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A FAULT LOCATION METHOD FOR MULTI-TERMINAL TRANSMISSION LINES BASED ON TIME DIFFERENCES OF MODULUS TRAVELING WAVES

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Abstract: *In order to solve the fault location problem for multi-terminal line, a traveling-wave-based fault location method is proposed using arrival time differences of zero-mode and aerial-mode waves detected at each terminal. In this work, fault section judgement matrixes are set up and the rules for searching and determining fault section are established, after that the fault point can be located. The proposed method could ensure fault location accuracy once some synchronized devices are out of operation in multi-terminal lines. The simulation results show that the effectiveness and reliability of the proposed method.*

Introduction. The fault location is important for faster system restoration and reducing economic loss. Traveling-wave-based fault methods have more advantages compared to impedance-based approaches and have been widely used for achieving satisfactory results in two-terminal transmission lines [1,2]. However, due to the limitation introduced by being a complex line structure and multi-terminal synchronous measurement, the traveling-wave-based methods perform poorly for fault location in multi-terminal lines and it is necessary to be better solved. Multi-terminal traveling wave techniques to locate faults on branched networks have also been described [3-5]. However, the arrival times detected from all terminals must be synchronized by using GPS, the loss of a common time reference will cause fault location errors. In [2], additional communication devices are added to exchange data in order to replace the use of GPS, but the hardware cost is increased.

The classical one-terminal methods are independent of time synchronization, but reflected wave from the fault point is hard to identify in multi-terminal lines. For the ground faults, the one-terminal method based on initial aerial-mode and zero-mode traveling waves can be used to eliminate the need for the reflected wave. In this paper, the time-differences of modulus traveling waves detected at each terminal are used to identify fault section and locate fault point for multi-terminal lines. It cannot be restricted by the changes of line parameters and the multi-terminal time synchronization.

Proposed fault location method. The time differences of zero-mode and aerial-mode voltage traveling waves are obtained by Clarke's transformation and discrete wavelet transformation (DWT). Fig.1 shows a multi-terminal line, M1-M2 is the main line and Tk-Bk (k=1,2,…,n) are the branch line. Based on the time difference of modes, fault distances from X are obtained as follows:

$$l_{FX} = \Delta t_X v_0 v_1 / (v_1 - v_0) \tag{1}$$

where X is terminal index, $\Delta t_X = t_{X(0)} - t_{X(1)}$, t_{X0} and t_{X1} are the arrival times of initial zero-mode and aerial-mode waves at each terminal. v_0 and v_1 are the zero and aerial-mode propagation velocities, respectively.

A series of fault distance ratios are calculated, for example, $R_{M1M2} = l_{FM1}/l_{FM2} = \Delta t_{M1}/\Delta t_{M2}$, $R_{M1Bk} = l_{FM1}/l_{FBk} = \Delta t_{M1}/\Delta t_{Bk}$, and so on. It is shown that the velocity terms are eliminated in this way, the synchronized time is dispensable because the time differences are measured at terminals separately. In addition, the multi-terminal line can be seen as a structure of n layers, one layer with terminals M1, M2, Bk and tap node Tk. Thus, a series of branch distance ratios are pre-calculated at the tap node Tk, such as l_{TkM1}/l_{TkM2}, l_{TkM1}/l_{TkBk} and l_{TkM2}/l_{TkBk}. Then fault section judgement matrixes are set up and the kth is as follows:

$$\mathbf{D}_{Tk}=\begin{array}{c} \\ M1 \\ M2 \\ Bk \end{array}\begin{array}{c} \begin{array}{ccc} M1 & M2 & Bk \end{array} \\ \begin{bmatrix} 0 & l_{FM1}/l_{FM2}-l_{TkM1}/l_{TkM2} & l_{FM1}/l_{FBk}-l_{TkM1}/l_{TkBk} \\ - & 0 & l_{FM2}/l_{FBk}-l_{TkM2}/l_{TkBk} \\ - & - & 0 \end{bmatrix}\end{array}=\begin{array}{c} \\ M1 \\ M2 \\ Bk \end{array}\begin{array}{c} \begin{array}{ccc} M1 & M2 & Bk \end{array} \\ \begin{bmatrix} 0 & \Delta t_{M1}/\Delta t_{M2}-l_{TkM1}/l_{TkM2} & \Delta t_{M1}/\Delta t_{Bk}-l_{TkM1}/l_{TkBk} \\ - & 0 & \Delta t_{M2}/\Delta t_{Bk}-l_{TkM2}/l_{TkBk} \\ - & - & 0 \end{bmatrix}\end{array} \quad (2)$$

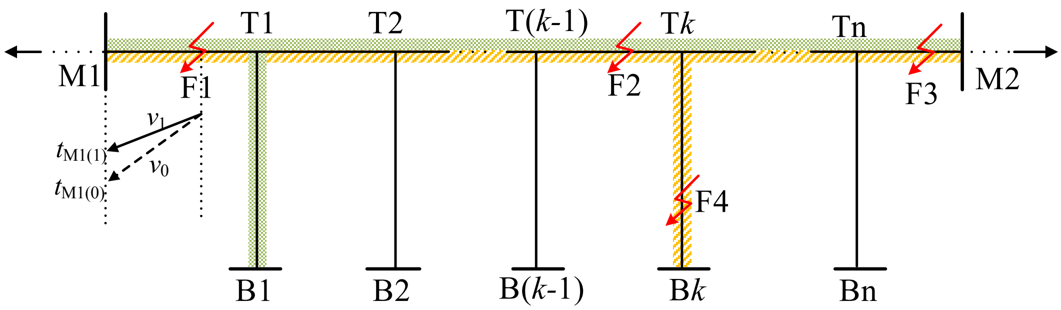

Figure 1 – Diagram of a multi-terminal transmission line

In these matrixes, the values of elements are compared with 0. In different fault sections (fault in Tk-M1, Tk-M2 and Tk-Bk), different results are obtained. Through calculating the elements in the upper and lower triangular part of the matrix, it can be found they are symmetrical and opposite in sign. In the upper triangular part, the element with uncertain value is related to the non-fault section and the other two elements are related to the fault section. Thus, the certain elements in the upper triangular part are sufficient to identify the fault section and rules are shown in Table1.

Table 1 – Rules to identify fault section

Fault section	M1-Tk	M2-Tk	Tk-Bk
Rules	rule1: $\mathbf{D}_{Tk}=\begin{bmatrix} 0 & <0 & <0 \\ - & 0 & - \\ - & - & 0 \end{bmatrix}$	rule2: $\mathbf{D}_{Tk}=\begin{bmatrix} 0 & >0 & - \\ - & 0 & <0 \\ - & - & 0 \end{bmatrix}$	rule3: $\mathbf{D}_{Tk}=\begin{bmatrix} 0 & - & >0 \\ - & 0 & >0 \\ - & - & 0 \end{bmatrix}$

When a fault occurs, searching and determining the fault section in multi-terminal line is by calculating the upper triangular part of D_{Tk}.

(1) If the D_{T1} is calculated and it satisfies rule1, the line M1-T1 can be judged as the fault section.

(2) If D_{T1} to $D_{T(k-1)}$ satisfy rule2 and D_{Tk} satisfies rule1, the line T(k-1)-Tk can be judged as the fault section.

(3) If $D_{T1}$to D_{Tn} satisfy rule2, the line Tn-M2 can be judged as the fault section.

(4) If D_{Tk} satisfies rule3, the branch line Tk-Bk can be judged as the fault section.

After the fault section is identified according to the aforementioned method, the fault location can be determined by two terminals connecting each other through the fault section. The fault point in the main line and the fault point in the branch line can be calculated as follows:

$$\begin{cases} l_{FM1}=R_{M1M2}l_{M1M2}/(1+R_{M1M2})\cdots \text{Fault in main line} \\ l_{FM1}=R_{M1Bk}l_{M1Bk}/(1+R_{M1Bk})\cdots \text{Fault in branch B}k \end{cases} \quad (3)$$

Simulation results. To evaluate the proposed method, a 5-terminal 220-kV/50-Hz line (Fig. 2) is simulated in PSCAD and MATLAB/Simulink, whose parameters were taken from Chinese northeast power system. The sample frequency is 1MHz. Set an AG fault in line section T2-T3, the time differences are detected at each terminal and the voltage wavelet coefficients are shown in Fig. 3. According to the calculations, both D_{T1} and D_{T2}satisfies rule2, D_{T3} satisfies rule1, so the line section T2-T3 is identified as the fault section. Because the line section T2-T3 is a part of the main line, the fault distance from the terminal M1 is calculated as $l_{FM1\text{-main line}}$=(7.61/(1+7.61)*300=265.16 km, and the fault location relative error is calculated using *Error*(%)=|265.16-265|/530*100%=0.030%.

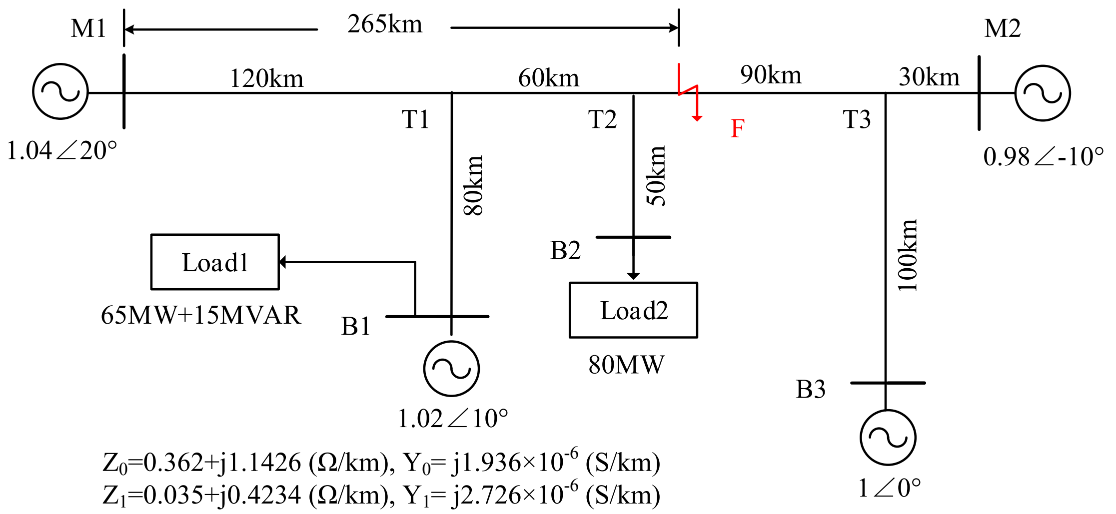

Figure 2 – Five-terminal lines simulation system

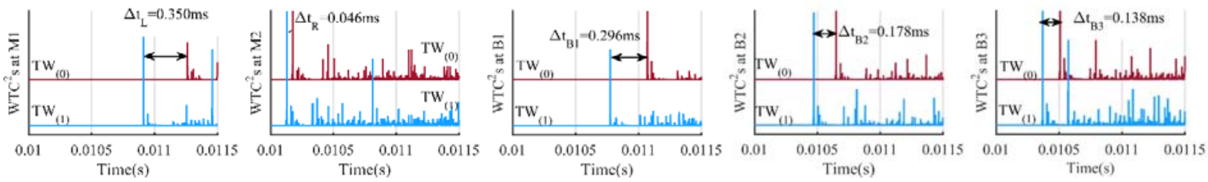

Figure 3 – Voltages wave coefficients for zero-mode and aerial-mode waves and arrival time difference at each terminal

To show the advantages of the proposed method, it is compared with the existing method in [5], a line parameter error ε (ε is set as +10% of the real line parameter) and GPS synchronized error δ (a 0.02 ms time delay is added at terminal M2) are introduced. The compared results are shown in Table 2. The proposed method locates the fault as accurately as the existing method in the ideal case. However, after adding errors ε and δ, the proposed method presents better performances because ε can cause error in the velocities of calculation, and the unsynchronized data in the two-terminal method [5] can result in great fault location error in the previous method, but the accuracy of fault location in the proposed method is not affected by these system errors.

Table 2 – Compared results of two methods

	Sources of errors		Method	
	ε	δ	[5]	Proposed method
Err(%)	-	-	0.082	0.075
	√	-	0.104	0.075
	-	√	8.936	0.075
	√	√	10.025	0.075

Conclusion. A Fault location method for multi-terminal transmission lines based on time differences of modulus traveling waves was presented. It cannot be restricted by the multi-terminal time synchronization and wave propagation velocities. The obtained results reveal the proposed method is quite useful for fault location in multi-terminal transmission line.

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ОПЫТ КИТАЙСКОЙ НАРОДНОЙ РЕСПУБЛИКИ В РАЗВИТИИ ПРОМЫШЛЕННОЙ РОБОТОТЕХНИКИ

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***Abstract**. The article is devoted to the development of industrial robotics in China. The historical stages of formation of automation of production processes in the country are considered. The basic state plans of development of this branch are stated. The important problems of the development of the robotics industry in China are listed. Conclusions are drawn about the prospects of industrial robotics development in the country.*

Президент Китая Си Цзиньпин, в своем выступлении в июне 2014 года, подчеркнул важность развития науки и инноваций, а также растущее значение робототехники. Си Цзиньпин заявил о планах реализации «третьей промышленной революции» и призвал мировую общественность рассматривать промышленных роботов в качестве «драгоценного камня в короне производства».

Начиная с 1970-х годов, создание и применение промышленных роботов в КНР были незначительными. После 2000 года, рынок Китая в данной области стремительно возрастал, и уже к 2013 году стал крупнейшим в мире. Ключевыми факторами этого роста были соответствующие планы правительства, иностранные поставщики и растущая экономика Китая в целом.

В историческом аспекте развития индустрии робототехники в Китае выделяют пять этапов:

1970-е годы: «Период изучения базовых технологий».

1980-е годы: «Период импорта и исследований базовых конструкций промышленных роботов».

1990-2000 год: «Период разработки прототипов, первых проектов и ограниченного производства».

2001-2010 год: «Стадия начальной индустриализации, применения и внедрения промышленных роботов».