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Fault location based on single terminal travelling wave analysis in radial distribution network

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ABSTRACT

Fault location remains a challenging problem in order to restore power supply rapidly. In this paper, a novel single-terminal traveling wave fault location procedure is proposed in a radial distribution network. Firstly, the propagating speed of zero mode traveling wave is determined by BP neutral network method. Then the preliminary estimation of fault distance is calculated based on the difference of velocities by discriminating the accurate timestamps of initial zero and aerial mode wave fronts. With this preliminary fault distance, the exact arrival timestamps of reflected wave fronts from fault position and far terminal end can be successful yielded. Finally, depended on mathematical relation of selected pairs-timestamps, the fault distance can be calculated precisely. Simulations have performed in PSCAD/EMTDC and the results show the accuracy and validity of procedures proposed above.

Introduction

Single-phase-to-ground fault represents the majority of fault events in distribution power networks. Fault location is referred to as accurate estimation of both the faulted feeder and fault position along the feeder. Various procedures have been proposed in [1–5].

The traveling wave fault location methods are generally divided into two research areas, time-domain analysis and frequency-domain analysis [6,7]. As the traveling wave acquisition methods, single-terminal and two-terminal fault location procedures are the main methods. The two-terminal fault location procedure is proceeded by the traveling wave data acquired from both ends of feeders. By discriminate the timestamps difference of the wave fronts which achieved from the both ends, the fault position is easily yielded. But this method is costly because the huge investment in equipments communication and GPS synchronization between two ends. As the time accuracy is delimited to a few microseconds at least, GPS synchronization equipments do not meet the accuracy requirement in some applications. Compared with data acquired from both ends, fault location based on single-terminal traveling wave method is also studied, only one traveling measurement equipment is required and it is more economical and more applicable [8–10]. However, accurate identification of the reflected wave fronts is a tough challenge. When a fault initiate in a power networks, the different mode of traveling waves have different transmission velocity. Based on the different velocity of different mode traveling wave, many scholars propose fault locating procedures by identification reflected wave fronts. Fault location is approximately yielded by discriminate the timestamps of different mode of traveling waves, but the uncertain wave velocity of mode 0 is neglected, and except for the first wave fronts of different modes, the next wave fronts which contain other valuable information are all discarded. Commonly, the traveling wave velocity of propagation mode 1 and 2 is roughly constant, while wave velocity of propagation mode 0 is frequency-dependent [11–13], and the transmission speed gets higher as fault distance decreases along the faulted line [8,14,15].

In this paper, we assume the wave velocity of zero mode component as a constant, and the preliminary fault position is deduced. With the difference of traveling wave transmission velocity of different modes, there has an arrival time gap between two initial traveling wave fronts which refer to the mode 1 and mode 0 respectively. The preliminary fault position is a clue for further accurate fault location. When network parameters are determined, the mathematical relationships between arrival time of initial reflected wave fronts from fault position and far terminal end bus at faulted feeder are also determined and unique. The two reflected wave fronts of mode 1 are exactly identified and fault position is further yielded from two single-terminal fault location equations. Finally, their average is calculated, fault location is more accurately and its results are verified by PSCAD/EMTDC.

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The choice of signal process method

Transient traveling wave signal has obvious singularity after the fault occurred. Wavelet transform can detect the transient signal singularity effectively and denoise at the same time, its properties are suitable for identifying transient traveling waves. Each modulus maximum point refers to unique signal singularity point [16–19]. Its amplitude represents the intensity of signal singularity, and its polarity represents fluctuation direction of signal. The results of wavelet transform show change rates of signal at one time point. Modulus maximum represents the highest change rates at this point that are arriving time of traveling wave.

Through lots of researches, it is found that wavelets applied in fault location contain the following features: (1) Varies of transient noises can be distinguished; (2) Perfectly recognize arrival time of transient signal, easy to identify the singular point, *viz*; (3) Small number of oscillations in order to analyze result; (4) High time-domain resolution and easy to regulate in frequency-domain resolution; (5) Concentrated energy with small product of time window and frequency window.

Compared with other wavelets, Daubechies wavelet family (DbN) performs better in the application. Therefore, DbN is selected to identify the transient fault signals. Table 1 shows energy concentration degree D_{cent} from Db3 to Db9 [17]. Db6 and Db5 mother wavelets show better concentration degree. As N increases, amplitude–frequency characteristic gets better, but resolution of frequency gets worse. In the light of factors above, Db6 is selected as the optimal mother wavelet. Original signal and wavelet analysis results using Db2 & Db6 are pictured in Fig. 1, in which the latter Db6 performs better, because it is easily to identify the exactly timestamp of the wave front.

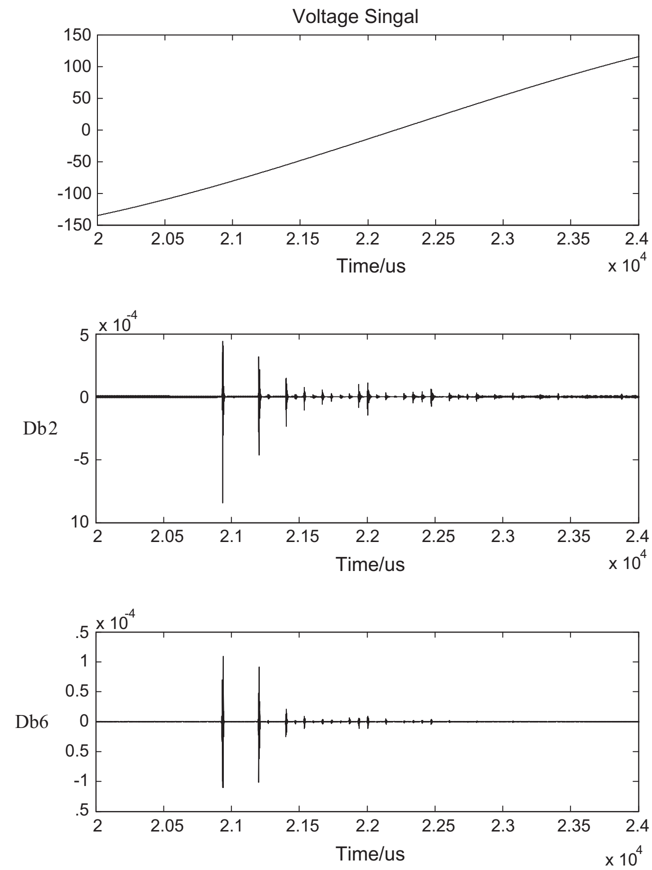

Fig. 1. Comparison of Db wavelets analysis.

Traveling wave analysis on different mode components

Voltage and current satisfy following equation on three-phase uniform transmission line [2,20], frequency domain transient Eq. (1) of each propagation mode,

$$\begin{cases} \frac{d^2 \boldsymbol{u}_m}{\partial x^2} = \mathbf{S}^{-1}\mathbf{PS}\boldsymbol{u}_m \\ \frac{d^2 \boldsymbol{i}_m}{\partial x^2} = \mathbf{Q}^{-1}\mathbf{P}^T\mathbf{Q}\boldsymbol{i}_m \end{cases} \tag{1}$$

where $\boldsymbol{i}_m = [i^{(0)}, i^{(1)}, i^{(2)}] = \mathbf{Q}^{-1}[i_A, i_B, i_C]$, $\boldsymbol{u}_m = [u^{(0)}, u^{(1)}, u^{(2)}]^T = \mathbf{S}^{-1}[u_A, u_B, u_C]^T$, $\boldsymbol{u}_m$ and $\boldsymbol{i}_m$ refer to propagation modes, $\mathbf{Q}$ and $\mathbf{S}$ are phase-to-mode transform matrix, $u^{(0)}$ and $i^{(0)}$ are zero-mode voltage and current, others are aerial mode components, x is the distance away from measurements along the line. $\mathbf{P} = \mathbf{ZY}^T$, $\mathbf{P}^T = \mathbf{YZ}$, $\mathbf{Z}$ and $\mathbf{Y}$ are respectively series impedance matrix and parallel admittance matrix, $Z = R + j\omega L$, $Y = G + j\omega C$.

The equations of phase-to-mode transformation and inverse transformation matrix are denoted as,

$$\begin{bmatrix} x^{(0)} \\ x^{(1)} \\ x^{(2)} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix}\begin{bmatrix} x_A \\ x_B \\ x_C \end{bmatrix} \tag{2}$$

$x^{(1)}$ and $x^{(2)}$ are aerial mode components of voltage and current traveling wave, $x^{(0)}$ is zero mode component.

Table 1
The energy concentrating degree from Db3 to Db9.

Db	3	4	5	6	7	8	9
D_{cent}	0.73	0.74	0.82	0.83	0.78	0.80	0.78

Frequency-dependent model is applied to measure the transient voltage and current. In this model, wave impedance and propagation coefficient of mode components are,

$$Z_m^{(k)} = \sqrt{\frac{R_m^k + j\omega L_m^{(k)}}{G_m^k + j\omega C_m^{(k)}}} \tag{3}$$

$$\gamma_m^{(k)} = \alpha_m^{(k)} + j\beta_m^{(k)} \tag{4}$$

The propagation velocity of different mode component is defined as followed,

$$v_m^{(k)} = \frac{\omega}{\beta_m^{(k)}} \tag{5}$$

where $k = 0, 1, 2$. $R_m^{(k)}$, $L_m^{(k)}$, $G_m^{(k)}$ and $C_m^{(k)}$ refer to resistor, inductance, conductance and capacitance of each propagation mode per unit length respectively. $\alpha_m^{(k)}$ refers to attenuation coefficient, $\beta_m^{(k)}$ refers to phase distortion coefficient.

Aerial mode components $R_m^{(k)}$, $L_m^{(k)}$ are frequency independent generally [11,12]. Frequency-dependent velocity is neglected here, wave velocity of aerial mode is worked out by the equation below,

$$v_1 = \frac{\omega}{\beta_m^{(k)}} = \frac{1}{\sqrt{LC}} = 2.967 \times 10^5 \text{ km/s}$$

where $L = 2.95 \times 10^{-3}$ H/km, $C = 3.85 \times 10^{-9}$ F/km.

Resistance and inductance of zero mode components are closely related to frequency for skin effect. Zero mode resistance $R_m^{(0)}$ increases and inductance $L_m^{(0)}$ decreases as frequency rises. And attenuation coefficient $\alpha_m^{(0)}$ and wave velocity v_0 of zero mode component increases as frequency rises, in other words, the higher