PMU-based Fault Localization in Distribution Networks

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Abstract. In this paper, a fault localization method for distribution networks, based on PMU measurements and compensation theory, is presented. Voltage and current phasors of pre-fault and post-fault are used to determine the faulted bus in the network. The method was verified using the Real Time Digital Simulator (RTDS) with the simulation of real electric power system.

Keywords: Fault Localization, Distribution Network, Real Time Digital Simulator.

1 Introduction

In today's world, all industrial and economic branches are increasingly dependent on electric power. However, the continuity of electric power supply is often compromised due to faults or short circuits caused by either natural conditions (lightning strikes, extreme wind, snow etc.), poor vegetation management, animal contact or simply as a consequence of the aging equipment. Therefore, the faults must be detected and localized quickly and accurately to ensure swift restoration and minimize the time of customers not being supplied.

2 State-of-the-Art

Fault localization is theoretically well-known and developed field with variety of applicable methods [1], which can be roughly divided into three groups.

The impedance based methods are characterized by low complexity and offer a fairly accurate performance in case of the grounded systems. Their main drawback is that they often rely on the iterative processes to produce results or even yield multiple possible solutions [2], [3].

The second category of methods relies on the use of the travelling waves. A travelling wave is a high-frequency electro-magnetic pulse due to unexpected change of the current at the faulted point which propagates away from the fault. Therefore, costly measurement equipment with high-sampling frequency (order of MHz or higher) and precise time synchronization is needed to detect wavefronts. Furthermore, most of those methods were developed for transmission networks that are more homogenous in terms of line parameters and far less branched than distribution networks. Some representative traveling wave techniques and their application are provided in [4]–[6]. The last category of methods is based on pattern recognition and are also known as knowledge-based methods [7]–[9]. They are based on a large training database that contains reference fault cases for a given network. Even though those methods generally do not require complicated formulation, it is worth noting that they need to be retrained in case of any modification to the existing system.

It is evident that each group of methods have their pros and cons in terms of accuracy and complexity. Given that the phasor measurement units (PMUs) are becoming increasingly adopted in the context of smart grids, a fault localization method relying on PMU data is used in this paper.

3 Methodology

The method similar to the one proposed in [10] was implemented for the purposes of this paper and is explained hereinafter. To produce credible results, a real electric system was simulated with electro-magnetic transient (EMT) based simulation tool RTDS, which is currently the closest approximation (to the real-life conditions) achievable with simulations.

The main idea of the algorithm is to estimate fault location with a minimal number of PMU devices using their respective voltage and current phasors. Optimal observability of the feeder, when using just two PMUs, is achieved when one PMU is installed at the beginning of the feeder (substation) and the other is placed at the end of the feeder. Both PMUs stream information about frequency and Rate-of-Change-of-Frequency (RoCoF) and time-tagged phasors for phase voltages and currents (all three phases), that serve as a basis for the operation of the algorithm. A criterion for identifying the fault location is finding a bus with minimal difference in voltage, as seen from both PMUs. To achieve this, each bus voltage needs to be calculated twice (once with each PMU data).

For a detailed explanation of the method some indexes need to be introduced. The total number of busses on the main feeder is n, so each bus is assigned its respective position as a subscript. Counting starts at the beginning of the feeder, where the first PMU is installed and ends with the last, n-th bus, where the second PMU is installed. Bus subscripts are also used to designate other quantities referring to that particular bus, for instance voltages and currents measured from the first PMU will be called U_1 and I_1, whereas voltages and currents measured from the second PMU are denoted as U_n and I_n, respectively. We already mentioned that the voltage of each bus is calculated twice, therefore superscript needs to be introduced to avoid ambiguities. When using data from the first PMU and applying the propagation model from 1-st toward n-th bus the quantaties are denoted by superscript f (forward propagation). In the case of the second PMU the backward propagation is denoted with b superscript. Knowledge of current and voltage from the first PMU (at the beginning of the line) and information about line parameters of first line (marked Z_1 in Fig. **1**) enables us to calculate the voltage and current of the second bus. If there is a load connected to that bus, we need to subtract load current from current flowing into a bus to get the value of current flowing into the next line segment. This procedure can then be repeated until we get to the end of the feeder and voltage of each network bus, as seen from the first PMU, is known. A similar process is repeated for the second PMU, with the only difference being, that this time we start with the voltage and current of the last bus (obtained by the second PMU) and that load currents need to be added (instead of subtracted) to bus currents, to get values of currents flowing into next segment.

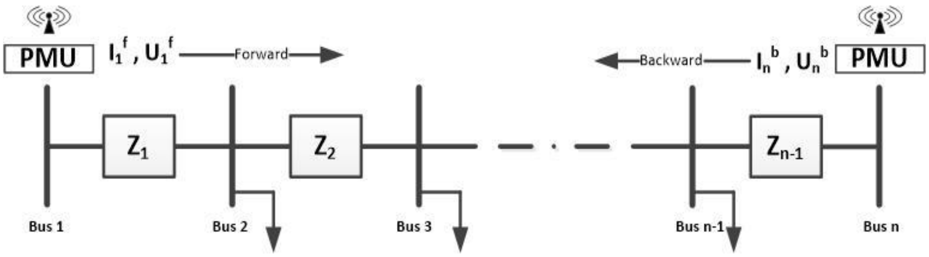

Fig. 1. Forward and backward calculation of bus voltages

In the pre-fault condition, forward and backward voltages in each bus should be the same and therefore their difference equal to zero. This condition changes however with the introduction of a fault. Let's assume that the fault occurs at bus j. Voltages and currents from the first PMU will be propagated correctly up to this bus (meaning that voltages $U_1^f, U_2^f, \dots U_j^f$ will still be correctly calculated), but since we do not take fault current into account, the calculated voltages for the next bus, and all subsequent busses, will be wrong (meaning $U_{j+1}^f, U_{j+2}^f, \dots, U_n^f$ will be incorrect values). Similar observation can be done for the second PMU. Again, voltages and currents will be correctly propagated up to j-th bus ($U_n^b, U_{n-1}^b, \dots, U_j^b$- correct values), but voltages for subsequent busses will be wrong ($U_{j-1}^b, U_{j-2}^b, \dots U_1^b$ will be incorrect values).

It is evident, that voltages are correctly calculated from both sides only for the bus, where the fault occurred. Therefore we can expect the difference between backward and forward voltage to reach its minimum in a faulted bus, which can be formulated as:

$$bus_{faulted} = \text{index}\left(\min_k \Delta U_k^{b-f}\right),$$

where

$$\Delta U_k^{b-f} = \left|\Delta U_k^b - \Delta U_k^f\right|, \qquad \forall k, \qquad k \in \{1,2,\dots,n\},$$

and

$$\Delta U_k^f = U_k^{f,postfault} - U_k^{f,prefault},$$
$$\Delta U_k^b = U_k^{b,postfault} - U_k^{b,prefault}.$$

Note that ΔU_k^{b-f} would have almost identical value, have we decided to only use post-fault measurements of PMUs, since the following condition holds true for pre-fault:

$$U_k^{b,prefault} - U_k^{f,prefault} \cong 0, \forall k.$$

The reason for including the pre-fault measurement is, that current and voltage transformers can introduce some error in measurements which is stable over a short period of time. With the subtraction of pre-fault and post-fault measurements, we can achieve to cancel this error out.

It is worth pointing out that with this method only the busses of the feeder can be identified as a fault location. This means that when a fault happens between two busses, a bus that is electrically closer to the fault location will be identified as faulted, however the actual position on the line will not be calculated.

4 Results

Performance of the method was tested on the 14-bus MV system for various fault locations and fault types. The resistance of the fault was set to 1Ω for all scenarios. On the x-axis of the diagrams busses of the main feeder are presented, whereas their corresponding voltage differences (introduced in section 3 and labelled as ΔU_k^{b-f}) are given on the y-axis of the diagram.

The performance of the method for three different types of fault is presented in Fig. **2**.

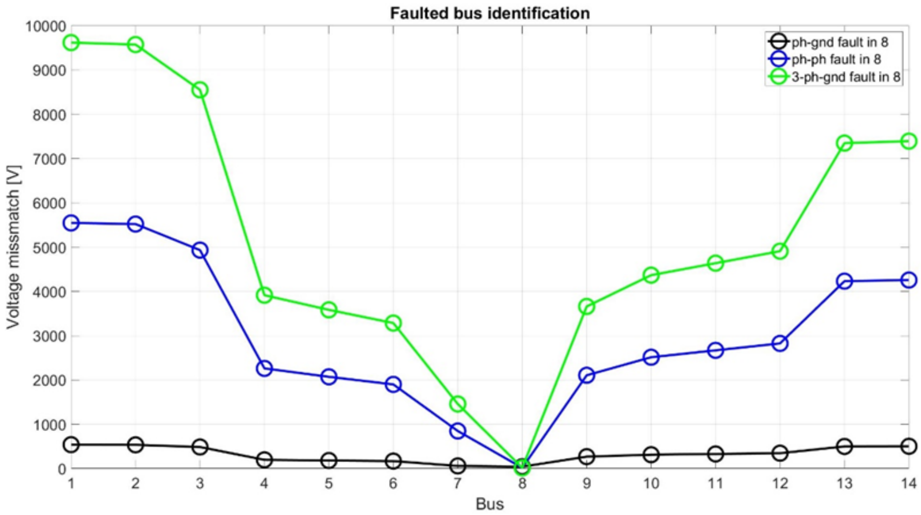

Fig. 2. Results for phase to ground, phase to phase and three phase to ground fault.

In all three cases, bus 8 was correctly identified as the faulted one. However, difference in magnitude of voltage mismatch can be observed between different fault scenarios. As already explained in Section 3, the voltage mismatch (voltage difference as seen from two PMUs) of a certain bus is a consequence of not involving fault current in post-fault analysis. Therefore it comes to no surprise, that voltage mismatches are much higher in cases of 3-phase to ground and phase-phase faults, as the fault currents of those events are much higher than in case of a single phase-ground fault.

Performance of the method for three different fault locations is presented in Figure3. Again the method correctly identified the faulted bus for all three cases.

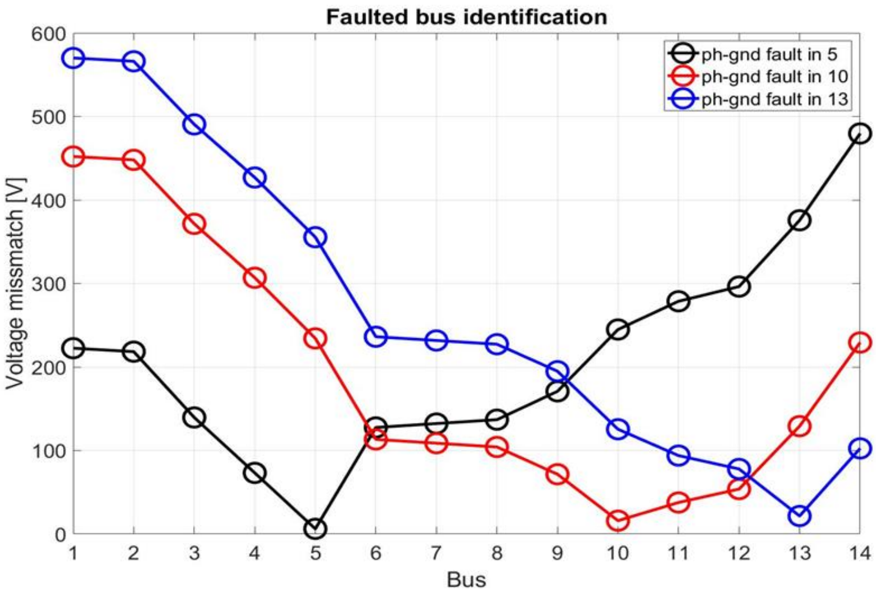

Fig. 3. Results for phase to ground fault in 3 different busses.

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