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Fault location for power grid based on transient travelling wave data fusion via asynchronous voltage measurements

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ABSTRACT

Considering the complex topology of power grids and their important application, finding an effective fault location algorithm is mandatory. This paper presents a fault location method for power grid based on transient travelling wave data fusion and asynchronous voltage measurements. Firstly, the refraction regularity, attenuation rule and main factors affecting the amplitude of the initial travelling wave are analyzed. Then the modulus maxima of detail coefficients, treated as the feature variables of the initial travelling wave, are extracted via wavelet transform. At last, according to the configuration of the measuring points, fault location scheme based on data fusion theory is proposed. In data level fusion, phase-mode and wavelet transform are carried out in order to obtain the feature variables. In feature level fusion, the fault section is determined through the fault feature variables filtered by the network topology and the artificial neural network is used to fit the relationship between the fault distance and the time difference of arrival between single-terminal aerial-mode and zero-mode voltage. In decision level fusion, the double-terminal fault location algorithm based on the single-ended uploaded data is proposed. The IEEE 30-Bus System is simulated in PSCAD/EMTDC and the fault location algorithm is carried out in MATLAB. The simulation results demonstrate that high-precision fault location could be realized and that practicality and economy are improved without requirements on synchronous sampling.

1. Introduction

In recent years, with the rapid development of power grids, higher requirements are put forward for the reliability of power supply. If the fault cannot be precisely located and quickly eliminated, it will cause incredible damage to national economy, which greatly affects people's life. Therefore, fault location is a hot research topic. At present, fault location methods can be classified into two categories: (1) steady-state data based method, and (2) transient-state data based method. The former is susceptible to the influence of distributed capacitance and transition resistance, which restricts its uses [1–5], while the latter is widely used for its high-precision [6–12]. Nowadays, wide-area measurement system (WAMS) based on phasor measurement unit (PMU) and other equipment to obtain the transient information of power grid in real time is expanding rapidly, which provides a new means for the transient analysis of power system [13]. Based on modern fault location principle using travelling waves, the experts and scholars put forward multi-terminal fault location methods based on WAMS [14]. But most current based fault location methods require strict synchronization which seriously affects the accuracy of fault location [15–21]. Literature [16] extends the double-terminal fault location principles, using wide-area information of travelling waves to identify the disturbance line and locate the disturbance point in power system, but the simulation model is simple in structure and the applicability of this algorithm in more complex networks remains to be further validated. Literature [17] proposes a fault location method, in which the measuring devices are installed on both ends of each line to record fault information synchronously. The correctness of the proposed method is verified in IEEE 118-Bus system. However, this method requires high investment in equipment and thus it's difficult to obtain the practical application. Literature [18–21] uses synchronous measurement devices installed in a few substations to acquire the arrival time of travelling waves. But the accuracy is susceptible to synchronous sampling. There are also some transient-state data based methods don't require synchronization offered by WAMS, which need to distinguish the second travelling wave head [22,23]. In [22], the accurate fault location is realized by using the time difference of arrival of the first two travelling waves detected at the measuring

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points. The difficulties lie in the second travelling wave head detection. Combined impedance and travelling wave fault location scheme for multi-terminal transmission lines is presented in [23]. The faulted line section and faulted half of the line section are determined based on a simplified impedance method. Accurate fault location is finally achieved by using the time difference of arrival of the first two current travelling wave heads. The disadvantages of the method are the same as [22]. Besides above methods, some scholars researched the attenuation phenomenon of travelling waves in HVDC transmission lines and distribution lines, and the neural network is used to fit the mathematical relationship between the attenuation of fault features and fault distance [24,25], yet the study on the attenuation rule of travelling waves in AC transmission lines is still at the preliminary stage. From above research, the fault location based on transient travelling wave has been thoroughly studied, but the synchronous measurement or the identification of the second wave-head are required generally, which increase the investment and the robustness is poor. Those shortcomings limit the practical application.

To solve the above problems, this paper presents a fault location method for power grid based on transient travelling wave data fusion and asynchronous voltage measurements. While the fault occurs on a certain transmission line, the fault travelling waves travel from the fault point to the whole power grid following the refraction regularity, and the fault feature can be extracted by wavelet transform and used to determine the fault section. Then, by means of the study on the attenuation rule of travelling waves in AC transmission lines, this paper proposes a fault location method based on the theory of transient data fusion. This approach does not require accurate synchronous sampling and distinguish the second travelling wave head. Besides, the investment can be greatly saved with proposed reasonable configuration. These characteristics are beneficial to further enhancement of the practicability of the travelling wave location.

This paper is organized as follows. Section 2, provides a brief introduction to refraction and reflection principle of travelling wave and extracts feature of fault information. In Section 3, graph theory is used for dealing with the measurement points. The methodology that is used to located faults is presented in Section 4, while the training and testing results are presented in Section 5 followed by conclusion in Section 6.

2. Determination and extraction of fault features

When a fault occurs in power system, the travelling waves propagate along the transmission lines, which produces the phenomenon of refraction, reflection and attenuation. The influence of refraction and reflection can be reduced if only the initial travelling wave is considered. Besides, the initial fault travelling wave could be reliably identified via wavelet analysis [26]. Thus, all the research work in this paper is based on the analysis of the amplitude of initial travelling wave.

As shown in Fig. 1, the line consists of N branches, each of whose impedances is assumed to be the same, that is, $Z_1 = Z_2 = \cdots = Z_N$. According to refractive law, the refractive index of line 2 is:

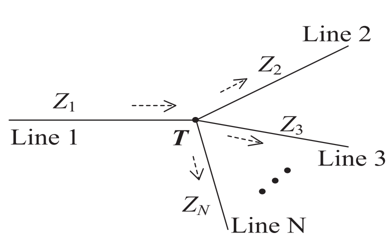

Fig. 1. Multi-branch line model.

$$\gamma_\mu = \frac{2Z}{Z + Z_1} = \frac{2Z_1}{NZ_1} = \frac{2}{N} \tag{1}$$

where Z is the equivalent parallel impendence of $N-1$ lines except for line 1.

Similarly, the refractive index of each of the rest lines is 2/N, which demonstrates that the refraction wave is equally distributed on homogeneous lines.

After phase-model transformation, the propagation coefficients of positive and negative sequence are:

$$\begin{aligned}\gamma_m^{(k)}(\omega) &= \sqrt{\left[R_m^{(k)}(\omega) + j\omega L_m^{(k)}(\omega)\right]\left[G_m^{(k)} + j\omega C_m^{(k)}\right]} \\ &= \alpha_m^{(k)}(\omega) + j\beta_m^{(k)}(\omega) \quad (k = 0, 1, 2)\end{aligned} \tag{2}$$

where $R_m^{(k)}(\omega)$, $L_m^{(k)}(\omega)$, $G_m^{(k)}(\omega)$ and $C_m^{(k)}(\omega)$ represent the resistance, inductance, conductance and capacitance in per unit length, respectively.

For signals at a single frequency, amplitude decay and phase delay are directly proportional to the length of line during the propagation of travelling waves. Paper [24] points out that the zero-mode voltage travelling wave is generated in ground faults and its amplitude decay is far greater than that of the aerial-mode voltage with the wave propagation. In the following, aerial-model is used for extracting the fault feature and the result is suitable for zero-model whose attenuation is more obvious and the simulation has been verified.

PSCAD/EMTDC is used to build a simulation model shown in Fig. 2, where the length of line 1 and line 2 is 150 km and 40 km respectively. A-phase to ground fault is set at the point 100 km from the transformer on line 1. The sampling frequency is 1 MHz. The initial travelling wave will refract at bus 1 and bus 2 after the fault. There are three outlets of bus 1 and two outlets of bus 2. The corresponding refractive indexes obtained from Eq. (1) are 1/2 and 2/3 respectively.

The influence of the attenuation factor could be eliminated by using variable-controlling approach: the length of line 3 and 4 and the length of line 5 and 6 are set to be 1 km and 20 km respectively in simulation; the refractive law at load 3, load 4 and bus 1 are the criterion for feature selection, and so is the refractive law at load 1, load 2 and bus 2.

In order to verify the refractive law and extract the fault features, the data acquired at bus 1 is converted to load 3 side. The specific method is divided into the following two steps: (a) Multiply the wavelet transform modulus maxima of each level of the aerial-mode voltage of bus 1 by its refractive index; (b) Consider the influence of transformer. Due to the fact that the fault travelling wave cannot pass through the transformer, the total reflection occurs at the transformer of load 3 side and the final converted coefficient of bus 1 is $1/2 \times 2 = 1$. Similarly, the converted coefficient of bus 2 is $2/3 \times 2 = 4/3$. The results are listed in Tables 1 and 2.

The following conclusions can be drawn from Tables 2 and 1: (1) The coefficients of each level conform to the law of average distribution; (2) The data of d1 and d2 level follow the refractive law, but the data of d3, d4 and d5 level do not; (3) The attenuation degree of the modulus maximum of d2 level is not proportional to the length of line, which does not comply with the attenuation rule.

Based on the above conclusions, the modulus maximum of d1 level, in this paper, is used as the fault feature to represent the amplitude of the initial travelling wave.

3. Configuration of measuring points

According to graph theory, for any graph G, it is composed of 2 sets: non-empty node set V (G) and finite-edge set E (G). If $V(G) = \{v_1, v_2, \ldots, v_n\}$, $E(G) = \{e_1, e_2, \ldots, e_m\}$, then: