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Unsynchronized fault-location technique for two- and three-terminal transmission lines

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ABSTRACT

In this work, a novel fault-locator technique for two- and three-terminal power transmission lines is introduced. Unsynchronized three-phase current and voltage measurements of all line ends are processed for estimating the required synchronization angle/s and the fault location via exploiting the initial conditions of each fault type. To realize this target, the computations of the required synchronization angle/s are initially accomplished independent of the fault location via considering a lumped charging current at the reference terminal which is selected arbitrarily. Consequently, the initial fault location is determined via equating the deduced equations of the positive-sequence voltage at the faulty point from two sides of the faulted segment as a function of the measured data after their correction. The previous obtained fault location is, then, utilized as an input for the next iterative computations, where the distributed line model is used to update the charging current. This process is repeated until the change rate of the obtained fault location becomes negligible. The proposed technique has been examined and assessed under different fault scenarios simulated using MATLAB. The sample results of the assessment are declared and discussed.

1. Introduction

Power transmission system transfers electrical energy from the power plants to the substations near loads. Usually, the electrical power is transferred through overhead transmission lines. Conventional transmission lines have two terminals. Now, the use of three-terminal lines is growing for diverse economical and technical purposes [1]. Three terminal lines usually hold until installing new substation when the loads increase to a certain level [2]. Overhead transmission system suffers from occurrence of various faults. These faults usually are shunt faults triggered by lightning strokes, rain, birds, streamer, or insulators pollution. The malfunction of the transmission system leads to serious influences on highly electrified modern society. Therefore, various protection devices are installed on the transmission lines in order to isolate the faulted line. Also, it is very important to accurately locate the faulty point to quickly accomplish the necessary repair process, thus, reducing operating costs [3–7].

The difficulty of fault-location determination for transmission lines is due to that the measurements at transmission line terminals may be unsynchronized. This reason is related to using fault location algorithms based on two-terminal measurements recorded by the intelligent electronic devices (IEDs) with unsynchronized measurements. Earlier, the single-ended fault location techniques based on the Phasor estimation were used. However, they required necessary assumptions to remove the effect of fault impedance such as considering its value to be zero or purely resistive, or considering that the impedances behind line ends are constant and have known values [8]. Therefore, the synchronized two-terminal measurement-based fault location techniques were used after developing the phasor-measurement units (PMUs) based on the global positioning system (GPS) in the early 1980s [9–14]. In these techniques, the common time reference for recorded measurements was obtained by the GPS signal. However, practically now, the IEDs have been installed on most substations for protection purposes [15] instead of the GPS-based PMUs. Consequently, a synchronization factor ($e^{j\delta}$) is required in order to synchronize the recorded measurements. The angle δ is the required synchronization angle. Also, the procedures of fault location determination for three-terminal lines are more difficult than those of the traditional two-terminal ones due to the outfeed/infeed from the third terminal [16–18]. Consequently, fault location determination based on

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unsynchronized measurements for transmission lines represents a challenge for engineers due to these various problems.

Set of the phasor based-algorithms have been presented for overcoming the aforementioned fault-location problems [19–28]. These algorithms can be categorized from number-of-line-terminals point of view into techniques presented for two-terminal transmission lines [19–23] and others presented for three-terminal transmission lines [24–28].

In Ref. [19], a fault location scheme was developed via equating the equation of the negative- or zero-sequence voltage at the faulty point from two sides as a function of measured currents only using the short-distance line model to locate phase-to-phase or earth faults, respectively. However, this scheme considered that the source impedance's value is constant. In Ref. [20], a fault-location algorithm was presented to find, unknown variables, the fault distance and the synchronization angle (δ). Relationship that combines the unknown variables was based on equating the positive-sequence voltage at the faulty point from two sides as a function of two-end unsynchronized measurements based on the distributed line model. These unknown variables are obtained via the Newton–Raphson method-based iterative calculations. The initial values for these variables are obtained via firstly solving the problem considering the short-distance line model to guarantee the convergence behavior. In Ref. [21], a numerical method was proposed to obtain δ value by a proposed equation exploiting that the estimated fault distance must be a real value only at the actual value of δ. The fault distance was estimated after correcting unsynchronized measurements by equating the positive-sequence voltage from two sides using the distributed line model. However, the estimated fault distance may also be a real value at a false δ value. Hence, three constraints were used to treat multiple-solution conditions and then single out the precise δ. The first constraint is that the estimated fault distance should be less than the total line length at the precise δ. The second constraint is that the fault distance obtained via using positive-sequence variables is very close to that obtained via using negative-sequence variables at the correct δ. The third constraint is that at the correct δ, the calculated fault impedance is almost real value. In Ref. [22], the algorithm is based on obtaining the fault impedance equation as a function of only an unknown variable which is the fault distance where its equation was independent of the δ value. Then, the fault distance is obtained via assuming that the fault impedance is purely resistive. However, this algorithm can not locate the faults associated with a fault impedance having an imaginary part as faults in electrical cables. In Ref. [23], an unsynchronized fault-location method is presented via equating only the magnitudes of the positive-sequence voltages at the faulty point computed form two sides. The equation was solved by assuming that the variations of the voltage magnitudes along the line length were linear. The slopes of the two straight lines were firstly assumed to be equal to that at line terminals. Hence, the precise solution was obtained by an iterative algorithm to update the slope of the two straight lines based on the past fault distance calculated via the intersection point of these two lines.

Other algorithms were suggested to estimate the fault location in three-terminal transmission lines [24–28]. Some of these algorithms used synchronized measurements [24–26] and the others used the unsynchronized data [27,28]. In Ref. [24], the fault distance was estimated as a function of synchronized data measured only at two terminals. However, it is based on a pure resistance assumption for the fault impedance. In Ref. [25], the proposed formula is deduced based on the distributed line model. The suggested formula was solved via an iterative solving procedure. In Ref. [26], a fault-locator algorithm using only negative-sequence circuit was proposed to locate the unbalanced shunt faults. This method used the short-line model. The proposed formula is a function of negative-sequence currents and voltage at all line terminals. However, it is dependent of the negative-sequence impedance magnitude of the source. In Ref. [27], an unsynchronized fault-locator algorithm for two- and three-terminal lines based on equating the voltages at the faulty point from all terminals' directions was introduced. The proposed formula having two unknown variables was derived based on the short line model. The unknown variables were estimated by an iterative solving process. However, the initialization of the calculation process was random based on the probability distribution of fault location. Hence, this process may give rise to a divergent solution. In Ref. [28], an unsynchronized fault-locator method using only the negative-sequence voltages magnitudes at three line ends was proposed using the short line model to locate the unbalanced shunt faults. The faulted section identification and then the fault distance determination were obtained as a function of the ratios between the negative-sequence voltages magnitudes measured at line terminals, line parameters, and negative-sequence reactances behind measuring points. However, this method is sensitive to source reactance variation.

This paper presents an iterative unsynchronized fault-location technique for two- and three-terminal transmission lines. The paper concentrates on unbalanced faults. In the first iteration, the correction of the unsynchronized measurements is initially accomplished via assuming that the charging current is lumped at the reference terminal. Then, the initial fault distance is calculated. In order to cancel the error resulted from this assumption, other iterations are required. In the next iteration, the value of the charging current is updated based on the obtained fault distance from the previous iteration. Then, the synchronization angle and the fault distance values are also updated. This process is repeated until the change of the fault distance becomes insignificant. The proposed synchronization-angle calculation method and the fault-location algorithm are extended to be suitable for three-terminal transmission lines in conjunction with a faulty side identification method independent of the synchronization angle. The proposed algorithms are independent of both the fault and source impedances.

2. Proposed unsynchronized fault-locator scheme for transmission lines

The proposed unsynchronized fault-locator scheme is iterative in order to be adequate to short and long transmission lines. The proposed synchronization-angle calculation method does not need the transmission line parameters in case of short transmission lines via neglecting the charging current. However, it needs the line parameters and the fault distance in case of long transmission lines. Therefore, the algorithm must be iterative. In the first iteration, the synchronization operator ($e^{j\delta}$) is estimated independently of the fault distance whether the line is two or three terminals.

2.1. First iteration

2.1.1. Proposed synchronization-angle calculation technique

As aforementioned before, a synchronization factor ($e^{j\delta}$) is utilized to synchronize the recorded measurements. This factor should be applied on the phasors measured on all terminals except that arbitrarily considered the reference. The measured phasors at these selected terminals (V_j and I_j) are corrected via applying the synchronization factor as in Eq. (1). If the start time of the recording phasors at j terminal lags the reference by an angle Ø, the required synchronization angle δ must compensate for this angle Ø in the counter