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An adaptive fault location algorithm for power system networks based on synchrophasor measurements

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A B S T R A C T

This paper presents an adaptive fault location algorithm for power system networks based on synchronized phasor measurements obtained by Phasor Measurement Units (PMUs). To enhance its accuracy, the proposed algorithm is made to be independent of any data that shall be provided by the electric utility. The proposed algorithm requires three different sets of pre-fault voltage and current phasor measurements at both terminals of the faulty line to be obtained through PMUs. The three sets of local PMU measurements at each terminal are used for online calculation of the respective Thevenin's equivalent (TE). Using the method of multiple measurements with linear regression (MMLR), the three sets of PMU measurements are also employed for online calculation of the transmission line parameters. Online determination of the TEs and line parameters ensures avoiding any possible mismatch with the actual parameters due to system loading and other environmental conditions. The proposed method is applied to a 115 kV system selected from the Saudi Electricity Company (SEC) network. The simulation results obtained using PSCAD/EMTDC and MATLABreveal that the proposed algorithm is highly accurate and independent of fault type, fault location, fault resistance, fault inception angle and pre-fault loading.

I.. Introduction

Accurate and swift fault location on a power network can expedite repair of faulted components, speed-up power restoration and thus enhance power system reliability and availability. Rapid restoration of service could reduce customer complaints, outage time, loss of revenue and crew repair expense [1–10].

Phasor Measurement Units (PMUs) using synchronization signals from the GPS satellite system have recently evolved into mature tools and are now being utilized in the field of fault location. Recognizing the importance of the fault location function for electric power utilities, several PMU-based fault location algorithms have been proposed in the past literature. Some of them are based on using both synchronized current and voltage phasors at the two ends of a line [1–6,11]. Other algorithms are developed based on utilizing only voltage phasor measurements [12,13] to avoid the consequences of inappropriate operation of current transformers due to overvoltage and transient state of power network during fault period.

A fault detection/location algorithm that considers arcing faults is proposed in [14,15]. Fault location schemes for aged power cables [7], two- and three-terminal transmission lines [13], double-circuit transmission lines [16,17], overhead line combined with an underground power cable [9] and transposed/untransposed transmission lines [10] are also reported. To determine the fault location, these classical algorithms need the line impedance parameters and the system TEs at the line terminals to be known. Such parameters are assumed to be provided by the electric utility.

To improve the fault location accuracy of the classical PMU-based fault location algorithms, various adaptive fault location algorithms have been developed [10,18–26]. The idea of adaptive fault location on transmission lines boils down to proper estimation of line parameters and system impedance. The adaptive fault location algorithms reported in the literature either utilize voltage and current phasor measurements at both ends of a line for online calculation of the transmission line parameters or do not require the line parameters at all. These algorithms, however, still require the system TEs at the line terminals to be provided by the electric utility. In addition, the methods used in [19] and [25] are iterative and based on a single set of pre-fault and fault measurements while the algorithm presented in [26] is limited to single phase to ground faults on short lines where shunt capacitance of the line is not considered. However, the proposed algorithm is non-iterative and uses multiple pre-fault measurements to determine the line parameters and, therefore, it is more immune to random noise that might exist in such measurements. Moreover, the proposed algorithm is suitable for all fault types and takes the shunt capacitance of the line into consideration which makes it suitable to locate faults on long lines as well.

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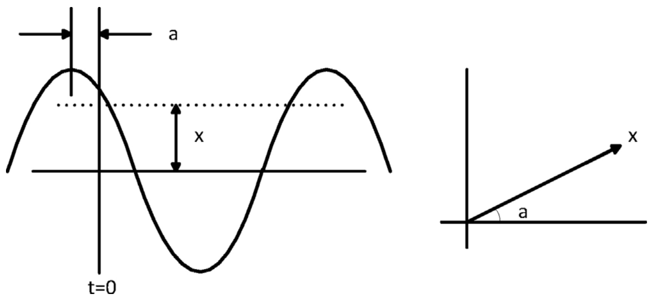

Fig. 1. Phasor representation of a sinusoidal waveform.

This paper extends the work presented in [20] by proposing an adaptive fault location algorithm that depends only on the synchronized phasor measurements obtained by PMUs and does not require any data to be provided by the electric utility. Data provided by the electric utility is usually ideal and does not reflect the effect of the surrounding environment and the practical operating conditions of the power system. Avoiding such source of error in fault location algorithms will, therefore, enhances the fault location accuracy. The proposed PMU-based fault location algorithm requires three different sets of pre-fault voltage and current phasor measurements at both terminals of the faulty line. The three sets of local PMU measurements at each terminal are used for online calculation of the respective TE. This enables us represent the power system pre-fault network with a reduced two-terminal equivalent system. The PMU measurements are also utilized, using the method of MMLR, for online calculation of the transmission line parameters. Moreover, the suddenly changed voltages and currents are utilized to obtain suddenly changed positive voltage and current components to solve the system's impedance at the fault time.

The rest of this paper is organized as follows. Section II introduces the PMUs. Section III describes how TE is determined for a node in a power system using local PMU measurements at that node. Calculation of transmission line parameters from PMU voltage and current measurements, using the method of MMLR, is discussed in Section IV. The proposed adaptive fault location algorithm is then explained in Section V. Simulation results obtained using both PSCAD/EMTDC and MATLAB are presented in Section VI followed by the conclusions.

II Phasor measurement units (PMUs)

Let us consider the steady-state waveform of a nominal power frequency signal as shown in Fig. 1. If the waveform observation starts at the instant $t = 0$, the steady-state waveform may be represented by a complex number with a magnitude equal to the *rms* value of the signal and with a phase angle equal to the angle a

In a digital measuring system, samples of the waveform for one (nominal) period are collected, starting at $t = 0$, and then the fundamental frequency component of the discrete Fourier transform (DFT) is calculated according to the relation:

$$X = \frac{\sqrt{2}}{N}\sum_{k=1}^{N} x_k e^{-j2\pi k/N} \tag{1}$$

where N is the total number of samples in one period, X is the phasor, and x_k is the waveform samples. This definition of the phasor has the merit that it uses a number of samples N of the waveform, and is the correct representation of the fundamental frequency component, when other transient components are present. Once the phasors (X_a, X_b and X_c) for the three phases are computed, a positive, negative and zero sequence phasors are obtained using the following transformation [27–29]:

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{2}$$

with $\alpha = e^{j2\pi/3}$.

When several voltages and currents in a power system are measured and converted to phasors in this fashion, they are on a common reference if they are sampled at precisely the same instant. This is easy to achieve in a substation, where the common sampling clock pulses can be distributed to all the measuring systems. However, to measure common-reference phasors in substations separated from each other by long distances, the task of synchronizing the sampling clocks is not a trivial one. Only with the advent of the global positioning system (GPS) satellite transmissions, the PMU technology has now reached a stagewhereby we can synchronize the sampling processes in distant substations economically and with an error of less than 1 μs. This error corresponds to 0.021° for a 60 Hz system and 0.081° for a 50 Hz system and is certainly more accurate than any presently conceived application would demand [26,29].

III Online Thevenin's equivalent using local PMU measurements

One important aspect of adaptive fault location is concerned with online determination of system TEs at the terminals of the line under study. Among their various potential applications in power systems, PMUs can be utilized for such purpose. This is possible with PMUs as voltage and current phasors are provided at high rates of one measurement per cycle but not possible with the conventional SCADA systems that are too slow. Three consecutive voltage and current (V, I) measurements are used to determine an exact TEat the two line terminals. It is essential to have the three sets of phasor measurements be referred to the same reference. As detailed in [30], from the first and second sets of voltage and current measurements, the following equation can be written:

$$\left(r + \frac{P_1 - P_2}{I_1^2 - I_2^2}\right)^2 + \left(r + \frac{Q_1 - Q_2}{I_1^2 - I_2^2}\right)^2 = \frac{V_2^2 - V_1^2}{I_1^2 - I_2^2} + \left(\frac{P_1 - P_2}{I_1^2 - I_2^2}\right)^2 + \left(\frac{Q_1 - Q_2}{I_1^2 - I_2^2}\right)^2 \tag{3}$$

r and x are the resistance and the reactance of the Thevenin impedance (Z_{th}). P and Q are the real and reactive powers. Eq. (3) represents a circle in the impedance plane defining the locus for Z_{th} that satisfies the two measurements but it does not define a specific value for Z_{th}. Therefore, a third measurement is required which can be used with either the first or the second measurement in the same way to produce another circle. Among the two intersection points of the two circles, we apply the selection criteria detailed in [30] to determine the equivalent impedance Z_{th}. The equivalent Thevenin voltage (E_{th}) at a node is found knowing Z_{th} and the local V and I measurements at that node as shown in Eq. (4):

$$V = E_{th} + Z_{th} \times I \tag{4}$$

IV Online measurement of transmission line parameter using PMU

The other important aspect of adaptive fault location is concerned with online determination of series resistance, series reactance and shunt admittance of the line under study. PMUs