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A practical first-zone distance relaying algorithm for long parallel transmission lines

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ABSTRACT

This paper presents a novel non-iterative first-zone distance relaying algorithm for single-line-to-ground fault detection in long parallel transmission lines. The conventional distance protection scheme is based on the series impedance line model, in which the shunt capacitance and propagation effects are neglected. Such a simplification, despite being adequate for short lines, can lead to significant errors in the apparent impedance estimation for long-distance faults. The proposed algorithm is derived from a distributed parameter line model applicable to long parallel lines, in which the shunt capacitance and mutual impedance and admittance are all fully considered. Sliding faults simulations were carried out in MATLAB using symmetrical components and graph theory assuming two long parallel transmission lines. It is shown that the proposed algorithm leads to a very good agreement between the apparent and positive-sequence impedances to the faults for line lengths up to approximately 800 km, without using iterative methods. This indicates that the proposed algorithm prevents the distance relay from underreaching for long-distance faults in parallel lines, without additional computational cost.

1. Introduction

The growing demand for electricity in countries where hydropower plants are located far away from major load centres suggests the need of constructing long and extra-long transmission lines (TLs) [1]. In general, such lines are optimized to reach a high power carrying capacity. Therefore, they require effective and efficient protection systems.

In the conventional distance protection formulation, the TL is modelled as a lumped parameter circuit in terms of its total series impedance, disregarding the capacitive and propagation effects. This is a suitable approach for short lines. However, it can cause significant errors if applied to long lines, in which the capacitive effect is pronounced. As the line length increases, the capacitive current also increases. This has the effect of cancelling out inductive currents, which reduces the total current and increases the apparent impedance seen by the relay. In this case, the relay is likely to underreach. To overcome this difficulty, distance protection schemes based on a distributed parameter line model were proposed in Refs. [2,3] to allow the correct estimation of the apparent impedance in long single-circuit lines.

Parallel TLs have been widely used in transmission systems. One important characteristic of parallel lines is the impossibility to eliminate the zero-sequence mutual coupling between the lines even if each individual circuit is perfectly transposed. For example, the influence of the zero-sequence mutual coupling on the distance relay performance in parallel TLs is analysed in Ref. [4]. In Ref. [5], an adaptive distance protection scheme for parallel lines considering the mutual coupling effect is introduced. In Ref. [6], a method that is independent of fault resistance for estimating the fault distance in parallel TLs is suggested. In Ref. [7], an algorithm that requires only local data of the protected line is proposed. First-zone distance protection algorithms for cross-country ground faults are presented in Refs. [8,9]. However, all the protection schemes cited above were derived from the series impedance line model, which is valid for short lines only. Thus, they may cause the relay to underreach for long-distance faults.

Efforts are under way to develop more accurate methods for protecting long parallel lines. In Ref. [10], an adaptive digital distance relaying scheme using a radial basis function neural network is proposed. Nevertheless, mutual coupling and shunt capacitance are not considered simultaneously. In Ref. [11], an adaptive distance protection scheme based on the back-propagation neural network is proposed, which takes into account mutual impedance and shunt capacitance under different power system conditions. However, mutual admittance and propagation effects are disre-

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garded. In Ref. [12], an auxiliary module is proposed for first-zone conventional distance relays of double-circuit TLs to remove the underreach caused by high-resistance faults. The fault distance is in this case estimated from the solution of a nonlinear equation that is derived from a distributed parameter line model. This nonlinear equation is solved through an iterative method. Ref. [13] suggests a fault location algorithm for parallel lines based on the exact π-model, which uses the Newton–Raphson iterative method to solve for the unknowns.

This paper proposes a novel non-iterative first-zone distance relaying algorithm for identifying single-line-to-ground (SLG) faults in long parallel TLs. Its main advantage over the existing algorithms is that it fully considers the shunt capacitance, propagation effects, and the mutual coupling between the lines without using iterative methods. The proposed algorithm is therefore suitable for real time implementation. It is also shown that it prevents the relay from underreaching for long-distance faults.

This paper is organized as follows. Section 2 presents the system modelling. For convenience in explanation, Section 3 describes the distance protection schemes presented in Refs. [2,5], which serve as a starting point for the proposed algorithm. Section 4 details the proposed input signals for the ground distance elements in long parallel lines, which is the main contribution of this paper. Section 5 compares the performance of the proposed algorithm to that of a conventional distance relay. Section 6 concludes this paper.

2. System modelling

Fig. 1 shows the single-line diagram of the modelled system. The parallel TLs are assumed to be identical, both carrying three-phase alternating currents, with a total length (ℓ) of 800 km. They are totally transposed and operate in sinusoidal steady state at a 60-Hz frequency. Furthermore, it is considered that the entire system is balanced, having only positive-sequence currents and voltages.

The conductor arrangement suggested in Ref. [14] for a 1000 kV optimized line was adopted. The surge impedance loading (SIL) of each line is 7.548 GW. Therefore, they are suitable for transmitting large amounts of power over long distances. Each phase has 12 conductors (ACSR Bluejay 1113 MCM) and each tower has two ground wires (EHS 3/8″) [15]. A span length of 120 m between the towers was considered. The TL parameters per unit length were calculated using the Powergui Compute RLC Line Parameters Tool of the software MATLAB/Simulink. The temperatures assumed were 65 °C and 40 °C, for the conductors and the ground wires, respectively. The corresponding sags at midspan are 18.4 m and 7.4 m. The soil was assumed to be homogeneous with a resistivity of 1000 Ωm. The obtained positive-sequence, zero-sequence, and mutual zero-sequence resistance (R), inductance (L), and capacitance (C) are listed in Table 1, which also presents the remaining system data [14]. Typical source impedances were used.

Short-circuit calculations were carried out in MATLAB using symmetrical components and graph theory [16,17]. In the simulations, each TL was modelled as a cascade of equivalent π circuits. The positive- and the negative-sequence equivalent series impedance and shunt admittance were computed, respectively, according to:

$$Z_{\pi i} = \sqrt{\frac{Z_1}{Y_1}} \sin\text{h}\left(\sqrt{Z_1 Y_1}\ell\right) = Z_{C1} \sin\text{h}\left(\gamma_1 \ell\right) \tag{1}$$

$$\frac{Y_{\pi i}}{2} = \frac{1}{Z_{C1}} \tan\text{h}\left(\frac{\gamma_1 \ell}{2}\right) \tag{2}$$

where i is the symmetrical component index (i = 1, 2 for positive- and negative-sequence, respectively), Z_1 is the positive-sequence series impedance per unit length, Y_1 is the positive-sequence shunt admittance per unit length, Z_{C1} is the positive-sequence characteristic impedance, and γ_1 is the positive-sequence propagation constant [18].

Table 1
System parameters.

Transmission lines			
	Positive-sequence	Zero-sequence	Mutual zero-sequence
R (Ω/km)	0.005470	0.344293	0.320361
L (H/km)	0.000453	0.003175	0.001491
C (μF/km)	0.025822	0.009658	−0.000323
Transformers			
	Reactance (%)	Voltage (kV)	Total power (MVA)
T	13.4	500/1000	10 × 2000
T'	13.4	500/1000	10 × 2000
Equivalent source impedances (Ω)			
	Positive-sequence	Zero-sequence	
E	0.0794 + j 4.5493	0.2382 + j 6.8208	
E′	0.8930 + j 17.039	1.7835 + j 16.969	

The zero-sequence equivalent series impedance, mutual impedance, shunt admittance, and mutual admittance were calculated by means of the zero-sequence equivalent π circuit introduced in Ref. [19], given respectively by:

$$Z_{\pi 0} = \frac{1}{2}\left[Z_{Cm2} \sin\text{h}\left(\gamma_{m2}\ell\right) + Z_{Cm1} \sin\text{h}\left(\gamma_{m1}\ell\right)\right] \tag{3}$$

$$Z_{\pi 0m} = \frac{1}{2}\left[Z_{Cm2} \sin\text{h}\left(\gamma_{m2}\ell\right) - Z_{Cm1} \sin\text{h}\left(\gamma_{m1}\ell\right)\right] \tag{4}$$

$$Y_{\pi 0} = \frac{2 \tan\text{h}\left(\frac{\gamma_{m2}\ell}{2}\right)}{Z_{Cm2}} \tag{5}$$

$$Y_{\pi 0m} = \frac{\tan\text{h}\left(\frac{\gamma_{m1}\ell}{2}\right)}{Z_{Cm1}} - \frac{\tan\text{h}\left(\frac{\gamma_{m2}\ell}{2}\right)}{Z_{Cm2}} \tag{6}$$

where

$$\gamma_{m1} = \sqrt{(Z_0 - Z_{0m})(Y_0 + 2Y_{0m})} \tag{7}$$

$$\gamma_{m2} = \sqrt{(Z_0 + Z_{0m})Y_0} \tag{8}$$

$$Z_{Cm1} = \sqrt{\frac{Z_0 - Z_{0m}}{Y_0 + 2Y_{0m}}} \tag{9}$$

$$Z_{Cm2} = \sqrt{\frac{Z_0 + Z_{0m}}{Y_0}} \tag{10}$$

in which Z_0 is the zero-sequence series impedance per unit length, Z_{0m} is the mutual zero-sequence series impedance per unit length, Y_0 is the zero-sequence shunt admittance per unit length, and Y_{0m} is the mutual zero-sequence shunt admittance per unit length.

The configuration of the sequence networks for a SLG fault is illustrated in Fig. 2 and its associated oriented graph is depicted in Fig. 3. Due to the delta connection of the transformers and the zero-sequence equivalent mutual admittance, in order to obtain a single graph for the positive-, negative-, and zero-sequence networks, infinite impedance elements were properly inserted in the corresponding diagrams.