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Single-ended data based fault location method for multi-branch distribution network

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Abstract

A novel single-ended travelling wave fault location method applicable to the distribution network with multi-branches is presented in this paper. The method only depends on the arrival times of the initial aerial-mode and zero-mode travelling wave, and it can solve the truncation error problem caused by discrete sampling mechanism. In addition, the method is not affected by structure of a distribution system. The feasibility and effectiveness of the presented method is verified by PSCAD/EMTDC simulation results.

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Keywords: Fault location; Travelling waves; Distribution network; Improved correction algorithm

1. Introduction

According to Lin et al. [1], it has been illustrated that fault location method based on the travelling wave theory is widely used for transmission networks. In recent years, many scholars began to study the possibility of travelling wave fault location method being used in distribution network as well. The method proposed by Borghetti et al. [2] requires the installation of PT and CT on every sub-branch and complex calculations, which is not feasible in the distribution network applications. The method proposed by Dwivedi and Yu [3] needs to measure the reflected wave from the fault points, which can be confused with those from the node with uneven impedance.

According to Xu et al. [4] and Huibin [5], it can be illustrated that the traditional double-ended fault location method is able to achieve very high accuracy in theory, but it can only be used for locating the fault occurred on the trunk lines of distribution network and it will fail to work when the fault is located on the branch lines. A solution for the fault location of branch lines is to install the travelling-wave detection devices at both ends of each branch

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line. However, communication between these devices would be problematic, as well as the high cost to implement it. Therefore, this method is impractical.

According to Lin et al. [6], it can be illustrated that single-ended fault location method focusing on the time difference between initial and reflected wave head to locate the fault position is simple to implement. However, according to Dwivedi and Yu [3], we know that it is very difficult to accurately determine the arriving point of the reflective wave head due to the complex structured distribution networks with many branch lines. If we only install the travelling-wave detection devices at the in-feed point, the single-ended travelling wave fault location criterion based on reflected wave will fail to work. It is because that the wave being reflected at the infeed point and toward the fault point will be reflected again at any cross point instead of the real fault location due to uneven wave impedance, which may lead to the false judgement. On the other hand, taking the cost into account, installing sensors with auto-synchronization time function at both ends of each branch line is almost impossible.

In this paper, a fault location principle taking advantage of propagation time gap between zero-mode and aerial-mode travelling wave is investigated. Furthermore, based on the improved truncation error correction algorithm proposed in this paper, the recognition error of travelling wave head is reduced sufficiently. Therefore, good results can be achieved for precise fault locating in distribution networks.

2. Single-ended fault location method

Assume that a fault recording device is installed at the M end of a certain feeder on the distribution network, as shown in Fig. 1. When a single-phase to ground fault occurs at the point F , a superimposed voltage will occur at the fault point and the transient travelling wave will propagate toward both ends of the feeder.

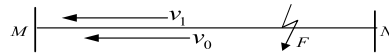


Fig. 1. Travelling wave propagation process.

Characteristic impedances and velocities of each mode can be expressed as:

$$v_1 = 1/\sqrt{L_1 C_1}, v_0 = 1/\sqrt{L_0 C_0}, \quad (1)$$

By observing Fig. 1, following equations can be given:

$$s = v_0 t_0, \quad s = v_1 t_1, \quad \Delta t = t_0 - t_1 \Rightarrow s = \frac{v_1 v_0 \Delta t}{v_1 - v_0} \quad (2)$$

where: s is the distance between the fault position and measuring point; v_1 and v_0 are the velocities of aerial-mode and zero-mode components, respectively; t_1 and t_0 are propagation times of aerial-mode and zero-mode travelling from fault position to measuring device respectively; Δt is the propagation time difference between aerial-mode and zero-mode travelling wave from the fault position to the measuring device.

The error with respect to a single sampling interval of the algorithm expressed by equation in (3) is:

$$e = \frac{v_1 v_0 T}{v_1 - v_0} \quad (3)$$

Where, T is the sampling interval.

From (2) and (3), this method is simpler and more likely to be implemented for a multiple-branch complex distribution network. The foremost problem rests with the improvement of the location accuracy.

3. The fault location correction algorithm

In this case, truncation error is inevitable due to the discrete sampling mechanism. The fault location correction algorithm proposed by Lin et al. [1] is used to correct the truncation error resulting from travelling wave based fault location methods. If actual arriving time of the travelling wave is between two adjacent samples, truncation error will appear no matter which sampling rate is used. Derivative has maximum value at the travelling wave head and linearly decreases linearly away from it. From Fig. 2 it can be seen that the derivative value of any point of the travelling wave has linear correlation with the distance from wave head.

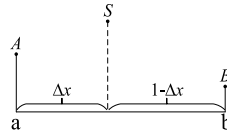


Fig. 2. The linear correlation of derivative and its distance from wave head.

The wave head labelled as S is located between a and b . Derivative of point a is denoted by A , and the distance between a and S is Δx . Derivative of point b is denoted by B , and the distance between b and S is $1 - \Delta x$. The correlation between derivative and distance is expressed as:

$$\frac{A}{B} = \frac{1 - \Delta x}{\Delta x} \Rightarrow \Delta x = \frac{B}{A + B}, S = A + B \quad (4)$$

If the sampling number of point a is M , the sampling number corresponding to wave head S will be $M - \Delta x$. By using modified sampling number in the fault location algorithm, the higher accuracy can be expected.

However, due to the complex non-linearity of fault transient wave process and the regularity of IED sampling at fixed intervals, it is impossible to exclude the possibility that the real wave head P is near A or coincides with A , as shown in Fig. 3. Once this happens, the correction interval Δx obtained by the modified algorithm shown in (4) will cause some errors artificially. In the case when derivative values of A and B are almost the same, Δx is approximately equal to 0.5, which would not reveal the exact arriving wave head position during the sampling interval. This is also the inherent defect of the two-point approximation method.

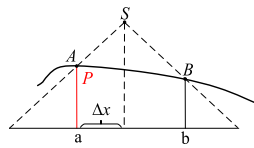


Fig. 3. The performance of two point approximation under the coincidence of the real wave head and the maximum of the derivation sequence.

In order to solve this problem, the “three-point approximation” is used instead of the “two-point approximation” proposed by Lin et al. [1]. By introducing the “third-point” that using the maximum sampling value C and the adjacent sub-maximum A and B , according to the linear proportional relationship shown in Fig. 4(1), (2), an improved correction wave head derivative value S' is obtained and the correction interval of the arrival time of the wave head is $\Delta x'$, which improves the problem of overcorrection of the correction algorithm proposed by Lin et al. [1].

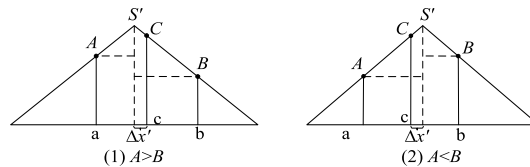


Fig. 4. A schematic diagram of three point approximation.

By observing geometric relations in Fig. 4, it is possible to extrapolate following equations:

- In a case when $A > B$, as shown in Fig. 4(1), the geometric relationship shows that:

$$\begin{cases} A + K(1 - \Delta x') = C + K \Delta x' \\ K = C - B \end{cases} \Rightarrow \Delta x' = \frac{A - B}{2(C - B)}, S' = C + \frac{A - B}{2} \quad (5)$$

- In a case when $A < B$, as shown in Fig. 4(2), the geometric relationship shows that:

$$\begin{cases} B + K(1 - \Delta x') = C + K \Delta x' \\ K = C - A \end{cases} \Rightarrow \Delta x' = \frac{B - A}{2(C - A)}, S' = C + \frac{B - A}{2} \quad (6)$$

From (5) and (6), it can be seen that when the real wave head P is exactly the maximum derivative value C or very close to C , the artificial error caused by the improved correction algorithm presented in this paper will be significantly reduced compared with the correction algorithm proposed by Lin et al. [1]. Taking the case of $A > B$ for example, the correction intervals Δx and $\Delta x'$ obtained by the two algorithms has following relationships:

$$\Delta x = \frac{A}{C+A} = \frac{(C+A) - (C-A)}{2(C+A)}, \Delta x' = \frac{A-B}{2(C-B)} = \frac{(A-C) + (C-B)}{2(C-B)}$$

$$\Rightarrow \Delta x = \frac{1}{2} \left(1 - \frac{C-A}{C+A} \right) > \frac{1}{2} \left(1 - \frac{C-A}{C-B} \right) = \Delta x' \quad (7)$$

In particular, when $A = B$, it is not difficult to deduce from the improved correction algorithm proposed in this paper that $\Delta x' = 0$, the correction wave head S' coincides with the maximum derivative value C . However, from (7) we can see that the Δx obtained by the correction algorithm proposed by Lin et al. [1] is still greater than 0 at this time, especially when the values of A , B and C are relatively close, the error will reach half of the sampling interval.

4. Simulation tests

PSCAD software is used for modelling and simulation of a 110 kV multiple-branch distribution network Xiaoshan Electric Power Co. Limited, Zhejiang, CHINA. Its simplified simulation model is shown in Fig. 5 with 9 branch lines. Lengths of the branches are: AB = 30 km, CD = 25 km, EF = 26 km, GH = 28 km, KL = 28 km, MN = 25 km, OP = 17 km, RS = 25 km, TU = 33 km. Travelling wave signals measured at the in-feed point A are used for locating the fault occurring on any position within the distribution network. Usually, FTUs are installed at the upstream end of each section of the line, which is helpful to achieve the fault sectionalization. Therefore, by means of limited installation of FTU together with the proposed fault location method, accurate fault location can be achieved.

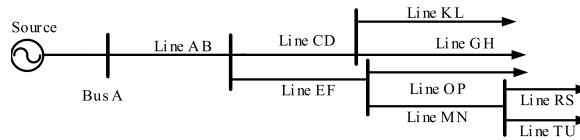


Fig. 5. Simplified distribution network simulation model.

When a fault occurs on a certain line, distribution automation (DA) system will be able to identify the faulty section successfully. Then, the algorithm described with (5) and (6) is used to locate the fault distance exactly. Combining the result of fault sectionalization and that of fault location, the exact fault position can be located.

Previously described distribution network is used in the following simulation scenarios. For each case, only one fault is occurred on a certain fault line and one sampling rate will be taken in consideration. According to simulation results in Table 1, following conclusions can be drawn:

(1) Considering the fault scenario at 100 kHz sampling rate, the average relative error of fault location is 8.82% when using method without correction algorithm, 2.37% for the correction algorithm proposed by Lin et al. [1], and 2.37% for the correction algorithm proposed in this paper. The average relative error of the correction algorithm proposed in this paper is 1.39%, and the max absolute error is within 1.68 km in the worst case. The comparison above shows that the accuracy of fault location can be greatly improved by correction algorithm proposed in this paper. Compared with the correction algorithm proposed by Lin et al. [1], the correction algorithm proposed in this paper has higher accuracy. Due to the complex and non-linear characteristics of fault travelling wave, some fault location results may show abnormal errors.

(2) With the increase of sampling rate, the accuracy of each algorithm improve to a certain extent. The average relative error of the correction algorithm proposed by Lin et al. [1] is 0.32% at 1000 kHz, which is 7 times higher than that at 100 kHz. The average relative error of the correction algorithm proposed in this paper is 0.08% at 1000 kHz and 17 times higher than that at 100 kHz. Thus, compared with the correction algorithm proposed by Lin et al. [1], the advantages of the correction algorithm proposed in this paper will be more obvious at high sampling rate.

Table 1. Fault location results for different sampling rates.

Sampling rate	Fault line section	Fault position [km]	Fault location distance				Sampling rate	Fault line section	Fault position [km]	Fault location distance			
			Actual fault location distance [km]	Calculated values						Actual fault location distance [km]	Calculated values		
				Without correction algorithm [km]	With correction algorithm [km]	Improved correction algorithm [km]					Without correction algorithm [km]	With correction algorithm [km]	Improved correction algorithm [km]
100 kHz	LineAB	10	10	13.443	9.990	10.307	500 kHz	LineAB	10	10	9.4104	10.001	9.8173
	LineCD	12	42	47.052	44.168	41.584		LineCD	12	42	41.675	42.526	41.971
	LineEF	15	45	47.052	42.907	44.973		LineEF	15	45	44.364	44.657	44.983
	LineGH	15	70	73.939	68.247	69.132		LineGH	15	70	69.906	69.998	70.068
	LineKL	10	65	67.217	67.040	65.979		LineKL	10	65	64.529	65.542	64.962
	LineMN	15	71	67.217	72.316	70.068		LineMN	15	71	71.250	71.188	71.109
	LineOP	10	66	67.217	62.304	64.849		LineOP	10	66	65.873	65.876	65.903
	LineRS	20	101	100.83	100.71	99.323		LineRS	20	101	100.83	100.85	100.97
LineTU	11	92	87.383	93.188	90.811	LineTU	11	92	92.760	91.566	92.107		
200 kHz	LineAB	10	10	10.083	10.003	10.262	1 MHz	LineAB	10	10	10.083	10.005	10.002
	LineCD	12	42	43.691	40.994	41.649		LineCD	12	42	41.675	42.263	41.963
	LineEF	15	45	47.052	44.184	44.815		LineEF	15	45	45.036	44.570	44.900
	LineGH	15	70	70.578	67.983	69.168		LineGH	15	70	69.685	69.871	69.895
	LineKL	10	65	63.857	63.956	64.394		LineKL	10	65	64.529	65.133	64.957
	LineMN	15	71	70.578	70.603	70.684		LineMN	15	71	70.578	71.186	70.988
	LineOP	10	66	67.217	64.369	65.298		LineOP	10	66	65.873	65.896	65.989
	LineRS	20	101	100.83	100.76	100.43		LineRS	20	101	100.83	100.84	100.91
LineTU	11	92	90.744	93.522	91.919	LineTU	11	92	92.088	92.069	91.987		

5. Conclusions

In view of the actual situation of distribution network that feeders are short and with lower attenuation, arriving time difference between different mode travelling waves is almost invariant. By virtue of above characteristics, a single-ended fault location method is proposed for the purposed of multi-branch distribution network fault location. Simulation test results show that the accuracy of the method proposed in this paper can meet the application requirements. Furthermore, it presents better performance under high sampling rate scenarios.

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