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Traveling wave protection based on asynchronously sampled time difference of arrival of modulus traveling waves in per unit line length

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ABSTRACT

Traditional traveling wave protection schemes are susceptible to many factors such as network topology change, environment interference and inaccurate identification of wave fronts, which may lead to mal-operation of protection. In addition, most traveling wave protection schemes need accurate synchronous measurement which adds to the implementation cost. This paper proposes a traveling wave protection for high voltage power grids based on the time difference of arrival (TDOA) of zero-mode and aerial-mode traveling wave. First, the time difference of arrival of the modulus voltage traveling waves (MVTWs) asynchronously sampled at each bus is captured. With the minimum TDOA, the key bus and fault area can be firstly determined. Then, the TDOA of the line in per unit length is defined as the ratio between the difference of the TDOAs at both terminal buses and line length. Finally, as for one case that key bus connects with no other bus, the line corresponding to the minimum TDOA of all the lines in the fault area is determined as the fault line. As for the other case, the calculated line length should be compared with the actual one to detect the fault line. PSCAD/EMTDC is used to conduct fault simulations and the calculation results verify that the proposed scheme is not affected by fault resistances, inception angles and distances. In addition, the operation time of the scheme does not exceed 20 ms, which makes it applicable for actual power grid protection.

1. Introduction

In China, the power grid has a rapid development, and long distance transmission becomes widespread. The energy base is far from the power load center so long transmission lines are necessary for power transmission. These transmission lines are hundreds of kilometers in length and may be damaged by severe weather and human activities, resulting in short circuit and ground fault. Whether or not the protection action is reliable after a fault occurs is of great significance to the safe and stable operation of the power grid [1]. The operation time of existing relay protection is long, thus fast protection are expected to be developed for wide area power grids [2].

Compared with traditional relay protection technologies, traveling wave protection boasts a fast response and is not affected by the factors such as distributed capacitance, system oscillation, and current transformer saturation [3–6]. In recent years, traveling wave protection has developed rapidly [7–10]. Current traveling wave protection mainly uses the amplitude and polarity information of the wave front to construct protection criteria and realizes distance, direction or differential protection [11–13]. Obviously, accurate identification of the arrival time of the traveling wave front is very important in traveling wave protection [14,15], thus wavelet transform is employed to reconstruct the waveform [16,17]. In Ref. [18], experiments have been conducted on a single-phase radial distribution line with off-line and on-line topological changes. It is clear from the analysis that using dominant frequency signature parameters, the wavelet network could successfully classify the transients on the basis of the circuit topology and could be used in protection for high voltage power grids.

In order to accelerate the protection, more improved traveling wave protection schemes have been proposed. A fast pilot directional protection based on waveform integral of traveling wave for high voltage transmission line is proposed in Ref. [19]. The protection method in Ref. [20] compares the polarities of current and voltage traveling waves measured immediately after the fault inception to determine the fault

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direction. Refs. [21,22] present two novel ultra-high-speed directional protection schemes based on mathematical morphology. Moreover, Teager energy operator is used to extract the arrival time of traveling wave front for the protection of transmission lines [23].

Although many of the current traveling wave protection schemes have been applied in practical engineering, there are still some defects and imperfect parts in these schemes. The protection scheme in Ref. [24] needs accurate identification of subsequent traveling wave fronts. In Ref. [25], the proposed protection scheme uses only the arrival time of first wave front at each line terminal but it needs synchronous measurements from both terminals. The arrival time of traveling wave is recorded using precise time stamps provided by GPS to achieve power network protection [26]. It is a simple protection but GPS adds to the implementation cost. In addition, the protection schemes in Refs. [20–24] are susceptible to many factors such as network topology change, environment interference and wave velocity, which may lead to mal-operation of protection.

This paper proposes a simple, fast and reliable traveling wave protection scheme for high voltage power networks. The fault area is determined by identifying the bus corresponding to the minimum time difference of arrival of MVTWs. The fault line can be accurately identified by three steps. (I) The minimum TDOA of each line in per unit length in the fault area is determined; (II) the calculated length and actual length of each line in the fault area are compared; (III) the TDOA of the lines whose calculated lengths are less than the actual ones are compared. Various fault simulations have been carried out to verify the selectivity, reliability, speed and sensitivity of the proposed protection scheme. Compared with the state-of-the-art traveling wave protection schemes, the proposed scheme only needs to identify the arrival time of initial wave front signal asynchronously sampled at each bus and has high practical engineering value.

2. Basic characteristics of TDOA of MVTWs

As for homogeneous transmission lines, the initial voltage traveling wave signal $U(x, \omega, t)$ can be expressed by [27]

$$\begin{cases} U(x,\omega,t) = \sqrt{2}U^{+}e^{-\alpha(\omega)x}\cos(\omega t - \beta(\omega)x + \phi_{+}) + \sqrt{2}U^{-}e^{\alpha(\omega)x}\cos(\omega t + \beta(\omega)x \\ \qquad + \phi_{-}) \\ \alpha_m(\omega) = \sqrt{\frac{1}{2}[R_m(\omega)G_m - \omega^2 L_m(\omega)G_m + \sqrt{(R^2{}_m(\omega) + \omega^2 L^2{}_m(\omega))(G^2{}_m + \omega^2 C^2{}_m)}]} \\ \beta_m(\omega) = \sqrt{\frac{1}{2}[\omega^2 L_m(\omega)C_m - R_m(\omega)G_m + \sqrt{(R^2{}_m(\omega) + \omega^2 L^2{}_m(\omega))(G^2{}_m + \omega^2 C^2{}_m)}]} \end{cases} \tag{1}$$

where $\alpha(\omega)$ and $\beta(\omega)$ are the amplitude attenuation and phase lag factors. $R_m(\omega)$, $L_m(\omega)$, $G_m(\omega)$ and $C_m(\omega)$ are the resistance, inductance, conductance and capacitance of transmission lines in per unit length, respectively. Eq. (1) discloses that the initial traveling wave is bandwidth signal whose amplitude attenuates and phase lags with propagation distance. The propagation velocity of the traveling wave is [27]

$$v(\omega) = \frac{\omega}{\beta(\omega)} \tag{2}$$

where $v(\omega)$ is the wave velocity at angular frequency ω. It can be observed from (2) that wave velocity varies with frequency and phase lag factor. In actual field, the measured velocity decreases with propagation distance due to the attenuation of traveling waves. Generally, the change of zero-mode velocity is more dramatic than that of the aerial-mode [27]. Thus, the aerial-mode velocity can be seen as constant while zero-mode cannot.

When a fault occurs in a transmission line shown in Fig. 1, the initial velocities of the zero-mode and the aerial-mode traveling wave are the same. Due to attenuation, the difference between the zero-mode and aerial-mode wave velocity increases with the propagation distance, which results in the variation of the difference of the propagation time between the zero-mode and aerial-mode traveling waves. In Fig. 1, the line is divided into many small line segments, the length of which are equal. $dx_1 = dx_2 = dx$ are the lengths of any two line segments (denoted as segments 1 and 2 respectively). v_{0_1} and v_{0_2} are the velocities when the zero-mode traveling wave arrives at these two segments.

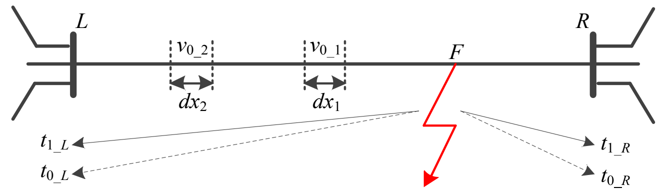

Fig. 1. Modulus traveling wave propagation along a transmission line.

The TDOAs of the zero-mode and aerial-mode traveling waves in the segment dx is defined as the TDOA of the line segment and shown by

$$\Delta t = \left| \frac{dx}{dv_1} - \frac{dx}{dv_0} \right| \tag{3}$$

where v_1 and v_0 represent the aerial-mode velocity and the zero-mode velocity when the initial modulus traveling waves arrive at segment dx. Similarly, the TDOAs of the two line segments in Fig. 1 can be expressed by

$$\begin{cases} \Delta t_1 = \frac{dx}{dv_{0\_1}} - \frac{dx}{dv_1} \\ \Delta t_2 = \frac{dx}{dv_{0\_2}} - \frac{dx}{dv_1} \end{cases} \tag{4}$$

where Δt_1 and Δt_2 are the TDOAs of the two line segments whose lengths are dx_1 and dx_2. Since $v_1 > v_{0\_1} > v_{0\_2}$, it can be seen from (4) that $\Delta t_1 < \Delta t_2$.

According to the above analysis, the TDOA of the line segment increases with the propagation distance of modulus traveling waves. In order to verify the variation of the TDOA of the line segment, a single-phase-to-earth fault is simulated by PSCAD at the point 200 km away from left terminal L of the transmission line shown in Fig. 1 where the line section between the fault point and terminal L is equally divided into 20 line segments. The calculated TDOA of each segment is shown in Fig. 2 where it can be seen that the simulation result consists well with the theoretical analysis.

3. Traveling wave protection based on the TDOA of MVTWs in per unit line length

When a fault occurs in a transmission network, the TDOAs of the MVTWs measured at all buses is related to the fault line location. The bus corresponding to the minimum TDOA is defined as key bus, which is obviously the closest to the fault. The TDOAs of the key bus and other adjacent buses can be used to construct the protection criteria. The TDOA is analyzed in two types of key bus connection shown in Fig. 3. The difference between the two types of connection lies in whether the key bus (bus 1 in Fig. 3) connects with branches. Based on the analysis, a uniform protection scheme is proposed for wide-area transmission networks.

When a fault occurs at the midpoint of a line, the TDOAs of the MVTWs measured at the two buses of the fault line are equal and

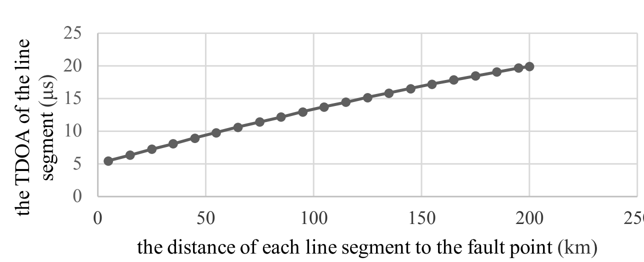

Fig. 2. Relationship between TDOA of the segment and propagation distance.