Electrical Power and Energy Systems 101 (2018) 234–242

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Fast accurate fault location on transmission system utilizing wide-area unsynchronized measurements

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ARTICLE INFO

Keywords:
Bus impedance matrix
Complex analysis
Fault location
Intelligent electronic device (IED)
Linear least squares estimation
Wide-area measurements

ABSTRACT

This article presents a closed-form solution for transmission line fault location without the need for GPS-synchronized sampling of wide-area measurements. Unsynchronized measurements recorded by sparse intelligent electronic devices (IEDs) across the grid are gathered and bus impedance matrix is utilized to relate the measurements to fault location by nonlinear complex functions. A linear reformulation of the problem allows for integrating unsynchronized voltage and current measurements, together with two auxiliary variables, into a linear least-squares problem. Schur-Banachiewicz inversion formula is next utilized to obtain a closed-form solution for fault location. The distributed parameter model of the line is considered and the method identifies the faulted line and locates the fault along it regardless of fault type and resistance. Furthermore, in contrast to previous methods, the proposed method on the one hand obviates the need for GPS-synchronized sampling, and on the other hand avoids iterative procedures. Extensive time-domain simulations for the WSCC 9-bus and a 22-bus subnetwork of the IEEE 118-bus test systems confirm the effectiveness of the method for different faults across the grid.

1. Introduction

Transmission grids are continuously subject to faults due to vast geographical spread of transmission lines. An accurate and reliable method for fault location is therefore crucial to transmission line restoration [1]. Emerging intelligent electronic devices [2] in substations as well as infrastructure and protocols for communication between substations [3] make it possible to integrate voltage and current waveforms recorded across an area. These integrated measurements lend themselves to many wide-area applications in power systems, including fault location [4].

Utilizing fundamental-frequency component of voltage and current waveforms, IEDs are apt to fault location and identification. Generally, impedance-based methods for fault location can be classified into single-end [5–8], double-end [9–21] and wide-area [22–36] methods, according to available measurements. Characteristics of these algorithms in terms of required measurements (single-end, double-end, wide-area), the need for GPS signal, tolerance of an IED loss, sensitivity to fault resistance and/or unreliable network parameters, and the need for iterations are summarized in Table 1. As such, the contribution of the proposed algorithm over previous algorithms can be distinguished.

Being simple yet inaccurate, single-end methods [5–8] use local voltage and current measurements of one end of the line. Among the sources of inaccuracy, the impact of infeed fault current into fault resistance and use of unreliable zero-sequence parameters of the line are more pronounced. Double-end methods use either synchronized or unsynchronized measurements from both line terminals. GPS-synchronized measurements [37] are apt to this problem as circuit equations grow linear [16–21] and can therefore be solved in closed form. Unsynchronized measurements have the advantage of avoiding global positioning system (GPS) signal for synchronized sampling, and therefore obviate the concern over GPS signal loss (GSL) [38] and synchronization errors [39]. On the one hand, double-end algorithms that use unsynchronized measurements lead to nonlinear equations, which cannot be solved in closed-form [9–15]. Double-end methods, on the other hand, require both line terminals to be equipped with measurements as well as a communication link between them, which may not be the case for many transmission lines.

Wide-area algorithms for fault location use two or more measurements, which are not necessarily taken from the faulted line terminals. Features of different wide-area algorithms and their differences are presented in Table 1.

This article presents a closed-form solution for fault location on transmission lines utilizing wide-area unsynchronized voltage and current measurements. One the one hand, in contrast to previous PMU-based methods, GPS signal loss and synchronization errors do not influence the proposed method. Relying too much on synchronized sampling jeopardizes the adopted algorithms based on PMUs, once the

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https://doi.org/10.1016/j.ijepes.2018.03.009
Received 9 January 2018; Received in revised form 24 February 2018; Accepted 6 March 2018

Table 1
Contribution of the proposed method over previous algorithms.

Feature	Method					
	[5–8]	[9–15]	[16–21]	[22–26]	[27,28]	[29]
Single-End	Yes	No	No	No	No	No
Double-End	No	Yes	Yes	No	No	No
Wide-Area	No	No	No	Yes	Yes	Yes
Need GPS	No	No	Yes	Yes	Yes	No
Loss of an IED	Intol.	Intol.	Intol.	Tol.	Inol.	Tol.
Sensitive	Yes	No	No	No	No	No
Iterative	Yes	Yes	No	No	No	Yes

Feature	Method					
	[30]	[31,32]	[33,34]	[35]	[36]	Proposed
Single-End	No	No	No	No	Yes	No
Double-End	No	No	No	No	No	No
Wide-Area	Yes	Yes	Yes	Yes	No	Yes
Need GPS	No	Yes	No	Yes	No	No
Loss of an IED	Tol.	Intol.	Tol.	Tol.	Intol.	Tol.
Sensitive	No	No	No	Yes	No	No
Iterative	Yes	No	Yes	Yes	No	No

GPS signal is lost or imperfect synchronization arises. On the other hand, as opposed to previous methods which use unsynchronized measurements, the concern over convergence is resolved by avoiding iterations.

Modified bus impedance matrix of the network is utilized to express measured voltage and currents across the grid in terms of fault location and positive-sequence component of total fault current. Two auxiliary functions of fault current and location, as well as unknown phase-angles of different measurements are rearranged for a linear least-squares problem. The auxiliary nonlinear functions of fault location are next obtained in closed form, thanks to Schur-Banachiewicz inversion formula [40]. In the case of unknown faulted line, a matching index is introduced to identify the faulted line using the same wide-area unsynchronized voltage and current measurements.

The rest of this article is organized as follows. Section 2 provides a nonlinear formulation for fault location by unsynchronized measurements. Section 3 presents a rearrangement of this formulation to form a linear LS estimation, which will be solved in closed form. Section 4 describes the process of identifying the faulted line by the unsynchronized measurements. Evaluation studies are presented in Section 5, followed by conclusions in Section 6.

2. Nonlinear least-squares formulation

2.1. Modeling unsynchronized voltage measurements

Similar to short-circuit studies in power systems [41], superposition theorem helps express any bus voltage following a fault in terms of bus impedance matrix. However, as the fault occurs along a transmission line, a fictitious bus at fault location, i.e. bus f, should be defined as shown in Fig. 1. Fig. 1(a) shows a single-line-to-ground along line i-j at point f. Fig. 1(b) depicts the equivalent positive-sequence circuit model of the faulted network, where fault point is included as fictitious bus f. Moreover, the current source represents positive-sequence fault current at point f due to fault. To express the relation between pre- and post-fault voltages at bus p, the superposition principle is applied to Fig. 1(b) as follows [41].

$$\boldsymbol{V}_p^{post} = \boldsymbol{V}_p^{pre} - \widehat{\boldsymbol{Z}}_{pf}\boldsymbol{I}_f \tag{1}$$

where $\widehat{\boldsymbol{Z}}_{pf}$, given below, is the p-f element of the modified bus-impedance matrix that includes fictitious bus f [31].

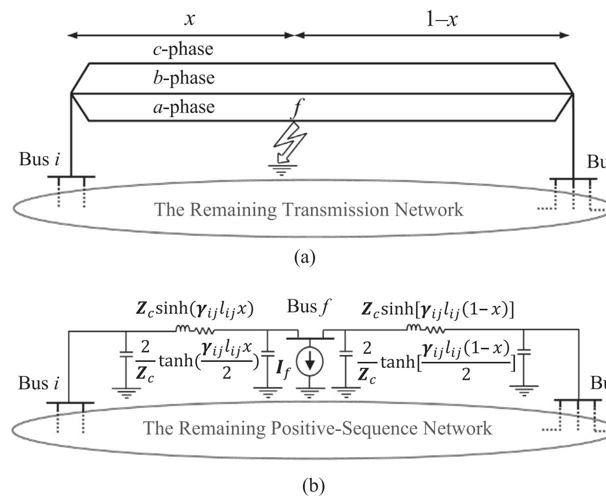

Fig. 1. Faulted network (a) three-phase representation and (b) positive-sequence circuit model.

$$\widehat{\boldsymbol{Z}}_{pf} = \frac{\dfrac{\boldsymbol{Z}_{ip}}{\sinh(\boldsymbol{\gamma}_{ij}l_{ij}x)} + \dfrac{\boldsymbol{Z}_{jp}}{\sinh(\boldsymbol{\gamma}_{ij}l_{ij}(1-x))}}{\dfrac{1}{\sinh(\boldsymbol{\gamma}_{ij}l_{ij}x)} + \dfrac{1}{\sinh(\boldsymbol{\gamma}_{ij}l_{ij}(1-x))} + \tanh\left(\dfrac{\boldsymbol{\gamma}_{ij}l_{ij}}{2}x\right) + \tanh\left(\dfrac{\boldsymbol{\gamma}_{ij}l_{ij}}{2}(1-x)\right)} \tag{2}$$

where $\boldsymbol{Z}_{ip}$ and $\boldsymbol{Z}_{jp}$ are the i-p and j-p entries of the original bus impedance matrix of the network, respectively. Rearranging (1) and considering the unknown phase-angle of unsynchronized measurement at bus p, we have

$$|\Delta\boldsymbol{V}_p|e^{j\delta_p} = \widehat{\boldsymbol{Z}}_{pf}(x)\boldsymbol{I}_f \tag{3}$$

where δ_p is the phase angle of $\Delta\boldsymbol{V}_p$. It is evident that (3) presents a nonlinear relationship between measured voltage magnitude and fault location.

2.2. Modeling unsynchronized current measurements

Besides bus voltages, IEDs record fault currents following a fault. To take unsynchronized current measurements into account, they should be expressed in terms of fault location (x). Since any voltage at either side of a line can be expressed by (3), modified bus impedance matrix is utilized again to express fault current through line p–l as [30]

$$\Delta\boldsymbol{I}_{pl}e^{j\delta_p} = [\boldsymbol{A}_{pl}\widehat{\boldsymbol{Z}}_{pf}(x) + \boldsymbol{B}_{pl}\widehat{\boldsymbol{Z}}_{lf}(x)]\boldsymbol{I}_f \tag{4}$$

where phase angle of $\boldsymbol{\Delta I}_{pl}$ is relative to $\Delta\boldsymbol{V}_p$, and hence known. A_{pl} and B_{pl} for healthy line p–l is obtained by KVL and KCL equations for this line as [30]

$$\boldsymbol{A}_{pl} = \frac{1}{\boldsymbol{Z}_{c,pl}}\left(\tanh\left(\frac{\boldsymbol{\gamma}_{pl}l_{pl}}{2}\right) + \frac{1}{\sinh(\boldsymbol{\gamma}_{pl}l_{pl})}\right) \tag{5}$$

$$\boldsymbol{B}_{pl} = \frac{-1}{\boldsymbol{Z}_{c,pl}\sinh(\boldsymbol{\gamma}_{pl}l_{pl})} \tag{6}$$

where $\boldsymbol{Z}_{c,pl}$ and $\boldsymbol{\gamma}_{pl}$ are characteristic impedance and propagation constant of line p-l, respectively [41]. To emphasize the utilization of unsynchronized measurements, and elaborate (1), (3) and (4), phasor diagrams of voltages and currents are shown in Figs. 2 and 3. Fig. 2 demonstrates how $\Delta\boldsymbol{V}_p$ in (3) is calculated from pre- and post-fault voltages. It should be noted that pre- and post-fault voltages are measured locally at bus p and therefore their relative phase angle are known without the need for GPS signal. Moreover if the same IED is used to measure pre- and post-fault currents, the phase angle of $\Delta\boldsymbol{I}_{pl}$ with respect to $\Delta\boldsymbol{V}_p$ is known without the need for GPS signal. Finally, Fig. 3