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Traveling-wave fault location algorithms in hybrid multi-terminal networks with a tree-like structure

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Abstract. Traveling-wave methods of the fault location prove their practical efficiency for the power transmission lines (TL) with an arbitrary configuration of any voltage class. This paper formulates algorithms to automate the process of the fault location in the TLs with a tree-like structure. The error of the simplified traveling-wave fault location (TWFL) algorithm based on the average propagation velocity of the transient signals (TS) is analyzed. A tabular algorithm for TWFL, which considers different propagation velocities of the TS in different segments of a hybrid network is proposed. An adaptive TWFL algorithm that considers the registration of the TSs with known places of their occurrence is proposed, to reduce the impact of the inaccuracy of the initial different network segments' lengths and TS's propagation velocity determination.

1 Introduction

Fast and accurate fault location in TLs is an important component of measures to eliminate the emergency mode in the network and ensure the fastest possible power supply to consumers. Distribution networks of 6(10) kV have a tree-like structure and often use grounding with an insulated neutral. These two features of the distribution network determine the impossibility of using of the impedance-based fault location [1], which is widespread in system-forming TLs of a higher voltage class 110-500 kV with a linear structure.

In recent decades in the 110-500 kV networks the TWFL [2-7] based on satellite synchronization of time scales and digital processing of signals, has come to replace the impedance-based fault location. With the advancement of modern traveling-wave theory and related technologies, TWFL has had significant development and has a good prospect in practical implementations.

At nowadays a considerable number of publications are devoted to the study of the TWFL in distribution networks, where traveling-wave acquisition units (TWU) can be located at different endings of a multi-terminal electric network [8-14]. It is noted that in this case a large amount of redundant information significantly increases the reliability of the TWFL with respect to two-terminal lines.

A large number of publications [15-18] are devoted to the formulation of TWFL in hybrid and multi-terminal lines. The work [19] deals with TWFL in networks with a ring structure.

This paper presents the methods, from the simplified to the more complicated one, which allow numerical algorithmization of the TWFL. The illustration of the error of these methods is based on the experimental measurements of the hardware-software system (HHS) of TWFL [20]. HHS consists of TWU installed at the ends of feeder's branches of the network and recording the beginning of the TS in a single satellite time scale. These data are transmitted via cellular communication channels to a remote server, where they are jointly processed, and the result of the fault location is output to the dispatcher's monitor.

In this paper a multi-terminal tree-like hybrid network consisting of the branches outgoing from the feeder is considered. TWU devices are located at the end of each branch. The lengths of network segments with a certain error are known from the working materials of the operating network organization and are updated on the basis of satellite maps. The results of the synchronous actuations of TWU, followed by the determination of the place of fault, allow us to determine the propagation velocity of the TS in the cable line (CL) and overhead line (OHL) segments of the network. These speeds correspond to the minimum of the objective function equal to the sum of the squares of the differences between the experimental time delays of the TWUs relative to the reference TWU and the calculated time delays [20].

2 TWFL algorithm №1

This algorithm of TWFL involves the allocation of sections (Figure 1) in the tree-like hybrid distribution network with two TWUs at the ends, which allow the using of the TWFL algorithm for TLs with a linear structure (1):

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$$X = \frac{L}{2} - \frac{V_{av} \cdot dT}{2}, \quad (1)$$

where L is the distance between TWU; Vav is the average propagation velocity of the TS; dT is the difference between the arriving times of the TS to the TWUs located at the ends of the line; X is the distance from one of the line's ends to the fault.

The simplified algorithm WTFL (algorithm № 1) is to use the average speed on the hybrid line between each pair of TWUs. The average speed of propagation of the TS in each area of length L is calculated by (2):

$$V_{av} = L \Big/ \left(\frac{L_1}{V_{OHL}} + \frac{L_2}{V_{CL}} \right), \quad (2)$$

where L_1 is the total length of the OHL in this line; L_2 is the total length of the CL in this area; $L = L_1 + L_2$.

Investigate the error TWFL on the scheme consisting of the OHL segment of length L_1 and the CL segment of length L-L_1 with a fault at the boundary at point D (Figure 1).

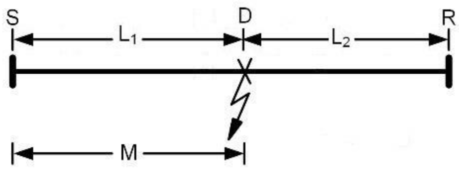

Fig. 1. Simplified scheme for the study of the TWFL's error according to the algorithm №1.

Establish the relationship between the TSs' propagation velocities (3), the TS's propagation time from the boundary D to the terminals S and R (4), the TS's propagation time from the boundary D to the terminal S (5), the TS's propagation time from the boundary D to the terminal R (6), the time delay between the arrival of the TS to the terminal R relative to the terminal S (7):

$$V_{OHL} = k \cdot V_{CL}, \quad (3)$$

where k is an arbitrary parameter.

$$T = \frac{L}{V}. \quad (4)$$

$$T_s = \frac{L_1}{V_{OHL}}. \quad (5)$$

$$T_r = \frac{k \cdot (L - L_1)}{V_{OHL}}. \quad (6)$$

$$dT = T_r - T_s. \quad (7)$$

These conditions allow us to calculate the TWFL's reduced error according to the algorithm №1 in the form of (8) and present it as a dependence on $L1/L$ at k=1.5 and 2 (Figure 2).

$$dM/L = (1-k) \cdot (L_1/L) \cdot (1 - L_1/L) \Big/ \Big/ \left(k + (L_1/L) \cdot (1-k) \right) \quad (8)$$

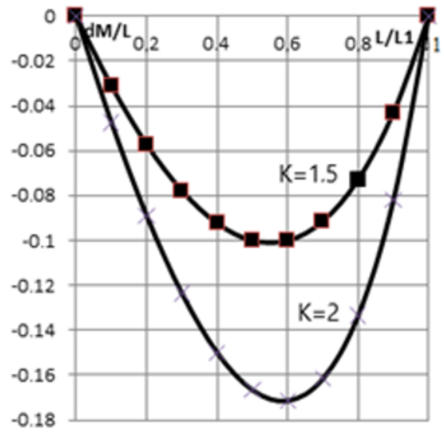

Fig. 2. Reduced error dM/L on L/L_1 at k = 1.5; 2.

It can be seen that the maximum value of the reduced error can reach 17% of the distance between the two TWUs. With an average length of this distance in a conventional distribution network, between the nearest two TWUs to the place of fault, equal to 3 km, the maximum possible error will be 510 m. With an increase in the number of intermittent OHL and CL segments in this area, the maximum error will be proportionally reduced.

3 TWFL algorithm №2

For reduce the error of fault location, it is proposed TWFL algorithm № 2 based on the table of calculated time delays of each TWU (table columns) relative to an arbitrary reference TWU (Table 1). Each row of the table corresponds to the individual location of the fault. As places of faults, nodes are used in which border the OHL and CL, where the branch line outgoing from the trunk line and at the terminals of the branch lines.

We describe the sequence of actions to determine the location of the fault according to algorithm №2:

1. When hardware registration of TSs it is determines the number of the TWU, which the first acquisitioned the TS. This TWU and corresponding to it the registration time of the beginning of the TS is defined as a reference;

2. It's calculated the time delays dM_I of the beginning of the TS, experimentally recorded by other TWUs relative to the reference, where the index I denotes the TWU number;

3. Two adjacent rows in Table 1 are defined in which the calculated time delays $T_{I,\ K-1}$ and $T_{I,\ K}$ are adjacent to the experimental time delay dM_I, where K is the node number of the fault;

4. A linear proportion is formed for the calculated time delays $T_{I,\ K-1}$ and $T_{I,\ K}$ and the its corresponding distances from the reference TWU, from which for the

experimental time delay dM_I it is determined the real distance to the fault from the reference TWU;

5. It is determined the distance to the fault by averaging over all TWUs.

3.1 The geometric illustration of the TWFL algorithm № 2

Let's perform the geometric illustration of the algorithm №2 using the example of a simplified three-terminal line (Figure 3), where L_1=SD; L_2=DR; L_3=DN.

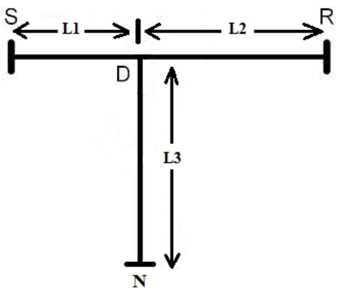

Fig. 3. Three-ended homogeneous TL.

The Table 1 is the time delay table for a three-ended homogeneous line with a reference TWU at point S.

Table 1. The time delay of the arrival of the TS to the terminals relative to the reference terminal, each row corresponds to a different node of the fault location.

Node\ Delays	Ts-Ts	Tr-Ts	Tn-Ts
S	0	(L1+L2)/V_{OHL}	(L1+L3)/V_{OHL}
D	0	(L2-L1)/V_{OHL}	(L3-L1)/V_{OHL}
N	0	(L2-L1)/V_{OHL}	-(L1+L3)/V_{OHL}
R	0	-(L1+L2)/V_{OHL}	(L3-L1)/V_{OHL}

According to the experimentally measured time delays of Tr-Ts and Tn-Ts, according to Table 1 and Figure 4, the distance from the reference TWU to the fault is determined. The error of the algorithm №2 is determined by the error of specifying the lengths of the segments and the propagation velocity. The experimental error is less than the algorithm №1 and ranges from tens to hundreds of meters [20].

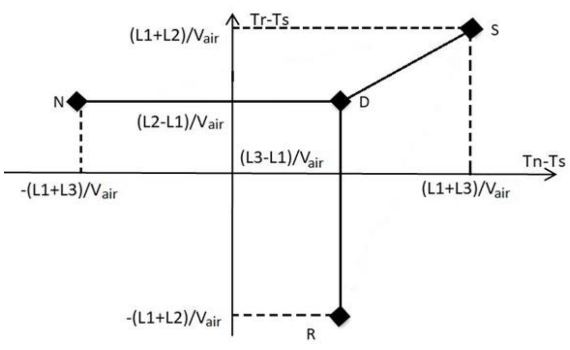

Fig. 4. Geometric interpretation of the algorithm №2 for a three-terminal homogeneous line, with reference point S.

4 TWFL algorithm №3

To reduce the error, it is proposed to take into account information about time delays obtained in experimental registrations with the detected coordinates of the fault. This algorithm is adaptable to experimental measurements. During the operation of the HSS, the table of time delays is permanently updated based on newly fault experimental measurements. The modernization of the time delays table consists of different experimental variants, the essence of which depends on the location of the identified fault relative to the nodes. Different experimental variants:

First variant – experimentally determined fault place coincides with the node. In the table of calculated TSs' time delays, the time delay obtained experimentally is written in its corresponding cell.

Second variant – involves the using of the experimentally determined time delays when the place of fault is in the gap between the nodes. Figure 5 shows two neighboring nodes N(k) and N(k-1) and the corresponding time delays from Table 1. It is applied a new experimentally determined fault point *M*. It is determined the new time delays for nodes N(k) and N(k-1) by parallel transfer of the initial line connecting N(k) and N(k-1) through the fault point *M*. The new values of the time delays for N(k) and N(k-1) are entered into the corresponding cells of Table 1.

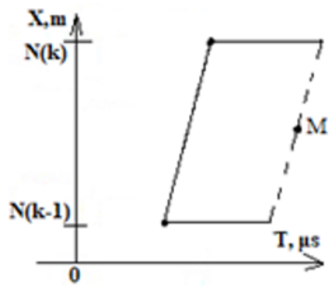

Fig. 5. Second variant.

Third variant – experimentally determined fault place is in the gap between the nodes, but the time delay for one of these nodes was previously modified on the basis of experimental measurements. Then, only the coordinates of the point N(k) are upgraded, based on the geometric construction in Figure 6.

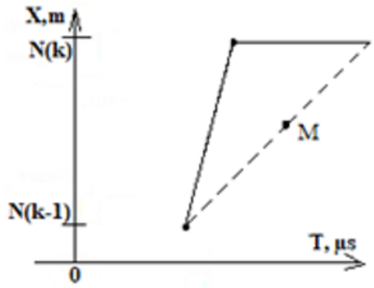

Fig. 6. Third variant.

Fourth variant – experimentally determined fault place is in the gap between the nodes, but the time delay for two of these nodes was previously modified on the basis of experimental measurements. The average value of *Mav* is taken for two (or more) earlier experimentally determined values of *M1* and *M2*, which determine the new average value for the content cells corresponding to the neighboring nodes N(k) and N(k-1) (Figure 7). .

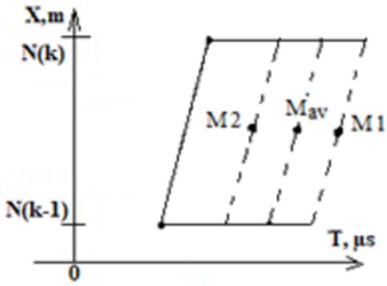

Fig. 7. Fourth variant.

5 Conclusions

1. The TWFL algorithms considered in the work have a practical significance in the development of the HHS of TWFL.

2. The error of the algorithm №3 is minimal, which is due to the use of previously registered experimental information, which links the network nodal points and the corresponding time delays. Thus, the error is reduced, which was caused by the inaccuracy of measuring the length of inter-node segments and the inaccuracy of specifying the TS's propagation velocity of the location of the fault in different inter-node segments.

3. The error of the TWFL of all algorithms is reduced by averaging using time delays from several pairs of HHS devices.

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