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Travelling Wave Single End Fault Location Method based on Network Information

***Abstract**. The single end travelling wave fault location method is usually difficult to discriminate the reflection wave of fault point. This paper employs wavelet transform to detect possible fault point in power system. Using the real time network topology and possible fault point, the travelling wave propagation waveform can be constructed. By comparing the constructed waveforms and real recorded waveform, the reflection wave of fault point can be identified. The simulation verifies its correctness, and the field application proves the feasibility of this method.*

***Streszczenie.** W artykule zaprezentowano metodę lokalizacji możliwych awarii w sieci energetycznej na podstawie Transformaty Falkowej. Wyniki badań symulacyjnych i eksperymentalnych potwierdzają skuteczność metody. (**Jednostronna metoda fali bieżącej w lokalizacji awarii na postawie danych o sieci**)*

Keywords: Travelling wave; Single end; Fault location; Network topology
Słowa kluczowe: Fala bieżąca, metoda jednostronna, lokalizacja awarii, topologia sieci.

Introduction

Because of the high accuracy and wide applicability, the travelling wave fault location method has been widely applied in the power system [1,2,3]. The existing travelling wave fault location system (TWFS) uses double ends method as major fault location principle, while the single end method is employed as complementary fault location means. Double ends method time tags the arrival of the fault generated surges at both ends of the line, while these two ends are time synchronized. The fault distance is determined by measuring the difference of the arrival time. To avoid the fault location failure when one end travelling wave data acquisition equipment (DAE) is abnormal, the wide area travelling wave fault location algorithm is presented [4,5]. It makes use of travelling wave data of many substations across the monitored network and therefore it has better reliability than the conventional double ends method.

Besides the lines that installed DAEs at double ends, the existing TWFS simultaneously monitors a lot of lines that only one end has the DAE. The TWFS needs to use the single end fault location method. It determines fault distance by analyzing the fault generated travelling wave waveforms. Time difference between the detected initial fault surge and the corresponding reflected surge from fault is the time interval for a surge to travel from terminal to fault and back. For this method, to identify the reflected surge is the key to fault location. It is normally very difficult because of the existence of reflection wave from adjacent bus, remote terminal bus and middle transposition point. The operating TWFS usually samples only the current travelling wave or the voltage travelling wave, so it's impossible to get the direction of the travelling wave, the surge can't be discriminated if it is from the faulty line.

Travelling waves are sharply varying signals. The wavelet transform that has a special feature of variable time-frequency localization, it is suitable for analyzing the travelling wave signal. The travelling wave surge arrival time and possible fault points can be detected by calculating the modulus maxima using wavelet transform [6,7]. Although the real fault point can't be identified, the possible fault points can be listed.

To determine the real fault point, an assembled fault location algorithm was presented [8]. It uses a robust single end fault location algorithm based on impedance to find the fault section of transmission line. Then, fault location algorithm based on current travelling waves and wavelet transform was taken to determine the fault point accurately. Because it depends on the impedance calculation, it isn't suitable to locate the distance of the disturbances that didn't trigger the relay. The disturbance points are normally with weak insulations, if the fault distance can be achieved, utilities can focus on these weak points during routine maintenance to avoid problems.

A new reflected surge identification method is introduced in this paper. The method employs wavelet transform to detect possible fault point. Using the real time network topology and possible fault point, the travelling wave propagation waveform can be constructed. By comparing the constructed waveforms and real recorded waveform, the reflection wave of fault point can be identified.

Propagation of travelling wave

After the fault occurs, the fault travelling wave propagates along the transmission line from the fault point. During the travelling of the fault travelling wave, it will have reflection and transmission where there is a junction, like disturbance point or bus, a portion of the travelling wave will be reflected back, while the remaining will transmit through the junction and travel forward to the nearby substations.

When the incident travelling wave travels u_i from dielectric with wave impedance z_1 to dielectric with wave impedance z_2, it will have reflection wave u_f and transmission wave u_t.

The reflection level of the travelling wave can be represented by the ratio between the reflection voltage (or current) and incident voltage (or current) at a junction, this ratio is known as reflection coefficient. The reflection coefficient of the travelling wave voltage is

$$\rho_u = \frac{u_f}{u_i} = \frac{z_2 - z_1}{z_2 + z_1} \qquad (1)$$

While the transmission coefficient of travelling wave is represented by the ratio between transmission voltage (or current) and incident voltage (or current), the propagation coefficient of travelling voltage and travelling current is the same. The propagation coefficient is

$$\gamma = \frac{u_t}{u_i} = \frac{2z_2}{z_1 + z_2} \qquad (2)$$

Bewley lattice diagram is the most common one for travelling wave analysis. That is to calculate every transmission wave and reflection wave at the nodes and show them in the lattice diagram according to the time. Then the voltage or current value of each node can be got by using the superposition method. Take Fig.1 as an example, it introduces two line segments with limited length between two lines with infinite length, *Z1~Z4* are the corresponding wave impedance of each line.

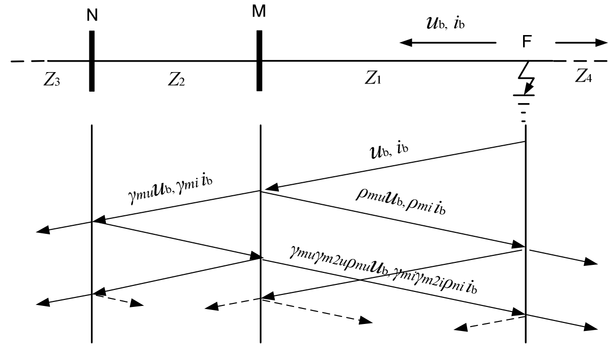

Fig.1. Bewley lattice diagram

When fault occurs at $t=t_0$ at point F, the voltage and current detected by point M are:

(3) $$u(t)=(1+\rho_{mu})u_b(t-t_0-\tau_{mf})+\gamma_{mu}\gamma_{m2u}\rho_{nu}u_b(t-t_0-\tau_{mf}-2\tau_{mn})+(1+\rho_{mu})\rho_{fu}\rho_{mu}u_b(t-t_0-3\tau_{mf})+...$$

(4) $$i(t)=(1+\rho_{mi})i_b(t-t_0-\tau_{mf})+\gamma_{mi}\gamma_{m2i}\rho_{ni}u_b(t-t_0-\tau_{mf}-2\tau_{mn})+(1+\rho_{mi})\rho_{fi}\rho_{mi}u_b(t-t_0-3\tau_{mf})+...$$

Where, τ_{mf} and τ_{mn} stand for the time needed for travelling wave propagating on line MF and MN.

Formula (3) and (4) also can be applied to the calculation of multiple transmission and reflection between multiple nodes. It is possible to figure out any recorded travelling wave signals on that basis.

Valid calculation network area

The number of lines, which in operation on the bus bar of substation, varies according to the operation mode and maintenance status. Thus the real time network topology when fault occurs is needed. As the traveling wave fault location devices have been widely applied in the power system, utilities established travelling wave fault location master station system in dispatching center. Master station system can obtain the real time network topology through the interfaces of the automation system. That makes the algorithm provided by this paper possible.

For a real power network, there might be hundreds of substations and lines. It will cost very large memory and very long time to compute by using the whole network directly. Known from the Fig.1, when fault occurs at the end of line, time difference between initial fault surge and reflection surge corresponded travelling wave propagation distance is 2 times the length of the line. For the fault location of the full fault line, it wouldn't affect the location when a surge's propagation distance is over 2 times length of the line. Therefore, we only need to compute within the valid calculation area instead of calculating the travelling wave's transmission and reflection in the whole power grid.

On account of the line length error and surge width, we can use the substation that recorded fault as source, 1.5 times fault line length as threshold value to search the valid calculation area.

Pre-processing of travelling wave signal

When the fault occurs, the travelling wave on transmission line can be transformed into three individual mode components. Among them, one is propagated through the ground namely ground mode component. And the other doesn't propagate through the ground namely aerial mode component.

Problems of severe attenuation and the parameter's diversification with frequency exist in ground mode component, thus the great attenuation and unstable travelling wave velocity having a great impact on accuracy of fault location. Therefore, the ground mode component should be filtrated from a utilizing perspective. Aerial mode component of travelling wave has a small attenuation and stable travelling wave velocity and exists under all fault conditions. Thus aerial mode component of travelling wave should be used as the basis for fault location in three-phase lines.

Algorithm

Based on the above analysis, the algorithm steps are as follows:

(1) Selection of the valid calculation network

When the fault occurs, the substation that records the fault travelling wave will be set as source. The breadth first search algorithm of graph will be taken from this point. Considering 1.5 times the length of the fault line as the threshold value, we can calculate the effective computing network topology.

The weighted graph G=<V,E,W> is used to represent the valid calculation area of travelling wave. The graph G consists of three finite sets, V, E and W. Each element of V is called a vertex. The elements of E, called edges, are unordered pairs of vertices. And each element of W is called an edge's weight. For this paper, V is substations, E is power lines and W is power lines' length. A weighted graph usually uses an adjacency matrix to represent. The length of the double-circuit transmission line between two substations can be filled in the upper triangular and lower triangular of the weighted adjacency matrix separately.

(2) Phase-modal transformation of faulty travelling wave

It is well known that the phase-modal transformations are often applied to decouple a three-phase system. In this paper, the Karenbauer transformation is used to transform the transient current signals into their modal components as follows:

(5) $$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

where i_a, i_b and i_c are the current travelling wave of the phase A,B and C; i_0, i_α and i_β are the current of modal 0, α and β, respectively. Through analyzing the aerial mode component i_α, we can get the possible fault locations.

(3) The acquisition of the possible fault location

The acquisition of the possible fault location is to identify the fault point reflected surge in the waveform of travelling wave. As the number of the bus lines will affect the reflection coefficient, the fault point reflected surge can not be uniquely identified by using the recorded travelling wave signals only. The modulus maxima position can be obtained by using the wavelet transform method. The position can also be the possible fault point.

According to the wavelet singularity detection theory [1], the calculated modulus maxima shows the point of the sharp variation of the traveling waves, corresponding to the arrival of the traveling wave at the record point is got. When using wavelet transform to analyze transient travelling waves, the dyadic wavelet transform was adopted and the cubic B-spline function was selected as the base wavelet function for finding singularity point. In this paper, the list of locations of possible fault points within the total length of the fault line can be calculated by the wavelet transformation. The details of the wavelet algorithm refers to [6] and not to be described here.

(4) Waveform’s construction of travelling wave

Choosing the possible fault point as the start point of initial fault surge, we can obtain the constructed waveform of travelling wave by iteratively calculating the surge of transmission and reflection wave within the valid calculation network area.

We can know from the Fig.1 that when incidence surge encounters impedance mismatch point, a reflection surge and several transmission surges will generate. When constructing waveform, the initial fault surge which propagates from the fault point to both ends of fault line will generate reflection surge and transmission surge when arrives at the end of faulty line. Every reflection surge and transmission surge generated can be calculated one by one.

As mentioned above, it wouldn't affect the fault location when surge’s propagation distance is greater than 2 times length of the fault line. Besides, the amplitude of reflection surge and transmission surge, which are generated when incidence surge encounters impedance mismatch point, are smaller than that of incidence surge commonly. After several processes of that, the amplitude becomes much too small and loses the necessity to continue calculating. These two criterions can help calculating and judging whether a surge needs to continue propagating in the valid calculation network.

The calculation process is finished when all surges propagate to meet one of the two conditions above. Choose the surges that passed through the appointed substation measuring points in all surges list, and then synthesize the final constructed waveform after superposition calculation.

(5) Identification of fault point

Compare the constructed waveforms of travelling wave with the waveform of fault line’s aerial mode component, possible fault point corresponded by constructed waveform with high similarity is the recognized line fault point location.

The flow chart of this algorithm is shown as below:

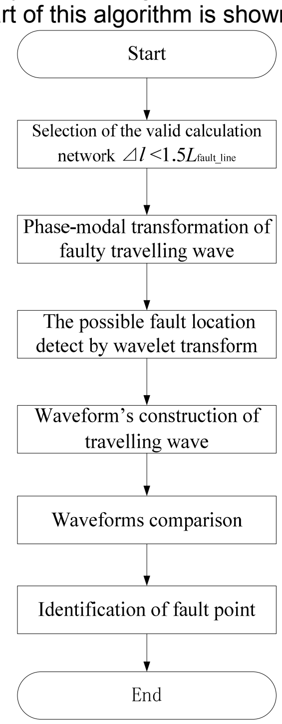

Fig.2. Algorithm Flow Chart

Fault simulation and analysis

In order to verify the correctness of the algorithm, especially the calculation of travelling waveform construction, a 500kV transmission system with seven buses is used, it is as Fig. 3 shows. The fault point is at the position F of line S1-S2, 20km to substation S1 and phase A is grounding. This system is simulated by using Matlab/Simulink program.

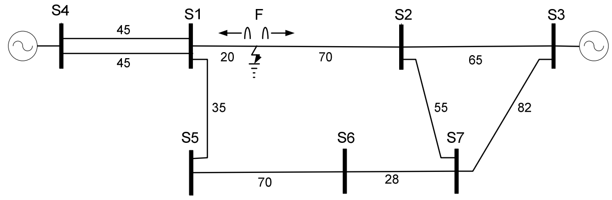

Fig.3. 500kV simulated System

The simulation results are shown in Fig.4.

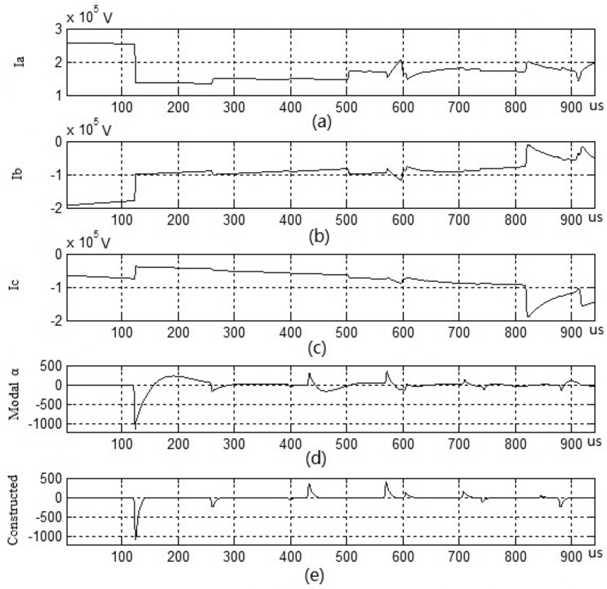

Fig.4. Travelling Wave Simulation after the line is faulty

Fig. 4(a),(b),(c) show the phase A,B,C current waveform recorded at substation S1 when fault occurs. Fig. 4(d) is the aerial mode component of travelling wave after the phase-modal transformation, and Fig. 4(e) is the constructed waveform according to the fault point and network topology relationship.

Comparing Fig. 4(d) with (e), we can know that the travelling wave surge position of constructed waveform coincides with the simulation waveform, which proves the correctness the construction waveform.

Case Studies

This case is from Guizhou province, China 500kV power grid. The fault occurred at Yafeng line at 10:11:01 826570us on January 4, 2011, which is the line between substation Yaxi and substation Xifeng. Fig. 5 shows the network topology corresponding to the fault. The fault is phase A grounding fault and failed to reclose.

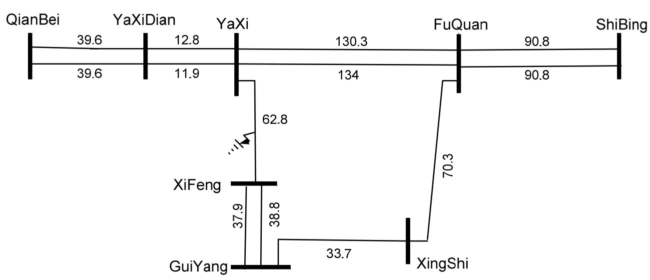

Fig.5. Network topology of the fault area

XC2000 travelling wave acquisition equipment has been installed in substation YaXi. After fault occurs, the current transient were captured and the data were transmitted to the travelling wave fault location master station via the communication network for further processing. Utilities can analyze the fault and guide the line patrol.

The recorded current travelling wave signals are shown in Fig.6.

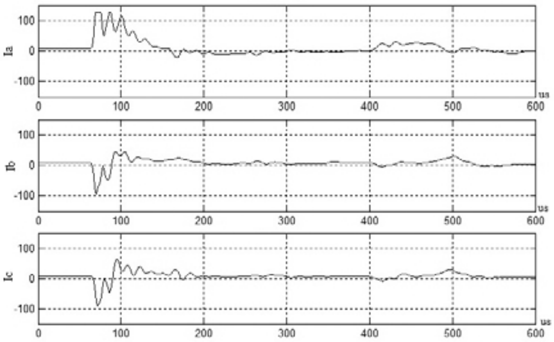

Fig.6. The recorded current travelling wave signals at Yafeng

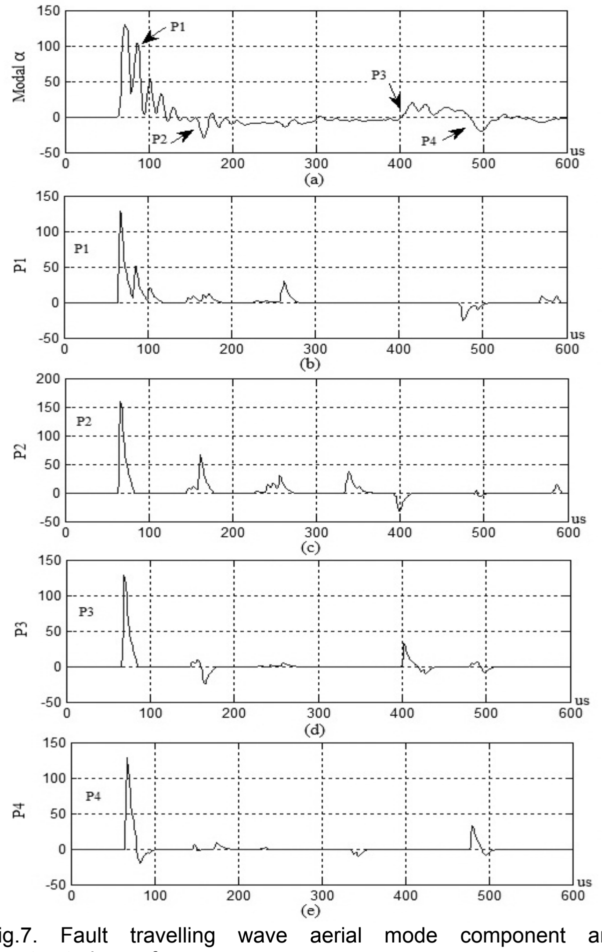

Fig.7. Fault travelling wave aerial mode component and constructed waveforms

By using phase-modal transformation, we can get the aerial mode component from the original fault current travelling wave signals. Through singular point detection, we can get a list of possible fault points, which are marked as P1~P4 in Fig. 7(a). Take them as the fault distance, we can get the constructed travelling waveform, it is shown in Fig. 7(b),(c),(d) and (e).

Comparing the constructed travelling waveform with the aerial mode component waveform of the original fault current travelling wave signals, we can identify the Fig. 7(d) has the best similarity. So the corresponding fault distance is the most possible fault point. After field patrol, the real fault distance is 48.5km, just same as the algorithm calculated result.

By comparing the constructed travelling waveform with the field records, the field case’s similarity is worse than that of the simulation result. The reason is that there is a certain difference between the line length, travelling wave speed in the actual power network and the value used by the constructed waveform. In addition, the attenuation of the line and bus-connecting components with lumped parameters will cause the distortion of the travelling wave. Even so, the positions of the fault wave head in the constructed travelling wave coincide well with the actual fault travelling wave head positions.

Conclusion

By using the power network topology, the travelling wave single end method can comprehensively consider the impact of lines neighbouring to the fault line. Since it only uses the travelling wave information, this method is also suitable to locate the distance of the disturbances that didn’t trigger the relay.

In addition, the method described in this paper also can be applied to some special line point fault. For example, if the fault occurs at the middle point of the line, the fault point reflected surge and the remote end bus reflected surge will arrival at the measure point synchronously and have opposite polarity, so it is hard to discriminate. By constructing a waveform and comparing it with the actual recorded waveform, the fault can still be determined.

For the travelling wave fault location principles, which was known worse by the utilities operation and maintenance people, this method can help them to analyze more easily the large number of single end travelling wave fault waveforms.

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REFERENCES

[1] Yaozhong G., New Types Protective Relaying and Fault Location Theory and Techniques [M], Xi’an, Xi’an Jiao Tong University Press,2007. (in Chinese)

[2] Gale P.F., Stokoe J., Crossley P.A., Practical experience with travelling wave fault locators on Scottish Power's 275 & 400 kV transmission system, *IET Developments in Power System Protection*, 1997, Nottingham, 192-196

[3] Bingyin X., Zhihuai S.,Gale P., The Application of Travelling Wave Fault Locators in China,. *IET Developments in Power System Protection*, 2008, Glasgow, 535-539

[4] Yu C., Dong L., Bingyin X, Travelling Wave Location Algorithm Based On The Wide Area Network Information, *Automation of Electric Power Systems*, 35 (2011), No. 11,65-70 (in Chinese).

[5] Nan C., Xiangjun Z., Zewen L., A novel algorithm for travelling wave fault location base on network, *IEEE .Industrial Technology*, 2008

[6] Dong X., Yaozhong G., Jiali H., Surge impedance relay, *IEEE Trans. Power Delivery*, 20 (2005), No. 2, 1247-1256

[7] Thomas D. W. P., Christopoulos C., Tang Y., Single ended travelling wave fault location scheme based on wavelet analysis, *IEE Developments in Power System Protection*, 2004, Vol.1, 196-199

[8] Xinzhou D., Zheng C., Xuanzhou H., Optimizing solution of fault location, *IEEE Power Engineering Society Summer Meeting*, 2002, Chicago, 1113 – 1117

[9] Aurangzeb M., Crossley P. A., Gale P., Fault location using the high frequency travelling waves measured at a single location on a transmission line, *IEE Developments in Power System Protection*, 2001, 403-406

[10] Elhaffar A., Lehtonen M.,Travelling waves based earth fault location in 400 kV transmission network using single end measurement, *Power Engineering*, 2004, LESCOPE-04, 53-56
[11] Jamali S., Ghezeljeh A., Fault location on transmission line using high frequency travelling waves, *IEE Developments in Power System Protection*, 2004, 220 - 223
[12]Zimath S. L., Ramos M. A. F., Filho J. E. S.,Comparison of impedance and travelling wave fault location using real faults, *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, 2010, 1-5
[13]Ping C., Bingyin X., Jing L, The Optimized Combination of Fault Location Technology Based on Traveling Wave *Principle,Power and Energy Engineering Conference, 2009. APPEEC 2009*. Asia-Pacific,2009, 1-5
[14]Haihong B.,Qingshan X., Study of fault location for parallel transmissions lines using one terminal current traveling waves, *Electric Utility Deregulation and Restructuring and Power Technologies, 2008*. DRPT ,Nanjing, 2296 – 2301
[15]Silva M., Oleskovicz M., Coury D.V., A fault locator for transmission lines using traveling waves and wavelet transform theory, *Developments in Power System Protection, 2004. Eighth IEE International Conference*, 2004, 212 - 215

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