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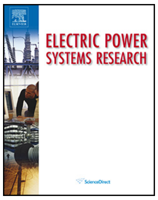

Fault location on transmission lines little longer than half-wavelength

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ABSTRACT

AC transmission lines little longer than half-wavelength have been widely investigated as an alternative for bulk power transmission in power networks where the generation plants are very distant from the load centers. However, studies regarding the performance of fault location methods applied to this type of line have not been done. In this paper, two contributions are presented. First, it is shown that conventional impedance-based fault location methods may fail to correctly identify the fault point even when the line shunt capacitance effect is taken into account. Then, to overcome this drawback, an innovative two-terminal impedance-based fault location algorithm is proposed. The algorithm considers the distributed parameter line model with line shunt capacitances thereby is able to reliably identify and correct erroneous fault point estimations that arise due to atypical operational features of this particular type of transmission line. The performance evaluation of the proposed algorithm is carried out by means of Electromagnetic Transients Program (EMTP) simulations, from which a wide variety of faults in a 1000 kV AC transmission line 2613 km long is analyzed. The obtained results indicate high reliability of the proposed algorithm, which is almost insensitive to the fault characteristics, power system load flow, power factor and line transposition schemes.

1. Introduction

Power systems have evolved from isolated generators feeding their own load to huge interconnected systems spanning entire countries. As a consequence, often load centers are very far from the main generation plants, what has driven researches toward studying unconventional solutions for bulk power transmission over very long distances. Among the feasible solutions, the AC transmission line little longer than half-wavelength (2500 km for 60 Hz)—here refereed as $\lambda/2^+$ transmission line—has shown advantages regarding technical and economical aspects [1–7], mainly for not requiring reactive compensation or intermediate substations between the terminals, providing a point-to-point power transmission and leading to reduced costs and environmental impact when compared to other alternatives [8,9].

The main concepts of the AC power transmission based on half-wave principles were first reported in the USSR in 1939 [10] and, in the 1960s, studies regarding lines with lengths greater than half-wavelength were presented [1,2]. However, at that time, restrictions related to available technology could not be overcome, discouraging further researches concerning this king of line. In recent years, with advances in power transmission technologies, these lines began to be treated as feasible, raising the interest of several utilities over the world. Some researchers believe that $\lambda/2^+$ lines will be put into service in the near future in huge interconnected power systems, such as those of Brazil, Russia, China and even those that connect more than one country. For instance, the use of these lines has been investigated to transmit hydropower from Siberia to South Korea and, in China, it has been analyzed as an alternative to transmit power from Xinjiang, where there is plenty of coal resources and the power is surplus, to the eastern China coastal areas [11].

In the case of Brazil, it is estimated that 63% of its hydroelectric potential is found on the northern region, more specifically on the Amazon River basin, and that less than 1% of such potential has been explored [12]. Concomitantly, the energetic demand in Brazil grows about 4.8% per year, what makes the energy exploration in the northern region a powerful strategy for the country development. In fact, the hydropower plants installed and under study or construction in the Amazon River basin result in an installed power of about 26 GW, which is much greater than the average load of the

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northern Brazil. The intention is to dispose such surplus power to the major load centers in the Northeast and Southeast regions of the country, which are approximately 2600 km far away. In this context, the $\lambda/2^+$ transmission line has shown to be very competitive and, therefore, it is being studied as a feasible solution to perform such power transmission and to interconnect future power plants in the Amazon River basin to the Brazilian power grid [11,6].

Due to their physical extension, transmission lines are frequently exposed to the most adverse environmental conditions, leading to the largest percentage rate of faults among power system components. After the fault clearance, the power system must be restored as fast as possible to reduce outage duration, requiring efficient and reliable fault location algorithms. Usually, fault location methods are classified into three main categories [13]: traveling wave-based methods [14,15], knowledge-based methods [16,17] and impedance-based methods [18–25]. Traveling wave-based methods are considered by many as the most accurate ones, but, as a rule, they need high sampling rates to properly analyze fault-induced transients, requiring more complex and expensive hardware setup. Knowledge-based methods, in turn, use artificial intelligence techniques, such as artificial neural networks, fuzzy-sets theory and expert systems, leading to accurate fault location estimation even for distribution networks in which conventional fault locators usually fail. Nevertheless, the generalization capability of these methods is not always guaranteed, as they must be reconfigured for each new power system, making it difficult to use them in actual systems. On the other hand, impedance-based methods are the most widely used by utilities, since they are at once simple and accurate, requiring low computational effort [13].

Considering impedance-based methods, some of those reported in the literature are based on the lumped line model and ignore the line shunt capacitances in their formulation [18,23–25], what is a valid assumption for short lines. However, as the line length increases, the fault location errors become noticeable and reach intolerable levels for lengths on the order of half-wavelength. In this context, it is known that methods based on the distributed parameter line model, which consider the line shunt capacitance effect, offer high accuracy for long lines [19–22]. Nevertheless, they have been designed, so far, for lines with lengths of about few hundred kilometers, resting no guarantee they will properly locate faults on $\lambda/2^+$ lines, whose operational characteristics are different from those observed in conventional lines [26,8].

Although distance protection schemes have been analyzed for very long lines [27], studies concerning the performance of impedance-based fault locators applied to $\lambda/2^+$ lines have not been reported in the literature. In this paper, two contributions for the $\lambda/2^+$ line research area are presented. First, a performance evaluation of conventional impedance-based fault location methods applied to this particular type of line is presented. It is shown that these methods may fail to correctly identify the fault point on any line longer than a quarter wavelength (about 1250 km for 60 Hz), even when the line shunt capacitance effect is taken into account. As the second contribution, an innovative fault location algorithm suited for this type of line is proposed. It is based on the analysis of variables taken from the formulation of classical impedance-based fault location methods, which take into account the distributed parameter line model with line shunt capacitances. The algorithm uses voltage and current phasors during the fault period, is non-iterative, simple and able to reliably identify and correct erroneous fault point estimations caused by the atypical operational features of lines with lengths greater than a quarter wavelength, as it is the case of the $\lambda/2^+$ transmission line.

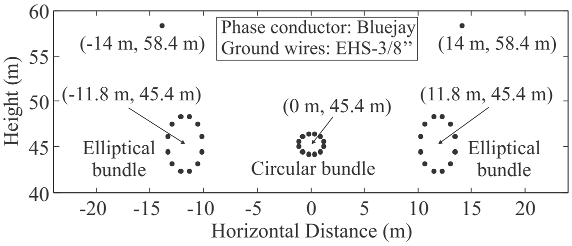

Fig. 1. Transmission line tower structure with 12 conductors per phase and 2 ground wires.

Table 1
Relative position of the conductors in the bundle as proposed in [6].

Conductor	Coordinates (m)	
	Circular bundle	Elliptical bundle
1	(0.31, −1.15)	(0.43, −3.00)
2	(0.84, −0.84)	(1.17, −2.20)
3	(1.15, −0.31)	(1.60, −0.80)
4	(1.15, 0.31)	(1.60, 0.80)
5	(0.84, 0.84)	(1.17, 2.20)
6	(0.31, 1.15)	(0.43, 3.00)
7	(−0.31, 1.15)	(−0.43, 3.00)
8	(−0.84, 0.84)	(−1.17, 2.20)
9	(−1.15, 0.31)	(−1.60, 0.80)
10	(−1.15, −0.31)	(−1.60, −0.80)
11	(−0.84, −0.84)	(−1.17, −2.20)
12	(−0.31, −1.15)	(−0.43, −3.00)

Aiming to highlight the effectiveness of the proposed algorithm, a statistical analysis of fault location errors was carried out using a wide variety of EMTP-simulated data from a 1000 kV transmission line 2613 km long. Cases of the $\lambda/2^+$ line modeled as a fully transposed line and as an actual transposed line were analyzed. The obtained results show that the proposed algorithm provides a very accurate and reliable fault point identification, irrespective to the fault characteristics, power system load flow, power factor and line transposition schemes.

2. Description of the studied power system

The transmission line proposed by Dias et al. [6] is used as a test case in this paper. It was designed to transmit AC power up to 8 GW at rated voltage of 1000 kV through about 2600 km. Two ground wires and a bundle of 12 conductors per phase are used. The transmission line tower structure is shown in Fig. 1 and the relative position of each conductor in each bundle is presented in Table 1. To simulate the transposed line case, 13 transposition

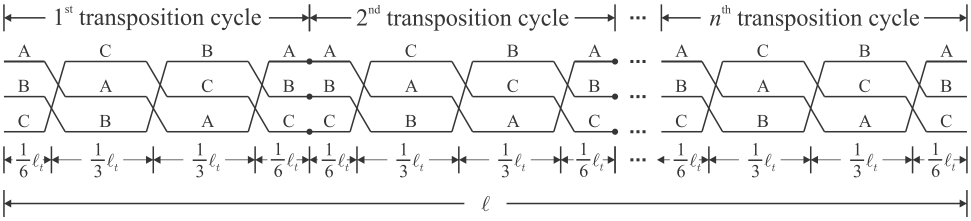

Fig. 2. Transposition scheme used to simulate the transposed line.