area power grid. However, if the loop network exists in the transmission grid, the shortest transmission path cannot be directly determined and needs further analysis.

The typical structure of the loop network shown in Fig. 1 is used for the analysis. In Fig. 1, M, N, R and S represent the busbar. In addition, let l_{ij} represent the transmission line length between i and j, and let $L_{ij}^{\rm shortest}$ represent the shortest transmission path between i and j, i and j can be the busbar or fault point.

2.1 External fault

Assuming that the fault occurs at the f_1 in Fig. 1, let $L_{\rm MNS}^{\rm shortest}$ represents the shortest transmission path in the loop network. $L_{\rm MNS}^{\rm shortest}$ consists of $L_{\rm MS}^{\rm shortest}$ and $L_{\rm NS}^{\rm shortest}$. According to Fig. 1, $L_{\rm MS}^{\rm shortest}$ and $L_{\rm NS}^{\rm shortest}$ are described as

$$\begin{aligned} L_{\rm MN}^{\rm shortest} &= \min\{l_{\rm MN}, l_{\rm MS} + l_{\rm NS}\} \\ L_{\rm NS}^{\rm shortest} &= \min\{l_{\rm NS}, l_{\rm MN} + l_{\rm MS}\} \end{aligned} \tag{2}$$

Let the N be the starting point for calculating the midpoint of the loop network. Assuming that the midpoint of the loop network is located on the transmission line MN, as the φ_1 shown in Fig. 1. According to the length of the loop network is describe as $l_{\rm MN} + l_{\rm NS} + l_{\rm MS}$, we get

$$l_{\rm MN} > l_{\rm NS} + l_{\rm MS};$$

- $l_{\rm NS} < l_{\rm MN} + l_{\rm MS}$.

According to (2), $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and NS.

Assuming that the midpoint is located at the busbar M, as φ_2 shown in Fig. 1, we obtain

$$l_{\rm MN} = l_{\rm NS} + l_{\rm MS};$$

- $l_{\rm NS} < l_{\rm MN} + l_{\rm MS}$.

Also $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and NS, or the transmission lines MS and NS.

Similarly, assuming that the midpoint is located at the φ_3, $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and NS. Assuming that the midpoint is located at the φ_4, $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and MS. Assuming that the midpoint is located at the φ_5, $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and MS, or transmission line NS and MS.

Then the following conclusions can be drawn:

- When external fault occurs, the shortest transmission path in the loop network is related to the length relationship of the transmission line in the loop network;
- When the structure of transmission grid and the length of transmission line are known information, the shortest transmission path in the loop network can be determined by eliminating the line where the midpoint locates;
- When the midpoint locates at the busbar, arbitrarily eliminate a transmission line in the loop network associated with the busbar.

It is notice that the midpoint is relative to a starting point, and the starting point can be determined according to the direction of the initial travelling wave.

2.2 Internal fault

Assuming that the fault occurs at the f_2, which is the midpoint of the transmission line MN, as shown in Fig. 1. $L_{\rm MNS}^{\rm shortest}$ consists of $L_{f_2M}^{\rm shortest}$, $L_{f_2\rm N}^{\rm shortest}$ and $L_{f_2\rm S}^{\rm shortest}$. According to Fig. 1, $L_{f_2M}^{\rm shortest}$, $L_{f_2\rm N}^{\rm shortest}$ and $L_{f_2\rm S}^{\rm shortest}$ are described as

$$\begin{aligned} L_{f_2M}^{\rm shortest} &= \min\{l_{f_2M}, l_{f_2N}+l_{\rm NS}+l_{\rm MS}\} \\ L_{f_2N}^{\rm shortest} &= \min\{l_{f_2N}, l_{f_2M}+l_{\rm MS}+l_{\rm NS}\} \\ L_{f_2S}^{\rm shortest} &= \min\{l_{f_2N}+l_{\rm NS}, l_{f_2M}+l_{\rm MS}\} \end{aligned} \tag{3}$$

Let f_2 be the starting point. Assuming that the midpoint of the loop network is located on the transmission line MN, as φ_4 shown in Fig. 1. It is can be seen that

$$l_{f_2\rm M} < l_{f_2\rm N} + l_{\rm NS} + l_{\rm MS};$$

- $l_{f_2\rm N} < l_{f_2\rm M} + l_{\rm MS} + l_{\rm NS}$;
- $l_{f_2\rm N} + l_{\rm NS} > l_{f_2\rm M} + l_{\rm MS}$.

According to (3), $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and MS.

Assuming that the midpoint of the loop network is located on the transmission line MN (φ_1, φ_2, and φ_6 in Fig. 1), $L_{\rm MNS}^{\rm shortest}$ does not contain the fault line, the fault distance cannot be calculated correctly.

Similarly, assuming that the midpoint is of the loop network located at the φ_3, $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and NS. Assuming that the midpoint is located at the φ_5, $L_{\rm MNS}^{\rm shortest}$ consists of the transmission lines MN and MS, or transmission lines MN and NS.

Consider the more general case, assuming that the fault occurs at one of the random points on the transmission line MN, as the f_2' shown in Fig. 1. In this circumstance, it is equivalent to the f_2 moves $\Delta l'$ towards the busbar M. The φ_1, φ_2, φ_3, φ_4, φ_6 and φ_6 move $\Delta l'$ correspondingly, as φ_1', φ_2', φ_3', φ_4', φ_6' and φ_6' shown in Fig. 1. The $L_{\rm MNS}^{\rm shortest}$ can be determined according to the position of φ_1', φ_2', φ_3', φ_4', φ_6', φ_6', and the analysis method previous statement.

Then the following conclusions can be drawn:

- When internal fault occurs, the shortest transmission path in the loop network is related to the fault position and the length relationship of the transmission line in the loop network;
- When the fault position, the structure of transmission grid and the length of transmission line are known information. Let the fault position be the starting point for calculating midpoint of the loop network, the shortest transmission path in the loop network can be determined by eliminating the line where the midpoint locates;
- When the midpoint locates on the fault line, the fault distance cannot be calculated correctly.

2.3 Determination method of the shortest transmission path

For the external fault, the shortest transmission path in the loop network can be directly determined according to the conclusions in Section 2.1.

For the internal fault, the shortest transmission path in the loop network cannot be determined in advance due to the fault position is unknown information. However, the shortest transmission path can be determined online by using the time difference of arrival of the initial travelling wave. The fault occurs on the transmission line MN in the loop network is used for illustration.

The k is set on the line as the reference point MN, and calculates the midpoint of the loop network $\varphi *$ starting at k. Since the position of k is known information, the theoretical transmission time of the travelling wave from k to busbar M and from k to busbar N can be calculated theoretically by (4). Also the reference time difference Δt^* can be calculated by (5).

$$\begin{aligned} t_{\rm M}^* &= \frac{l_{\rm M\mathit{k}}}{v} \\ t_{\rm N}^* &= \frac{l_{\rm N\mathit{k}}}{v} \end{aligned} \tag{4}$$

$$\Delta t_{\rm MN}^* = t_{\rm M}^* - t_{\rm N}^* \tag{5}$$

where $t_{\rm M}^*$ and $t_{\rm N}^*$ are, respectively, the transmission time of initial travelling wave from k to busbar M and N, $l_{\mathrm{M}k}$ and $l_{\mathrm{N}k}$ are, respectively, the length of the transmission line from k to busbar M and from k to busbar N, v is the travelling wave velocity.

When the fault occurs, the time difference of arrival of the initial travelling wave between busbar M and N can be online calculated as

$$\Delta t_{\rm MN} = t_{\rm M} - t_{\rm N} \tag{6}$$

where $t_{\rm M}$ and $t_{\rm N}$ are the arrival time of initial travelling wave of busbar M and N, respectively.

The moving distance Δl of $\varphi *$ can be calculated as

$$\Delta l = \frac{(\Delta t_{\rm MN} - \Delta t_{\rm MN}^*)v}{2} \tag{7}$$

Assuming that the midpoint of the loop network starting at fault point is φ_f. If the $\Delta l < 0$, the φ_f is equivalent to $\varphi *$ moves $|\Delta l|$ towards busbar N. If the $\Delta l > 0$, the $\varphi_{\rm f}$ is equivalent to $\varphi *$ moves $|\Delta l|$ towards busbar M.

Then according to the conclusions in Section 2.2, the shortest transmission path in the loop network can be determined by

- Eliminating the line where the φ_f locates.

3 Fault location method based on wide area travelling wave

3.1 Selection of the travelling wave signal and detection of the arrival time

Selection of the travelling wave signal: the phase travelling wave signal generated by the fault contains the ground-model component and the aerial-mode component. The dispersion phenomenon of the ground-mode component is much more serious than the dispersion of the aerial-mode component, so that the propagation velocity of the aerial-mode component is more stable. Therefore, it is generally believed that the aerial-mode component is more suitable for travelling wave fault location. Correspondingly, the phase-mode transformation is universally used for extracting the aerial-mode component. In fact, the wide area travelling-wave-based fault location only request to acquire the arrival time of the initial travelling wave. Since the propagation velocity of the aerial-mode component is much faster than the propagation velocity of the ground-mode component, the arrival time of the initial travelling wave is essentially the arrival time of the aerial-mode component of the initial travelling wave. Thus, the phase travelling wave can be directly applied to travelling-wave-based fault location. It means that the phase-mode transformation can be avoided. Further, the travelling wave generated by the fault can be detected at both three phases, since the coupling between the three phases of the transmission line. Even so, travelling wave of the fault phase is more conducive to be accurately detected, because the travelling wave signal intensity of the fault phase is much stronger than the travelling wave signal intensity of the non-fault phase. Therefore, travelling wave of the fault phase is used for fault location in this

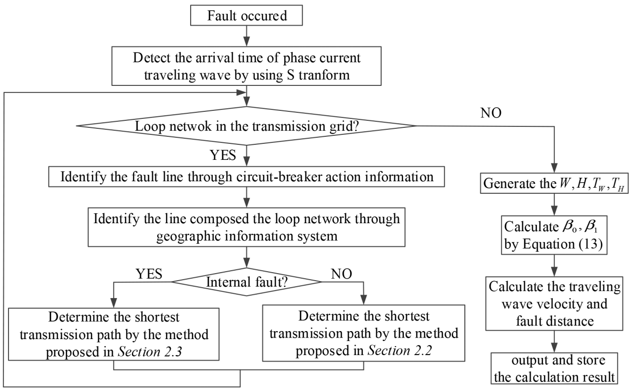

Fig. 2 *Fault location flowchart*

paper. It should be noted that the fault phase is not known in advance, but it can be determined by the existing fault phase selection method. Since fault phase selection is not the focus of this paper and its impact on the proposed fault location method is limited, this paper assumes that the fault phase is known. Meanwhile, the current travelling wave is used for fault location in this paper, because the measurement of the current travelling wave is more convenient.

Detection of the arrival time: since the redundant data is used for wide area travelling-wave-based method for fault location, the dimension of the fault location equation is increased. It implies that we can regard the travelling wave velocity as well as fault distance as the unknown parameters and can solve simultaneously, which avoids calculating travelling wave velocity in advance and the influence of the calculation accuracy of the travelling wave velocity on the accuracy of fault location can be eliminated. However, the dispersion of travelling wave is much serious in the wide area network, and even the velocity of the aerial-mode travelling wave is also uncertain (i.e. the travelling wave velocity on each line is different from the travelling wave velocity on any other line). The uncertainties of the travelling wave velocity may cause the number of unknown parameters more than the dimension of the fault location equation, which results that the fault location equation cannot be solved. Fortunately, the travelling wave velocity at each frequency is the constant; so that we can apply the travelling wave at the same frequency to wide area travelling-wave-based method for fault location to overcome the uncertainties of the travelling wave velocity. Therefore, in this paper, the S-transform-based detection method [21] is used for detecting the arrival time of phase current travelling wave at the Nyquist frequency, and the sampling time corresponding to the maximum amplitude value used as the arrival time of initial travelling wave.

3.2 Determination of the shortest transmission path

According to Section 2.3, external fault and internal fault have different determine methods of the shortest transmission path. Thus, it is should be able to identified the fault line and to determine whether the fault line in the loop network is the basis of the network topology information. If the fault line is the component of the loop network, the shortest transmission path can be determined by the method proposed in Section 2.2. If the fault line is not the component of the loop network, the shortest transmission path can be determined by the method proposed in Section 2.3. The fault line can be identified according to the circuit-breaker action information. Network topology information can be obtained by the geographic information system. The flowchart of determining the shortest transmission path is shown in Fig. 2.

3.3 Calculation of the travelling wave velocity and the fault distance

After detecting the initial travelling wave arrival time and determining the shortest transmission path. The busbars in the system are divided into two groups, one is the fault line upstream group $W = \{w_1, \ldots, w_m\}$, and another is the fault line downstream group $H = \{h_1, \ldots, h_n\}$. Correspondingly, the arrival time of initial travelling wave at the busbar can be divided into $T_W = \{t_{w_1}, \ldots, t_{w_m}\}$ and $T_H = \{t_{h_1}, \ldots, t_{h_m}\}$.

The busbar of either end of the fault line is set as the reference busbar. On the basis of the double-ended fault location method, the fault location equation group is written by using T_W and T_H, as shown in (8):

$$\begin{cases} \dfrac{(t_{w_1} - t_{h_1})v + l_{w_1,h_1}}{2} = l_{fw_1} \\ \quad\vdots \\ \dfrac{(t_{w_1} - t_{h_n})v + l_{w_1,h_n}}{2} = l_{fw_1} \\ \quad\vdots \\ \dfrac{(t_{w_m} - t_{h_1})v + l_{w_m,h_1}}{2} = l_{fw_1} + l_{w_1,w_m} \\ \quad\vdots \\ \dfrac{(t_{w_m} - t_{h_n})v + l_{w_m,h_n}}{2} = l_{fw_m} + l_{w_1,w_m} \end{cases} \tag{8}$$

where l_{fw_1} is the length of transmission line between the fault point and the busbar w_m, l_{w_m,h_n} is the length of transmission line between the busbar w_m and the busbar h_n.

In this paper, our aim is to regard the travelling wave velocity as well as the fault distance as the unknown parameters and to solve them. Thus, the (8) should be rewritten as

$$\begin{cases} t_{w_1} - t_{h_1} = \dfrac{2l_{fw_1}}{v} - \dfrac{l_{w_1,h_1}}{v} \\ \quad\vdots \\ t_{w_1} - t_{h_n} = \dfrac{2l_{fw_1}}{v} - \dfrac{l_{w_1,h_n}}{v} \\ \quad\vdots \\ t_{w_m} - t_{h_1} = \dfrac{2l_{fw_1}}{v} - \dfrac{l_{w_m,h_1} - 2l_{w_1,w_m}}{v} \\ \quad\vdots \\ t_{w_m} - t_{h_n} = \dfrac{2l_{fw_1}}{v} - \dfrac{l_{w_m,h_n} - 2l_{w_1,w_m}}{v} \end{cases} \tag{9}$$

Equation (9) can be expressed as

$$\Delta T = LH \tag{10}$$

where

$$\Delta T = \begin{bmatrix} \Delta t_1 \\ \vdots \\ \Delta t_k \end{bmatrix}, \quad L = \begin{bmatrix} 1 & l_1 \\ \vdots & \vdots \\ 1 & l_k \end{bmatrix}, \quad H = \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} \tag{11}$$

Equation (11) can be solved by least-square estimation:

$$H = (L^{\mathrm{T}}L)^{-1}L^{\mathrm{T}}\Delta T \tag{12}$$

According to the calculation results of (13), the travelling wave velocity and fault distance can be solved by

$$\begin{cases} v = -\dfrac{1}{\beta_1} \\ l_{\mathrm{f}w_1} = \dfrac{\beta_0 v}{2} \end{cases} \tag{13}$$

It should be pointed out that the travelling wave velocity is still the unknown parameter when determining the shortest transmission path, because the travelling wave velocity is the parameter to be solved. Therefore, a historical information database can be built to

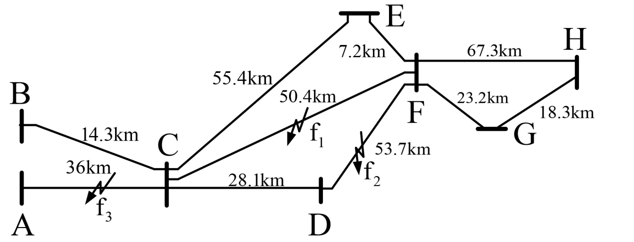

Fig. 3 *Simulation model*

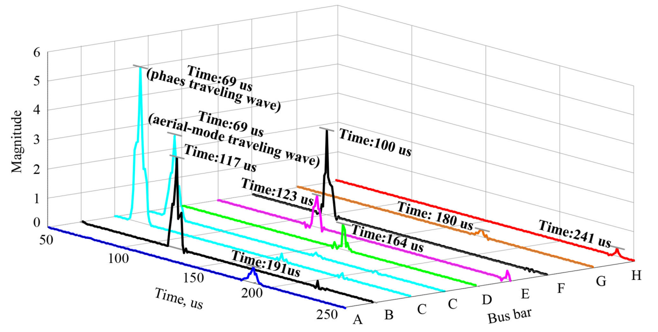

Fig. 4 *S-transformation result of the Nyquist frequency*

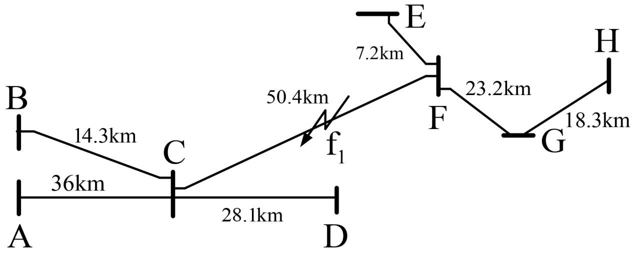

Fig. 5 *Shortest transmission path when fault occurs at f_1*

record the travelling wave velocity of each fault, and the shortest transmission path can be determined by using the historical travelling wave velocity.

3.4 Process of fault location

The flowchart of the fault location method proposed is shown in Fig. 2.

4 Results

4.1 Simulation model

The simulation model of a 220 kV transmission grid is established by PSCAD/EMTDC as shown in Fig. 3. Frequency-dependent model is used for transmission line, and the basic parameters of tower and line are given in [21]. The length of transmission lines are shown in Fig. 3. Simulation sampling frequency is 1 MHz. In this paper, taking the large number of previous simulation results as fault history information to determine travelling wave velocity at the Nyquist frequency is 2.94×10^8m/s. During the simulation, it is assumed that the fault occurs at $t = 0$.

In Fig. 3, there are four loop networks. Loop network 1 consists of the transmission lines CD, CF and DF. Loop network 2 consists of the transmission lines CF, CE and EF. Loop network 3 consists of the transmission lines CD, DF, EF and CE. Loop network 4 consists of the transmission lines FG, GH and FH.

4.2 Simulation results

The detection result of the travelling wave arrival time: the S transformation result of the Nyquist frequency of the phase current travelling wave is shown in Fig. 4. The S transform result of the Nyquist frequency of the aerial-mode current travelling wave extracted by the Karrenbauer transform [22] at busbar C is also shown in the figure. The arrival time of the phase current travelling wave t_{arrival} and the arrival time of the aerial-mode travelling wave t'_{arrival} are shown in Table 1. According to Fig. 4 and Table 1, it can be seen that the arrival time of the phase current travelling wave and the aerial-mode current travelling wave are exactly the same, which verifies the correctness and feasibility of the theoretical analysis in Section 3.1.

Table 1 Detection result of the arrival time

Busbar	t_{arrival}, μs	t'_{arrival}, μs
a	190	190
b	117	117
c	69	69
d	164	164
e	123	123
f	100	100
g	180	180
h	241	241

Table 2 Calculation result of β_0 and β_1

Fault position	β_0	β_1
f_1	3.397×10^{-4}	3.397×10^{-4}

Table 3 Calculation result of velocity and fault distance

Fault position	Velocity (m/s)	Fault distance (km)	Actual Distance (km)	Absolute error, m
f_1	2.944×10^8	20.561	20.4	161

The determination result of the shortest transmission path: the shortest transmission path when the fault occurs at the f_1 is shown in Fig. 5. Taking the loop networks 1 and 4 as the examples to illustrate the determination process of the shortest transmission path.

The fault f_1 is an internal fault for the loop network 1. The midpoint of the fault line is set as the reference point k. The length of the transmission line between $\varphi*$ and k is 66.1 km; therefore, $\varphi*$ locates on the transmission line FD. Since the k is the midpoint of the fault line, $\Delta t^*_{\text{MN}} = 0$. According to Table 1, $\Delta t_{\text{CF}} = 31\,\text{us}$. According to (7), the $\Delta l = -4.557\,\text{km}$. It means that φ_f is equivalent to $\varphi*$ moves 4.557 km towards the busbar F, and φ_f locates on the transmission line FD, the shortest transmission path in the loop network 1 can be determined by eliminating the line FD.

The fault f_1 is an external fault for the loop network 4. The shortest transmission path in the loop network 4 can be directly determined. As the initial travelling wave propagates from busbar F to the loop network 4, the busbar F is set as the starting point, and the midpoint of the loop networks 4 is located on the transmission line FH. The shortest transmission path in the loop network 4 can be determined by eliminating the line FH.

The calculation result of the travelling wave velocity and the fault distance: according to Fig. 5, $W = \{A, B, C, D\}$, $H = \{E, F, G, H\}$, $T_W = \{190, 117, 69, 164\}$, $T_H = \{123, 100, 180, 241\}$. The busbar C is set as the reference busbar, and the travelling wave velocity and the fault distance can be calculated by from (9) to (14). The calculation result is shown in Tables 2 and 3.

4.3 Analysis of algorithm performance

Analysis of the reliability: because the method proposed in this paper uses wide area travelling wave information, the fault location information is redundant. Even if a part of the fault location information is missing, the fault can be reliably located. However, the lack of information may result in poor positioning accuracy.

When the fault occurs at f_1, assuming that the arrival time of the travelling wave at busbar C and F cannot be obtained. The busbar

Table 4 Theoretical arrival time

Busbar	Arrival time, μs
a	192.49
b	118.43
c	69.62
d	165.53
e	126.96
f	102.39
g	181.57
h	244.03

Table 5 Calculation results at different transition resistance

transition resistance, Ω	Velocity, m/s	Fault distance, km	Actual distance, km	Absolute error, m
0	2.944×10^8	20.561	20.4	161
100	2.944×10^8	20.561	20.4	161
200	2.944×10^8	20.561	20.4	161

Table 6 Calculation results at different fault position

Fault position	Velocity, m/s	Fault distance, km	Actual distance, km	Absolute error, m
f_2	2.986×10^8	23.942	23.7	242
f_3	2.945×10^8	16.101	16.0	101

Table 7 Calculation results at different initial fault angle

Initial fault angle (°)	Velocity, m/s	Fault distance, km	Actual distance, km	Absolute error, m
5	2.944×10^8	20.561	20.4	161
60	2.952×10^8	20.264	20.4	136
90	2.962×10^8	20.499	20.4	99

Table 8 Calculation results at different fault type

Fault type	Velocity, m/s	Fault distance, km	Actual distance, km	Absolute error, m
AB	$2.944\text{x } 10^8$	20.561	20.4	161
ABG	$2.944\text{x } 10^8$	20.561	20.4	161
ABC	$2.944\text{x } 10^8$	20.561	20.4	161
ABCG	$2.944\text{x } 10^8$	20.561	20.4	161

C is still set as the reference point. The calculation results are as follows: travelling wave velocity is 2.92×10^8 m/s, fault distance is 20.57 km and absolute error is 170 m. Thus, the proposed method can still locate the fault accurately in the circumstances of lack of information. However the positioning accuracy decreases slightly.

It should be pointed out that because the travelling wave arrival time at busbar C and F cannot be obtained, the shortest transmission path cannot be determined by calculating the arrival time difference between busbar C and F. At this point, the initial travelling wave arrival time at busbar B and E can be used to calculate the initial travelling wave arrival time at busbar C and F. Then, the shortest transmission path can be determined by using the proposed method in Section 3.3.

Analysis of the fault tolerant ability: in order to verify the fault tolerant ability of the proposed method, the theoretical wave velocity 2.93×10^8 m/s is selected to invert the arrival time of the initial travelling wave, as shown in Table 4. The theoretical wave velocity is calculated based on the line parameters corresponding to simulation model in this paper.

Comparing Table 4 with Table 1, if the double-ended method is adopted, the maximum error of the initial travelling wave arrival time difference is 1.47 μs and the maximum fault location error is 215.35 m. Meanwhile, the fault location error of the proposed method is 161 ms and the fault location accuracy is improved 54.35 m. It means that the proposed method improves fault tolerance ability compared to the double-ended method.

Analysis of the adaptability: in order to verify the adaptability of the proposed algorithm, the different transition resistances, initial fault angle, fault position and different fault types are set for simulation. The simulation results are shown in Tables 5–8. The results in Table 8 are calculated by only using the current travelling wave of the phase A. The simulation results show the proposed method can locate the fault reliably under different fault conditions and its maximum absolute error does not exceeds 250 m.

5 Conclusion

This paper proposes a novel time difference of arrival of wide area travelling-wave-based fault location method for complex transmission grids via the phase current travelling wave. The proposed method determines the shortest transmission path online by comparing the reference time difference of arrival of initial travelling wave with the measured time difference of arrival. Then, on the basis of the redundant time difference of arrival of the initial travelling wave, the proposed method calculates the accurate travelling wave velocity and the fault distance by using the least-square estimation. The simulation results show that the fault location error is $< \pm 250$ m in different fault conditions. The precision, reliability, tolerant ability and adaptability of the fault location can be guaranteed.

Comparing with the existing travelling-wave-based methods for fault location, following conclusions can be drawn:

- The proposed method omits the phase-mode transformation, which can significantly reduce the calculation amount of wide area travelling-wave-based fault location.
- The proposed method determines the shortest transmission path online. It does not require a large amount of data pre-processing to pre-determine the transmission path, and avoids the matching between the actual fault condition and the pre-determined shortest transmission path.
- The proposed method can accurately calculate the fault distance without obtaining the travelling wave velocity, so that the fault location precision is immune to the calculation error of the travelling wave velocity.

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7 References

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