A New Data Fusion Method for Multi Terminal Fault Location Based on Sensor Networks

Qing-Sen Cai[1,*]

[1]Electrical engineering, Xi'an Aeronautical Institute, Lianhu District, Xi'an, Shaanxi, China

Abstract. Data fusion with different types of data that used for grid fault location can bring more accurate and clear results. Therefore, a new method for fault location which contains multi grid current and voltage, time and coordinate data information is proposed. Transient traveling wave is analyzed for determine the required data information in the first place, and then affirm the positioning principle and the selection rules of positioning network according to characteristics of multi fault traveling wave. Finally, Grid fault location will be precisely positioned by applying multiple data grid fault location algorithm. Simulation results shows that the proposed method is feasible, and the new algorithm has higher positioning accuracy.

1 Introduction

The existing fault location system adopts traveling wave information generally. There are two kinds of positioning principle: single-terminal location and double-terminal location. For single-terminal location, the information that needs to be identified include first arrival time of fault wave, arrival time of reflected wave from fault point and arrival time of reflected wave from opposite end bus etc. The process of identify is complicated so that the precision of location is low. Double-terminal location only needs to identify the first arrival time of fault wave form two terminal, it is easy to implement machine analysis and automation. Therefore, double-terminal location is widely used in practical positioning systems, single-terminal location as an auxiliary method [1].

Double-terminal location needs synchronization at both ends of the fault line. As long distance measurement and synchronization system has been widely used, the existing power grid monitoring technology is changing rapidly, and the synchronization problem of double-terminal positioning is solved. However, most of lines are single-circuit line so that huge amounts of resources need to be consumed in the process of fault location [2]. Multi-terminal location could integrate data from all the grid, so it is good at improve the accuracy of fault location and optimize the structure of networks [3]. It is an important research direction that built a network with multi-terminal sensors to locate the position of fault.

The research of multi-terminal location has achieved some results. References[4] presents the development and implementation in a computational routine of algorithms for

[*] Corresponding author: oddnewlife@126.com

fault location in multi-terminal transmission lines. References [5] proposed a new fault feeder selection scheme and choose the fault feeder by calculating the rank of every feeder's matrix and using the first transient traveling wave can realize fault location. References [6] proposed a traveling wave fault location method based on the multi measuring points. Detection device with Rogowski coil as the core was installed along the DC line long range.

Setting a main terminal in a fixed position is necessary under any existing fault location system, other terminals transmit data to the main terminal. The result of fault location is length between main terminal and fault position. Thera are some defects, for instance: 1. Traveling wave arrival time will be inaccurate because of the traveling wave speed varies on different lines. 2. Massive energy will be consumed during the long distance transmission. 3. Traveling wave attenuation will be very large when the fault point is far from the main terminal. 4. The main purpose of fault location is display the geographical position of fault but not the length from the main terminal.

In view of the above shortcomings, this paper presents the following characteristics: 1. Main terminal is not fixed, the terminal which traveling wave arrival time is shortest will be used as main terminal. 2. The result of fault location is in the form of plane coordinates, for the maintenance personnel, plane coordinates is a definite location information.

2 Location data extraction and analysis

When the power line short circuit to ground somewhere, there will be a transient traveling wave spread to the whole grid, this traveling wave will refract and reflect when the impedance of the line is discontinuous. Fault locating required extract data from this transient traveling wave and analyse the data in order to locate the fault point through the algorithm. For the single-terminal and double-terminal location, the data that arrival time of traveling wave needs to be extracted [7]. References [8] presents a new method for single-terminal traveling wave location with amended wave velocity by double-terminal asynchronous data. This method analyse the data that changes of polarity of the wave after catadioptric. References [9] presents a method of locating fault based on the calculation of the ratio of amplitudes of components at different frequencies. The wavelet modulus maxima of the travelling wave head at two different scales, the ratio of the wavelet modulus maxima at the two corresponding central frequencies can be obtained. References[10]extract the propagation path information of traveling wave to location the fault point.

2.1 Voltage and current traveling wave

When the power line occurs grounding fault, the situation equivalent to connect a power source to the grid, from the micro angle of the line, the distributed capacitance that close to the fault point will charge fast, and then discharge to the neighboring distributed capacitor, the neighboring distributed capacitance also charge and discharge. This process proceeds along the line to a distance, at the same time, the inductance of an electric current through a wire produces a magnetic field, this is the process of traveling wave of voltage and current. Fault location that use traveling wave should obtain the voltage and current traveling wave firstly. Sensors that could be used include CVT[11], CT, traveling wave data acquisition device[12] etc.

2.2 Aerial mode component of transient traveling wave

Power grid adopts three-phase circuit, electromagnetic coupling exists in each phase of the line, so the wave equations that established by the data from sensors immediately are not independent, this brings some difficulties to the calculation. According to the mode transmission theory, three phase voltage and current traveling wave could be transform to line module and zero module. Common method include symmetrical components transform, Clarke transform, Park transform, Karenbauer transform etc.[13]

Zero modulus component flows through the earth, it contact with the power system grounding closely. The situation is very complex, so line mode component is used in the fault location system usually and zero mode component is used rarely[14].

2.3 Maximum modulus of transient traveling wave

Transient traveling wave contains a lot of fault information such as fault distance, fault angle, fault frequency etc. The most important data that this paper need is arriving time of fault traveling wave, it could be extract from singularity characteristics of fault traveling wave.

Singularity characteristics of fault traveling wave could use the Lipschitz index to express. The transient traveling wave is transformed by wavelet. With the increase of the scale of wavelet transform, the data which Lipschitz index is non negative are the point that maximum modulus of transient traveling wave is increased or unchanged, in those data, the earliest time data will be used in this paper.

3 Location principle and location algorithm

In the two-dimensional space, the difference in the distance between the points on the hyperbola and the two focus is constant. Location principle and location algorithm in this paper use this feature, connect the difference in distance and the difference in arriving time of traveling wave.

3.1 Location principle

The pictorial representation of the location principle is shown in Fig.1. The fault is generated at point P, and the difference between arrival time of the main terminal O and the auxiliary terminal A is known, that P could be located in a hyperbola with the focus of O and A. In the same way, point P could be located in another hyperbola with the focus of O and B. The intersection of those two hyperbolas is the fault point P accurately.

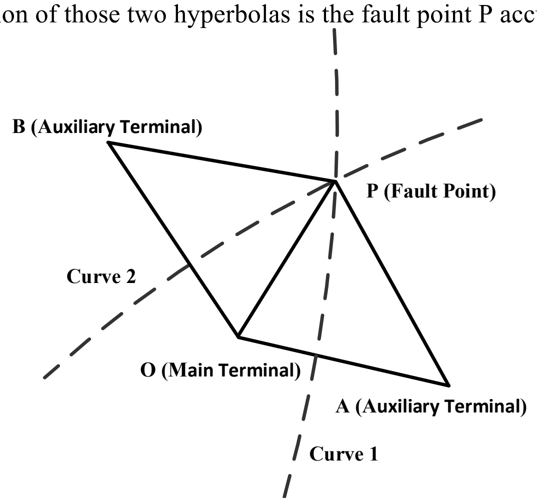

Fig.1. Schematic diagram of Location principle

3.2 Location network selection

From the aforementioned location principle, among the many sensors in the grid, three terminal sensor constitute a location network could locate the fault point. When fault occurs, transient traveling wave propagation to the whole network from the fault point and the closer the fault point is, the faster the sensor will receive the transient traveling wave data.

In order to avoid lower localization accuracy caused by traveling wave dispersion, the location network should contains the fault line ends terminal, so the data that traveling wave polarity is fused in the method in this paper. When the internal fault occurs, the traveling wave polarity of two line ends terminal is reversed, and when the external circuit fault occurs, the traveling wave polarity of two line ends terminal is same [15].

Selection rules of the location network and each terminal number are as follows:

1. In accordance with the order of arrival time of the transient traveling wave, the terminal is selected to constitute location network. The terminal which traveling wave arrival time is the first will be treated as 'main terminal', and will be numbered '0'. This terminal is responsible for receiving data, calculation of positioning and export the location result.
2. The terminal which traveling wave arrival time is the second will be add to location network, and then determine the current traveling wave polarity, if the polarity is contrary to terminal '0', this terminal will be treated as 'major auxiliary terminal', and will be numbered '1'. Or else, this terminal will be treated as 'minor auxiliary terminal', and will be numbered '2'.
3. The terminal which traveling wave arrival time is the third needs to be judged. If the location network already has terminal '1', this terminal will be add to the location work directly as terminal '2'. If there is no terminal '1' in the location work, the polarity of this terminal should be judged, if the polarity is contrary to terminal '0', this terminal will be treated as terminal '1', or else ,this terminal will be eliminated.
4. In accordance with the foregoing rules, select another terminal add to the location network and numbered '3'.

The purpose that add terminal '3' is in order to avoid the situation that three terminal of location network are in a straight line. In this special situation, positioning accuracy will be reduced greatly.

3.3 Location algorithm

In the location network, we assume $i = 0,1,2,3$ represent the number of terminal. The coordinates of terminal is (x_i, y_i). The traveling wave arrival time of each terminal is t_i. The distance between terminal and fault point is l_i. The velocity of traveling wave is v.

We can define a measurement matrix by subtracting arrival of 'main terminal' from arrival time of each 'auxiliary terminal':

$$\mathrm{T}=[\mathrm{dt}_1,\mathrm{dt}_2,\mathrm{dt}_3]^{\mathrm{T}} \tag{1}$$

The covariance matrix of measurement matrix is:

$$P = E[TT^T] = \sigma^2 \begin{bmatrix} 1 & 0.5 & \cdots & 0.5 \\ 0.5 & 1 & \cdots & 0.5 \\ \vdots & \vdots & \ddots & \vdots \\ 0.5 & 0.5 & \cdots & 1 \end{bmatrix} \tag{2}$$

Where “ σ^2 ” is variance of measurement error.

The actual value matrix of the difference between arrival time of auxiliary terminal and main terminal is:

$$D = \frac{1}{v}[dr_1, dr_2, dr_3]^T = D(X) \tag{3}$$

Where“ X ” is a vector containing coordinates of fault point.

We can get the quadratic estimate of measurement and actual value:

$$J = \left[T - D\right]^T P^{-1}\left[T - D\right] \tag{4}$$

Set the gradient of “ J ”zero, we can get the minimum value of the error between the measured and actual values:

$$\frac{\partial J}{\partial X} = W\Lambda a = 0 \tag{5}$$

Where:

$$W = \left[\frac{\partial D(X)}{\partial X}\right]^T P^{-1} \tag{6}$$

$$\Lambda = diag\left[\frac{1}{l_0 + l_1 + v\cdot dt_1}\cdots\frac{1}{l_0 + l_3 + v\cdot dt_3}\right] \tag{7}$$

$$a = \left[l_1^2 - (l_0 + v\cdot dt_1)^2 \cdots l_3^2 - (l_0 + v\cdot dt_3)^2\right] \tag{8}$$

Substituting“ a ”into formula (5), we can get:

$$2AX = V_d + l_0\varphi \tag{9}$$

Where:

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 \\ x_0 - x_2 & y_0 - y_2 \\ x_0 - x_3 & y_0 - y_3 \end{bmatrix} \tag{10}$$

$$V_d = [(v\cdot dt_1)^2 + K_0 - K_1 \text{L} \ (v\cdot dt_3)^2 + K_0 - K_3]^T \tag{11}$$

$$\varphi = 2[v\cdot dt_1, \text{L} \ , v\cdot dt_3]^T \tag{12}$$

The weighted least squares solution is:

$$X = \frac{1}{2}(A^T P^{-1} A)^{-1} A^T P^{-1}(V_d + l_0\varphi) \tag{13}$$

$$l_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{14}$$

Substituting" X "into formula (14), we can get a quadratic equation with one unknown " l_0 ", solve this equation, then substituting " l_0 "into location equation (14), we can calculate the coordinates of the fault point.

4 Simulation implementation of localization method

Now, in this paper we made a simulation mold with 11 terminals system whose single-line diagram is depicted in Fig.2. Simulation analysis is performed using EMTDC and MATLAB.

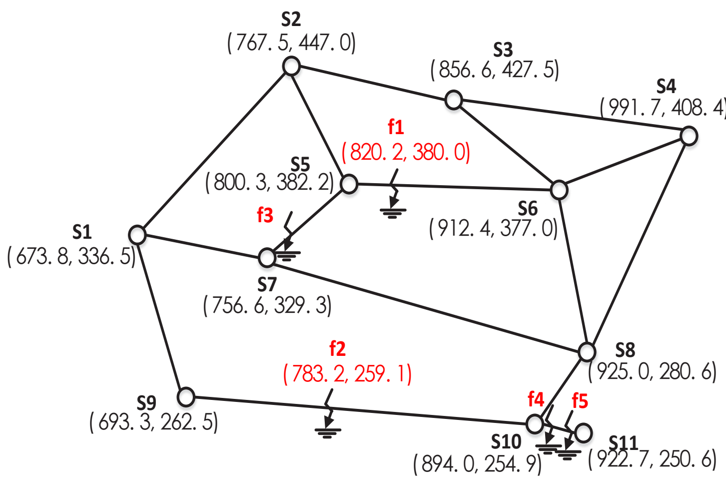

Fig.2. Simulation mold of power grid

4.1 Fault location process

Take the fault 'f1' in Fig.2 as an example, the simulation adopts single-phase grounding fault, fault location process as follows:

1. Analyze fault traveling wave data and select location network.

The fault occurs between terminal 'S5' and 'S6', transient traveling wave arrive at 'S5' first, so 'S5' is the 'main terminal'-terminal '0'.

Then transient traveling wave reach at 'S7', by analyze the polarity of transient current traveling wave data we find that 'S7' and 'S5' have the same polarity, it means 'S7' and 'S5' are on the same side of the fault point, so add 'S7' into the location network as terminal '2'.

Arrival time of 'S1'and 'S6'is very close, in the actual grid, exist phenomenon of wave dispersion[16], transient traveling wave reach at 'S6' is earlier, and the polarity is contrary to the 'S5', it means 'S6' and 'S5' are on the different side of the fault point, so add 'S6'into the location network as terminal '1'. 'S1' add into the location network as terminal '3'. Transient current traveling wave at each terminal is shown in Fig.A1.

From this, location network selection is complete, it consist of (S5,S6,S7,S2).

2. Analyze fault traveling wave at each terminal, extract arrival time of traveling wave.

Transform the forward (backward) traveling wave of each terminal by wavelet, increase scale of wavelet transform successively, and extract the time of point which arrival time is shortest and Lipschitz index is nonnegative.

Take ‘S5’as an example, the transient forward traveling wave is subjected to 6 different scales of wavelet transform, as shown in Fig.A2, there is a maximum modulus point at 80ns, and its Lipschitz index is zero, so 80ns is treated as the arrival time of terminal ‘0’.
Arrival time of each terminal in the location network is shown in Table 1.
3. Extract coordinate data at each terminal of location network, as shown in Fig.2, the data format using two-dimensional coordinates, coordinates of terminal ‘0’ is (800.3,382.2)km. Coordinates of each terminal in the location network is shown in Table 1.

Table 1 Data at each terminal of Location network

Component of Location network	**Coordinate/km**	**Arrival time/ns**
Terminal‘0’(S5)	(800.3,382.2)	80
Terminal‘1’(S6)	(912.4,377.0)	328
Terminal‘2’(S7)	(756.6,329.3)	316
Terminal‘3’(S2)	(767.5,447.0)	330

4. Substituting arrival time data and coordinate data into the location algorithms, we can obtain the coordinate of fault point (f1) is (820.1.380.3) km, and the actual coordinate of fault point is (820.2,380.0) km, the deviation is (0.1,0.3)km.

4.2 Influencing factors of positioning accuracy

The fault location method of this paper has some factors that affect the positioning accuracy, mainly including the following points:

1. Transient traveling wave velocity. In the simulation of this paper, the transient traveling wave is regarded as electromagnetic wave, but in the actual grid the velocity is related to frequency, so it is different in different lines. We will fuse line parameter data in next step.

2. Sampling frequency of traveling wave calculation. The sampling frequency in this paper is 109(1/s), the unit of time data obtained is nanosecond. If the sampling frequency is increased, the positioning error can be reduced.

3. Coordinate precision of each terminal. The location algorithm of this paper is directly related to the coordinates of each terminal, improve coordinate precision can effectively improve the positioning accuracy.

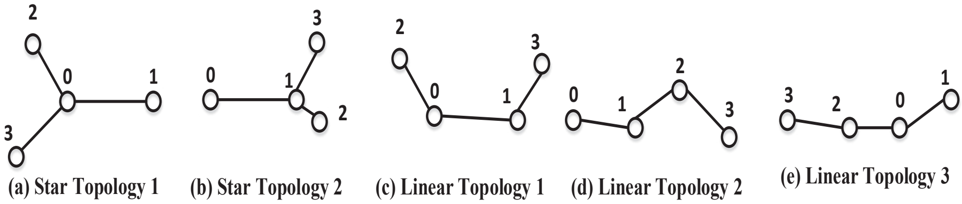

Fig. 3. Common location network topology

4. Topology of location network. Because the more lines the transient traveling wave crosses, the more distorted it will be, the topology of location network will affect the

accuracy of location. The location network usually has several topologies as shown in Fig.3, topology (a) and (b) is star. In topology (a) the location error is minimum because there is only one line between 'auxiliary terminal' and 'main terminal'. In topology (b), the location error is bigger than (a), because there are two lines between terminal '2' or '3' and 'main terminal'. Topology (c), (d), (e) is linear, the location error will be bigger, because always there are over two lines between 'auxiliary terminal' and 'main terminal'.

4.3 Special case analysis

The fault location method of this paper has some factors that affect the positioning accuracy, mainly including the following points:

According to the different topologies of location network in Fig.3, this paper proposes to add the data 'number of connected lines of each terminal' to reduce the positioning error.

1. For the topology (b) in Fig.3, after location network is selected, we can compare the number of connected lines of terminal '0' and '1', if this number of terminal '0' is bigger than terminal '1', the location network remain unchanged , if not, exchange terminal '0' and '1', create a new location network.

Take the fault 'f2' in the Fig.2 as an example, the location network selected by the aforementioned location process is (S9,S10,S11,S12), its topology as (b) in Fig.3, the actual coordinate of fault point is (783.2,259.1), Fault location coordinates that obtained by using method of this paper is (783.5,269.4), the deviation is (0.3,10.3.) Then we extract the number of connected lines of terminal '0' and '1', it is 1 and 3, so we exchange the terminal '0' and '1', new location network is (S10,S9,S11,S12), its topology as (a) in Fig.3, we obtain the coordinate by using method of this paper is (783.0,259.2), the deviation is (0.2,0.1).

2. For the three linear topology in Fig.3, there are severe lines between terminal '2' or '3' and 'main terminal', we some appropriate changes in the location network selected rules:

Firstly, same as the modification in topology (b), we extract the number of connected lines of terminal '0' and '1', set the terminal which this number is big as terminal '0'. Then delete the terminal '3' from the location network, seek a new terminal which is connect with terminal '0', set it as terminal '3', create a new location network.

Take 'f3', 'f4', 'f5' in Fig.2 as examples, adopt the above modification method then simulate, we obtain the results as shown in Table 2.

The method of fault location in this paper requires mutual communication between the terminals, after fuse the data of each terminal, select the location network, then locate the fault point. In this process, if some terminals failure to communicate with other terminals, some data will lose. Under this special situation, the location network perhaps contains some terminal that across multiple lines from fault point, this leads to a decrease in location accuracy.

Take the 'f1' fault in the Fig.1 as an example, we analyze the situation that one terminal is failure as follow:

1. According to the aforementioned positioning process, when 'f1' fault occur, the selected location network is (S5,S6,S7,S2), if one terminal that in addition to these four terminals is failure, the location network is unchanged, so the location result is unchanged.

2. Terminal '3' (S2) is failure, according to the aforementioned positioning process, the location network is (S5,S6,S7,S3), location result is (819.8,380.3), the deviation is (0.4,0.3)km.

3. Terminal '2' (S7) is failure, the location network is (S5,S6,S7,S3), location result is (819.7,380.5), the deviation is (0.5,0.5)km.

4. Terminal '1' (S6) is failure, the location network is (S5,S3,S7,S2), location result is (819.2,381.2), the deviation is (1.0,1.2)km.

5. Terminal '0' (S5) is failure, the location network is (S7,S6,S2,S1), location result is (823.7,378.3), the deviation is (3.5,1.7)km.

We can see from those results that when one terminal is failure, the location accuracy in this paper will be influence. Failure terminal more close to 'main terminal', the more location accuracy decrease.

5 Conclusion

This paper proposes a new method of fault location, data fusion a variety of data in power grid and the location results use the form of two-dimensional coordinates. Through simulation experiment we can see that this method has high location precision, adapt to the needs of intelligent grid, suitable for the development of fault location software.

In the matter of topology of location network, two kinds of topological relations of star type and linear type are analyzed respectively in five cases, obtained the topology with minimal location error, for other topology, we make appropriate changes of location network selection, the experiment results show that the location accuracy has been improved.

By analyzing the main factors that affect the location accuracy, it is found that the location accuracy has decreased under the special conditions. Therefore, the subsequent in-depth study is how to improve location accuracy measures under special circumstances

Table 2 Simulation results of linear topology

Topology	Fault Point	Location Network Before modification / After	Result Before modification / After	Deviation Before modification/ After
(c)	(769.3,344.7) f3	S7,S5,S1,S2/ S7,S5,S1,S8	(766.1,348.9)/ (769.5,344.1)	(3.2,4.2)/ (0.2,0.6)
(d)	(903.6,253.8) f4	S10,S11,S8,S6/ S10,S11,S8,S9	(873.7,279.5)/ (903.4,254.1)	(29.9,25.7)/ (0.2,0.3)
(e)	(913.1,252.7) f5	S11,S10,S8,S6/ S10,S11,S8,S9	(887.1,302.1)/ (913.2,252.8)	(26.0,50.2)/ (0.1,0.1)

Appendix A

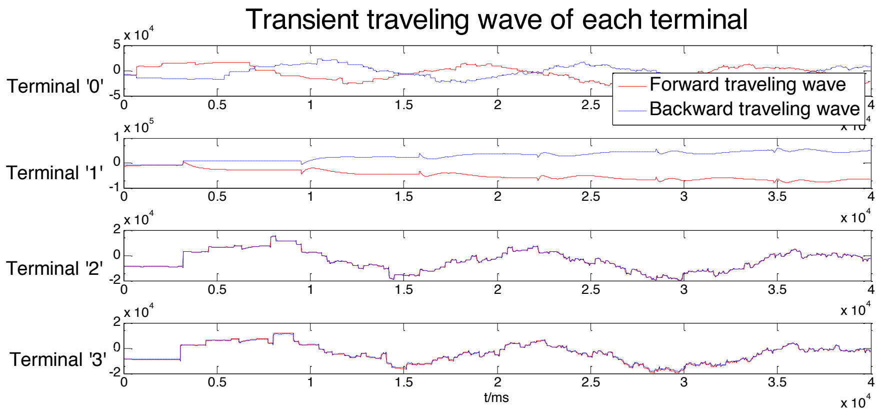

Fig. A1. Transient traveling wave of each terminal

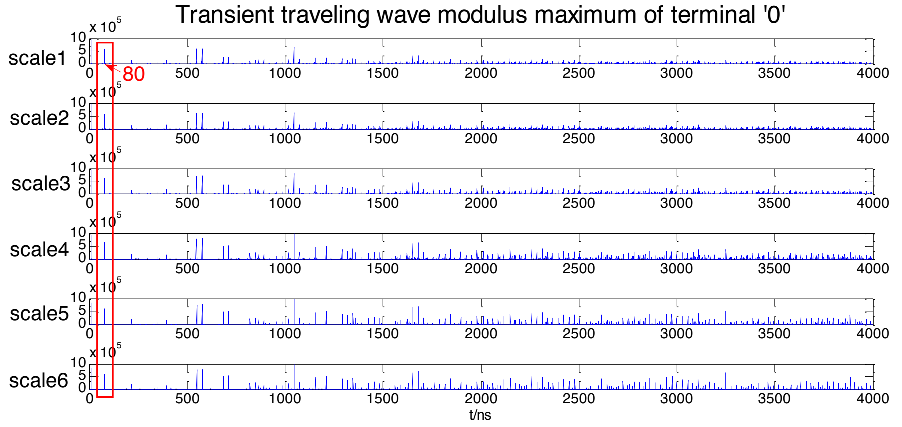

Fig. A2. Transient traveling wave modulus maximum of terminal ‘0’

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